DOCUMENT RESUME

ED 071 C87 SE 015 524

TITLE Project Physics Reader 2, Motion in the Heavens.
INSTITUTION Harvard Univ., Cambridge, Mass. Harvard Project Physics.
SPONS AGENCY Office of Education (DHEW), Washington, D.C. Bureau of Research.
BUREAU NO BR-5-1038
PUB DATE 68
CONTRACT OEC-5-10-058
NOTE 233p.; Authorized Interim Version

EDRS PRICE MF-$0.65 HC-$9.87
DESCRIPTORS Astronomy; Instructional Materials; *Motion; *Physics; Science Fiction; Science Materials; Secondary Grades; *Secondary School Science; *Space; *Supplementary Reading Materials
IDENTIFIERS Harvard Project Physics

ABSTRACT

As a supplement to Project Physics Unit 2, specially selected articles are presented in this reader for student browsing. Eight excerpts are given under headings: the starry messenger, Newton and the principia, an appreciation of the earth, space the unconquerable, "Is there intelligent life beyond the earth?," the life story of a galaxy, expansion of the universe, and Dyson sphere. Seven book passages are included under the headings of the black cloud, roll call, a night at the observatory, Kepler's celestial music, universal gravitation, a table of stars within twenty-two light years that could have habitable planets, and three poetic fragments about astronomy. The remaining articles include a preface to the books of the revolutions, Kepler, Kepler on Mars, laws of motion and proposition one, garden of Epicurus, a search for life on earth at Kilometer resolution, the boy who redeemed his father's name, great comet of 1965, gravity experiments, unidentified flying objects, and negative mass. Illustrations for explanation purposes are provided. The work of Harvard Project Physics has been financially supported by: the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education, and Harvard University. (CC)

Project Physics **Reader**

An Introduction to Physics

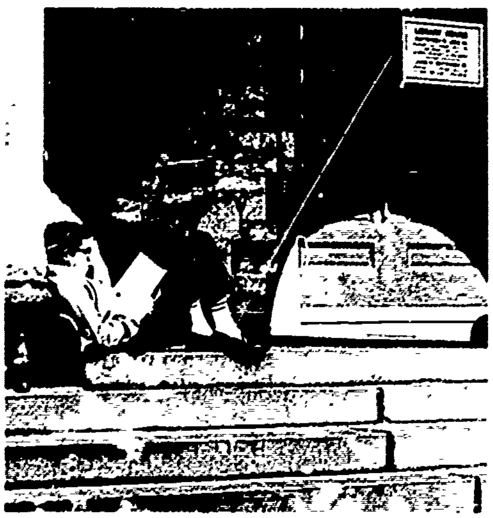
Motion in the Heavens

Project Physics **Reader**

An Introduction to Physics 2 Motion in the Heavens

Authorized Interim Version 1968-69

Distributed by Holt, Rinehart and Winston, Inc., New York • Toronto



This is not a physics textbook. Rather, it is a physics reader, a collection of some of the best articles and book passages on physics. A few are on historic events in science, others contain some particularly memorable description of what physicists do; still others deal with philosophy of science, or with the impact of scientific thought on the imagination of the artist.

There are old and new classics, and also some little-known publications; many have been suggested for inclusion because some teacher or physicist remembered an article with particular fondness. The majority of articles is not drawn from scientific papers of historic importance themselves, because material from many of these is readily available, either as quotations in the Project Physics text or in special collections.

This collection is meant for your browsing. If you follow your own reading interests, chances are good that you will find here many pages that convey the joy these authors have in their work and the excitement of their ideas. If you want to follow up on interesting excerpts, the source list at the end of the reader will guide you for further reading.

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In this introductory chapter to his science fiction novel, the noted astronomer Fred Hoyle gives a realistic picture of what goes on within an astronomy laboratory. The emphasis is on experimental astronomy.

1 The Black Cloud

Fred Hoyle

1957

Opening Scenes

It was eight o'clock along the Greenwich meridian. In England the wintry sun of 7th January, 1964, was just rising. Throughout the length and breadth of the land people were shivering in ill-heated houses as they read the morning papers, ate their breakfasts, and grumbled about the weather, which, truth to tell, had been appalling of late.

The Greenwich meridian southward passes through western France, over the snow-covered Pyrenees and through the eastern corner of Spain. The line then sweeps to the west of the Balearic Islands, where wise people from the north were spending winter holidays—on a beach in Minorca a laughing party might have been seen returning from an early morning bathe. And so to North Africa and the Sahara.

The primary meridian then swings towards the equator through French Sudan, Ashanti, and the Gold Coast, where new aluminium plants were going up along the Volta River. Thence into a vast stretch of ocean, unbroken until Antarctica is reached. Expeditions from a dozen nations were rubbing elbows with each other there.

All the land to the east of this line, as far as New Zealand, was turned towards the Sun. In Australia, evening was approaching. Long shadows were cast across the cricket ground at Sydney. The last overs of the day were being bowled in a match between New South Wales and Queens-land. In Java, fishermen were busying themselves in preparation for the coming night's work.

Over much of the huge expanse of the Pacific, over America, and over the Atlantic it was night. It was three a.m. in New York. The city was blazing with light, and there was still a good deal of traffic in spite of recent snow and a cold wind from the north-west. And nowhere on the Earth at that moment was there more activity than in Los Angeles. The evening was still young there, twelve o'clock: the boulevards were crowded, cars raced along the freeways, restaurants were still pretty full.

A hundred and twenty miles to the south the astronomers on Mount Palomar had already begun their night's work. But although the night was clear and stars were sparkling from horizon to zenith, conditions from the point of view of the professional astronomer were poor, the 'seeing' was bad—there was too much wind at high levels. So nobody was sorry to down tools for the midnight snack. Earlier in the evening, when the outlook for the night already looked pretty dubious, they had agreed to meet in the dome of the 48-inch Schmidt.

Paul Rogers walked the four hundred yards or so from the 200-inch telescope to the Schmidt, only to find Bert Emerson was already at work on a bowl of soup. Andy and Jim, the night assistants, were busy at the cooking stove.

"Sorry I got started," said Emerson, "but it looks as though tonight's going to be a complete write-off."

Emerson was working on a special survey of the sky, and only good observing conditions were suitable for his work.

"Bert, you're a lucky fellow. It looks as though you're going to get another early night."

"I'll keep on for another hour or so. Then if there's no improvement I'll turn in."

"Soup, bread and jam, sardines, and coffee," said Andy. "What'll you have?"

"A bowl of soup and cup of coffee, thanks," said Rogers.

"What're you going to do on the 200-inch? Use the jiggle camera?"

"Yes, I can get along tonight pretty well. There's several transfers that I want to get done."

They were interrupted by Knut Jensen, who had walked the somewhat greater distance from the 18-inch Schmidt.

He was greeted by Emerson.

"Hello, Knut, there's soup, bread and jam, sardines, and Andy's coffee."

"I think I'll start with soup and sardines, please."

The young Norwegian, who was a bit of a leg-puller, took a bowl of cream of tomato, and proceeded to empty half a dozen sardines into it. The others looked on in astonishment.

"Judas, the boy must be hungry," said Jim.

Knut looked up, apparently in some surprise.

"You don't eat sardines like this? Ah, then you don't know the real way to eat sardines. Try it, you'll like it."

Then having created something of an effect, he added:

"I thought I smelled a skunk around just before I came in."

"Should go well with that concoction you're eating, Knut," said Rogers.

When the laugh had died away, Jim asked:

"Did you hear about the skunk we had a fortnight ago? He degassed himself near the 200-inch air intake. Before anybody could stop the pump the place was full of the stuff. It sure was some hundred per cent stink. There must have been the best part of two hundred visitors inside the dome at the time."

"Lucky we don't charge for admission," chuckled Emerson, "otherwise the Observatory'd be sunk in for compensation."

"But unlucky for the clothes cleaners," added Rogers.

On the way back to the 18-inch Schmidt, Jensen stood listening to the wind in the trees on the north side of the mountain. Similarities to his native hills set off an irrepressible wave of homesickness, longing to be with his family again, longing to be with Greta. At twenty-four, he was in the United States on a two-year studentship. He walked on, trying to kick himself out of what he felt to be a ridiculous mood. Rationally he had no cause whatsoever to be dispirited. Everyone treated him with great kindness, and he had a job ideally suited to a beginner.

Astronomy is kind in its treatment of the beginner. There are many jobs to be done, jobs that can lead to important results but which do not require great experience. Jensen's was one of these. He was searching for supernovae, stars that explode with uncanny violence.

Within the next year he might reasonably hope to find one or two. Since there was no telling when an outburst might occur, nor where in the sky the exploding star might be situated, the only thing to do was to keep on photographing the whole sky, night after night, month after month. Some day he would strike lucky. It was true that should he find a supernova located not too far away in the depths of space, then more experienced hands than his would take over the work. Instead of the 18-inch Schmidt, the full power of the great 200-inch would then be directed to revealing the spectacular secrets of these strange stars. But at all events he would have the honour of first discovery. And the experience he was gaining in the world's greatest observatory would stand well in his favour when he returned home—there were good hopes of a job. Then he and Greta could get married. So what on earth was he worried about? He cursed himself for a fool to be unnerved by a wind on the mountainside.

By this time he had reached the hut where the little Schmidt was housed. Letting himself in, he first consulted his notebook to find the next section of the sky due to be photographed. Then he set the appropriate direction, south of the constellation of Orion: mid-winter was the only time of the year when this particular region could be reached. The next step was to start the exposure. All that remained was to wait until the alarm clock should signal its end. There was nothing to do except sit waiting in the dark, to let his mind wander where it listed.

Jensen worked through to dawn, following one exposure by another. Even so his work was not at an end. He had still to develop the plates that had accumulated during the night. This needed careful attention. A slip at this stage would lose much hard work, and was not to be thought of.

Normally he would have been spared this last exacting task. Normally he would have retired to the dormitory, slept for five or six hours, breakfasted at noon, and only then would he have tackled the developing job. But this was the end of his 'run.' The moon was now rising in the evening, and this meant the end of observing for a fortnight, since the supernova search could not be carried on during the half of the month when the moon was in the night sky—it was simply that the moon gave so much light that the sensitive plates he was using would have been hopelessly fogged.

So on this particular day he would be returning to the Observatory offices in Pasadena, a hundred and twenty-five miles away. The transport to Pasadena left at half-past eleven, and the developing must be done before then. Jensen decided that it would be best done immediately. Then he would have four hours sleep, a quick breakfast, and be ready for the trip back to town.

It worked out as he had planned, but it was a very tired young man who travelled north that day in the Observatory transport. There were three of them: the driver, Rogers, and Jensen. Emerson's run had still another two nights to go. Jensen's friends in wind-blown, snow-wrapped Norway would have been surprised to learn that he slept as the car sped through the miles of orange groves that flanked the road.

Jensen slept late the following morning and it wasn't until eleven that he reached the Observatory offices. He had about a week's work in front of him, examining the plates taken during the last fortnight. What he had to do was to compare his latest observations with other plates that he had taken in the previous month. And this he had to do separately for each bit of the sky.

So on this late January morning of 8th January, 1964, Jensen was down in the basement of the Observatory buildings setting up an instrument known as the 'blinker.' As its name implies, the 'blinker' was a device that enabled him to look first at one plate, then at the other, then back to the first one again, and so on in fairly rapid succession. When this was done, any star that had changed appreciably during the time interval between the taking of the two plates stood out as an oscillating or 'blinking' point of light, while on the other hand the vast majority of stars that had not changed remained quite steady. In this way it was possible to pick out with comparative ease the one star in ten thousand or so that had changed. Enormous labour was therefore saved because every single star did not have to be examined separately.

Great care was needed in preparing plates for use in the 'blinker.' They must not only be taken with the same instrument, but so far as possible must be shot under identical conditions. They must have the same exposure times and their development must be as similar as the observing astronomer can contrive. This explains why Jensen had been so careful about his exposures and development.

His difficulty now was that exploding stars are not the only sort to show changes. Although the great majority of stars do not change, there are a number of brands of oscillating stars, all of which 'blink' in the manner just described. Such ordinary oscillators had to be checked separately and eliminated from the search. Jensen had estimated that he would probably have to check and eliminate the best part of ten thousand ordinary oscillators before he found one supernova. Mostly he would reject a 'blinker' after a short examination, but sometimes there were doubtful cases. Then he would have to resort to a star catalogue, and this meant measuring up the exact position of the star in question. So all in all there was quite a bit of work to do before he got through his pile of plates—work that was not a little tedious.

By 14th January he had nearly finished the whole pile. In the evening he decided to go back to the Observatory. The afternoon he had spent at the California Institute of Technology, where there had been an interesting seminar on the subject of the spiral arms of the galaxies. There had been quite a discussion after the seminar. Indeed he and his friends had argued throughout dinner about it and during the drive back to the Observatory. He reckoned he would just about get through the last batch of plates, the ones he had taken on the night of 7th January.

He finished the first of the batch. It turned out a finicking job. Once again, every one of the 'possibilities' resolved into an ordinary, known oscillator. He would be glad when the job was done. Better to be on the mountain at the end of a telescope than straining his eyes with this damned instrument, he thought, as he bent down to the eye-piece. He pressed the switch and the second pair flashed up in the field of view. An instant later Jensen was fumbling at the plates, pulling them out of their holders. He took them over to the light, examined them for a long time, then replaced them in the blinker, and switched on again. In a rich star field was a large, almost exactly circular, dark patch. But it was the ring of stars surrounding the patch that he found so astonishing. There they were, oscillating, blinking, all of them. Why? He could think of no satisfactory answer to the question, for he had never seen or heard of anything like this before.

Jensen found himself unable to continue with the job. He was too excited about this singular discovery. He felt he simply must talk to someone about it. The obvious man of course was Dr. Marlowe, one of the senior staff members. Most astronomers specialise on one or other of the many facets of their subject. Marlowe had his specialities too, but he was above all a man of immense general knowledge. Perhaps because of this he made fewer mistakes than most people. He was ready to talk astronomy at all hours of the day and night, and he would talk with intense enthusiasm to anyone, whether a distinguished scientist like himself or a young man at the threshold of his career. It was natural therefore that Jensen should wish to tell Marlowe about his curious find.

He carefully put the two plates in question in a box, switched off the electrical equipment and the lights in the basement, and made his way to the notice board outside the library. The next step was to consult the observing list. He found to his satisfaction that Marlowe was not away either at Palomar or Mount Wilson. But, of course, he might have gone out for the evening. Jensen's luck was in, however, for a phone call soon elicited that Marlowe was at home. When he explained that he wanted to talk to him about something queer that had turned up, Marlowe said:

"Come right over, Knut, I'll be expecting you. No, it's all right. I wasn't doing anything particular."

It says much for Jensen's state of mind that he rang for a taxi to take him to Marlowe's house. A student with an annual emolument of two thousand dollars does not normally travel by taxi. This was particularly so in Jensen's case. Economy was important to him because he wished to travel around the different observatories in the United States before he returned to Norway, and he had presents to buy, too. But on this occasion the matter of money never entered his head. He rode up to Altadena, clutching his box of plates, and wondered whether in some way he'd made a fool of himself. Had he made some stupid mistake?

Marlowe was waiting.

"Come right in," he said. "Have a drink. You take it strong in Norway, don't you?"

Knut smiled.

"Not so strong as you take it, Dr. Marlowe."

Marlowe motioned Jensen to an easy chair by the log fire (so beloved by many who live in centrally heated houses), and after moving a large cat from a second chair, sat down himself.

"Lucky you rang, Knut. My wife's out for the evening, and I was wondering what to do with myself."

Then, typically, he plunged straight to the issue—diplomacy and political finesse were unknown to him.

"Well, what've you got there?" he said, nodding at the yellow box that Jensen had brought.

Somewhat sheepishly, Knut took out the first of his two pictures, one taken on 9th December, 1963, and handed it over without comment. He was soon gratified by the reaction.

"My God!" exclaimed Marlowe. "Taken with the 18-inch, I expect. Yes, I see you've got it marked on the side of the plate."

"Is there anything wrong, do you think?"

"Nothing so far as I can see." Marlowe took a magnifying glass out of his pocket and scanned carefully over the plate.

"Looks perfectly all right. No plate defects."

"Tell me why you're so surprised, Dr. Marlowe."

"Well, isn't this what you wanted me to look at?"

"Not by itself. It's the comparison with a second plate that I took a month later that looks so odd."

"But this first one is singular enough," said Marlowe. "You've had it lying in your drawer for a month! Pity you didn't show it to me right away. But of course, you weren't to know."

"I don't see why you're so surprised by this one plate though."

"Well, look at this dark circular patch. It's obviously a dark cloud obscuring the light from the stars that lie beyond it. Such globules are not uncommon in the Mil'y Way, but usually they're tiny things. My God, look at this! It's huge, it must be the best part of two and a half degrees across!"

"But, Dr. Marlowe, there are lots of clouds bigger than this, especially in the region of Sagittarius."

"If you look carefully at what seem like very big clouds, you'll find them to be built up of lots of much smaller clouds. This thing you've got here seems, on the other hand, to be just one single spherical cloud. What really surprises me is how I could have missed anything as big as this."

Marlowe looked again at the markings on the plate.

"It is true that it's in the south, and we're not so concerned with the winter sky. Even so, I don't see how I could have missed it when I was working on the Trapezium in Orion. That was only three or four years ago and I wouldn't have forgotten anything like this."

Marlowe's failure to identify the cloud—for this is undoubtedly what it was—came as a surprise to Jensen. Marlowe knew the sky and all the strange objects to be found in it as well as he knew the streets and avenues of Pasadena.

Marlowe went over to the sideboard to renew the drinks. When he came back, Jensen said:

"It was this second plate that puzzled me."

Marlowe had not looked at it for ten seconds before he was back to the first plate. His experienced eye needed no 'blinker' to see that in the first plate the cloud was surrounded by a ring of stars that were either absent or nearly absent in the second plate. He continued to gaze thoughtfully at the two plates.

"There was nothing unusual about the way you took these pictures?"

"Not so far as I know."

"They certainly look all right, but you can never be quite sure."

Marlowe broke off abruptly and stood up. Now, as always when he was excited or agitated, he blew out enormous clouds of aniseed-scented tobacco smoke, a South African variety. Jensen marvelled that the bowl of his pipe did not burst into flames.

"Something crazy may have happened. The best thing we can do is to get another plate shot straight away. I wonder who is on the mountain tonight."

"You mean Mount Wilson or Palomar?"

"Mount Wilson. Palomar's too far."

"Well, as far as I remember one of the visiting astronomers is using the 100-inch. I think Harvey Smith is on the 60-inch."

"Look, it would probably be best if I went up myself. Harvey won't mind letting me have a few moments. I won't be able to get the whole nebulosity of course, but I can get some of the star fields at the edge. Do you know the exact co-ordinates?"

"No. I phoned as soon as I'd tried the plates in the 'blink.' I didn't stop to measure them."

"Well, never mind, we can do that on the way. But there's no real need to keep you out of bed, Knut. Why don't I drop you at your apartment? I'll leave a note for Mary saying I won't be back until sometime tomorrow."

Jensen was excited when Marlowe dropped him at his lodging. Before he turned in that night he wrote letters home, one to his parents telling them very briefly of the unusual discovery, and another to Greta saying that he believed that he'd stumbled on something important.

Marlowe drove to the Observatory offices. His first step was to get Mount Wilson on the phone and to talk to Harvey Smith. When he heard Smith's soft southern accent, he said:

"This is Geoff Marlowe. Look, Harvey, something pretty queer has turned up, so queer that I'm wondering if you'd let me have the 60-inch for tonight. What is it? I don't know what it is. That's just what I want to find out. It's to do with young Jensen's work. Come down here at ten o'clock tomorrow and I'll be able to tell you more about it. If you're bored I'll stand you a bottle of Scotch. That's good enough for you? Fine! Tell the night assistant that I'll be up at about one o'clock, will you?"

Marlowe next put through a call to Bill Barnett of Caltech.

"Bill, this is Geoff Marlowe ringing from the offices. I wanted to tell you that there'll be a pretty important meeting here tomorrow morning at ten o'clock. I'd like you to come along and to bring a few theoreticians along. They don't need to be astronomers. Bring several bright boys. . . . No I can't explain now. I'll know more tomorrow. I'm going on the 60-inch tonight. But I'll tell you what, if you think by lunch-time tomorrow that I've got you out on a wild-goose chase, I'll stand you a crate of Scotch. . . . Fine!"

He hummed with excitement as he hurried down to the basement where Jensen had been working earlier in the evening. He spent some three-quarters of an hour measuring Jensen's plates. When at last he was satisfied that he would know exactly where to point the telescope, he went out, climbed into his car, and drove off towards Mount Wilson.

Dr. Herrick, the Director of the Observatory, was astonished to find Marlowe waiting for him when he reached his office at seven-thirty the following morning. It was the Director's habit to start his day some two hours before the main body of his staff, "in order to get some work done," as he used to say. At the other extreme, Marlowe usually did not put in an appearance until ten-thirty, and sometimes later still. This day. however, Marlowe was sitting at his desk, carefully examining a pile of about a dozen positive prints. Herrick's surprise was not lessened when he heard what Marlowe had to say. The two men spent the next hour and a half in earnest conversation. At about nine o'clock they slipped out for a quick breakfast, and returned in time to make preparations for a meeting to be held in the library at ten o'clock.

When Bill Barnett's party of five arrived they found some dozen members of the Observatory already assembled, including Jensen, Rogers, Emerson and Harvey Smith. A blackboard had been fitted up and a screen and lantern for showing slides. The only member of Barnett's party who had to be introduced round was Dave Weichart. Marlowe, who had heard a number of reports of the abilities of this brilliant twenty-seven-year-old physicist, noted that Barnett had evidently done his best to bring a bright boy along.

"The best thing I can do," began Marlowe, "is to explain things in a chronological way, starting with the plates that Knut Jensen brought to my house last night. When I've shown them you'll see why this emergency meeting was called."

Emerson, who was working the lantern, put in a slide that Marlowe had made up from Jensen's first plate, the one taken on the night of 9th December, 1963.

"The centre of the dark blob," went on Marlowe, "is in Right Ascension 5 hours 49 minutes, Declination minus 30 degrees 16 minutes, as near as I can judge."

"A fine example of a Bok globule," said Barnett.

"How big is it?"

"About two and a half degrees across."

There were gasps from several of the astronomers.

"Geoff, you can keep your bottle of whisky," said Harvey Smith.

"And my crate, too," added Bill Barnett amidst the general laughter.

"I reckon you'll be needing the whisky when you see the next plate. Bert, keep rocking the two backwards and forwards, so that we can get some idea of a comparison," went on Marlowe.

"It's fantastic," burst out Rogers, "it looks as if there's a whole ring of oscillating stars surrounding the cloud. But how could that be?"

"It can't," answered Marlowe. "That's what I saw straight away. Even if we admit the unlikely hypothesis that this cloud is surrounded by a halo of variable stars, it is surely quite inconceivable that they'd all oscillate in phase with each other, all up together as in the first slide, and all down together in the second."

"No, that's preposterous," broke in Barnett. "If we're to take it that there's been no slip-up in the photography, then surely there's only one possible explanation. The cloud is moving towards us. In the second slide it's nearer to us, and therefore it's obscuring more of the distant stars. At what interval apart were the two plates taken?"

"Rather less than a month."

"Then there must be something wrong with the photography."

"That's exactly the way I reasoned last night. But as I couldn't see anything wrong with the plates, the obvious thing was to take some new pictures. If a month made all that difference between Jensen's first plate and his second, then the effect should have been easily detectable in a week—Jensen's last plate was taken on 7th January. Yesterday was 14th January. So I rushed up to Mount Wilson, bullied Harvey off the 60-inch, and spent the night photographing the edges of the cloud. I've got a whole collection of new slides here. They're not of course on the same scale as Jensen's plates, but you'll be able to see pretty well what's happening. Put them through one by one, Bert, and keep referring back to Jensen's plate of 7th January."

There was almost dead silence for the next quarter of an hour, as the star fields on the edge of the cloud were carefully compared by the assembled astronomers. At the end Barnett said:

"I give up. As far as I'm concerned there isn't a shadow of a doubt but that this cloud is travelling towards us."

And it was clear that he had expressed the conviction of the meeting. The stars at the edge of the cloud were being steadily blacked out as it advanced towards the solar system.

"Actually there's no doubt at all about it," went on Marlowe. "When I discussed things with Dr. Herrick earlier this morning he pointed out that we have a photograph taken twenty years ago of this part of the sky."

Herrick produced the photograph.

"We haven't had time to make up a slide," said he, "so you will have to hand it round. You can see the black cloud, but it's small on this picture, no more than a tiny globule. I've marked it with an arrow."

He handed the picture to Emerson who, after passing it to Harvey Smith, said:

"It's certainly grown enormously over the twenty years. I'm a bit apprehensive about what's going to happen in the next twenty. It seems as if it might cover the whole constellation of Orion. Pretty soon astronomers will be out of business."

It was then that Dave Weichart spoke up for the first time.

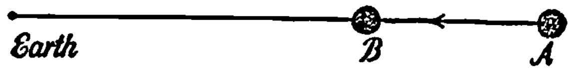
"I've two questions that I'd like to ask. The first is about the position of the cloud. As I understand what you've said, the cloud is growing in its apparent size because it's getting nearer to us. That's clear enough. But what I'd like to know is whether the centre of the cloud is staying in the same position, or does it seem to be moving against the background of the stars?"

"A very good question. The centre seems, over the last twenty years, to have moved very little relative to the star field," answered Herrick.

"Then that means the cloud is coming dead at the solar system."

Weichart was used to thinking more quickly than other people, so when he saw hesitation to accept his conclusion, he went to the blackboard.

"I can make it clear with a picture. Here's the Earth. Let's suppose first that the cloud is moving dead towards us, like this, from A to B. Then at B the cloud will look bigger but its centre will be in the same direction. This is the case that apparently corresponds pretty well to the observed situation."



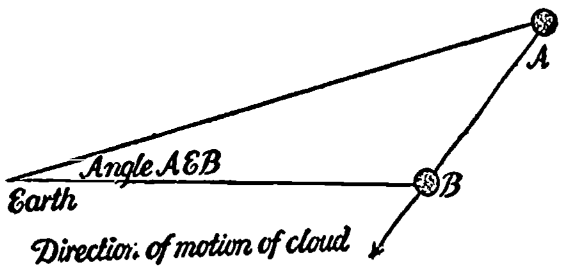
There was a general murmur of assent, so Weichart went on:

"Now let's suppose that the cloud is moving sideways, as well as towards us, and let's suppose that the motion sideways is about as fast as the motion towards us. Then the cloud will move about like this. Now if you consider the motion from A to B you'll see that there are two effects—the cloud will seem bigger at B than it was at A, exactly as in the previous case, but now the centre will have moved. And it will move through the angle AEB which must be something of the order of thirty degrees."

"I don't think the centre has moved through an angle of more than a quarter of a degree," remarked Marlowe.

"Then the sideways motion can't be more than about one per cent of the motion towards us. It looks as though the cloud is heading towards the solar system like a bullet at a target."

"You mean, Dave, that there's no chance of the cloud missing the solar system, of it being a near-miss, let us say?"



"On the facts as they've been given to us that cloud is going to score a bull's eye, plumb in the middle of the target. Remember that it's already two and a half degrees in diameter. The transverse velocity would have to be as much as ten per cent or so of the radial velocity if it were to miss us. And that would imply a far greater angular motion of the centre than Dr. Marlowe says has taken place. The other question I'd like to ask is, why wasn't the cloud detected sooner? I don't want to be rude about it, but it seems very surprising that it wasn't picked up quite a while ago, say ten years ago."

"That of course was the first thing that sprang to my mind," answered Marlowe. "It seemed so astonishing that I could scarcely credit the validity of Jensen's work. But then I saw a number of reasons. If a bright nova or a supernova were to flash out in the sky it would immediately be detected by thousands of ordinary people, let alone by astronomers. But this is not something bright, it's something dark, and that's not so easy to pick up—a dark patch is pretty well camouflaged against the sky. Of course if one of the stars that has been hidden by the cloud had happened to be a bright fellow it would have been spotted. The disappearance of a bright star is not so easy to detect as the appearance of a new bright star, but it would nevertheless have been noticed by thousands of professional and amateur astronomers. It happened, however, that all the stars near the cloud are telescopic, none brighter than eighth magnitude. That's the first mischance. Then you must know that in order to get good seeing conditions we prefer to work on objects near the zenith, whereas this cloud lies rather low in our sky. So we would naturally tend to avoid that part of the sky unless it happened to contain some particularly interesting material, which by a second mischance (if we exclude the case of the cloud) it does not. It is true that to observatories in the southern hemisphere the cloud would be high in the sky, but observatories in the southern hemisphere are hard put to it with their small staffs to get through a host of important problems connected with the Magellanic Clouds and the nucleus of the Galaxy. The cloud had to be detected sooner or later. It turned out to be later, but it might have been sooner. That's all I can say."

"It's too late to worry about that now," said the Director. "Our next step must be to measure the speed with which the cloud is moving towards us. Marlowe and I have had a long talk about it, and we think it should be possible. Stars on the fringe of the cloud are partially obscured, as the plates taken by Marlowe last night show. Their spectrum should show absorption lines due to the cloud, and the Doppler shift will give us the speed."

"Then it should be possible to calculate how long the cloud will be before it reaches us," joined in Barnett. "I must say I don't like the look of things. The way the cloud has increased its angular diameter during the last twenty years makes it look as if it'll be on top o. us within fifty or sixty years. How long do you think it'll take to get a Doppler shift?"

"Perhaps about a week. It shouldn't be a difficult job."

"Sorry I don't understand all this," broke in Weichart. "I don't see why you need the speed of the cloud. You can calculate straight away how long the cloud is going to take to reach us. Here, let me do it. My guess is that the answer will turn out at much less than fifty years."

For the second time Weichart left his seat, went to the blackboard, and cleaned off his previous drawings.

"Could we have Jensen's two slides again please?"

When Emerson had flashed them up, first one and then the other, Weichart asked: "Could you estimate how much larger the cloud is in the second slide?"

"I would say about five per cent larger. It may be a little more or a little less, but certainly not very far away from that," answered Marlowe.

"Right," Weichart continued, "let's begin by defining a few symbols."

Then followed a somewhat lengthy calculation at the end of which Weichart announced:

"And so you see that the black cloud will be here by August, 1965, or possibly sooner if some of the present estimates have to be corrected."

Then he stood back from the blackboard, checking through his mathematical argument.

"It certainly looks all right—very straightforward in fact," said Marlowe, putting out great volumes of smoke.★

"Yes, it seems unimpeachably correct," answered Weichart.

At the end of Weichart's astonishing calculation, the Director had thought it wise to caution the whole meeting to secrecy. Whether they were right or wrong, no good could come of talking outside the Observatory, not even at home. Once the spark was struck the story would spread like wildfire, and would be in the papers in next to no time. The Director had never had any cause to think highly of newspaper reporters, particularly of their scientific accuracy.

From mid-day to two o'clock he sat alone in his office, wrestling with the most difficult situation he had ever ex-

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★ The details of Weichart's remarks and work while at the blackboard were as follows:

"Write α for the present angular diameter of the cloud, measured in radians,

- d for the linear diameter of the cloud,
- D for its distance away from us,
- V for its velocity of approach,
- T for the time required for it to reach the solar system.

To make a start, evidently we have $\alpha = d/D$

Differentiate this equation with respect to time t and we get

$$\frac{d\alpha}{dt} = \frac{-d}{D^2}\frac{dD}{dt}.$$

But $V = -\frac{dD}{dt}$, so that we can write $\frac{d\alpha}{dt} = \frac{d}{D^2}V$.

Also we have $\frac{D}{V} = T$. Hence we can get rid of V, arriving at

$$\frac{d\alpha}{dt} = \frac{d}{DT}.$$

This is turning out easier than I thought. Here's the answer already

$$T = \alpha\frac{dt}{d\alpha}.$$

The last step is to approximate $\frac{dt}{d\alpha}$ by finite intervals, $\frac{\Delta t}{\Delta\alpha}$, where $\Delta t = 1$ month corresponding to the time difference between Dr. Jensen's two plates; and from what Dr. Marlowe has estimated $\Delta\alpha$ is about 5 per cent of α, i.e. $\frac{\alpha}{\Delta\alpha} = 20$. Therefore $T = 20\Delta t = 20$ months."

perienced. It was utterly antipathetic to his nature to announce any result or to take steps on the basis of a result until it had been repeatedly checked and cross-checked. Yet would it be right for him to maintain silence for a fortnight or more? It would be two or three weeks at least before every facet of the matter were fully investigated. Could he afford the time? For perhaps the tenth time he worked through Weichart's argument. He could see no flaw in it.

At length he called in his secretary.

"Please will you ask Caltech to fix me a seat on the night plane to Washington, the one that leaves about nine o'clock. Then get Dr. Ferguson on the phone."

James Ferguson was a big noise in the National Science Foundation, controlling all the activities of the Foundation in physics, astronomy, and mathematics. He had been much surprised at Herrick's phone call of the previous day. It was quite unlike Herrick to fix appointments at one day's notice.

"I can't imagine what can have bitten Herrick," he told his wife at breakfast, "to come chasing over to Washington like this. He was quite insistent about it. Sounded agitated, so I said I'd pick him up at the airport."

"Well, an occasional mystery is good for the system," said his wife. "You'll know soon enough."

On the way from the airport to the city, Herrick would commit himself to nothing but conventional trivialities. It was not until he was in Ferguson's office that he came to the issue.

"There's no danger of us being overheard, I suppose?"

"Goodness, man, is it as serious as that? Wait a minute."

Ferguson lifted the phone.

"Amy, will you please see that I'm not interrupted—no, no phone calls—well, perhaps for an hour, perhaps two, I don't know."

Quietly and logically Herrick then explained the situation. When Ferguson had spent some time looking at the photographs, Herrick said:

"You see the predicament. If we announce the business and we turn out to be wrong then we shall look awful fools. If we spend a month testing all the details and it turns out that we are right then we should be blamed for procrastination and delay."

"You certainly would, like an old hen sitting on a bad egg."

"Well, James, I thought you have had a great deal of experience in dealing with people. I felt you were someone I could turn to for advice. What do you suggest I should do?"

Ferguson was silent for a little while. Then he said:

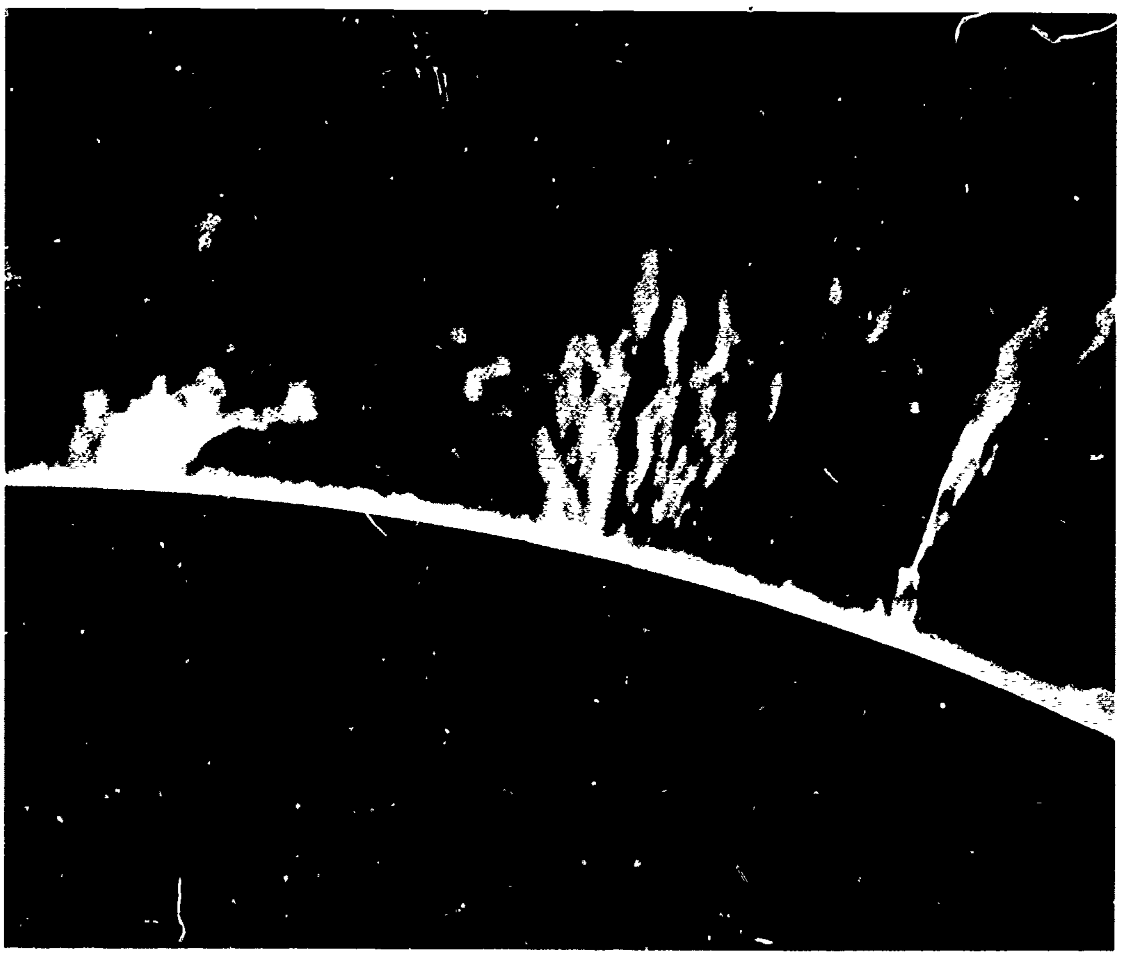
"I can see that this may turn out to be a grave matter. And I don't like taking grave decisions any more than you do, Dick, certainly not on the spur of the moment. What I suggest is this. Go back to your hotel and sleep through the afternoon—I don't expect you had much sleep last night. We can meet again for an early dinner, and by then I'll have had an opportunity to think things over. I'll try to reach some conclusion."

Ferguson was as good as his word. When he and Herrick had started their evening meal, in a quiet restaurant of his choice, Ferguson began:

"I think I've got things sorted out fairly well. It doesn't seem to me to make sense wasting another month in making sure of your position. The case seems to be very sound as it is, and you can never be quite certain—it would be a matter of converting a ninety-nine per cent certainty into a ninety-nine point nine per cent certainty. And that isn't worth the loss of time. On the other hand you are ill-prepared to go to the White House just at the moment. According to your own account you and your men have spent less than a day on the job so far. Surely there are a good many other things you might get ideas about. More exactly, how long is it going to take the cloud to get here? What will its effects be when it does get here? That sort of question.

"My advice is to go straight back to Pasadena, get your team together, and aim to write a report within a week, setting out the situation as you see it. Get all your men to sign it—so that there's no question of the tale getting round of a mad Director. And then come back to Washington.

"In the meantime I'll get things moving at this end. It isn't a bit of good in a case like this starting at the bottom by whispering into the ear of some Congressman. The only thing to do is to go straight to the President. I'll try to smooth your path there."



Solar prominence, 80,000 miles high

This pleasant introduction to the planets and the solar system is by a writer well known as a scientist, a popularizer of science, and a writer of science fiction. Asimov approaches the solar system historically, briefly considering the discovery of some of the planets.

2 Roll Call

Isaac Asimov

1963

When all the world was young (and I was a teen-ager), one way to give a science fiction story a good title was to make use of the name of some heavenly body. Among my own first few science fiction stories, for instance, were such items as "Marooned off Vesta," "Christmas on Ganymede," and "The Callistan Menace." (Real swinging titles, man!)

This has gone out of fashion, alas, but the fact remains that in the 1930's, a whole generation of science fiction fans grew up with the names of the bodies of the Solar System as familiar to them as the names of the American states. Ten to one they didn't know why the names were what they were, or how they came to be applied to the bodies of the Solar System or even, in some cases, how they were pronounced—but who cared? When a tentacled monster came from Umbriel or Io, how much more impressive that was than if it had merely come from Philadelphia.

But ignorance must be battled. Let us, therefore, take up the matter of the names, call the roll of the Solar System in the order (more or less) in which the names were applied, and see what sense can be made of them.

The *Earth* itself should come first, I suppose. Earth is an old Teutonic word, but it is one of the glories of the English language that we always turn to the classic tongues as well. The Greek word for Earth was *Gaia* or, in Latin spelling, *Gaea*. This gives us "geography" ("earth-writing"), "geology" ("earth-discourse"), "geometry" ("earth-measure"), and so on.

The Latin word is *Terra*. In science fiction stories a human being from Earth may be an "Earthling" or an "Earthman," but he is frequently a "Terrestrial," while a creature from another world is almost invariably an "extra-Terrestrial."

The Romans also referred to the Earth as *Tellus Mater* ("Mother Earth" is what it means). The genitive form of *tellus* is *telluris,* so Earthmen are occasionally referred to in s.f. stories as "Tellurians." There is also a chemical element "tellurium," named in honor of this version of the name of our planet.

But putting Earth to one side, the first two heavenly bodies to have been noticed were, undoubtedly and obviously, the *Sun* and the *Moon,* which, like Earth, are old Teutonic words.

To the Greeks the Sun was *Helios,* and to the Romans it was *Sol.* For ourselves, Helios is almost gone, although we have "helium" as the name of an element originally found in the Sun, "heliotrope" ("sun-turn") for the sunflower, and so on.

Sol persists better. The common adjective derived from "sun" may be "sunny," but the scholarly one is "solar." We may speak of a sunny day and a sunny disposition, but never of the "Sunny System." It is always the "Solar System." In science fiction, the Sun is often spoken of as Sol, and the Earth may even be referred to as "Sol III."

The Greek word for the Moon is *Selene,* and the Latin word is *Luna.* The first lingers on in the name of the chemical element "selenium," which was named for the Moon. And the study of the Moon's surface features may be called "selenography." The Latin name appears in the common adjective, however, so that one speaks of a "lunar crescent" or a "lunar eclipse." Also, because of the theory that exposure to the light of the full Moon drove men crazy ("moon-struck"), we obtained the word "lunatic."

I have a theory that the notion of naming the heavenly bodies after mythological characters did not originate with the Greeks, but that it was a deliberate piece of copycattishness.

To be sure, one speaks of *Helios* as the god of the Sun and *Gaea* as the goddess of the Earth, but it seems obvious to me that the words came first, to express the physical objects, and that these were personified into gods and goddesses later on.

The later Greeks did, in fact, feel this lack of mythological character and tried to make Apollo the god of the Sun and Artemis (Diana to the Romans) the goddess of the Moon. This may have taken hold of the Greek scholars but not of the ordinary folk, for whom Sun and Moon remained *Helios* and *Selene*. (Nevertheless, the influence of this Greek attempt on later scholars was such that no other important heavenly body was named for Apollo and Artemis.)

I would like to clinch this theory of mine, now, by taking up another heavenly body.

After the Sun and Moon, the next bodies to be recognized as important individual entities must surely have been the five bright "stars" whose positions with respect to the real stars were not fixed and which therefore, along with the Sun and the Moon, were called planets (see Chapter 4).

The brightest of these "stars" is the one we call Venus, and it must have been the first one noticed—but not necessarily as an individual. Venus sometimes appears in the evening after sunset, and sometimes in the morning before sunrise, depending on which part of its orbit it happens to occupy. It is therefore the "Evening Star" sometimes and the "Morning Star" at other times. To the early Greeks, these seemed two separate objects and each was given a name.

The Evening Star, which always appeared in the west near the setting Sun, was named *Hesperos* ("evening" or "west"). The equivalent Latin name was *Vesper*. The Morning Star was named *Phosphoros* ("light-bringer"), for when the Morning Star appeared the Sun and its light were not far behind. (The chemical element "phosphorus"—Latin spelling—was so named because it glowed in the dark as the result of slow combination with oxygen.) The Latin name for the Morning Star was *Lucifer*, which also means "light-bringer."

Now notice that the Greeks made no use of mythology here. Their words for the Evening Star and Morning Star were logical, descriptive words. But then (during the sixth century B.C.) the Greek scholar, Pythagoras of Samos, arrived back in the Greek world after his travels in Babylonia. He brought with him a skull-full of Babylonian notions.

At the time, Babylonian astronomy was well developed and far in advance of the Greek bare beginnings. The Babylonian interest in astronomy was chiefly astrological in nature and so it seemed natural for them to equate the powerful planets with the powerful gods. (Since both had power over human beings, why not?) The Babylonians knew that the Evening Star and the Morning Star were a single planet—after all, they never appeared on the same day; if one was present, the other was absent, and it was clear from their movements that the Morning Star passed the Sun and became the Evening Star and vice versa. Since the planet representing both was so bright and beautiful, the Babylonians very logically felt it appropriate to equate it with Ishtar, their goddess of beauty and love.

Pythagoras brought back to Greece this Babylonian knowledge of the oneness of the Evening and Morning Star, and Hesperos and Phosphoros vanished from the heavens. Instead, the Babylonian system was copied and the planet was named for the Greek goddess of beauty and love, Aphrodite. To the Romans this was their corresponding goddess *Venus*, and so it is to us.

Thus, the habit of naming heavenly bodies for gods and goddesses was, it seems to me, deliberately copied from the Babylonians (and their predecessors) by the Greeks.

The name "Venus," by the way, represents a problem. Adjectives from these classical words have to be taken from the genitive case and the genitive form of "Venus" is *Veneris*. (Hence, "venerable" for anything worth the respect paid by the Romans to the goddess; and because the Romans respected old age, "venerable" came to be applied to old men rather than young women.)

So we cannot speak of "Venusian atmosphere" or "Venutian atmosphere" as science fiction writers sometimes do. We must say "Venerian atmosphere." Unfortunately, this has uncomfortable associations and it is not used. We might turn back to the Greek name but the genitive form there is *Aphrodisiakos*, and if we speak of the "Aphrodisiac atmosphere" I think we will give a false impression.

But something must be done. We are actually exploring the atmosphere of Venus with space probes and some adjective is needed. Fortunately, there is a way out. The Venus cult was very prominent in early days in a small island south of Greece. It was called Kythera (Cythera in Latin spelling) so that Aphrodite was referred to, poetically, as the "Cytherean goddess." Our poetic astronomers have therefore taken to speaking of the "Cytherean atmosphere."

The other four planets present no problem. The second brightest planet is truly the king planet. Venus may be brighter but it is confined to the near neighborhood of the Sun and is never seen at midnight. The second brightest, however, can shine through all the hours of night and so it should fittingly be named for the chief god. The Babylonians accordingly named it "Marduk." The Greeks followed suit and called it "Zeus," and the Romans named it *Jupiter.* The genitive form of Jupiter is *Jovis,* so that we speak of the "Jovian satellites." A person born under the astrological influence of Jupiter is "jovial."

Then there is a reddish planet and red is obviously the color of blood; that is, of war and conflict. The Babylonians named this planet "Nergal" after their god of war, and the Greeks again followed suit by naming it "Ares" after theirs. Astronomers who study the surface features of the planet are therefore studying "areography." The Latins used their god of war, *Mars,* for the planet. The genitive form is *Martis,* so we can speak of the "Martian canals."

The planet nearest the Sun, appears, like Venus, as both an evening star and morning star. Being smaller and less reflective than Venus, as well as closer to the Sun, it is much harder to see. By the time the Greeks got around to naming it, the mythological notion had taken hold. The evening star manifestation was named "Hermes," and the morning star one "Apollo."

The latter name is obvious enough, since the later Greeks associated Apollo with the Sun, and by the time the planet Apollo was in the sky the Sun was due very shortly. Because the planet was closer to the Sun than any other planet (though, of course, the Greeks did not know this was the reason), it moved more quickly against the stars than any object but the Moon. This made it resemble the wing-footed messenger of the gods, Hermes. But giving the planet two names was a matter of conservatism. With the Venus matter straightened out, Hermes/Apollo was quickly reduced to a single planet and Apollo was dropped. The Romans named it "Mercurius," which was their equivalent of Hermes, and we call it *Mercury*. The quick journey of Mercury across the stars is like the lively behavior of droplets of quicksilver, which came to be called "mercury," too, and we know the type of personality that is described as "mercurial."

There is one planet left. This is the most slowly moving of all the planets known to the ancient Greeks (being the farthest from the Sun) and so they gave it the name of an ancient god, one who would be expected to move in grave and solemn steps. They called it "Cronos," the father of Zeus and ruler of the universe before the successful revolt of the Olympians under Zeus's leadership. The Romans gave it the name of a god they considered the equivalent of Cronos and called it "Saturnus," which to us is *Saturn*. People born under Saturn are supposed to reflect its gravity and are "saturnine."

For two thousand years the Earth, Sun, Moon, Mercury, Venus, Mars, Jupiter, and Saturn remained the only known bodies of the Solar System. Then came 1610 and the Italian astronomer Galileo Galilei, who built himself a telescope and turned it on the heavens. In no time at all he found four subsidiary objects circling the planet Jupiter. (The German astronomer Johann Kepler promptly named such subsidiary bodies "satellites," from a Latin word for the hangers-on of some powerful man.)

There was a question as to what to name the new bodies. The mythological names of the planets had hung on into the Christian era, but I imagine there must have been some natural hesitation about using heathen gods for new bodies. Galileo himself felt it wise to honor Cosimo Medici II, Grand Duke of Tuscany from whom he expected (and later received) a position, and called them *Sidera Medicea* (the Medicean stars). Fortunately this didn't stick. Nowadays we call the four satellites the "Galilean satellites" as a group, but individually we use mythological names after all. A German astronomer, Simon Marius, gave them these names after having discovered the satellites one day later than Galileo.

The names are all in honor of Jupiter's (Zeus's) loves, of which there were many. Working outward from Jupiter, the first is *Io* (two syllables please, eye'oh), a maiden whom Zeus turned into a heifer to hide her from his wife's jealousy. The second is *Europa,* whom Zeus in the form of a bull abducted from the coast of Phoenicia in Asia and carried to Crete (which is how Europe received its name). The third is *Ganymede,* a young Trojan lad (well, the Greeks were liberal about such things) whom Zeus abducted by assuming the guise of an eagle. And the fourth is *Callisto,* a nymph whom Zeus's wife caught and turned into a bear.

As it happens, naming the third satellite for a male rather than for a female turned out to be appropriate, for Ganymede is the largest of the Galilean satellites and, indeed, is the largest of any satellite in the Solar System. (It is even larger than Mercury, the smallest planet.)

The naming of the Galilean satellites established once and for all the convention that bodies of the Solar System were to be named mythologically, and except in highly unusual instances this custom has been followed since.

In 1655 the Dutch astronomer Christian Huygens discovered a satellite of Saturn (now known to be the sixth from the planet). He named it *Titan.* In a way this was appropriate, for Saturn (Cronos) and his brothers and sisters, who ruled the Universe before Zeus took over, were referred to collectively as "Titans." However, since the name refers to a group of beings and not to an individual being, its use is unfortunate. The name was appropriate in a second fashion, too. "Titan" has come to mean "giant" because the Titans and their allies were pictured by the Greeks as being of superhuman size (whence the word "titanic"), and it turned out that Titan was one of the largest satellites in the Solar System.

The Italian-French astronomer Gian Domenico Cassini was a little more precise than Huygens had been. Between 1671 and 1684 he discovered four more satellites of Saturn, and these he named after individual Titans and Titanesses. The satellites now known to be 3rd, 4th, and 5th from Saturn he named *Tethys, Dione,* and *Rhea,* after three sisters of Saturn. Rhea was Saturn's wife as well. The 8th satellite from Saturn he named *Iapetus* after one of Saturn's brothers. (Iapetus is frequently mispronounced. In English it is "eye-ap'ih-tus.") Here finally the Greek names were used, chiefly because there were no Latin equivalents, except for Rhea. There the Latin equivalent is *Ops.* Cassini tried to lump the four satellites he had discovered under the name of "Ludovici" after his patron, Louis XIV—*Ludovicus,* in Latin—but that second attempt to honor royalty also failed.

And so within 75 years after the discovery of the telescope, nine new bodies of the Solar System were discovered, four satellites of Jupiter and five of Saturn. Then something more exciting turned up.

On March 13, 1781, a German-English astronomer, William Herschel, surveying the heavens, found what he thought was a comet. This, however, proved quickly to be no comet at all, but a new planet with an orbit outside that of Saturn.

There arose a serious problem as to what to name the new planet, the first to be discovered in historic times. Herschel himself called it "Georgium Sidus" ("George's star") after his patron, George III of England, but this third attempt to honor royalty failed. Many astronomers felt it should be named for the discoverer and called it "Herschel." Mythology, however, won out.

The German astronomer Johann Bode came up with a truly classical suggestion. He felt the planets ought to make a heavenly family. The three innermost planets (excluding the Earth) were Mercury, Venus, and Mars, who were siblings, and children of Jupiter, whose orbit lay outside theirs. Jupiter in turn was the son of Saturn, whose orbit lay outside his. Since the new planet had an orbit outside Saturn's, why not name it for *Uranus*, god of the sky and father of Saturn? The suggestion was accepted and Uranus* it was. What's more, in 1798 a German chemist, Martin Heinrich Klaproth, discovered a new element he named in its honor as "uranium."

In 1787 Herschel went on to discover Uranus's two largest satellites (the 4th and 5th from the planet, we now know). He named them from mythology, but *not* from Graeco-Roman mythology. Perhaps, as a naturalized Englishman, he felt 200 per cent English (it's that way, sometimes) so he turned to English folktales and named the satellites *Titania* and *Oberon*, after the queen and king of the fairies (who make an appearance, notably, in Shakespeare's *A Midsummer Night's Dream*).

In 1789 he went on to discover two more satellites of Saturn (the two closest to the planet) and here too he disrupted mythological logic. The planet and the five satellites then known were all named for various Titans and Titanesses (plus the collective name, Titan). Herschel named his two *Mimas* and *Enceladus* (en-sel′a-dus) after two of the giants who rose in rebellion against Zeus long after the defeat of the Titans.

After the discovery of Uranus, astronomers climbed hungrily upon the discover-a-planet bandwagon and searched particularly in the unusually large gap between Mars and Jupiter. The first to find a body there was the Italian astronomer Giuseppe Piazzi. From his observatory at Palermo, Sicily he made his first sighting on January 1, 1801.

Although a priest, he adhered to the mythological convention and named the new body *Ceres*, after the tutelary goddess of his native Sicily. She was a sister of Jupiter and the goddess of grain (hence "cereal") and agriculture. This was the second planet to receive a feminine name (Venus was the first, of course) and it set a fashion. Ceres turned out to be a small body (485 miles in diameter), and many more were found in the gap between Mars

* Uranus is pronounced "yoo′ruh-nus." I spent almost all my life accenting the second syllable and no one ever corrected me. I just happened to be reading Webster's Unabridged one day . . .

and Jupiter. For a hundred years, all the bodies so discovered were given feminine names.

Three "planetoids" were discovered in addition to Ceres over the next six years. Two were named *Juno* and *Vesta* after Ceres' two sisters. They were also the sisters of Jupiter, of course, and Juno was his wife as well. The remaining planetoid was named *Pallas*, one of the alternate names for Athena, daughter of Zeus (Jupiter) and therefore a niece of Ceres. (Two chemical elements discovered in that decade were named "cerium" and "palladium" after Ceres and Pallas.)

Later planetoids were named after a variety of minor goddesses, such as *Hebe*, the cupbearer of the gods, *Iris*, their messenger, the various Muses, Graces, Horae, nymphs, and so on. Eventually the list was pretty well exhausted and planetoids began to receive trivial and foolish names. We won't bother with those.

New excitement came in 1846. The motions of Uranus were slightly erratic, and from them the Frenchman Urbain J. J. Leverrier and the Englishman John Couch Adams calculated the position of a planet beyond Uranus, the gravitational attraction of which would account for Uranus's anomalous motion. The planet was discovered in that position.

Once again there was difficulty in the naming. Bode's mythological family concept could not be carried on, for Uranus was the first god to come out of chaos and had no father. Some suggested the planet be named for Leverrier. Wiser council prevailed. The new planet, rather greenish in its appearance, was named *Neptune* after the god of the sea.

(Leverrier also calculated the possible existence of a planet inside the orbit of Mercury and named it *Vulcan*, after the god of fire and the forge, a natural reference to the planet's closeness to the central fire of the Solar System. However, such a planet was never discovered and undoubtedly does not exist.)

As soon as Neptune was discovered, the English astronomer William Lassell turned his telescope upon it and discovered a large satellite which he named *Triton*, appropriately enough, since Triton was a demigod of the sea and a son of Neptune (Poseidon).

In 1851 Lassell discovered two more satellites of Uranus, closer to the planet than Herschel's Oberon and Titania. Lassell, also English, decided to continue Herschel's English folklore bit. He turned to Alexander Pope's *The Rape of the Lock*, wherein were two elfish characters, *Ariel* and *Umbriel*, and these names were given to the satellites.

More satellites were turning up. Saturn was already known to have seven satellites, and in 1848 the American astronomer George P. Bond discovered an eighth; in 1898 the American astronomer William H. Pickering discovered a ninth and completed the list. These were named *Hyperion* and *Phoebe* after a Titan and Titaness. Pickering also thought he had discovered a tenth in 1905, and named it *Themis*, after another Titaness, but this proved to be mistaken.

In 1877 the American astronomer Asaph Hall, waiting for an unusually close approach of Mars, studied its surroundings carefully and discovered two tiny satellites, which he named *Phobos* ("fear") and *Deimos* ("terror"), two sons of Mars (Ares) in Greek legend, though obviously mere personifications of the inevitable consequences of Mars's pastime of war.

In 1892 another American astronomer, Edward E. Barnard, discovered a fifth satellite of Jupiter, closer than the Galilean satellites. For a long time it received no name, being called "Jupiter V" (the fifth to be discovered) or "Barnard's satellite." Mythologically, however, it was given the name *Amalthea* by the French astronomer Camille Flammarion, and this is coming into more common use. I am glad of this. Amalthea was the nurse of Jupiter (Zeus) in his infancy, and it is pleasant to have the nurse of his childhood closer to him than the various girl and boy friends of his maturer years.

In the twentieth century no less than seven more Jovian satellites were discovered, all far out, all quite small, all probably captured planetoids, all nameless. Unofficial names have been proposed. Of these, the three planetoids nearest Jupiter bear the names *Hestia, Hera,* and *Demeter,* after the Greek names of the three sisters of Jupiter (Zeus). Hera, of course, is his wife as well. Under the Roman versions of the names (Vesta, Juno, and Ceres, respectively) all three are planetoids. The two farthest are *Poseidon* and *Hades,* the two brothers of Jupiter (Zeus). The Roman version of Poseidon's name (Neptune) is applied to a planet. Of the remaining satellites, one is *Pan,* a grandson of Jupiter (Zeus), and the other is *Adrastea,* another of the nurses of his infancy.

The name of Jupiter's (Zeus's) wife, Hera, is thus applied to a satellite much farther and smaller than those commemorating four of his extracurricular affairs. I'm not sure that this is right, but I imagine astronomers understand these things better than I do.

In 1898 the German astronomer G. Witt discovered an unusual planetoid, one with an orbit that lay closer to the Sun than did any other of the then-known planetoids. It inched past Mars and came rather close to Earth's orbit. Not counting the Earth, this planetoid might be viewed as passing between Mars and Venus and therefore Witt gave it the name of *Eros,* the god of love, and the son of Mars (Ares) and Venus (Aphrodite).

This started a new convention, that of giving planetoids with odd orbits masculine names. For instance, the planetoids that circle in Jupiter's orbit all received the names of masculine participants in the Trojan war: *Achilles, Hector, Patroclus, Ajax, Diomedes, Agamemnon, Priamus, Nestor, Odysseus, Antilochus, Aeneas, Anchises,* and *Troilus.*

A particularly interesting case arose in 1948, when the German-American astronomer Walter Baade discovered a planetoid that penetrated more closely to the Sun than even Mercury did. He named it *Icarus,* after the mythical character who flew too close to the Sun, so that the wax holding the feathers of his artificial wings melted, with the result that he fell to his death.

Two last satellites were discovered. In 1948 a Dutch-American astronomer, Gerard P. Kuiper, discovered an innermost satellite of Uranus. Since Ariel (the next innermost) is a character in William Shakespeare's *The Tempest* as well as in Pope's *The Rape of the Lock,* free association led Kuiper to the heroine of *The Tempest* and he named the new satellite *Miranda.*

In 1950 he discovered a second satellite of Neptune. The first satellite, Triton, represents not only the name of a particular demigod, but of a whole class of merman-like demigods of the sea. Kuiper named the second, then, after a whole class of mermaid-like nymphs of the sea, *Nereid.*

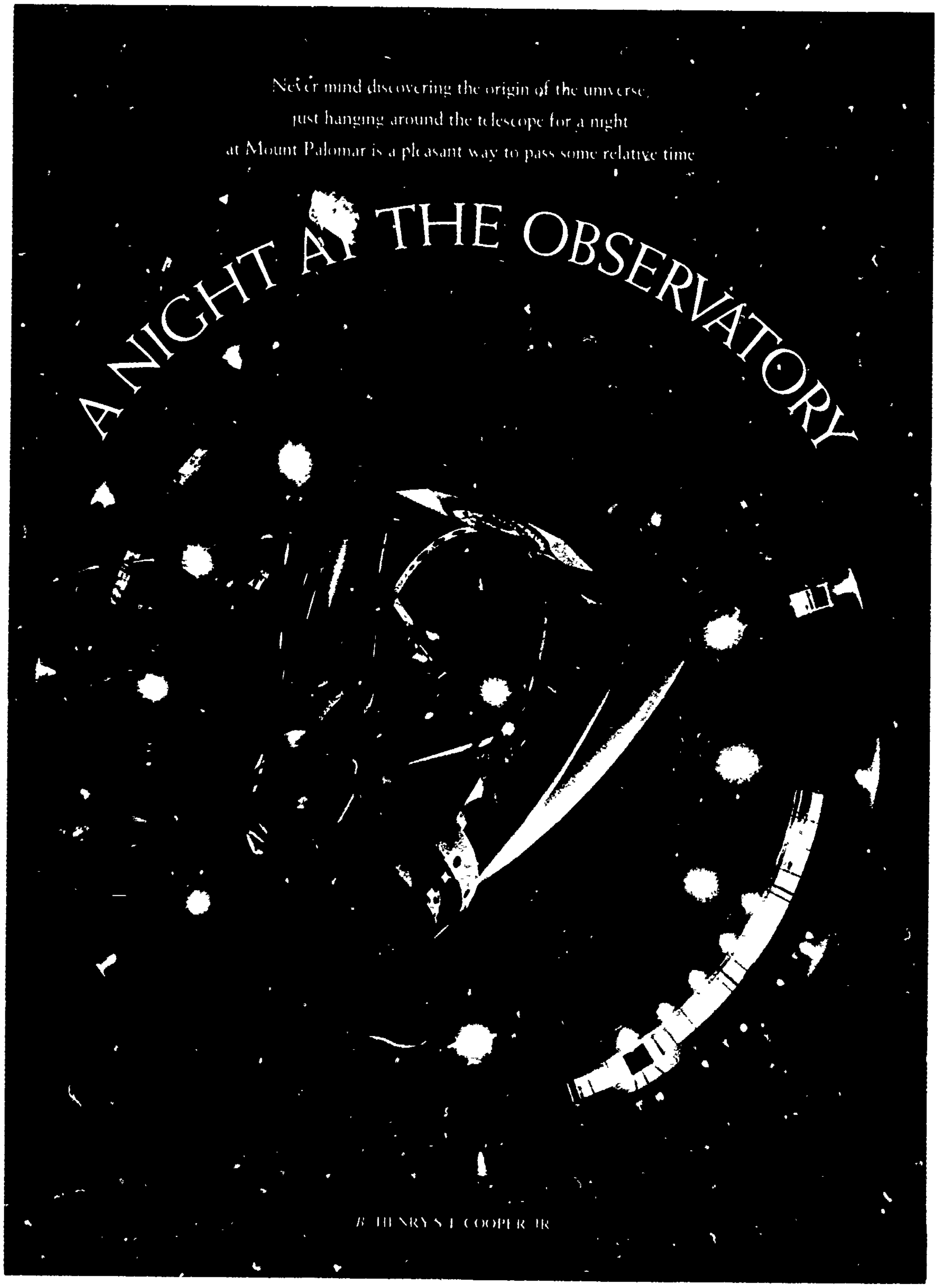
Meanwhile, during the first decades of the twentieth century, the American astronomer Percival Lowell was searching for a ninth planet beyond Neptune. He died in 1916 without having succeeded but in 1930, from his observatory and in his spirit, Clyde W. Tombaugh made the discovery.

The new planet was named *Pluto,* after the god of the Underworld, as was appropriate since it was the planet farthest removed from the light of the Sun. (And in 1940, when two elements were found beyond uranium, they were named "neptunium" and "plutonium," after Neptune and Pluto, the two planets beyond Uranus.)

Notice, though, that the first two letters of "Pluto" are the initials of Percival Lowell. And so, finally, an astronomer got his name attached to a planet. Where Herschel and Leverrier had failed, Percival Lowell had succeeded, at least by initial, and under cover of the mythological conventions.

Never mind discovering the origin of the universe,
just hanging around the telescope for a night
at Mount Palomar is a pleasant way to pass some relative time

A NIGHT AT THE OBSERVATORY



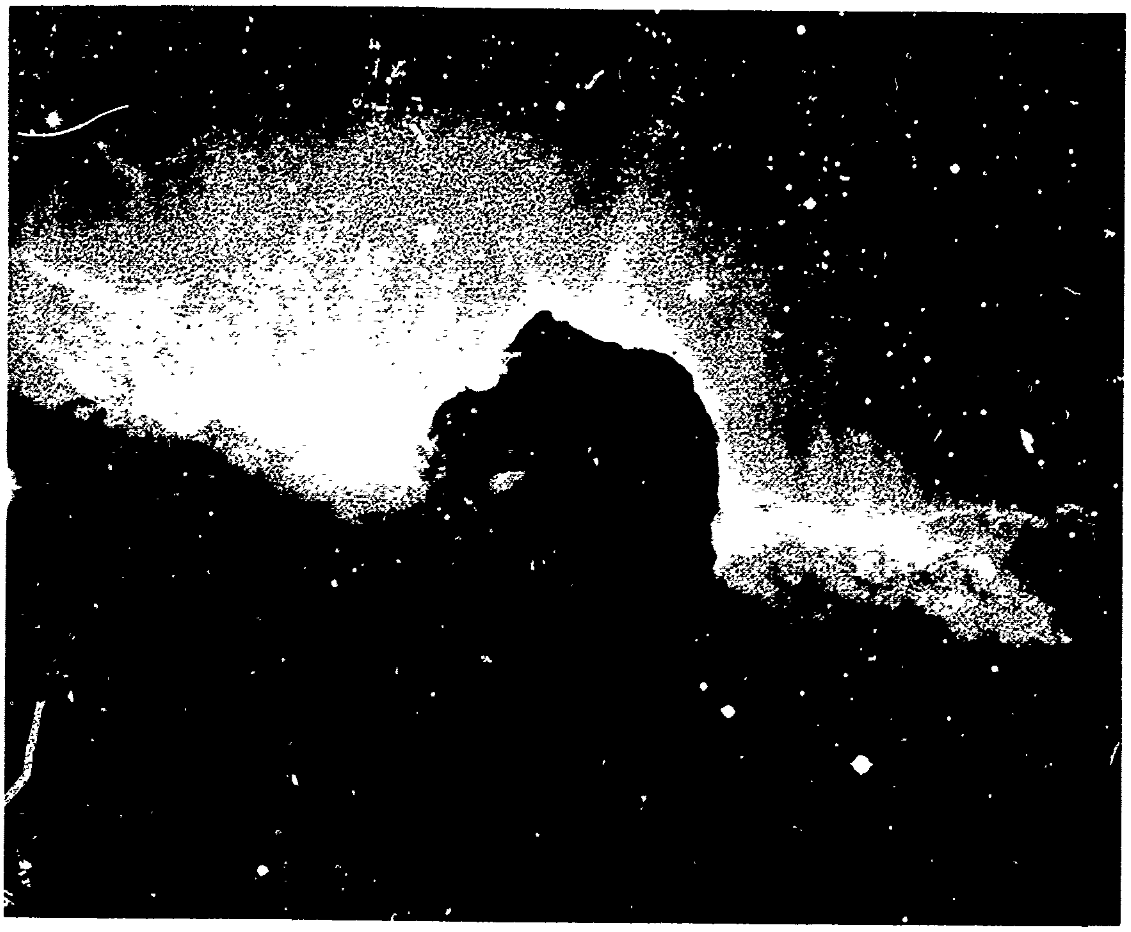
By HENRY S. F. COOPER JR.

What is it like to work at a major observatory? A reporter spends a night on Mt. Palomar talking about astronomy with Dr. Jesse L. Greenstein as he photographs star spectra with the 200-inch telescope.

3 A Night at the Observatory

Henry S. F. Cooper, Jr.

1967



"Horsehead" Nebula

A Night at the Observatory

A year ago last summer, I was invited out to Mount Palomar, the big observatory in southern California, to spend a night on the two-hundred-inch telescope A member of the observatory's staff wrote me exuberantly, "The scientists here feel that the last couple of years have been the most exciting in astronomy since Galileo." He was referring to observations of the quasars, most of which had been made at Mount Palomar. Quasars are thought to be tremendously distant objects that may be almost as old as the universe itself; as yet, not a great deal is known about them. "Dr. Jesse L. Greenstein, Executive Officer of the Department of Astronomy at Cal Tech, will be going down to Palomar soon, and he says he will be glad to have you go along," my correspondent continued. "He says to warn you not to expect any great discoveries." That was an acceptable condition. As a final admonition, he added that the telescope is extremely delicate, and before I went out I had to promise to do my best not to break it. This, I thought, would be an easy promise to keep, since the telescope is as big as a small freighter.

On my way to Palomar, I stopped in Pasadena at the California Institute of Technology, which runs the observatory. A smog that made one's eyes smart hung over the city. I found that Dr. Greenstein was already at Palomar, a hundred and thirty-five miles to the south and fifty-six hundred feet up in the clearer, cooler air. I headed south, too. The road wound through ranches and forest up and up a mountain. Soon I saw across a valley, perched on the edge of a plateau, the glistening aluminum dome of the observatory. The huge slit for the telescope to peer through was shut like a closed eyelid

On top of the plateau, which was dotted with nine sturdy yellow cottages, I headed toward the Monastery, where I expected to find Dr. Greenstein. The Monastery is the dormitory where the astronomers stay when they are using the two-hundred-inch telescope or the smaller forty-eight-inch Schmidt telescope. The Monastery is a solid building fitted out with black leather blinds for daytime sleeping. It was six o'clock in the evening. Dr Greenstein, who had been up all the night before, was in the dining room having a solitary supper; a stocky, graying man in his mid-fifties who sported a tiny, pencil-thin moustache, he was the only astronomer on the mountain. Dr. Greenstein complained about not being able to sleep. "The first night I'm down here, I can't sleep at all," he said. "It isn't until the fifth day that I get a full night's, or rather morning's, sleep, and then it's time to go back to Pasadena." I asked him how often he had to go through this sleepless state, and he answered that in his case it was about thirty-five nights a year.

"I get up here whenever I can," he went on, planting an elbow next to a half-empty coffee cup. "Time on the telescope is so valuable that you snatch at it whenever you can get it. Just *having* the two-hundred-inch telescope puts Cal Tech in a tough spot. It's a national asset, so we can't do anything trivial. Any reasonably good astronomer would have to try hard in order *not* to make an interesting discovery with it. In practice it is used mainly by the members of the Department of Astronomy, and even with just sixteen of us, we are forever feuding to get time on the telescope. Cloudy time can be a real disaster."

I said I hoped Dr. Greenstein wouldn't be clouded out tonight, and he replied that he didn't think he would be. Since he had some preparations to make for the evening's work, I accompanied him along a path from the Monastery through a dry, prickly field toward the dome. It was partially hidden over the brow of a hill; for all anyone could tell, a big silver balloon had crash-landed there.

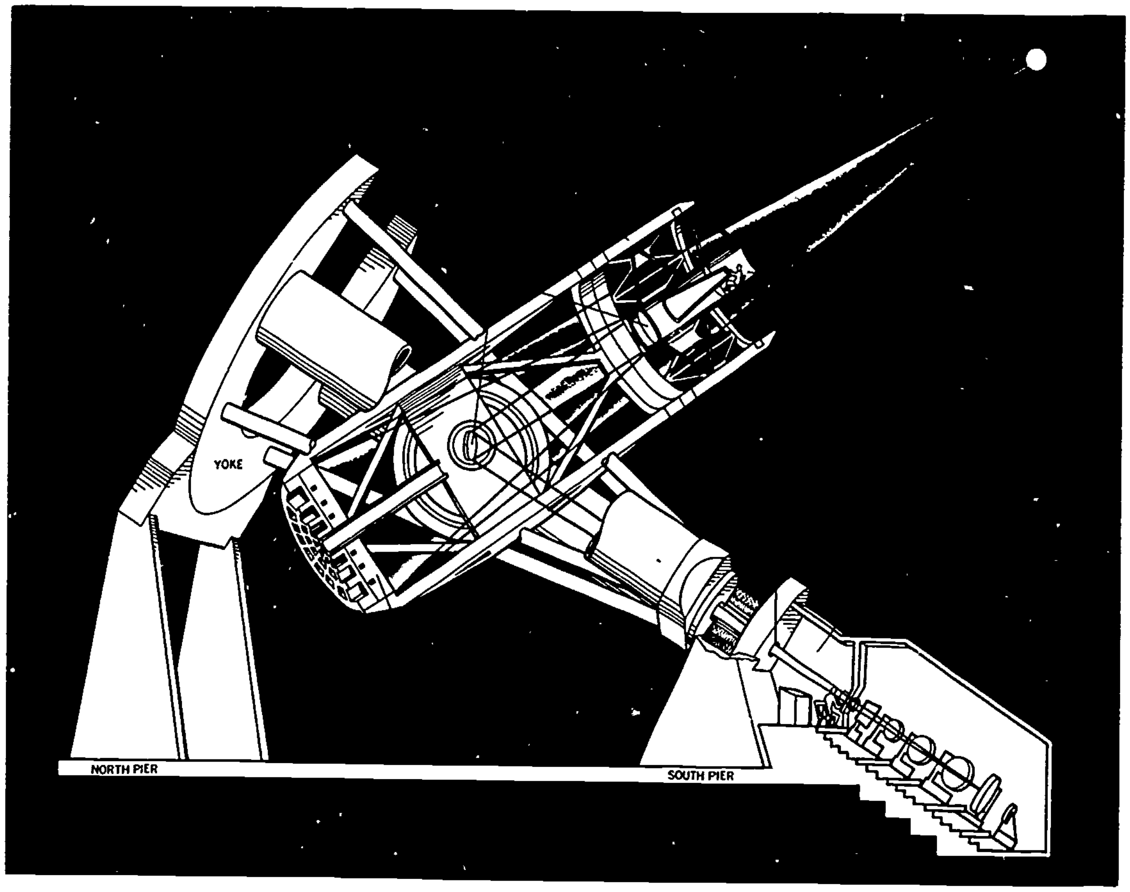
I asked Dr. Greenstein whether he had been involved with quasars lately. He shrugged. "I feel that my work, which is mostly the composition of stars within our galaxy, is more important; and current interpretations of quasars may be obsolete by next week." Although Dr. Greenstein is best known for his studies of the evolution of stars and galaxies, and of the elements within the stars, he is a top quasar man, too, and he has made observations to learn what their composition might be.

Quasars were first noticed in 1960 by radio astronomers as invisible sources of radio waves. One of these sources, 3C-48, was identified with what appeared to be a tiny, sixteenth-magnitude star. Three years later Dr. Maarten Schmidt, at Palomar, managed to concentrate on film enough of the feeble light from a quasar to get a spectrum. It appeared that quasars were not tiny stars within our own galaxy, as had been thought, but instead probably were intense and incredibly distant sources of light and radio waves. Quasar 3C-48 appears to be almost four billion light-years away, and subsequently other quasars have been measured out to almost nine billion light-years away; this is four-fifths of the way back to the "big bang" with which the universe supposedly began.

By studying the quasars, it may be possible to learn whether the universe will expand indefinitely; or whether it will stop some day; or whether it will fall back in upon itself for another big bang—and if so, when these events will take place. But a great deal more information is needed about the quasars, including the answer to why they shine so much more brightly than even the brightest galaxies. This is a problem that Dr. Greenstein is working on.

"As it happens, I don't like working with quasars," Dr. Greenstein continued as we trudged along. "They're tricky little things. I don't even like the word 'quasar.' It was invented by a Chinese astronomer in New York

The huge Hale telescope, seen from the floor of the Palomar observatory in the "fish-eye" photograph opposite, is the largest reflecting telescope in the world Its 200-inch mirror is at lower left, at right, silhouetted by a patch of sky, is the elevator to the prime-focus cage



In operation the Hale telescope resembles nothing so much as a large bucket made to gather light. The mirror collects light and bounces it fifty-five feet up to a focal point where the prime-focus cage is located. For spectrographic analysis, the light is reflected back down and out to the room at lower right

who doesn't speak English well. Chinese is like Hebrew, which has no vowels. He saw the letters QSRS, which stand for quasi-stellar radio source, on a chart, and called them 'quasars.' We shouldn't have a vocabulary for what we don't know, and when we do know what the quasars are, we will have a better word for them. Quasar sounds as if it's short for quasi-star, and that's the one thing we know a quasar isn't." Dr. Greenstein observed that the sky, darkening fast now, was beautifully clear. The moon, about half full, was rising in the east, clear crystal against the dark blue background, which, Dr. Greenstein said, augured well for seeing tonight. The setting sun glinted red on the dome. Dr. Greenstein glanced at the cirrus clouds in the west, which were reddening as the sun sank. "Sunsets are nice," he said, "but you haven't seen anything until you see a sunrise at Palomar."

The dome, which is nine stories tall and as much as that in diameter, rises from a round, yellow, cement drum. Dr. Greenstein fitted a key in a latch, and soon we were blinking our eyes inside a cavernous, pitch-black room three stories below the telescope. Dr. Greenstein said he had some work to do in his darkroom and suggested I go to the third floor and take a look at the telescope.

The inside of the dome was stuffy, dim, mysterious, and silent ex[illegible]r the echo of some approaching footsteps. The telescope loomed in the center of the room, shadowy and intricate, its works mostly exposed, like a fine timepiece under a glass bell. The telescope, Dr. Greenstein had told me, works something like a clock. Its tube has to keep time exactly with the movement of the stars so that a star's light can stay riveted to a photographic plate for several hours at a stretch. The telescope, with its reflecting mirror two hundred inches in diameter, serves as a sort of bucket to catch as much light as possible from a star and concentrate it on film. it could pick up the light of a ten-watt bulb a million miles away The purpose of the telescope is not to magnify, for no matter how great the magnification, no star would ever show up as more than a point of light.

The footsteps I had heard belonged to the night assistant for the telescope, Gary Tuton, a lean young man with short, wavy hair. Tuton is the technician who runs the telescope for the astronomers He walked over to a control console and pressed a button The telescope sprang into life. The big mirror, which weighs almost fifteen tons, rests at the bottom of the telescope tube, an open steel cylinde some sixty feet long The tube swivels north and south inside a huge frame called the yoke, and the yoke swivels from east to west on two enormous bearings, so that the tube, with the mirror at its bottom, can aim at any point in the sky

Now the yoke spun to the east and the tube swiveled to the north, only, since both these motions happened simultaneously, the movement was one smooth undulation The tube can be locked on a star, just as the pencil in a compass can be locked at any given radius. Then the star can be tracked along its path simply by turning the yoke, which is fixed on the North Star as if it were the dot at the center of a circle. The movement of the yoke has to be very delicate. Tuton explained that the huge bearings at either end of the yoke are floated on thin films of oil so that the telescope, which weighs five hundred tons, can be turned by hand. The oil pumps under the enormous bearings whined. The observatory sounded like a very active railroad yard

Slowly and ponderously the two-hundred-and-twenty-five-ton doors that covered the slit in the dome pulled aside, revealing a widening band of dark blue sky. It was like being inside the eye of an awakening animal. "Sometimes, in winter, when the dome is covered with snow, I have to go up top and sweep the snow off the slit," Tuton said "One night last winter it got so cold that the gears on the doors that cover the slit in the dome froze. No matter what I did, one shutter would shut and the other wouldn't, and there was a snowstorm coming But by and large the weather is pretty good up here. Last year we used the telescope on three hundred and ten nights"

A door banged and Dr Greenstein appeared, struggling under a load of lenses and photographic film. Since it was still too early to begin taking pictures, Dr. Greenstein said that he was going up into the prime-focus cage at the top of the telescope tube and invited me to come along "I want to take a look at a group of stars, a globular cluster called Messier 13," he said. "There's a peculiar star in it that I want to get a spectrum of later on It's in with such a mass of other stars that I want to make sure I get my bearings straight."

Dr. Greenstein explained that the prime focus was the simplest and most direct way of looking through the telescope. There are several different ways, and none of them is the conventional one, used with binoculars or refractor telescopes, of holding the telescope up to your eyes. Instead of focusing light through a lens, the big mirror bounces the light back up the tube and concentrates it at a point fifty-five feet above. The exact spot is called the prime focus The astronomer sits in the prime-focus cage, which is like a balloonist's basket high inside the telescope tube, and from this vantage point he can photograph the image directly.

"I like it in the prime-focus cage," Dr. Greenstein concluded "You feel closer to the stars" Then he frisked himself and me, removing any hard objects, such as coins and pens, that might fall on the mirror and damage it. It had taken eleven years to polish the mirror into exactly the right configuration; a scratch could mean years more polishing. We climbed to a balcony, boarded the dome elevator, and began a long, hair-raising ascent as the elevator rose upward and outward, following the overhanging contour of the dome Through the slit we could see the ground several stories below, and several thousand feet below that, the lights of the valley floor The dome elevator is a peculiar, unenclosed contraption like a long spoon, we stood at the outer end of it where the bowl would be. After a bumpy ride, the elevator deposits the astronomer, like a dollop of medicine, inside the mouth of the telescope. At this point, the astronomer is about seventy feet above the floor of the dome, with very little to hang on to

"People have gotten killed on telescopes," Dr. Greenstein said with what I thought was poor timing as we lurched unevenly up and out. "Sometimes astronomers get squashed by a telescope slewing about, but that doesn't happen very often."

I gripped the railing of the elevator, fixed my eyes firmly on the top of the dome, and asked Dr Greenstein to tell me more about the peculiar star in Messier 13. "Glo ular clusters, like Messier 13, are sort of suburbs of our galaxy which contain some of the oldest stars, and for this reason they might have a bearing on the quasars, which are supposed to be primordial objects, too," he said. "However, the star I want to look at now is blue, a color usually associated with younger stars, so in this case it must represent a peculiar stage of evolution. Although this star—Barnard 29—is blue, it has a peculiar energy distribution. Its spectrum is too much in the red, and one possibility I want to check tonight is whether it couldn't in fact be a close pair, a double star, one blue and one red."

Soon we were directly on top of the telescope tube, and Dr. Greenstein flung open a flimsy gate at the end of the elevator platform. The prime-focus cage—a bucket perhaps five feet in diameter and five feet deep—was about eighteen inches below us. Dr. Greenstein explained that the elevator couldn't go all the way to the cage because of

the danger of collision with the telescope we would have to travel across the remaining gap ourselves So saying, he flung himself into the void and disappeared into the mouth of the telescope

Inside the bucket was a chair and an empty well that looked straight down at the mirror, the astronomer fits his instruments into the well. When Tuton was sure that we were safely installed, and that nothing could drop on the mirror, he opened the diaphragm that covered it Slowly, like a water lily, the petals of the diaphragm lifted, revealing what looked like a pond of rippling, shimmering water beneath The stars, which wouldn't stay still, were streaking like meteors, the mirror, it seemed, was popping a few millionths of an inch with the change of temperature. Tuton slewed the telescope off in search of Messier 13 and Barnard 29. As one side of the bucket dipped suddenly down, the chair, which was on rails, moved around and down with gravity, so that the astronomer was always upright, the sensation was like riding very slowly in a Ferris wheel. Stars shot through the big mirror as we sailed along. The telescope came to a smooth halt, moving just fast enough to keep the stars still in spite of the rotation of the earth. Dr. Greenstein peered into the pool of light for a moment. Then he maneuvered a tiny lens that looked like a magnifying glass—it was tied to the well with a string—until he found the exact spot where the image was clearest This was the prime focus

"We're right on the beam," Dr. Greenstein said, handing the lens to me As I looked down, I felt my glasses begin to slide down my nose; I grabbed them just before they dropped down the well toward the mirror. The lens resolved the chaotic splotches of dancing light, and I saw an enormous rash of stars, each one a point of hard, brilliant light. I couldn't make out Barnard 29. Dr. Greenstein was able to converse with Tuton over an intercom. and he asked him to stop the telescope's tracking drive No sooner had the telescope stopped moving than Messier 13 and Barnard 29 slipped out of the field of vision Other stars whizzed across the mirror, following Messier 13 into seeming oblivion. a given star crossed the mirror in about ten seconds, before vanishing That, Dr Greenstein said, showed how fast the earth, with the telescope, was turning. Tuton's voice crackled through the microphone, asking how I felt. I replied that I was getting a little dizzy. Tuton started up the tracking device; the telescope passed all the stars that had been whipping by, and soon we were safely back with Messier 13.

Dwarfed by the telescope's huge frame, an astronomer stands on the mirror casing prior to its intallation at the observatory in 1948.

"Did Dr. Greenstein tell you about the time I was stuck up there?" Tuton asked; and his voice crackled on, "I was in the prime-focus cage when the power for the telescope shorted out It was a cold winter night. I had to climb down, which was the hairiest thing I ever did. What made me do it was not the cold so much as what the men who came in the morning would say I'd never have lived it down."

At last Tuton wafted the telescope toward the elevator platform for us to board. I fixed my eye on the top of the dome again. Dr. Greenstein glanced at his watch and said that he wished the elevator would hurry, because it was already dark enough to start using the spectrograph. He shouted down to Tuton to start setting up the telescope for the coudé focus. The coudé focus is in a room outside the telescope altogether, and the light from a star is deflected to it by a mirror—called the coudé flat—which bounces the starlight in a thin beam down through a hole in the southern foundation of the telescope and into the coudé room one floor below, where the spectrographs are kept. The film to record the spectrum of a star is in this room, which serves something of the purpose of an old Brownie box camera. As we reached the ground, an electronic engine whirred and the coudé flat, weighing a ton and a half, lifted slowly into position just below the prime-focus cage It glittered like a jewel inside a watch

Dr Greenstein fetched the films he had brought with him and disappeared down the steps into the coudé room. a tiny chamber that descends steeply in line with the yoke, pointing at the North Star. It was already after eight o'clock. Barnard 29 was nestled among so many stars that the final zeroing in had to be done by dead reckoning "There's a sort of triangle of stars," said Dr. Greenstein, who had returned to the control room at the top of the steps "See it? There ought to be a double star on the upper left. Got it?" He sounded like a man finding his way with a road map. Tuton said he had it "Do you know what the most difficult object to find is?" Tuton asked as he turned a knob for fine adjustment; I said I didn't "It's the moon The moon is so close, and it's moving so fast, that it's like trying to aim a rifle at a moving target close by, instead of at the trees standing behind it "

All of a sudden, Barnard 29 disappeared from view. It was as if the telescope had gone dead. Tuton raced out into the dome and peered up at the sky through the slit; a long, wispy cloud was obstructing the view. "Looks like it's going to be a cloud-dodging night," he said. Quickly Tuton and Greenstein flipped the telescope to another star, called HD 165195, which was in a cloudless part of the sky.

I asked Dr. Greenstein whether we would see any quasars that night. "The moon is up, so we can't work on anything as dim as quasars," he said. "That's probably just as well There isn't much you can tell by looking at a quasar anyway. Instead, I will be doing long exposures on some of the oldest stars in the galaxy, The procedure is much the same as with quasars; and in fact part of what we'll be doing is related to quasars. There is a theory that has to be explored that the quasars are a remnant of the first formation of galaxies According to this theory, during the contraction of the gases that formed the galaxies, some super-massive objects formed within them. These objects may have become extremely dense and pulled themselves together so rapidly that they exploded Perhaps that is what the quasars are. I don't know I'm fairly neutral on the subject There is evidence in our own galaxy of a superexplosion far greater than the explosion of a supernova, but less, I think, than a quasar explosion In any event, if the quasars represent monumental explosions within galaxies during the half-billion years or so that the galaxies and the stars were condensing out of primeval gas clouds, then you would expect that the oldest stars, the first to condense from the gases, would be heavily contaminated by the elements in the quasars They would have been loaded with the products of quasar evolution "

Dr Greenstein turned out the lights in the control room and pressed a button to start the exposure The control room was lit only by the soft-green glow of the dials on the control panel, like the cockpit of an airplane at night. "So I will be looking at some of the oldest stars in our galaxy, like this one, to see whether they have the same elements and in roughly the same proportions, as the quasars. We don't know yet the exact composition of the quasars, but we may be able to do something with oxygen or iron. If they have the same elements, it might indicate quasars were the raw material in forming stars. But if there are other elements aside from those found in quasars, it might prove that the quasars are not important in star evolution, for the oldest stars don't seem to have manufactured many new elements after their formation, such as metals. But if I find a trace of metal in HD 165195, I have to decide whether it might have been cooked within the star after all, or whether the metal was part of the original gases of which the star was composed. The chances are we won't know much more after tonight I'll need this type of information on hundreds of stars before I can begin to get anywhere "

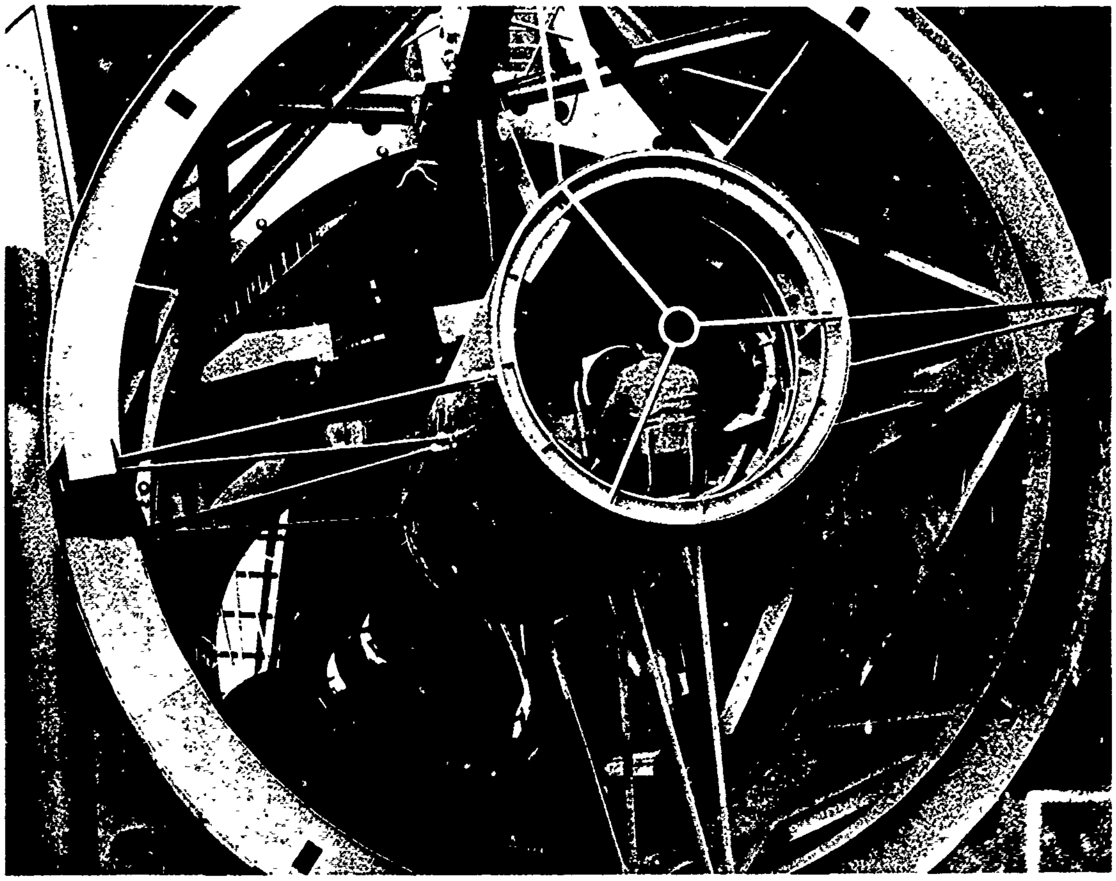
The time was eight-thirty I found myself standing in the path of the slender stream of light from HD 165195, and Dr Greenstein asked me to step out of the way, which wasn't easy, since the control room was cramped and narrow A ticking sound filled the room Dr Greenstein said that the ticking came from the photoelectric scaler, which counts the number of photons coming from a star, like a light meter Each tick meant twenty thousand photons of light A dial kept count of the ticks, and Dr Greenstein said that, for this exposure, he wanted about thirty-three hundred

He invited me to look through the eyepiece of the spectrograph A spectrograph, an apparatus in the control room that intercepted the light coming from HD 165195, refracts and spreads out the light from a star into its component wave lights, giving a spectrum something like the light from a prism The lines in a spectrum show the elements in a star They also show how fast an object is receding from the earth by how much the lines are shifted to the red end of the spectrum This is called the red shift, and it was in this way that Schmidt first decided the quasars were tremendously distant objects Through the eyepiece, the star appeared as a fuzzy, bright-green spark, the star's light had been shattered by passing through a slit and some gratings inside the spectrograph. Dr. Greenstein said the light had left the star ten thousand years ago. Tuton darted across to the telescope's control panel and slowed down the telescope's tracking drive by a tiny fraction. "We want to make the star trail along the slit in the spectrograph," he said "This is what we have to do with faint objects It's like painting one brush stroke over another, until you get the proper intensity on the plate."

With everything squared away, Tuton settled down by the eyepiece, stretched, yawned, and tuned in a radio to a rock-'n'-roll station in San Bernardino He kept an ear cocked to make sure the ticking didn't stop, and every once in a while he checked the eyepiece to make sure the star was still there. I asked Dr Greenstein why he and the other astronomers couldn't stay in Pasadena, and phone down to Tuton whenever they wanted a plate taken of a star. "There are too many things that can go wrong," Dr. Greenstein said "I wouldn't know whether a plate was any good or not unless I was here " Tuton concurred with him "I've never been trained in astronomy," he said "I can run the telescope all right, and find a star, but when it comes to astronomy, I just haven't the foggiest idea what's going on The astronomer never says what he's doing Half the time he doesn't know what he's done until he's gotten back to Pasadena I didn't know anything about quasars until I read about them in the papers " Then Tuton pulled out a magazine, which he squinted at by the light of the dials

Dr. Greenstein suggested that we go out on the catwalk Except for a gentle breeze, the plateau was absolutely still I could see the smaller dome of the Schmidt telescope about half a mile to the east. Dr. Greenstein pointed out a spot between the two domes where an Air Force bomber had crashed four years earlier, killing the crew and two horses that belonged to the superintendent of the observatory but miraculously doing no damage to the telescope. Away to the northwest, the smog over Los Angeles glowed—possibly in something of the way the outer gases of the quasars shine, powered by some mysterious force inside. There was a light mist on the mountain, and the half-moon glowed overhead "Only spectrograph work can be done in full moonlight, and even that is terribly difficult," Dr. Greenstein said. "You have to be very careful that the moonlight doesn't contaminate your plate. I thought I'd made a great spectro-

MOUNT WILSON AND PALOMAR OBSERVATORIES



Seated in the prime-focus cage his back to the sky an astronomer photographs images reflected up from the 200-inch mirror

graphic discovery once, only to find that it was the light of the moon, and not of the star There is a gadget called a moon eliminator I wish we could get rid of the moon for good!"

Dr Greenstein glanced at his watch It was eleven o'clock. "The night's young yet," he said energetically He went inside, bustled into the control room, checked the dial that counted the ticks, and shut down the spectrograph Tuton slewed the telescope to another star, BD 39°4926, which Dr Greenstein explained was also very old and might shed light on whether quasars had to do with galaxy formation Then, since the exposure would last for three hours, Dr Greenstein went downstairs to his darkroom to develop the plate on HD 165195

Amid a sloshing of water and the acrid odor of hypo Dr Greenstein said, "I don't really believe that the older stars are residues of quasars I don't believe the quasars are a part of galaxies, and therefore I don't happen to believe that they have anything to do with star evolution There is evidence of giant explosions in galaxies now, but whether these caused quasars or not, we don't know But what we know of quasars really isn't conducive to the formation of stars I don't believe quasars come from explosions, though other astronomers do Speculation is like the stock market I feel that the quasars instead may be in some kind of balance condition, like a star, and that they are isolated objects, and that they are formed of matter between galaxies Other people feel they are little things which have been blown out of galaxies Another group believes that the quasars are extremely dense objects and that their red shifts are caused by gravity, rather than by speed or distance I don't know The best we can do is to test the different theories, which is what I'm trying to do now "

Just after midnight, Dr Greenstein came up from the darkroom: He checked the star, which was ticking away nicely on the slit, and sat on a table "That's all the developing I do tonight," he said "It's too risky when you're tired" He had evidently lost his second wind. I asked him if he had been able to tell anything about HD 165195, and he said he hadn't "It's too late at night for discoveries," he said with a yawn. "There's nothing like making a great discovery that you might absent-mindedly wipe off the plate with a wet finger. I make it a rule never to make great discoveries after midnight."

Dr. Greenstein yawned again I followed him over to a couple of reclining chairs by the control console under the north bearing. Just visible in the starlight, he lay back with his arms folded behind his head as a pillow and his eyes shut. The moon, for the time being, was obscured, so it was unusually dark inside the dome. As I became more accustomed to the darkness—it was much darker than in the control room, which contained a number of luminous dials—I could make out more and more of the telescope. Dr. Greenstein opened his eyes. "I could look at it forever," he said. "No matter how long you look at it, it always looks different It looks different now, when you can barely see it in the dim starlight, from what it did a few minutes ago in the light of the half-moon. It's different from whatever side you look at it Right now, it just sits there and broods. It is a remarkable subordination of brute force for delicate ends All this mechanism is for is to move one piece of glass, and all the glass is for is to carry one thin layer of aluminum that reflects starlight. I wish it were quieter! We must get rid of those oil pumps."

At last Dr. Greenstein's voice drifted off He was fast asleep. After a time he sat bolt upright and looked at his watch. It was two fifteen. Above him, the telescope was almost completely on its side, as if it, too, had been asleep. Over the last three hours, its tracking of BD 39°4926 had caused it to assume this position. The ticking ceased abruptly when Dr. Greenstein checked the meter and ended the exposure After rummaging around in the inky coudé room to change plates, Dr Greenstein came back to the control room and decided to return to Barnard 29. "We need about three hours, though with this much moon, I doubt if we'll get it," he said briskly as he zeroed in the telescope. As he was talking, the ticking became more and more sporadic, slowing down; finally it stopped altogether. Tuton, who had had no nap, and who looked a little scruffy, went out under the dome and squinted up through the slit. Barnard 29 was obscured by clouds again. "What do we do now?" Tuton asked Greenstein Tuton said that what he would like to do now would be go home and go to bed.

"We're getting only about ten minutes' exposure time to the hour, but as long as I can get even that much, I can't shut down," Dr. Greenstein said, and added unhappily, "the telescope's time is more valuable than my own" It costs one thousand dollars a night to operate the telescope. Suddenly a great rift appeared in the clouds, and the moon emerged. It was greeted with a terrific burst of ticks Dr Greenstein shouted to Tuton to shut off the spectrograph. "We're better off wasting exposure time and not getting contamination," Dr. Greenstein grumbled, exhaling a cloud of cigar smoke that glowed derisively in the moonlight. It was a little after two forty-five, and I had the impression that Dr. Greenstein was about to call it a night

At three fifteen the sky cleared and Tuton started the exposure once more. Since he was stiff and tired, Dr. Greenstein suggested another spin around the catwalk. There was low-lying mist on the plateau, and not far away a jay woke up raucously. The air was chill and damp. The east was as dark as ever, but Dr. Greenstein said he could see the zodiacal light, which heralds the dawn "We won't be able to keep the exposure going much longer," he went on. "The sun is already beginning to heat up the atmosphere to the east, which makes it bubble a bit." Groggily, I looked for bubbles in the east, but saw none. A flush of pink appeared and spread rapidly; the stars to the east blinked out, though the ones to the west were, for the time being, as hard and brilliant as they had been for most of the night. Shadows grew where none had been before, and we could begin to see colors—the green of the pines, the pink clay of the road. Dr. Greenstein went back inside and called down to Tuton to turn off the exposure before it was contaminated

The inside of the dome was suffused with pink; the dome's interior, too, was of brilliant aluminum, and caught the dawn through the slit. The telescope was visible again, like a dinosaur emerging from a misty bog. "This is *my* time on the telescope," Tuton said, "the time after dawn, but before all the stars are washed out. It's useless for spectrography or photography, so I just aim the telescope at what I want to look at. I think Saturn is in a good position for viewing."

He consulted an astronomy book and quickly swung the telescope to a new position. He snapped the eyepiece into place, focusing it. He stepped aside, and I took a look. There was Saturn, as big as a football and, with its rings forming an oval around it, somewhat the same shape Through the two-hundred-inch telescope, Saturn was so brilliant that it hurt the eyes. Dr. Greenstein squinted through the eyepiece, grunting "I never particularly liked the solar system," he said, relinquishing the telescope. I looked again; Saturn was less brilliant than before, and it was fading fast in the sunlight. Soon it vanished altogether, like the Cheshire cat, leaving nothing behind but a patch of pale-blue sky.

Henry S. F. Cooper, Jr., a member of the editorial staff of The New Yorker, *writes frequently on scientific subjects*

Copernicus addresses this preface of his revolutionary book on the solar system to Pope Paul III.

4 Preface to De Revolutionibus

Nicolaus Copernicus

1543

TO THE MOST HOLY LORD, POPE PAUL III.

THE PREFACE OF NICOLAUS COPERNICUS TO THE BOOKS OF THE REVOLUTIONS

I may well presume, most Holy Father, that certain people, as soon as they hear that in this book *On the Revolutions of the Spheres of the Universe* I ascribe movement to the earthly globe, will cry out that, holding such views, I should at once be hissed off the stage. For I am not so pleased with my own work that I should fail duly to weigh the judgment which others may pass thereon; and though I know that the speculations of a philosopher are far removed from the judgment of the multitude—for his aim is to seek truth in all things as far as God has permitted human reason so to do—yet I hold that opinions which are quite erroneous should be avoided.

Thinking therefore within myself that to ascribe movement to the Earth must indeed seem an absurd performance on my part to those who know that many centuries have consented to the establishment of the contrary judgment, namely that the Earth is placed immovably as the central point in the middle of the Universe, I hesitated long whether, on the one hand, I should give to the light these my Commentaries written to prove the Earth's motion, or whether, on the other hand, it were better to follow the example of the Pythagoreans and others who were wont to impart their philosophic mysteries only to intimates and friends, and then not in writing but by word of mouth, as the letter of Lysis to Hipparchus witnesses. In my judgment they did so not, as some would have it, through jealousy of sharing their doctrines, but as fearing lest these so noble and hardly won discoveries of the learned should be despised by such as either care not to study aught save for gain, or—if by the encouragement and example of others they are stimulated to philosophic liberal pursuits—yet by reason of the dulness of their wits are in the company of philosophers as drones among bees. Reflecting thus, the thought of the scorn which I had to fear on account of the novelty and incongruity of my theory, well-nigh induced me to abandon my project.

These misgivings and actual protests have been overcome by my friends. First among these was Nicolaus Schönberg, Cardinal of Capua, a man renowned in every department of learning. Next was one who loved me well, Tiedemann Giese, Bishop of Kulm, a devoted student of sacred and all other good literature, who often urged and even importuned me to publish this work which I had kept in store not for nine years only, but to a fourth period of nine years. The same request was made to me by many other eminent and learned men. They urged that I should not, on account of my fears, refuse any longer to contribute the fruits of my labours to the common advantage of those interested in mathematics.

They insisted that, though my theory of the Earth's movement might at first seem strange, yet it would appear admirable and acceptable when the publication of my elucidatory comments should dispel the mists of paradox. Yielding then to their persuasion I at last permitted my friends to publish that work which they have so long demanded.

That I allow the publication of these my studies may surprise your Holiness the less in that, having been at such travail to attain them, I had already not scrupled to commit to writing my thoughts upon the motion of the Earth. How I came to dare to conceive such motion of the Earth, contrary to the received opinion of the Mathematicians and indeed contrary to the impression of the senses, is what your Holiness will rather expect to hear. So I should like your Holiness to know that I was induced to think of a method of computing the motions of the spheres by nothing else than the knowledge that the Mathematicians are inconsistent in these investigations.

For, first, the mathematicians are so unsure of the movements of the Sun and Moon that they cannot even explain or observe the constant length of the seasonal year. Secondly, in determining the motions of these and of the other five planets, they do not even use thesame principles and hypotheses as in their proofs of seeming revolutions and motions. So some use only concentric circles, while others eccentrics and epicycles. Yet even by these means they do not completely attain their ends. Those who have relied on concentrics, though they have proven that some different motions can be compounded therefrom, have not thereby been able fully to establish a system which agrees with the phenomena. Those again who have devised eccentric systems, though they appear to have well-nigh established the seeming motions by calculations agreeable to their assumptions, have yet made many admissions which seem to violate the first principle of uniformity in motion. Nor have they been able thereby to discern or deduce the principal thing—namely the shape of the Universe and the unchangeable symmetry of its parts. With them it is as though an artist were to gather the hands, feet, head and other members for his images from divers models, each part excellently drawn, but not related to a single body, and since they in no way match each other, the result would be monster rather than man. So in the course of their exposition, which the mathematicians call their system (μέθοδος) we find that they have either omitted some indispensable detail or introduced something foreign and wholly irrelevant. This would of a surety not have been so had they followed fixed principles; for if their hypotheses were not misleading, all inferences based thereon might be surely verified. Though my present assertions are obscure, they will be made clear in due course.

I pondered long upon this uncertainty of mathematical tradition in establishing the motions of the system of the spheres. At last I began to chafe that philosophers could by no means agree on any one certain theory of the mechanism of the Universe, wrought for us by a supremely good and orderly Creator, though in other respects they investigated with meticulous care the minutest points relating to its orbits. I therefore took pains to read again the works of all the philosophers on whom I could lay hand to seek out whether any of them had ever supposed that the motions of the spheres were other than those demanded by the mathematical schools. I found first in Cicero that Hicetas * had realized that the Earth moved. Afterwards I found in Plutarch that certain others had held the like opinion. I think fit here to add Plutarch's own words, to make them accessible to all: —

> "The rest hold the Earth to be stationary, but Philolaus the Pythagorean says that she moves around the (central) fire on an oblique circle like the Sun and Moon. Heraclides of Pontus and Ecphantus the Pythagorean also make the Earth to move, not indeed through space but by rotating round her own centre as a wheel on an axle † from West to East."

Taking advantage of this I too began to think of the mobility of the Earth; and though the opinion seemed absurd, yet knowing now that others before me had been granted freedom to imagine such circles as they chose to explain the phenomena of the stars, I considered that I also might easily be allowed to try whether, by assuming some motion of the Earth, sounder explanations than theirs for the revolution of the celestial spheres might so be discovered.

Thus assuming motions, which in my work I ascribe to the Earth, by long and frequent observations I have at last discovered that, if the motions of the rest of the planets be brought into relation with the circulation of the Earth and be reckoned in proportion to the orbit of each planet, not only do their phenomena presently ensue, but the orders and magnitudes of all stars and spheres, nay the heavens themselves, become so bound together that nothing in any part thereof could be moved from its place without producing confusion of all the other parts and of the Universe as a whole.

In the course of the work the order which I have pursued is as here follows. In the first book I describe all positions of the spheres together with such movements as I ascribe to Earth; so that this book contains, as it were, the general system of the Universe. Afterwards, in the remaining books, I relate the motions of the other planets and all the spheres to the mobility of Earth, that we may gather thereby how far the motions and appearances of the rest of the planets and spheres may be preserved, if related to the motions of the Earth.

I doubt not that gifted and learned mathematicians will agree with me if they are willing to comprehend and appreciate, not superficially but thoroughly, according to the demands of this science, such reasoning as I bring to bear in support of my judgment. But that learned and unlearned alike may see that I shrink not from any man's criticism, it is to your Holiness rather than anyone else that I have chosen to dedicate these studies of mine, since in this remote corner of Earth in which I live

* C. writes Nicetas here, as always.

† Reading 'ενηξοι ισμένηι.

you are regarded as the most eminent by virtue alike of the dignity of your Office and of your love of letters and science. You by your influence and judgment can readily hold the slanderers from biting, though the proverb hath it that there is no remedy against a sycophant's tooth. It may fall out, too, that idle babblers, ignorant of mathematics, may claim a right to pronounce a judgment on my work, by reason of a certain passage of Scripture basely twisted to suit their purpose. Should any such venture to criticize and carp at my project, I make no account of them; I consider their judgment rash, and utterly despise it. I well know that even Lactantius, a writer in other ways distinguished but in no sense a mathematician, discourses in a most childish fashion touching the shape of the Earth, ridiculing even those who have stated the Earth to be a sphere. Thus my supporters need not be amazed if some people of like sort ridicule me too.

Mathematics are for mathematicians, and they, if I be not wholly deceived, will hold that these my labours contribute somewhat even to the Commonwealth of the Church, of which your Holiness is now Prince. For not long since, under Leo X, the question of correcting the ecclesiastical calendar was debated in the Council of the Lateran. It was left undecided for the sole cause that the lengths of the years and months and the motions of the Sun and Moon were not held to have been yet determined with sufficient exactness. From that time on I have given thought to their more accurate observation, by the advice of that eminent man Paul, Lord Bishop of Sempronia, sometime in charge of that business of the calendar. What results I have achieved therein, I leave to the judgment of learned mathematicians and of your Holiness in particular. And now, not to seem to promise your Holiness more than I can perform with regard to the usefulness of the work, I pass to my appointed task.

The introduction to Galileo's Starry Messenger not only summarizes his discoveries, but also conveys Galileo's excitement about the new use of the telescope for astronomical purposes.

5 The Starry Messenger

Galileo Galilei

1610

ASTRONOMICAL MESSAGE
Which contains and explains recent observations
made with the aid of a new spyglass[3]
concerning the surface of the moon,
the Milky Way, nebulous stars, and
innumerable fixed stars,
as well as four planets never before seen, and
now named
THE MEDICEAN STARS

Great indeed are the things which in this brief treatise I propose for observation and consideration by all students of nature. I say great, because of the excellence of the subject itself, the entirely unexpected and novel character of these things, and finally because of the instrument by means of which they have been revealed to our senses.

Surely it is a great thing to increase the numerous host of fixed stars previously visible to the unaided vision, adding countless more which have never before been seen, exposing these plainly to the eye in numbers ten times exceeding the old and familiar stars.

It is a very beautiful thing, and most gratifying to the sight, to behold the body of the moon, distant from us almost sixty earthly radii,[4] as if it were no farther away than

[3] The word "telescope" was not coined until 1611. A detailed account of its origin is given by Edward Rosen in *The Naming of the Telescope* (New York, 1947). In the present translation the modern term has been introduced for the sake of dignity and ease of reading, but only after the passage in which Galileo describes the circumstances which led him to construct the instrument (pp. 28–29).

[4] The original text reads "diameters" here and in another place. That this error was Galileo's and not the printer's has been convincingly shown by Edward Rosen (*Isis*, 1952, pp.

two such measures—so that its diameter appears almost thirty times larger, its surface nearly nine hundred times, and its volume twenty-seven thousand times as large as when viewed with the naked eye. In this way one may learn with all the certainty of sense evidence that the moon is not robed in a smooth and polished surface but is in fact rough and uneven, covered everywhere, just like the earth's surface, with huge prominences, deep valleys, and chasms.

Again, it seems to me a matter of no small importance to have ended the dispute about the Milky Way by making its nature manifest to the very senses as well as to the intellect. Similarly it will be a pleasant and elegant thing to demonstrate that the nature of those stars which astronomers have previously called "nebulous" is far different from what has been believed hitherto. But what surpasses all wonders by far, and what particularly moves us to seek the attention of all astronomers and philosophers, is the discovery of four wandering stars not known or observed by any man before us. Like Venus and Mercury, which have their own periods about the sun, these have theirs about a certain star that is conspicuous among those already known, which they sometimes precede and sometimes follow, without ever departing from it beyond certain limits. All these facts were discovered and observed by me not many days ago with the aid of a spyglass which I devised, after first being illuminated by divine grace. Perhaps other things, still more remarkable, will in time be discovered by me or by other observers with the aid of such an instrument, the form and construction of which I shall first briefly explain, as well as the occasion of its having been devised. Afterwards I shall relate the story of the observations I have made.

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344 ff.). The slip was a curious one, as astronomers of all schools had long agreed that the maximum distance of the moon was approximately sixty terrestrial radii. Still more curious is the fact that neither Kepler nor any other correspondent appears to have called Galileo's attention to this error; not even a friend who ventured to criticize the calculations in this very passage.

The end of this summary of Kepler's work in mechanics shows how seriously Kepler took the idea of the harmony of the spheres.

6 Kepler's Celestial Music

I. Bernard Cohen

1960

Since Greek times scientists have insisted that Nature is simple. A familiar maxim of Aristotle is, "Nature does nothing in vain, nothing superfluous." Another expression of this philosophy has come down to us from a fourteenth-century English monk and scholar, William of Occam. Known as his "law of parsimony" or "Occam's razor" (perhaps for its ruthless cutting away of the superfluous), it maintains, "Entities are not to be multiplied without necessity." "It is vain to do with more what can be done with fewer" perhaps sums up this attitude.

We have seen Galileo assume a principle of simplicity in his approach to the problem of accelerated motion, and the literature of modern physical science suggests countless other examples. Indeed, present-day physics is in distress, or at least in an uneasy state, because the recently discovered nuclear "fundamental particles" exhibit a stubborn disinclination to recognize simple laws. Only a few decades ago physicists complacently assumed that the proton and the electron were the only "fundamental particles" they needed to explain the atom. But now one "fundamental particle" after another has crept into the ranks until it appears that there may be as many of them as there are chemical elements. Confronted with this bewildering array, the average physicist is tempted to echo Alfonso the Wise and bemoan the fact that he was not consulted first.

Anyone who examines Fig. 14 on page 58 will see at

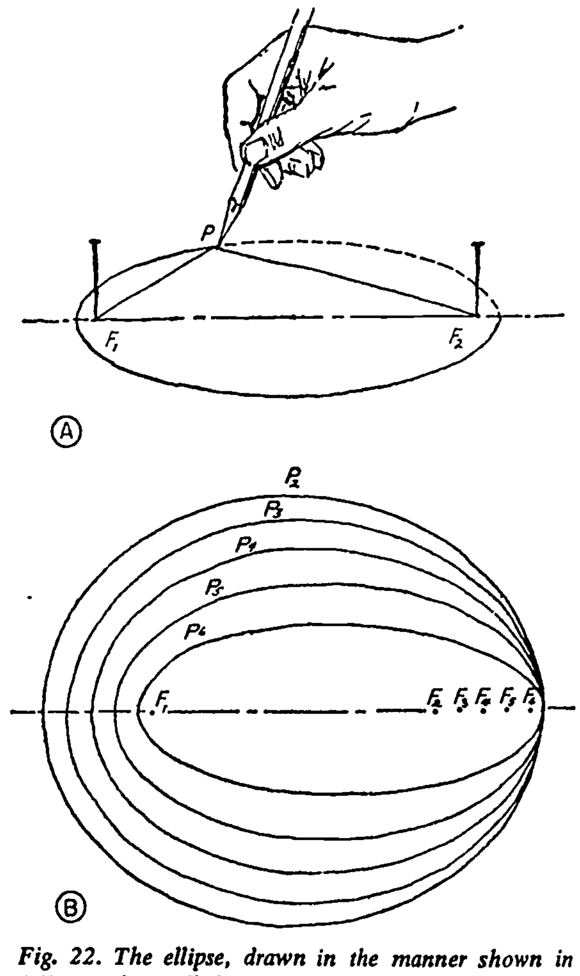


Fig. 22. The ellipse, drawn in the manner shown in (A), can have all the shapes shown in (B) if you use the same string but vary the distance between the pins, as at F_2, F_3, F_4, *etc.*

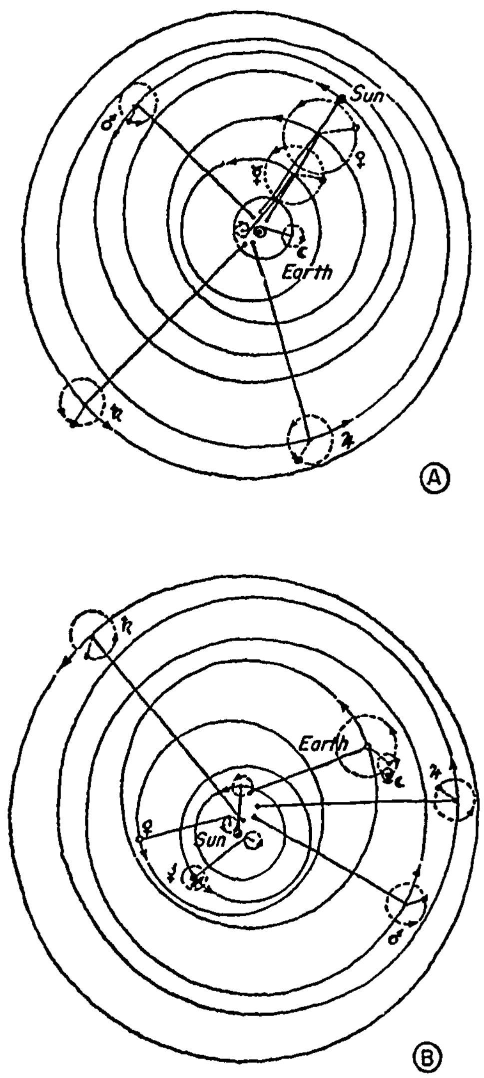


Fig. 14. The Ptolemaic system (A) and the Copernican system (B) were of about equal complexity, as can be

once that neither the Ptolemaic nor Copernican system was, in any sense of the word, "simple." Today we know why these systems lacked simplicity: restricting celestial motion to the circle introduced many otherwise unnecessary curves and centers of motion. If astronomers had used some other curves, notably the ellipse, a smaller number of them would have done the job better. It was one of Kepler's great contributions that he stumbled upon this truth.

The Ellipse and the Keplerian Universe

The ellipse enables us to center the solar system on the true sun rather than some "mean sun" or the center of the earth's orbit as Copernicus did. Thus the Keplerian system displays a universe of stars fixed in space, a fixed sun, and a *single* ellipse for the orbit of each planet, with an additional one for the moon. In actual fact, most of these ellipses, except for Mercury's orbit, look so much like circles that at first glance the Keplerian system seems to be the simplified Copernican system shown on page 58 of Chapter 3: one circle for each planet as it moves around the sun, and another for the moon.

An ellipse (Fig. 22) is not as "simple" a curve as a circle, as will be seen. To draw an ellipse (Fig. 22A), stick two pins or thumbtacks into a board, and to them tie the ends of a piece of thread. Now draw the curve by moving a pencil within the loop of thread so that the thread always remains taut. From the method of drawing the ellipse, the following defining condition is apparent: every point P on the ellipse has the property that the sum of the distances from it to two other points F_1 and F_2, known as the *foci*, is constant. (The sum is equal to the length of the string.) For any pair of foci, the chosen length of the string determines the size and shape of the ellipse, which may also be varied by using one string-length and placing the pins near to, or far from, one another. Thus an ellipse may have a shape (Fig. 22B) with more or less the proportions of an egg, a cigar, or a needle, or may be almost round and like a circle. But unlike the true egg, cigar, or needle, the ellipse must always be symmetrical (Fig. 23) with respect to the axes,

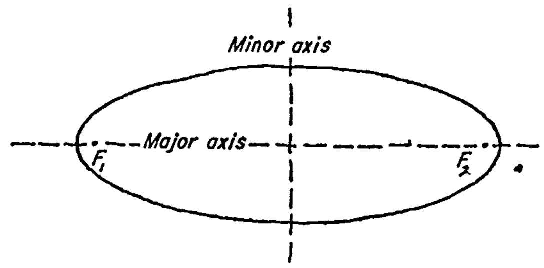


Fig. 23. The ellipse is always symmetrical with respect to its major and minor axes.

one of which (the major axis) is a line drawn across the ellipse through the foci and the other (the minor axis) a line drawn across the ellipse along the perpendicular bisector of the major axis. If the two foci are allowed to coincide, the ellipse becomes a circle; another way of saying this is that the circle is a "degenerate" form of an ellipse.

The properties of the ellipse were described in antiquity by Apollonius of Perga, the Greek geometer who inaugurated the scheme of epicycles used in Ptolemaic astronomy. Apollonius showed that the ellipse, the parabola (the path of a projectile according to Galilean mechanics), the circle, and another curve called the hyperbola may be formed (Fig. 24) by passing planes at different inclinations through a right cone, or a cone of revolution. But until the time of Kepler and Galileo, no one had ever shown that the conic sections occur in natural phenomena, notably in the phenomena of motion.

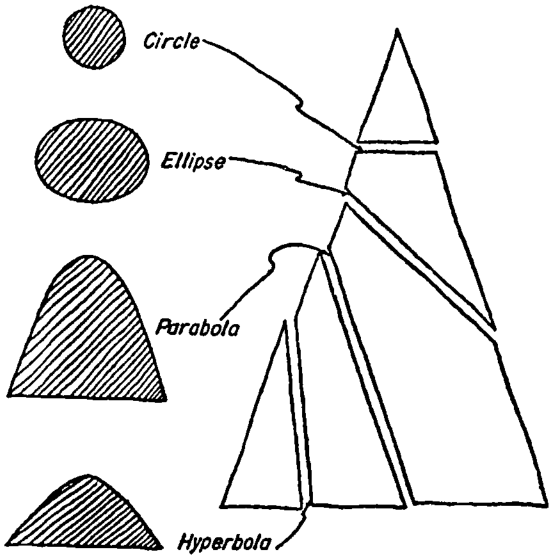


Fig. 24. The conic sections are obtained by cutting a cone in ways shown. Note that the circle is cut parallel to the base of the cone, the parabola parallel to one side.

In this work we shall not discuss the stages whereby Johannes Kepler came to make his discoveries. Not that the subject is devoid of interest. Far from it! But at present we are concerned with the rise of a new physics, as it was related to the writings of antiquity, the Middle Ages, the Renaissance and the seventeenth century. Aristotle's books were read widely, and so were the writings of Galileo and Newton. Men studied Ptolemy's *Almagest* and Copernicus's *De revolutionibus* carefully. But Kepler's writings were not so generally read. Newton, for example, knew the works of Galileo but he probably did not read Kepler's books. He may even have acquired his knowledge of Kepler's laws at secondhand, very likely from Seth Ward's textbook on astronomy. Even today there is no major work of Kepler available in a complete English, French, or Italian translation!

This neglect of Kepler's texts is not hard to understand. The language and style were of unimaginable difficulty and prolixity, which, in contrast with the clarity and vigor of Galileo's every word, seemed formidable beyond endurance. This is to be expected, for writing reflects the personality of the author. Kepler was a tortured mystic, who stumbled onto his great discoveries in a weird groping that has led his most recent biographer,* to call him a "sleepwalker." Trying to prove one thing, he discovered another, and in his calculations he made error after error that canceled each other out. He was utterly unlike Galileo and Newton; never could their purposeful quests for truth conceivably merit the description of sleepwalking. Kepler, who wrote sketches of himself in the third person, said that he became a Copernican as a student and that "There were three things in particular, namely, the number, distances and motions of the heavenly bodies, as to which I [Kepler] searched zealously for reasons why they were as they were and not otherwise." About the sun-centered system of Copernicus, Kepler at another time wrote: "I certainly know that I owe it this duty: that since I have attested it as true in my deepest soul, and since I contemplate its beauty with incredible and ravishing delight, I should also publicly defend it to my readers with all the force at my command." But it was not enough to defend the system; he set out to devote his whole life to finding a law or set of laws that would show how the system held together, why the planets had the particular orbits in which they are found, and why they move as they do.

The first installment in this program, published in 1596, when Kepler was twenty-five years old, was en-

* Arthur Koestler, *The Sleepwalkers*, Hutchinson & Co., London, 1959.

titled *Forerunner of the Dissertations on the Universe, containing the Mystery of the Universe*. In this book Kepler announced what he considered a great discovery concerning the distances of the planets from the sun. This discovery shows us how rooted Kepler was in the Platonic-Pythagorean tradition, how he sought to find regularities in nature associated with the regularities of mathematics. The Greek geometers had discovered that there are five "regular solids," which are shown in Fig. 25. In the Copernican system there are six planets:

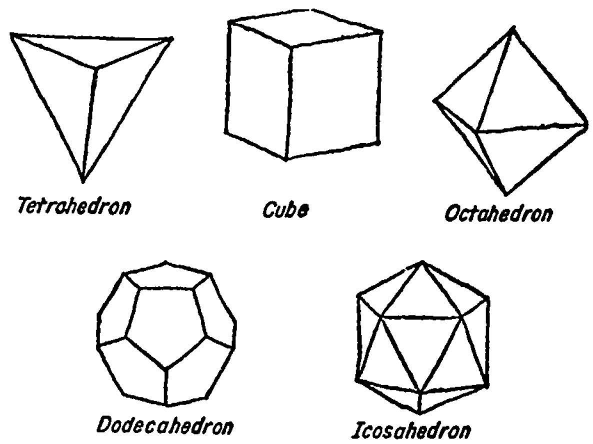


Fig. 25. The "regular" polyhedra. Tetrahedron has four faces, each an equilateral triangle. The cube has six faces, each a square. The octahedron has eight faces, each an equilateral triangle. Each of the dodecahedron's twelve faces is an equilateral pentagon. The twenty faces of the icosahedron are all equilateral triangles.

Mercury, Venus, Earth, Mars, Jupiter, Saturn. Hence it occurred to Kepler that five regular solids might separate six planetary orbits.

He started with the simplest of these solids, the cube.

A cube can be circumscribed by one and only one sphere, just as one and only one sphere can be inscribed in a cube. Hence we may have a cube that is circumscribed by sphere No. 1 and contains sphere No. 2. This sphere No. 2 just contains the next regular solid, the tetrahedron, which in turn contains sphere No. 3. This sphere No. 3 contains the dodecahedron, which in turn contains sphere No. 4. Now it happens that in this scheme the radii of the successive spheres are in more or less the same proportion as the mean distances of the planets in the Copernican system except for Jupiter—which isn't surprising, said Kepler, considering how far Jupiter is from the sun. The first Keplerian scheme (Fig. 26), then, was this:

Sphere of Saturn
Cube
Sphere of Jupiter
Tetrahedron
Sphere of Mars
Dodecahedron
Sphere of Earth
Icosahedron
Sphere of Venus
Octahedron
Sphere of Mercury.

"I undertake," he said, "to prove that God, in creating the universe and regulating the order of the cosmos, had in view the five regular bodies of geometry as known since the days of Pythagoras and Plato, and that He has fixed, according to those dimensions, the number of heavens, their proportions, and the relations of their movements." Even though this book fell short of unqualified success, it established Kepler's reputation as a clever mathematician and as a man who really knew something about astronomy. On the basis of this performance, Tycho Brahe offered him a job.

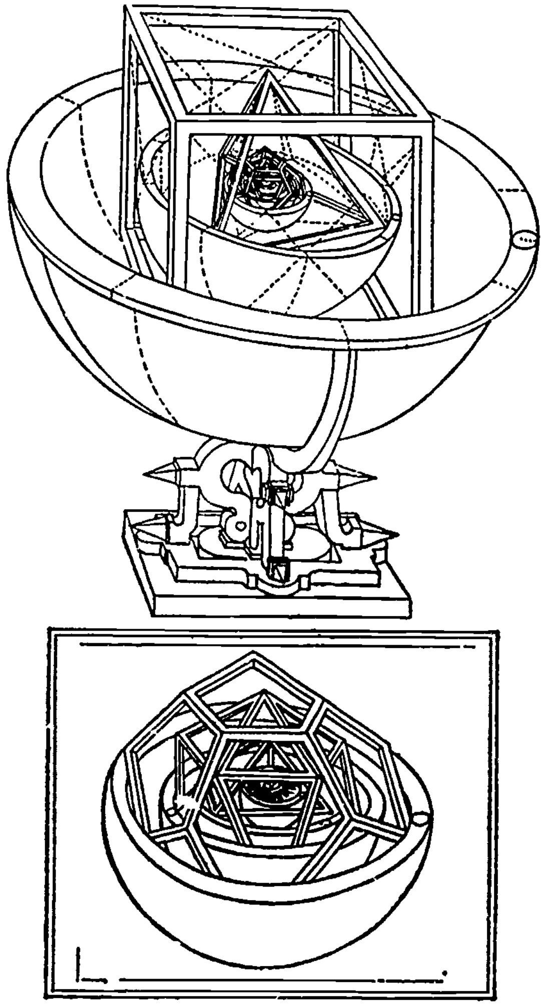


Fig. 26. Kepler's model of the universe. This weird contraption, consisting of the five regular solids fitted together, was dearer to his heart than the three laws on which his fame rests. From Christophorus Leibfried (1597).

Tycho Brahe (1546–1601) has been said to have been the reformer of astronomical observation. Using huge and well-constructed instruments, he had so increased the accuracy of naked-eye determinations of planetary positions and of the locations of the stars relative to one another that it was clear that neither the system of Ptolemy nor that of Copernicus would truly predict the celestial appearances. Furthermore, in contrast to earlier astronomers, Tycho did not merely observe the planets now and then to provide factors for a theory or to check such a theory; instead he observed a planet whenever it was visible, night after night. When Kepler eventually became Tycho's successor, he inherited the largest and most accurate collection of planetary observations—notably for the planet Mars—that had ever been assembled. Tycho, it may be recalled, believed in neither the Ptolemaic nor the Copernican system but had advanced a geocentric system of his own devising. Kepler, faithful to a promise he had made to Tycho, tried to fit Tycho's data on the planet Mars into the Tychonian system. He failed as he failed also to fit the data into the Copernican system. But twenty-five years of labor did produce a new and improved theory of the solar system.

Kepler presented his first major results in a work entitled *Commentaries on the Motions of Mars,* published in 1609, the year in which Galileo first pointed his telescope skyward. Kepler had made seventy different trials of putting the data obtained by Tycho into the Copernican epicycles and the Tychonian circles but always failed. Evidently it was necessary to give up all the accepted methods of computing planetary orbits or to reject Tycho's observations as being inaccurate. Kepler's failure may not appear as miserable as he seemed to think. After calculating eccentrics, epicycles, and equants in ingenious combinations, he was able to obtain an agreement between theoretical predictions and the observations of Tycho that was off by only 8 minutes (8′) of angle. Copernicus himself had never hoped to attain an accuracy greater than 10′, and the *Prussian Tables,* computed by Reinhold on the basis of Copernican methods, were off by as much as 5°. In 1609, before the application of telescopes to astronomy, 8′ was not a large angle; 8′ is just twice the minimum separation the unaided average eye can distinguish between two stars.

But Kepler was not to be satisfied by any approximation. He believed in the Copernican sun-centered system and he also believed in the accuracy of Tycho's observations. Thus, he wrote:

> "Since the divine goodness has given to us in Tycho Brahe a most careful observer, from whose observations the error of 8′ is shewn in this calculation . . . it is right that we should with gratitude recognise and make use of this gift of God. . . . For if I could have treated 8′ of longitude as negligible I should have already corrected sufficiently the hypothesis . . . discovered in chapter xvi. But as they could not be neglected, these 8′ alone have led the way towards the complete reformation of astronomy, and have been made the subject-matter of a great part of this work."

Starting afresh, Kepler finally took the revolutionary step of rejecting circles altogether, trying an egg-shaped oval curve and eventually the ellipse. To appreciate how revolutionary this step actually was, recall that both Aristotle and Plato had insisted that planetary orbits had to be combined out of circles, and that this principle was a feature common to both Ptolemy's *Almagest* and Copernicus's *De revolutionibus* Galileo, Kepler's friend, politely ignored the strange aberration. But the final victory was Kepler's. He not only got rid of innumerable circles, requiring but one oval curve per planet, but he made the system accurate and found a wholly new and unsuspected relation between the location of a planet and its orbital speed.

The Three Laws

Kepler's problem was not only to determine the orbit of Mars, but at the same time to find the orbit of the earth. The reason is that our observations of Mars are made from the earth, which itself does not move uniformly in a perfect circle in the Copernican system. Fortunately, however, the earth's orbit is almost circular. Kepler discarded Copernicus's idea that all planetary orbits should be centered on the mid-point of the earth's orbit. He stated, instead, that *the orbit of each planet is in the shape of an ellipse with the sun located at one focus.* This principle is known as Kepler's first law.

Kepler's second law tells us about the speed with which a planet moves in its orbit. This law states that *in any equal time intervals, a line from the planet to the sun will sweep out equal areas.* Fig. 27 shows equal areas for three regions in a planetary orbit. Since the three

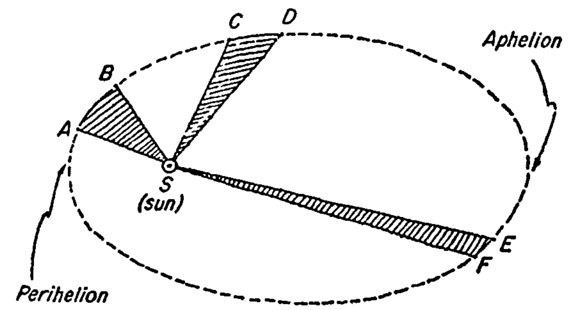


Fig. 27. Kepler's law of equal areas. Since a planet moves through the arcs $\widehat{AB}$, $\widehat{CD}$ *and* $\widehat{EF}$ *in equal times (because the areas* SAB, SCD, *and* SEF *are equal), it travels fastest at perihelion, when nearest the sun, and slowest at aphelion, when farthest from the sun. The shape of this ellipse is that of a comet's orbit. Planetary ellipses are more nearly circular.*

shaded regions are of equal area, the planet moves most quickly when nearest to the sun and most slowly when farthest from the sun. This second law thus tells us at once that the apparent irregularity in the speed with which planets move in their orbits is a variation obeying a simple geometric condition.

The first and second law plainly show how Kepler simplified the Copernican system. But the third law, known also as the harmonic law, is even more interesting. It is called the harmonic law because its discoverer thought it demonstrated the true celestial harmonies. Kepler even entitled the book in which he announced it *The Harmony of the World* (1619). The third law states a relation between the periodic times in which the planets complete their orbits about the sun and their average distances from the sun. Let us make a table of the periodic times (T) and average distances (D). In this table and in the following text, the distances are given in astronomical units. One astronomical unit is, by definition, the mean distance from the earth to the sun.

	Mercury	Venus	Earth	Mars	Jupiter	Saturn
periodic time T (years)	0.24	0.615	1.00	1.88	11.68	29.457
mean distance from the sun D (astronomical units)	0.387	0.723	1.00	1.524	5.203	9.539

This table shows us that there is no simple relationship between D and T. Kepler, therefore, tried to see what would happen if he took the squares of these values, D^2 and T^2. These may be tabulated as follows:

	Mercury	Venus	Earth	Mars	Jupiter	Saturn
T^2	0.058	0.38	1.00	3.54	140	868
D^2	0.147	0.528	1.00	2.323	27.071	90.792

There is still no relation discernible between D and T^2, or between D^2 and T, or even between D^2 and T^2. Any ordinary mortal would have given up at this point. Not

Kepler. He was so convinced that these numbers must be related that he would never have given up. The next power is the cube. T^3 turns out to be of no use, but D^3 yields the following numbers. Note them and then turn back to the table of squares.

	Mercury	Venus	Earth	Mars	Jupiter	Saturn
D^3	0.058	0.38	1.00	3.54	140	868

Here then are the celestial harmonies, the third law, which states that the *squares of times of revolution of any two planets around the sun* (earth included) *are proportional to the cubes of their mean distances from the sun.*

In mathematical language, we may say that "T^2 is always proportional to D^3" or

$$\frac{D^3}{T^2} = K,$$

where K is a constant. If we choose as units for D and T the astronomical unit and the year, then K has the numerical value of unity. (But if the distance were measured in miles and time in seconds, the value of the constant K is not unity.) Another way of expressing Kepler's third law is

$$\frac{D_1^3}{T_1^2} = \frac{D_2^3}{T_2^2} = \frac{D_3^3}{T_3^2} = \frac{D_4^3}{T_4^2} = \ldots \quad \ldots\ldots = K$$

where D_1 and T_1, D_2 and T_2, . . . , are the respective distances and periods of any planet in the solar system.

To see how this law may be applied, let us suppose that a new planet were discovered at a mean distance of $4AU$ from the sun. What is its period of revolution? Kepler's third law tells us that the ratio D^3/T^2 for this new planet must be the same as the ratio D_0^3/T_0^2 for the earth. That is,

$$\frac{D^3}{T^2} = \frac{(1AU)^3}{(1^y)^2}.$$

Since $D = 4AU$,

$$\frac{(4AU)^3}{T^2} = \frac{(1AU)^3}{(1^y)^2},$$
$$\frac{64}{T^2} = \frac{1}{(1^y)^2}$$
$$T^2 = 64 \times (1^y)^2$$
$$T = 8^y.$$

The inverse problem may also be solved. What is the distance from the sun of a planet having a period of 125 years?

$$\frac{D^3}{T^2} = \frac{(1AU)^3}{(1^y)^2}$$
$$\frac{D^3}{(125^y)^2} = \frac{(1AU)^3}{(1^y)^2}$$
$$\frac{D^3}{125 \times 125} = \frac{(1AU)^3}{1}$$
$$D^3 = 25 \times 25 \times 25 \times (1AU)^3$$
$$D = 25AU.$$

Similar problems can be solved for any satellite system. The significance of this third law is that it is a law of necessity; that is, it states that it is impossible in any satellite system for satellites to move at just any speed or at any distance. Once the distance is chosen, the speed is determined. In our solar system this law implies that the sun provides the governing force that keeps the planets moving as they do. In no other way can we account for the fact that the speed is so precisely related to distance from the sun. Kepler thought that the action of the sun was, in part at least, magnetic. It was known in his day that a magnet attracts another magnet even though considerable distances separate them. The motion of one magnet produces motion in another. Kepler was aware that a physician of Queen Elizabeth, William Gilbert (1544–1603), had shown the earth to be a huge magnet.

If all objects in the solar system are alike rather than different, as Galileo had shown and as the heliocentric system implied, why should not the sun and the other planets also be magnets like the earth?

Kepler's supposition, however tempting, does not lead directly to an explanation of why planets move in ellipses and sweep out equal areas in equal times. Nor does it tell us why the particular distance-period relation he found actually holds. Nor does it seem in any way related to such problems as the downward fall of bodies —according to the Galilean law of fall—on a stationary or on a moving earth, since the average rock or piece of wood is not magnetic. And yet we shall see that Newton, who eventually answered all these questions, based his discoveries on the laws found by Kepler and Galileo.

Kepler versus the Copernicans

Why were Kepler's beautiful results not universally accepted by Copernicans? Between the time of their publication (I, II, 1609; III, 1619) and the publication of Newton's *Principia* in 1687, there are very few references to Kepler's laws. Galileo, who had received copies of Kepler's books and who was certainly aware of the proposal of elliptic orbits, never referred in his scientific writings to any of the laws of Kepler, either to praise or to criticize them. In part, Galileo's reaction must have been Copernican, to stick to the belief in true circularity, implied in the very title of Copernicus's book: *On the Revolution of the Celestial Spheres.* That work opened with a theorem: 1. *That the Universe is Spherical.* Copernicus's arguments were given at the end of the last chapter. This is followed by a discussion of the topic, "That the motion of the heavenly bodies is uniform, circular, and perpetual, or composed of circular motions." The main line here is:

"Rotation is natural to a sphere and by that very act is its shape expressed. For here we deal with the simplest kind of body, wherein neither beginning nor end may be discerned nor, if it rotates ever in the same place, may the one be distinguished from the other.

"We must conclude [despite any observed apparent irregularities, such as the retrogradations of planets] that the motions of these bodies are ever circular or compounded of circles. For the irregularities themselves are subject to a definite law and recur at stated times, and this could not happen if the motions were not circular, for a circle alone can thus restore the place of a body as it was. So with the Sun which, by a compounding of circular motions, brings ever again the changing days and nights and the four seasons of the year."

Kepler thus was acting in a most un-Copernican way by not assuming that the planetary orbits are either "circles" or "compounded of circles"; furthermore he had come to his conclusion in part by reintroducing the one aspect of Ptolemaic astronomy to which Copernicus had most objected, the equant. Kepler said that a line from any planet to the empty focus of its ellipse (Fig. 28) rotates uniformly, or that such a line would rotate through equal angles in equal times because that other focus is the *equant*. (Incidentally, we may observe that this latter "discovery" of Kepler's is not true.)

From every point of view, the ellipses must have seemed objectionable. What kind of force could steer a planet along an elliptical path with just the proper variation of speed demanded by the law of equal areas? We shall not reproduce Kepler's discussion of this point, but shall confine our attention to one aspect of it. Kepler supposed that some kind of force or emanation comes out of the sun and moves the planets. This force—it is sometimes called an *anima motrix*—does not spread out

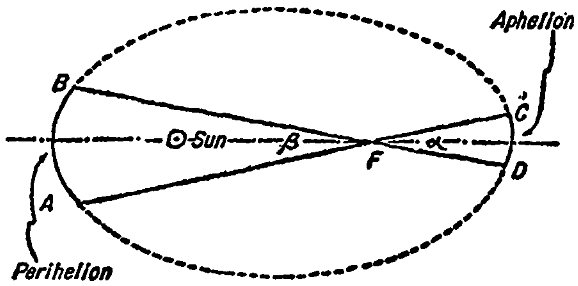


Fig. 28. Kepler's law of the equant. If a planet moves so that in equal times it sweeps out equal angles with respect to the empty focus at F*, it will move through arcs* $\widehat{AB}$ *and* $\widehat{CD}$ *in the same time because the angles* α *and* β *are equal. According to this law, the planet moves faster along arc* $\widehat{AB}$ *(at perihelion) than along arc* $\widehat{CD}$ *(at aphelion) as the law of equal areas predicts. Nevertheless, this law is false.*

in all directions from the sun. Why should it? After all, its function is only to move the planets, and the planets all lie in, or very nearly in, a single plane, the plane of the ecliptic. Hence Kepler supposed that this *anima motrix* spread out only in the plane of the ecliptic. Kepler had discovered that light, which spreads in all directions from a luminous source, diminishes in its intensity as the inverse square of the distance; that is, if there is a certain intensity or brightness three feet away from a lamp, the brightness six feet away will be one-fourth as great because four is the square of two and the new distance is twice the old. In equation form,

$$\text{intensity} \propto \frac{1}{(\text{distance})^2}$$

But Kepler held that the solar force does not spread out in all directions according to the inverse-square law, as the solar light does, but only in the plane of the ecliptic according to a quite different law. It is from this doubly erroneous supposition that Kepler derived his law of equal areas—and he did so *before* he had found that the planetary orbits are ellipses! The difference between Kepler's procedure and what we would consider to be "logical" is that Kepler did *not* first find the actual path of Mars about the sun, and then compute its speed in terms of the area swept out by a line from the sun to Mars. This is but one example of the difficulty in following Kepler through his book on Mars.

The Keplerian Achievement

Galileo particularly disliked the idea that solar emanations or mysterious forces acting at-a-distance could affect the earth or any part of the earth. He not only rejected Kepler's suggestion that the sun might be the origin of an attractive force moving the earth and planets (on which the first two laws of Kepler were based), but he especially rejected Kepler's suggestion that a lunar force or emanation might cause the tides. Thus he wrote:

> "But among all the great men who have philosophized about this remarkable effect, I am more astonished at Kepler than at any other. Despite his open and acute mind, and though he has at his fingertips the motions attributed to the earth, he has nevertheless lent his ear and his assent to the moon's dominion over the waters, and to occult properties, and to such puerilities."

As to the harmonic law, or third law, we may ask with the voice of Galileo and his contemporaries, Is this science or numerology? Kepler already had committed himself in print to the belief that the telescope should reveal not only the four satellites of Jupiter discovered by Galileo, but two of Mars and eight of Saturn. The reason for these particular numbers was that then the number of satellites per planet would increase according to a regular geometric sequence: 1 (for the earth), 2 (for Mars), 4 (for Jupiter), 8 (for Saturn). Was not Kepler's distance-period relation something of the same pure number-juggling rather than true science? And was not evidence for the generally nonscientific aspect of Kepler's whole book to be found in the way he tried to fit the numerical aspects of the planets' motions and locations into the questions posed in the table of contents for Book Five of his *Harmony of the World?*

"1. Concerning the five regular solid figures.
2. On the kinship between them and the harmonic ratios.
3. Summary of astronomical doctrine necessary for speculation into the celestial harmonies.
4. In what things pertaining to the planetary movements the simple consonances have been expressed and that all those consonances which are present in song are found in the heavens.
5. That the clefs of the musical scale, or pitches of the system, and the genera of consonances, the major and the minor, are expressed in certain movements.
6. That the single musical Tones or Modes are somehow expressed by the single planets.
7. That the counterpoints or universal harmonies of all the planets can exist and be different from one another.
8. That the four kinds of voice are expressed in the planets; soprano, contralto, tenor, and bass.
9. Demonstration that in order to secure this harmonic arrangement, those very planetary eccentricities which any planet has as its own, and no others, had to be set up.
10. Epilogue concerning the sun, by way of very fertile conjectures."

Below are shown the "tunes" played by the planets in the Keplerian scheme.

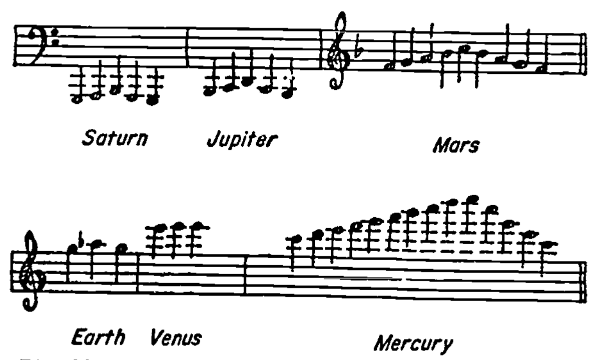


Fig. 29. Kepler's music of the planets, from his book Harmony of the World. *Small wonder a man of Galileo's stamp never bothered to read it!*

Surely a man of Galileo's stamp would find it hard to consider such a book a serious contribution to celestial physics.

Kepler's last major book was an *Epitome of Copernican Astronomy,* completed for publication nine years before his death in 1630. In it he defended his departures from the original Copernican system. But what is of the most interest to us is that in this book, as in the *Harmony of the World* (1619), Kepler again proudly presented his earliest discovery concerning the five regular solids and the six planets. It was, he still maintained, the reason for the number of planets being six.

It must have been almost as much work to disentangle the three laws of Kepler from the rest of his writings as to remake the discoveries. Kepler deserves credit for having been the first scientist to recognize that the Copernican concept of the earth as a planet and Galileo's discoveries demanded that there be one physics—applying equally to the celestial objects and ordinary terrestrial bodies. But, alas, Kepler remained so enmeshed in

Aristotelian physics that when he attempted to project a terrestrial physics into the heavens, the basis still came from Aristotle. Thus the major aim of Keplerian physics remained unachieved, and the first workable physics for heaven and earth derived not from Kepler but from Galileo and attained its form under the magistral guidance of Isaac Newton.

This brief sketch of Johannes Kepler's life and work was initially written as a review of Max Caspar's definitive biography of Kepler.

7 Kepler

Gerald Holton

1960

The early part of the 17th century was the hinge on which the world view of the West, which had been dominated by scholasticism, turned toward science. In this period of transition the center of gravity of intellectual life shifted from the Scriptures to the Book of Nature. The stage for the later triumph of Newtonianism was being prepared by men working on problems that sprawled across the then indistinctly separated disciplines of mathematics, physics, astronomy, cosmology, philosophy and theology. It was, in short, the time of Kepler, Galileo and Descartes.

Of the three Johannes Kepler is perhaps the most interesting, both as a scientist and as a personality. He is also the least known. Until now there has been no serious biography of him in English. This neglect has at last been remedied: The definitive biography by Max Caspar has been translated from the German by C. Doris Hellman of the Pratt Institute in New York.

As Caspar warns the reader, "No one who has once entered the magic sphere that surrounds [Kepler] can ever escape from it." Caspar devoted his whole life to Kepler; at the time of Caspar's recent death his monumental 13-volume edition of Kepler's collected works, his translation of Kepler's letters and his biography had already become a gold mine for scholars—and for popular writers The more meritorious passages of Arthur Koestler's *The Sleepwalkers*, for example, are little more than a paraphrase of Caspar.

Albert Einstein, who felt a deep kinship with Kepler (and who, like Kepler, was born in Swabia), said of him: "He belonged to those few who cannot do otherwise than openly acknowledge their convictions on every subject." Caspar's dedication and erudition consequently found an enormous amount of material on which to feed. This book is not merely a detailed portrait of Kepler. It is also an account of the intellectual ferment from which modern science arose, and of the historical context: the tragic and turbulent age of the Counter Reformation and the Thirty Years' War

From the beginning Kepler's personal life was unfortunate. His father Heinrich, as characterized by Kepler himself, was an immoral, rough and quarrelsome soldier; his mother Katharina, a querulous and unpleasant woman, did not waste much love on her son. Too weak and sickly for agricultural labor, the boy was sent through a school system leading to theological studies at the Protestant seminary in Tubingen. One of his teachers, Michael Maestlin, introduced him privately to the Copernican system, which Maestlin was prohibited from teaching in his public lectures. This was the spark that set the youthful mind afire.

At the age of 23, a few months before attaining the goal of his studies (the pulpit), Kepler was directed by his seminary to leave in order to serve as teacher of mathematics and astronomy at the seminary in Graz. He was a wretched teacher, and he had few students. This enabled him, however, to devote that much more time to other work. Although he spurned astrology as it was then practiced, he began to write horoscopes and prognostications He had good reasons to do so. It was part of his official duties as district mathematician and calendar-maker; he believed that he could "separate some precious stones from the dung", he was convinced that the harmonious arrangement of planets and stars could impart special qualities to the soul, he loved to spread his opinions among the noblemen and prelates who read these writings; he needed the money; and, last but not least, he found that his predictions were often accurate.

At this time he also began a work that combined a little of each of his previous studies. of Plato, Aristotle, Euclid, Augustine, Copernicus, Nicholas of Cusa and Luther. This was not merely astronomy, his aim was nothing less than to discover the plan of the Creator, "to think the thoughts of God over again," and to show that His plan was Copernican. In 1597 Kepler published the *Mysterium Cosmographicum*, in which he hoped to show the reasons for the number of planets, the size of their orbits and their specific motions. His method was to search for geometrical regularities with which to "explain" physical observation. His immense ingenuity, coupled with his unparalleled persistence, enabled him to uncover geometrical coincidences which satisfied him that his prejudices were correct. The key was his famous discovery that the relative radii of the planetary orbits in the heliocentric system correspond fairly well to the relative radii of thin spherical shells that may be thought to separate a nested arrangement of the five Platonic solids (The agreement is surprisingly good, the discrepancy between the radii of the shells and those of the orbits according to Copernicus was within about 5 per cent, except for the single case of Jupiter—"at which," Kepler said, "nobody will wonder, considering the great distance.")

Kepler soon saw that this was an incomplete effort at best, and changed his method of work. Still, the fundamental motivation behind the *Mysterium Cosmographicum*, namely the search for harmonies, remained strong throughout the remaining 33 years of his life. In 1597 he could feel the elation of the young man who, in Max Weber's phrase, "finds and obeys the demon who holds the fibers of his very life."

But in that same year the dark clouds that seemed always to hover over him sent down some lightning bolts. He married a young widow whom he described later as "simple-minded and fat, confused and perplexed." In 1600, the Counter Reformation having begun in earnest, all Protestants who did not choose to abandon their faith were banished from Graz. Kepler found an uncertain refuge in Prague with the aging and difficult Tycho Brahe, the foremost astronomer of his time, himself in exile from Denmark at the court of Emperor Rudolph.

Brahe lived for only one more year When he died, however, he left Kepler two great treasures: a healthy respect for accurate measurement, and a set of the best observations of planetary positions that had ever been made. Out of this raw material came Kepler's second great work, the *Astronomia Nova*, famous because it contained his first two laws of planetary motion. During this period Kepler also did fundamental work in optics.

In 1612 he was obliged to leave Prague. His protector, the Emperor, had been forced to abdicate; Bohemia had been devastated by warfare among the contenders for the throne, his wife had died of a disease sweeping the capital Kepler fled to Linz, where for 14 years he worked as a schoolteacher and district mathematician. At first this was the most tranquil time of his life He brought out his *Epitome*, an account of the Copernican system which was more persuasive than Galileo's, but which was neglected by contemporary scholars, including Galileo. He chose a new wife in a comically careful way from 11 candidates (the choice turned out rather well), and fought in his Lutheran congregation for the right to interpret the concept of transubstantiation as he saw fit (he was deeply hurt when, as a result, his pastor excluded him from communion).

This was also the time when Kepler's aged and feeble-minded mother was tried as a witch It was a miserable affair, involving the full spectrum of human fears and stupidities. Kepler devoted a full year to her defense He did not claim that witches did not exist, but only that his mother was not one. He barely managed to keep her from the rack and gallows. When one of his children died, he turned for solace to his work on the *Harmonice Mundi*, which contained his third law of planetary motion and was his last major book He wrote: "I set the *Tables* [the Rudolphine tables] aside, since they require peace, and turned my mind to the contemplation of the *Harmony*."

Kepler discovered the third law in May, 1618; the month also marked the beginning of the Thirty Years' War, which devastated Germany. Within a year the published part of his *Epitome* was placed on the Index of forbidden books. By 1626 his stay in Linz had become intolerable; his library had been sealed up by the Counter Reformation Commission; the countryside was swept by bloody peasant uprisings; the city of Linz was besieged; the press that had been printing the Rudolphine tables had gone up in flames. It seemed that he had no place to go He was received splendidly in Prague by Emperor Ferdinand II, but he refused employment at the court because he would have had to embrace Catholicism. For a time he found refuge in the retinue of the Austrian duke Wallenstein partly because of Wallenstein's interest in astrology Then in 1630, as he was passing through Regensburg on a fruitless journey to collect some money that was owed him, he was seized with a fever and died Soon afterward the churchyard in which he was buried was destroyed by one of the battles of the time Caspar writes "It is as though the fate which in life gave him no peace continued to pursue him even after death."

But Kepler had left something more durable than a headstone. the three laws of planetary motion During his lifetime they attracted little attention For a generation they slept quietly, then they awoke as the key inspiration for Newton's theory of universal gravitation

These three empirical rules for which Kepler is remembered are scattered through his voluminous work They are almost submerged in a flood of other ideas. from a means of calculating the optimum size for wine casks to an attempt to fix the year of Christ's birth, from an excellent discussion of lens optics to an attempt to connect the position of planets with the local weather (For 20 years Kepler faithfully made weather observations for this purpose, and at the end he bravely confessed that no connection was provable)

His whole work is characterized by this search for an arena of fruitful study in disciplines that, from our point of view, are incongruously mixed. physics and metaphysics, astronomy and astrology, geometry and theology, mathematics and music. But this was the time when the sciences were emerging from the matrix of general intellectual activity and assuming more specific forms. It fell to Kepler to show, through his successes and through his failures, where the fruitful ground for science lay. It was ground that he himself could not reach.

If we look into Kepler's turbulent life and work for those brief moments that best illuminate the man and the time, I would select passages from two letters. One, written to Guldin in 1626, described Kepler's life during the long siege of Linz. His house was situated at the city wall around which the fighting was raging, and a whole company of soldiers was stationed in it. "One had to keep all doors open for the soldiers, who through their continual coming day and night kept us from sleep and study." Here we find Kepler deep at work in technical chronology. "I set to work against Joseph Scaliger—one thought followed the next, and I did not even notice how time was passing."

The other revealing view of Kepler is provided by a letter to Herwart von Hohenburg in 1605. Here we come as close as we can to putting our finger on the moment when the modern mechanical-mathematical conception of science breaks out of its earlier mold. Kepler wrote: "I am much occupied with the investigation of the physical causes. My aim in this is to show that the celestial machine is to be likened not to a divine organism but rather to a clockwork . . . , insofar as nearly all the manifold movements are carried out by means of a single, quite simple magnetic force, as in the case of a clockwork all motions [are caused] by a simple weight. Moreover, I show how this physical conception is to be presented through calculation and geometry."

The celestial machine, driven by a single *terrestrial* force, in the image of a clockwork! This was indeed a prophetic goal. When the *Astronomia Nova* (on which Kepler was working at the time) was published four years later, it significantly bore the subtitle *Physica Coelestis*. Here we find the search for one universal force-law to explain terrestrial gravity and the oceanic tides as well as the motion of the planets. It is a conception of unity that is perhaps even more striking than Newton's, for the simple reason that Kepler did not have a predecessor.

Kepler did not, of course, succeed in his aim to find the physics that explains astronomical observations in terms of mechanics. The Achilles heel of his celestial physics was his Aristotelian conception of the law of inertia, which identified inertia with a tendency to come to rest. "Outside the field of force of another [rela]ted body, every bodily substance, insofar as it is corporeal, by nature tends to remain at the same place at which it finds itself." (The quotation is from the *Astronomia Nova*.) This axiom deprived him of the concepts of mass and force in useful form, and without them his world machine was doomed.

And yet, perhaps precisely because of the failure of his physics, he still had to see the world in one piece, holding before him an image in which there were three components: the universe as a physical machine, the universe as mathematical harmony and the universe as a central theological order. Taken by itself, any one of the three was incomplete and insufficient. It was Kepler's vision of all three together that makes him so interesting to us when we compare his view of the world to ours, so much more successful in each detail but —perhaps necessarily and irretrievably— so much more fragmented.

Kepler's description of how he came to take up the study of Mars, from his greatest book, The New Astronomy. Kepler records in a personal way everything as it occurred to him, not merely the final results.

8 Kepler on Mars

Johannes Kepler

1609

Johannes Kepler

(Translated by Owen Gingerich)

Astronomia Nova, Chapter 7, first part

On the Occasion When I Took up the Theory of Mars

The divine voice that calls men to learn astronomy is, in truth, expressed in the universe itself, not by words or syllables, but by things themselves and by the agreement of the human intellect and senses with the ensemble of celestial bodies and phenomena. Nevertheless, there is a certain destiny which secretly drives men toward different arts and gives them the assurance that just as they are part of the works of creation, so also they participate in the divine Providence.

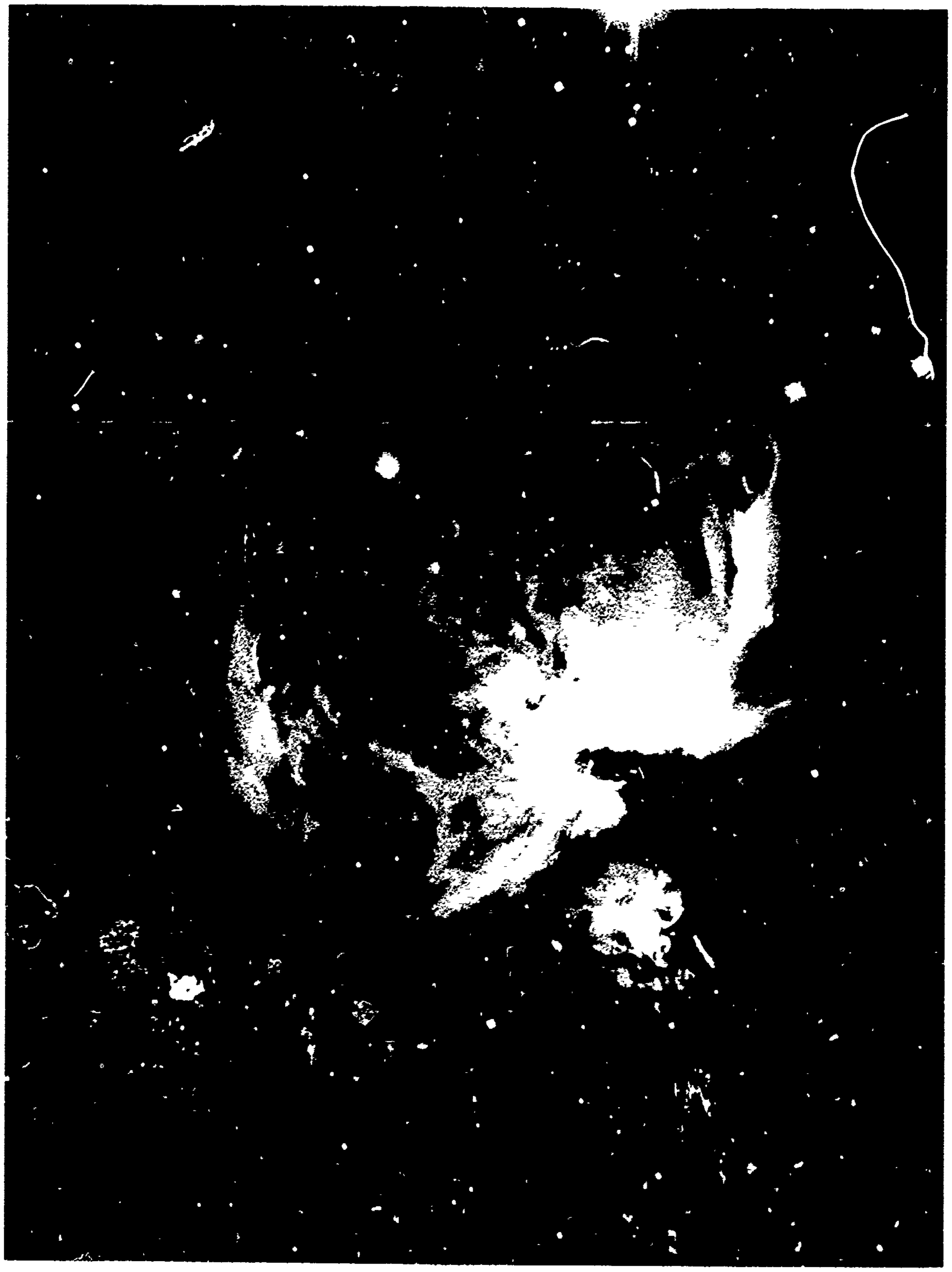
Thus when I was old enough to taste the sweetness of philosophy, I embraced it all with an extreme passion, without taking a particular interest in astronomy. I have for it, certainly, a sufficient intelligence, and I understood without difficulty the geometry and astronomy imposed by the program of studies, which depends on figures, numbers and proportions. But these were the prescribed studies, and nothing indicated to me a particular inclination for astronomy.

Since I was supported by a scholarship from the Duke of Württemberg and when I saw that my fellow students would excuse themselves when the Prince was soliciting for foreign countries, although in face they simply refused for love of their native land, I decided very quickly, being of a tougher nature, to go immediately where I might be sent.

The first place offered to me was an astronomical position into which, frankly, I was pushed only because of the authority of my teachers, not that I was frightened by the distance of the place—a fear I had condemned in the others (as I have said)—but because of the unexpected character and lowness of the position as well as the weakness of my knowledge in this part of philosophy. I accepted, therefore, being richer in ingenuity than in knowledge, and protesting highly that I would by no means abandon my right to another kind of life and ecclesiastical position that appeared to me much better. What was the success of my studies during the first two years appears in my Mysterium Cosmographicum. Moreover, what stimulus my teacher Maestlin applied to me for taking up astronomy, you will read in the same little book and in his letter prefixed to the Narratio of Rheticus. I have esteemed my discovery very high, and much more so when I saw that it was approved so highly by Maestlin. But he did not stimulate me as much by the untimely promise made by him to the readers, of a general astronomical work by me (Uranicum vel Cosmicum Opus, as it was called), inasmuch as I was eager to inquire into the restoration of astronomy and to see if my discovery could be exposed to the discrimination of observations. Indeed it was demonstrated in the book itself that it agreed within the precision of common astronomy.

Therefore at this time I began to think seriously of comparing it with observations. And when, in 1597, I wrote to Tycho Brahe asking him to tell me what he thought of my little work, in his answer he mentioned, among other things, his observations, he fired me with an enormous desire to see them. Moreover, Tycho Brahe, himself an important part in my destiny, did not cease from then on to urge that I come to visit him. But since the distance of the two places would have deterred me, I ascribe it to divine Providence that he came to Bohemia. I thus arrived there just before the beginning of the year 1600, with the hope of obtaining the correct eccentricities of the planetary orbits. When, in the first week, I learned that he himself along with Ptolemy and Copernicus employed the mean motion of the sun, but in fact the apparent motion agreed more with my little book, (as shown by the book itself), I was authorized to use the observations in my manner. Now at that time, his personal aide, Christian Severinus Longomontanus had taken up the theory of Mars, which was placed in his hands so that they might study the observation of the acronycal place, or opposition of Mars, with the sun in nine degrees of Leo. Had Christian been occupied with another planet, I would have started with that same one.

This is why I consider it again an effect of divine Providence that I arrived at Benatek at the time when he was directed toward Mars; because for us to arrive at the secret knowledge of astronomy, it is absolutely necessary to use the motion of Mars; otherwise it would remain eternally hidden.



Great Nebula in Orion

9 Newton and the Principia

C. C. Gillispie

1960

AFTER 1676 Newton gave over contending for his theory of colors and withdrew into his alternate posture of renunciation. "I had for some years past," he wrote in 1679, "been endeavouring to bend myself from philosophy to other studies in so much that I have long grutched the time spent in that study unless it be perhaps at idle hours sometimes for a diversion." It is not known in detail how he spent those years. On theology and biblical antiquities certainly, on mathematics probably, on chemistry and on perfecting his optics perhaps, for it is in character that he should have nursed his disenchantment in public and continued his work in private. In 1679 he was recalled to science, but to dynamics this time, by a further letter from Hooke, now become Secretary of the Royal Society. Hooke approached him on two levels. Privately, the letter was an olive branch. Officially, it was the new secretary bespeaking the renewed collaboration of the most potent of his younger colleagues, sulking in his tent.

Newton answered, correctly enough in form, but not very frankly, not at all cordially, affecting ignorance of an "hypothesis of springynesse" (Hooke's law of elasticity) on which Hooke had invited his opinion. So as to disguise without taking the edge off his snub, he threw in as a crumb "a fancy of my own," the solution of a curious problem he had toyed with in one of those idle hours. It concerned the trajectory of a body falling freely from a high tower, supposing the earth permeable and considering only the diurnal rotation. This was in fact a famous puzzle suggested by the Copernician theory, the same problem which Galileo had so curiously and erroneously answered with a semi-circle to the center of the earth. Since then it had been much discussed in obscure and learned places. And having brought it up himself, as if to flex a mental muscle in Hooke's face, Newton gave an answer as wrong as Galileo's. The trajectory, he casually said and drew it, will be a spiral to the center of the earth.

Now, Hooke did not know the right answer. The forces are in fact complex: the force of gravity increases by the inverse square relationship as far as the surface of the earth and thereafter as the first power of the distance. Hooke, along with many others, surmised the former (though he was too feeble a mathematician to handle gravity other than as constant) but was ignorant—as Newton then was—of the latter fact He did have the happy thought of eliminating Coriolis forces by putting his tower on the equator. But Hooke did not need to solve the problem correctly to perceive that the initial tangential component of motion will not only, as Newton pointed out with an air of correcting vulgar errors, carry the body east of the foot of the tower, but by the same reasoning will insure that one point which the body can never traverse, either on a spiral or on any other path, is the center of the earth. Hooke was not the man to resist this opportunity. He had invited Newton to a private correspondence. He communicated Newton's reply to the Royal Society, and corrected his error publicly.

It would be tedious to follow the ensuing correspondence: the outward forms of courtesy, the philosophical tributes to truth as the goal, the underlying venom, the angry jottings in the margin. Newton "grutched" admitting error far more than the time spent on philosophy. He never did solve the problem. But he left it as the most important unsolved problem in the history of science. For it drew his mind back to dynamics and gravity, back to where he had left those questions thirteen years before. And in the course of these geometrical investigations, he solved the force law of planetary motion: "I found the Proposition that by a centrifugal force reciprocally as the square of the distance a Planet must revolve in an Ellipsis about the center of the force placed in the lower umbilicus of the Ellipsis and with a radius drawn to that center describe areas proportional to the times." He would prove the point mass theorem only after 1685. But he had proved the law of gravity on the celestial scale, not just approximately for circular orbits as in 1666, but as a rigorous geometric deduction combining Kepler's laws with Huygens' law of centrifugal force. And he told no one, "but threw the calculations by, being upon other studies."

It is one of the ironies attending the genesis of Newton's *Principia* that no one knew beforehand of his work on celestial mechanics. In inviting Newton's correspondence, Hooke may even have thought that he was taking his rival onto his own ground. For the problem of gravity was constantly under discussion. Hooke had certainly surmised that a gravitating force of attraction was involved in the celestial motions, and that it varied in power inversely as the square of the distance. So, too, had Christopher Wren, then one of the most active of the virtuosi, and the young astronomer, Edmund Halley. But none of them was mathematician enough to deduce the planetary motions from a force law.

Far more than Boyle, Hooke was the complete Baconian. The only plausible explanation of his later conduct is that he truly did not understand the necessity for mathematical demonstration. He relied uniquely upon experiment to sort out the good from the bad ideas that crowded out of his fertile imagination. He seems to have been prepared to build even celestial mechanics out of experiments on falling bodies like those improvised to test out

Newton's spiral. Nor could he see that the rigorous geometrical demonstrations of the *Principia* added anything to his own idea. They gave the same result. Once again, thought Hooke on seeing the manuscript, Newton had wrapped his intellectual property in figures and stolen it away.

Halley was more sophisticated. He was also an attractive and sympathetic young man. In August 1684 he went up from London to consult Newton. An account of this visit by John Conduitt, who later married Newton's niece, is generally accepted.

> Without mentioning either his own speculations, or those of Hooke and Wren, he at once indicated the object of his visit by asking Newton what would be the curve described by the planets on the supposition that gravity diminished as the square of the distance. Newton immediately answered, *an Ellipse*. Struck with joy and amazement, Halley asked him how he knew it? Why, replied he, I have calculated it; and being asked for the calculation, he could not find it, but promised to send it to him.

While others were looking for the law of gravity, Newton had lost it. And yielding to Halley's urging, Newton sat down to rework his calculations and to relate them to certain propositions *On Motion* ...ually Newton's laws) on which he was lecturing that term. He had at first no notion of the magnitude of what he was beginning. But as he warmed to the task, the materials which he had been turning over in his mind in his twenty-five years at Cambridge moved into place in an array as orderly and planned as some perfect dance of figures. Besides proving Halley's theorem for him, he wrote the *Mathematical Principles of Natural Philosophy*. The *Principia*, it is always called, as if there were no other principles. And in a sense there are none. For that book contains all that is classical in classical physics. There is no work in science with which it may be compared.

"I wrote it," said Newton, "in seventeen or eighteen months." He employed an amanuensis who has left an account of his working habits.

> I never knew him to take any recreation or pasttime either in riding out to take the air, walking, bowling, or any other exercise whatever, thinking all hours lost that was not spent in his studies, to which he kept so close that he seldom left his chamber except at term time, when he read in the schools as being Lucasianus Professor. . . . He very rarely went to dine in the hall, except on some public days, and then if he has not been minded, would go very carelessly, with shoes down at heels, stockings untied, surplice on, and his head scarcely combed. At some seldom times when he designed to dine in the hall, [he] would turn to the left hand and go out into the street, when making a stop when he found his mistake, would hastily turn back, and then sometimes instead of going into the hall, would return to his chamber again.

Mostly Newton would have meals sent to his rooms and forget them. His secretary would ask whether he had eaten. "Have I?" Newton would reply.

The Royal Society accepted the dedication, undertook to print the work, and like a true learned organization found itself without funds. The expense, therefore, as well as the editing came upon Halley. He was not a rich man, but he bore both burdens cheerfully, with devotion and tact. He had the disagreeable task of informing Newton that upon receipt of the manuscript Hooke had said of the inverse square law, "you had the notion from him," and demanded acknowledgment in a preface. Upon this Newton threatened to suppress the third book, the climax of the argument, which applied the laws of motion to the system of the world. He was dissuaded, as no doubt he meant to be, but one can understand how his feeling for Hooke turned from irritable dislike to scornful hatred:

> Now is not this very fine? Mathematicians, that find out, settle, and do all the business, must content themselves with being nothing but dry calculators and drudges; and another that does nothing but pretend and grasp at all things, must carry away all the invention, as well of those that were to follow him, as of those that went before. Much after the same manner were his letters writ to me, telling me that gravity, in descent from hence to the centre of the earth, was reciprocally in a duplicate ratio of the altitude, that the figure described by projectiles in this region would be an ellipsis and that all the motions of the heavens were thus to be accounted for; and this he did in such a way, as if he had found out all, and knew it most certainly. And, upon this information, I must now acknowledge, in print, I had all from him, and so did nothing myself but drudge in calculating, demonstrating, and writing, upon the inventions of this great man. And yet, after all, the first of those three things he told me of is false, and very unphilosophical; the second is as false; and the third was more than he knew, or could affirm me ignorant of by any thing that past between us in our letters.

The provocation was great, as was the strain under which it was given. A few years after completing the *Principia* Newton suffered a nervous collapse. He wrote very strange letters. One of them accused Locke of trying to embroil him with women—Newton, who was as oblivious to women as if they were occult qualities. Alarmed, his friends had arranged a move to London, to bring him more into company. He gave up solitude in Cambridge with no regrets, became after a few years Master of the Mint, then President of the Royal Society which once he had held at such a haughty distance. Knighted in 1705 he lived out his years until 1727, the incarnation of science in the eyes of his countrymen, a legend in his own lifetime.

But he did very little more science.

The Latin original of Newton's statement of the three Laws of Motion and the proof of Proposition One is followed here by the English translation by Andrew Motte and Florian Cajori.

10 The Laws of Motion and Proposition One

Isaac Newton

1687

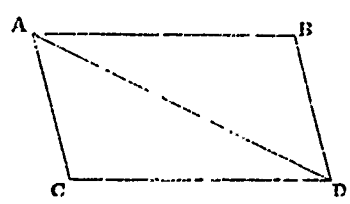
LEX III.

Actioni contrariam semper & æqualem esse reactionem: sive corporum duorum actiones in se mutuo semper esse æquales & in partes contrarias dirigi.

Quicquid premit vel trahit alterum, tantundem ab eo premitur vel trahitur. Si quis lapidem digito premit, premitur & hujus digitus a lapide. Si equus lapidem funi alligatum trahit, retrahetur etiam & equus (ut ita dicam) æqualiter in lapidem: nam funis utrinque distentus eodem relaxandi se conatu urgebit equum versus lapidem, ac lapidem versus equum; tantumque impediet progressum unius quantum promovet progressum alterius. Si corpus aliquod in corpus aliud impingens, motum ejus vi sua quomodocunque mutaverit, idem quoque vicissim in motu proprio eandem mutationem in partem contrariam vi alterius (ob æqualitatem pressionis mutuæ) subibit. His actionibus æquales fiunt mutationes, non velocitatum, sed motuum; scilicet in corporibus non aliunde impeditis. Mutationes enim velocitatum, in contrarias itidem partes factæ, quia motus æqualiter mutantur, sunt corporibus reciproce proportionales. Obtinet etiam hæc lex in attractionibus, ut in scholio proximo probabitur.

COROLLARIUM I.

Corpus viribus conjunctis diagonalem parallelogrammi eodem tempore describere, quo latera separatis.



Si corpus dato tempore, vi sola M in loco A impressa, ferretur uniformi cum motu ab A ad B; & vi sola N in eodem loco impressa, ferretur ab A ad C: compleatur parallelogrammum $ABDC$, & vi utraque feretur corpus illud eodem tempore in diagonali ab A ad D. Nam quoniam vis N agit secundum lineam AC ipsi BD parallelam, hæc vis per legem II nihil mutabit velocitatem accedendi ad lineam illam *BD* a vi altera genitam. Accedet igitur corpus eodem tempore ad lineam *BD*, sive vis *N* imprimatur, sive non; atque ideo in fine illius temporis reperietur alicubi in linea illa *BD*. Eodem argumento in fine temporis ejusdem reperietur alicubi in linea *CD*, & idcirco in utriusque lineæ concursu *D* reperiri necesse est. Perget autem motu rectilineo ab *A* ad *D* per legem I.

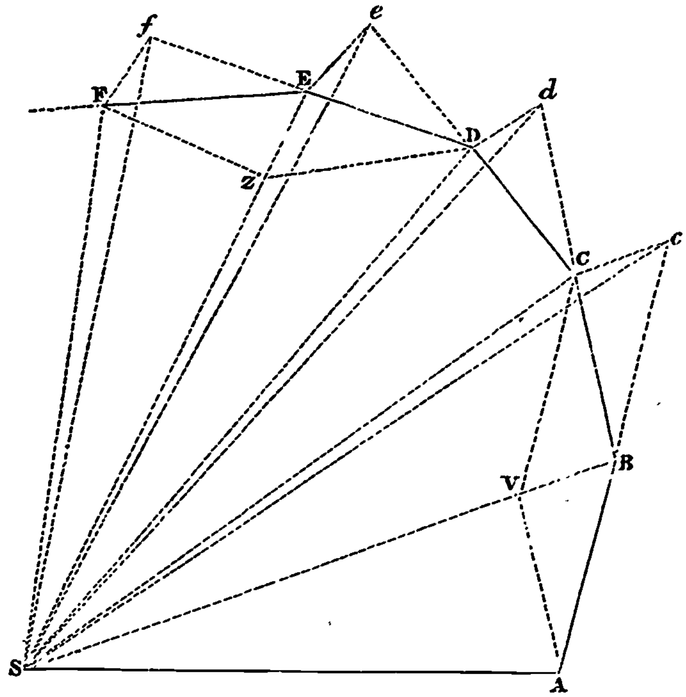
SECTIO II.

De inventione virium centripetarum.

PROPOSITIO I. THEOREMA I.

Areas, quas corpora in gyros acta radiis ad immobile centrum virium ductis describunt, & in planis immobilibus consistere, & esse temporibus proportionales.

Dividatur tempus in partes æquales, & prima temporis parte describat corpus vi insita rectam *AB*. Idem secunda temporis parte, si nil impediret, recta pergeret ad *c*, (per leg. I.) describens lineam *Bc* æqualem ipsi AB; adeo ut radiis AS, BS, cS ad centrum actis, confectæ forent æquales areæ ASB, BSc. Verum ubi corpus venit ad B, agat vis centripeta impulsu unico sed magno, efficiatque ut corpus de recta Bc declinet & pergat in recta BC. Ipsi BS parallela agatur cC, occurrens BC in C; & completa secunda temporis parte, corpus (per legum corol. 1.) reperietur in C, in eodem plano cum triangulo ASB. Junge



SC; & triangulum SBC, ob parallelas SB, Cc, æquale erit triangulo SBc, atque ideo etiam triangulo SAB. Simili argumento si vis centripeta successive agat in C, D, E, &c. faciens ut corpus singulis temporis particulis singulas describat rectas CD, DE, EF, &c. jacebunt hæ omnes in eodem plano; & triangulum SCD triangulo SBC, & SDE ipsi SCD, & SEF ipsi SDE æquale erit. Æqualibus igitur temporibus æquales areæ in plano immoto describuntur: & componendo, sunt arearum summæ quævis $SADS$, $SAFS$ inter se, ut sunt tempora descriptionum. Augeatur jam numerus & minuatur latitudo triangulorum in infinitum; & eorum ultima perimeter ADF, (per corollarium quartum lemmatis tertii) erit linea curva: ideoque vis centripeta, qua corpus a tangente hujus curvæ perpetuo retrahitur, aget indesinenter; areæ vero quævis descriptæ $SADS$, $SAFS$ temporibus descriptionum semper proportionales, erunt iisdem temporibus in hoc casu proportionales. *Q. E. D.*

AXIOMS, OR LAWS OF MOTION[1]

LAW I

Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

PROJECTILES continue in their motions, so far as they are not retarded by the resistance of the air, or impelled downwards by the force of gravity. A top, whose parts by their cohesion are continually drawn aside from rectilinear motions, does not cease its rotation, otherwise than as it is retarded by the air. The greater bodies of the planets and comets, meeting with less resistance in freer spaces, preserve their motions both progressive and circular for a much longer time.

LAW II[2]

The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

If any force generates a motion, a double force will generate double the motion, a triple force triple the motion, whether that force be impressed altogether and at once, or gradually and successively. And this motion (being always directed the same way with the generating force), if the body moved before, is added to or subtracted from the former motion, according as they directly conspire with or are directly contrary to each other; or obliquely joined, when they are oblique, so as to produce a new motion compounded from the determination of both.

LAW III

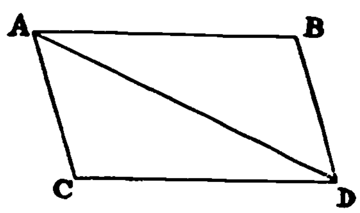
To every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone. If a horse draws a stone tied to a rope, the horse (if I may so say) will be equally drawn back towards the stone; for the distended rope, by the same endeavor to relax or unbend itself, will draw the horse as much towards the stone as it does the stone towards the horse, and will obstruct the progress of the one as much as it advances that of the other. If a body impinge upon another, and by its force change the motion of the other, that body also (because of the equality of the mutual pressure) will undergo an equal change, in its own motion, towards the contrary part. The changes made by these actions are equal, not in the velocities but in the motions of bodies; that is to say, if the bodies are not hindered by any other impediments. For, because the motions are equally changed, the changes of the velocities made towards contrary parts are inversely proportional to the bodies. This law takes place also in attractions, as will be proved in the next Scholium.

COROLLARY I

A body, acted on by two forces simultaneously, will describe the diagonal of a parallelogram in the same time as it would describe the sides by those forces separately.

If a body in a given time, by the force M impressed apart in the place A, should with an uniform motion be carried from A to B, and by the force N impressed apart in the same place, should be carried from A to C, let the parallelogram ABCD be completed, and, by both forces acting together, it will in the same time be carried in the diagonal from A to D. For since the force N acts in the direction of the line AC, parallel to BD, this force (by the second Law) will not at all alter the velocity generated by the other force M, by which the body is carried towards the line BD. The body therefore will arrive at the line BD in the same time, whether the force N be impressed or not; and therefore at the end of that time it will be found somewhere in the line BD. By the same argument, at the end of the same time it will be found somewhere in the line CD. Therefore it will be found in the point D, where both lines meet. But it will move in a right line from A to D, by Law I.



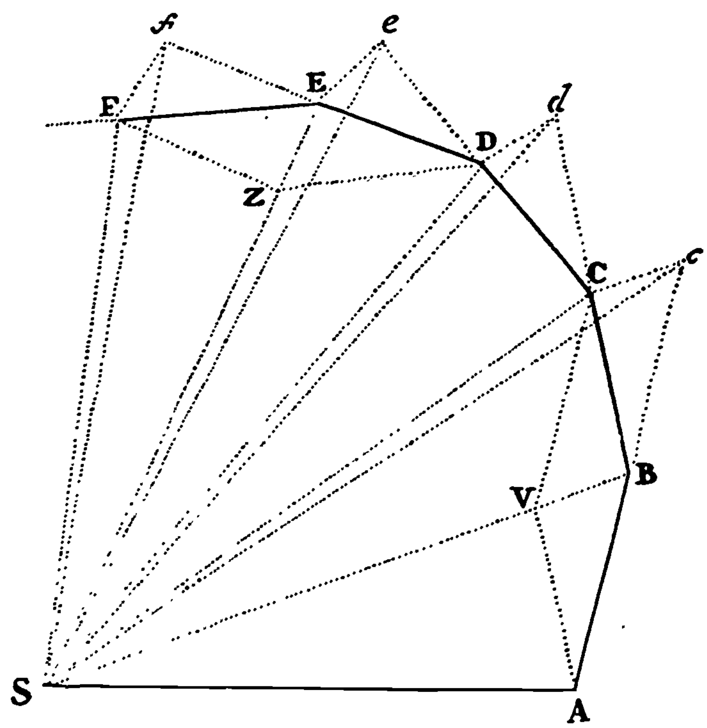
SECTION II

The determination of centripetal forces.

PROPOSITION I. THEOREM I

The areas which revolving bodies describe by radii drawn to an immovable centre of force do lie in the same immovable planes, and are proportional to the times in which they are described.

For suppose the time to be divided into equal parts, and in the first part of that time let the body by its innate force describe the right line AB. In the second part of that time, the same would (by Law 1), if not hindered,



proceed directly to *c*, along the line B*c* equal to AB; so that by the radii AS, BS, *c*S, drawn to the centre, the equal areas ASB, BS*c*, would be described. But when the body is arrived at B, suppose that a centripetal force acts at once with a great impulse, and, turning aside the body from the right line B*c*, compels it afterwards to continue its motion along the right line BC.

Draw cC parallel to BS, meeting BC in C; and at the end of the second part of the time, the body (by Cor. I of the Laws) will be found in C, in the same plane with the triangle ASB. Join SC, and, because SB and Cc are parallel, the triangle SBC will be equal to the triangle SBc, and therefore also to the triangle SAB. By the like argument, if the centripetal force acts successively in C, D, E, &c., and makes the body, in each single particle of time, to describe the right lines CD, DE, EF, &c., they will all lie in the same plane; and the triangle SCD will be equal to the triangle SBC, and SDE to SCD, and SEF to SDE. And therefore, in equal times, equal areas are described in one immovable plane: and, by composition, any sums SADS, SAFS, of those areas, are to each other as the times in which they are described. Now let the number of those triangles be augmented, and their breadth diminished *in infinitum;* and (by Cor. IV, Lem. III) their ultimate perimeter ADF will be a curved line: and therefore the centripetal force, by which the body is continually drawn back from the tangent of this curve, will act continually; and any described areas SADS, SAFS, which are always proportional to the times of description, will, in this case also, be proportional to those times. Q.E.D.

Anatole France is best known as the writer of novels such as Penguin Island. This brief passage shows that he, along with many writers, is interested in science.

11 The Garden of Epicurus

Anatole France

1920

WE find it hard to picture to ourselves the state of mind of a man of older days who firmly believed that the Earth was the center of the Universe, and that all the heavenly bodies revolved round it. He could feel beneath his feet the writhings of the damned amid the flames; very likely he had seen with his own eyes and smelt with his own nostrils the sulphurous fumes of Hell escaping from some fissure in the rocks. Looking upwards, he beheld the twelve spheres, —first that of the elements, comprising air and fire, then the sphere of the Moon, of Mercury, of Venus, which Dante visited on Good Friday of the year 1300, then those of the Sun, of Mars, of Jupiter, and of Saturn, then the incorruptible firmament, wherein the stars hung fixed like so many lamps. Imagination carried his gaze further still, and his mind's eye discerned in a remoter distance the Ninth Heaven, whither the Saints were translated to glory, the *primum mobile* or crystalline, and finally the Empyrean, abode of the Blessed, to which, after death, two angels robed in white (as he steadfastly hoped) would bear his soul, as it were a little child, washed by baptism and perfumed with the oil of the last sacraments. In those times God had no other children but mankind, and all His creation was administered after a fashion at once puerile and poetical, like the routine of a vast cathedral. Thus conceived, the Universe was so simple that it was fully and adequately represented, with its true shape and proper motion, in sundry great clocks compacted and painted by the craftsmen of the Middle Ages.

We are done now with the twelve spheres and the planets under which men were born happy or unhappy, jovial or saturnine. The solid vault of the firmament is cleft asunder. Our eyes and thoughts plunge into the infinite abysses of the heavens. Beyond the planets, we discover, instead of the Empyrean of the elect and the angels, a hundred millions of suns rolling through space, escorted each by its own procession of dim satellites, invisible to us. Amidst this infinitude of systems *our* Sun is but a bubble of gas and the Earth a drop of mud. The imagination is vexed and startled when the astronomers tell us that the luminous ray which reaches us from the pole-star has been half a century on the road; and yet that noble star is our next neighbour, and with Sirius and Arcturus, one of the least remote of the suns that are sisters of our own. There are stars we still see in the field of our telescopes which ceased to shine, it may be, three thousand years ago.

Worlds die,—for are they not born? Birth and death are unceasingly at work. Creation is never complete and perfect; it goes on for ever under incessant changes and modifications. The stars go out, but we cannot say if these daughters of light, when they die down into darkness, do not enter on a new and fecund existence as planets,—if the planets themselves do not melt away and become stars again. All we know is this; there is no more repose in the spaces of the sky than on earth, and the same law of strife and struggle governs the infinitude of the cosmic universe.

There are stars that have gone out under our eyes, while others are even now flickering like the dying flame of a taper. The heavens, which men deemed incorruptible, know of no eternity but the eternal flux of things.

That organic life is diffused through all parts of the Universe can hardly be doubted,—unless indeed organic life is a mere accident, an unhappy chance, a deplorable something that has inexplicably arisen in the particular drop of mud inhabited by ourselves.

But it is more natural to suppose that life has developed in the planets of our solar system, the Earth's sisters and like her, daughters of the Sun, and that it arose there under conditions analogous in the main to those in which it manifests itself with us,—under animal and vegetable forms. A meteoric stone has actually reached us from the heavens containing carbon. To convince us in more gracious fashion, the Angels that brought St. Dorothy garlands of flowers from Paradise would have to come again with their celestial blossoms. Mars to all appearance is habitable for living things of kinds comparable to our terrestrial animals and plants. It seems likely that, being habitable, it is inhabited. Rest assured, there too species is devouring species, and individual individual, at this present moment.

The uniformity of composition of the stars is now proved by spectrum analysis. Hence we are bound to suppose that the same causes that have produced life from the nebulous nucleus we call the Earth engender it in all the others.

When we say life, we mean the activity of organized matter under the conditions in which we see it manifested in our own world. But it is equally possible that life may be developed in a totally different environment, at extremely high or extremely low temperatures, and under forms unthinkable by us. It may even be developed under an ethereal form, close beside us, in our atmosphere; and it is possible that in this way we are surrounded by angels,—beings we shall never know, because to know them implies a point of common contact, a mutual relation, such as there can never be between them and us.

Again, it is possible that these millions of suns, along with thousands of millions more we cannot see, make up altogether but a globule of blood or lymph in the veins of an animal, of a minute insect, hatched in a world of whose vastness we can frame no conception, but which nevertheless would itself, in proportion to some other world, be no more than a speck of dust.

Nor is there anything absurd in supposing that centuries of thought and intelligence may live and die before us in the space of a minute of time, in the confines of an atom of matter. In themselves things are neither great nor small, and when we say the Universe is vast we speak purely from a human standpoint. If it were suddenly reduced to the dimensions of a hazel-nut, all things keeping their relative proportions, we should know nothing of the change. The pole-star, included together with ourselves in the nut, would still take fifty years to transmit its light to us as before. And the Earth, though grown smaller than an atom, would be watered with tears and blood just as copiously as it is to-day. The wonder is, not that the field of the stars is so vast, but that man has measured it.

A physical concept, such as gravitation, can be a powerful tool, illuminating many areas outside of that in which it was initially developed. As these authors show, physicists can be deeply involved when writing about their field.

12 Universal Gravitation

Richard P. Feynman, Robert B. Leighton, and Matthew Sands

1964

What else can we understand when we understand gravity? Everyone knows the earth is round. Why is the earth round? That is easy; it is due to gravitation. The earth can be understood to be round merely because everything attracts everything else and so it has attracted itself together as far as it can! If we go even further, the earth is not *exactly* a sphere because it is rotating, and this brings in centrifugal effects which tend to oppose gravity near the equator. It turns out that the earth should be elliptical, and we even get the right shape for the ellipse. We can thus deduce that the sun, the moon, and the earth should be (nearly) spheres, just from the law of gravitation.

What else can you do with the law of gravitation? If we look at the moons of Jupiter we can understand everything about the way they move around that planet. Incidentally, there was once a certain difficulty with the moons of Jupiter that is worth remarking on. These satellites were studied very carefully by Roemer, who noticed that the moons sometimes seemed to be ahead of schedule, and sometimes behind. (One can find their schedules by waiting a very long time and finding out how long it takes on the average for the moons to go around.) Now they were *ahead* when Jupiter was particularly *close* to the earth and they were *behind* when Jupiter was *farther* from the earth. This would have been a very difficult thing to explain according to the law of gravitation—it would have been, in fact, the death of this wonderful theory if there were no other explanation. If a law does not work even in *one place* where it ought to, it is just wrong. But the reason for this discrepancy was very simple and beautiful: it takes a little while to *see* the moons of Jupiter because of the time it takes light to travel from Jupiter to the earth. When Jupiter is closer to the earth the time is a little less, and when it is farther from the earth, the time is more. This is why moons appear to be, on the average, a little ahead or a little behind, depending on whether they are closer to or farther from the earth. This phenomenon showed that light does not travel instantaneously, and furnished the first estimate of the speed of light. This was done in 1656.

If all of the planets push and pull on each other, the force which controls, let us say, Jupiter in going around the sun is not just the force from the sun; there is also a pull from, say, Saturn. This force is not really strong, since the sun is much more massive than Saturn, but there is *some* pull, so the orbit of Jupiter should not be a perfect ellipse, and it is not; it is slightly off, and "wobbles" around the correct elliptical orbit. Such a motion is a little more complicated. Attempts were made to analyze the motions of Jupiter, Saturn, and Uranus on the basis of the law of gravitation. The effects of each of these planets on each other were calculated to see whether or not the tiny deviations and irregularities in these motions could be completely understood from this one law. Lo and behold, for Jupiter and Saturn, all was well, but Uranus was "weird." It behaved in a very peculiar manner. It was not travelling in an exact ellipse, but that was understandable, because of the attractions of Jupiter and Saturn. But even if allowance were made for these attractions, Uranus *still* was not going right, so the laws of gravitation were in danger of being overturned, a possibility that could not be ruled out. Two men, Adams and Leverrier, in England and France, independently,

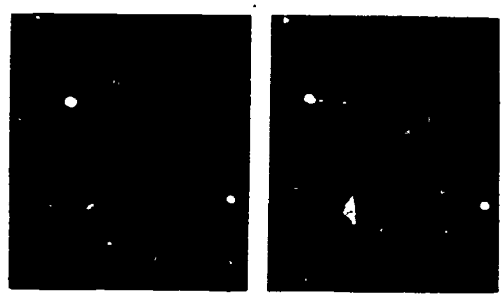


Fig. 7–6. A double-star system.

arrived at another possibility: perhaps there is *another* planet, dark and invisible, which men had not seen. This planet, *N*, could pull on Uranus. They calculated where such a planet would have to be in order to cause the observed perturbations. They sent messages to the respective observatories, saying, "Gentlemen, point your telescope to such and such a place, and you will see a new planet." It often depends on with whom you are working as to whether they pay any attention to you or not. They did pay attention to Leverrier; they looked, and there planet *N* was! The other observatory then also looked very quickly in the next few days and saw it too.

This discovery shows that Newton's laws are absolutely right in the solar system; but do they extend beyond the relatively small distances of the nearest planets? The first test lies in the question, do *stars* attract *each other* as well as planets? We have definite evidence that they do in the *double stars.* Figure 7–6 shows a double star—two stars very close together (there is also a third star in the picture so that we will know that the photograph was not turned). The stars are also shown as they appeared several years later. We see that, relative to the "fixed" star, the axis of the pair has rotated, i.e., the two stars are going around each other. Do they rotate according to Newton's laws? Careful measurements of the relative positions of one such double star system are shown in Fig. 7–7. There we see a beautiful ellipse, the measures starting in 1862 and going all the way around to 1904 (by now it must have gone around once more). Everything coincides with Newton's laws, except that the star Sirius A is *not at the focus.* Why should that be? Because the plane of the ellipse is not in the "plane of the sky." We are not looking at right angles to the orbit plane, and when an ellipse is viewed at a tilt, it remains an ellipse but the focus is no longer at the same place. Thus we can analyze double stars, moving about each other, according to the requirements of the gravitational law.

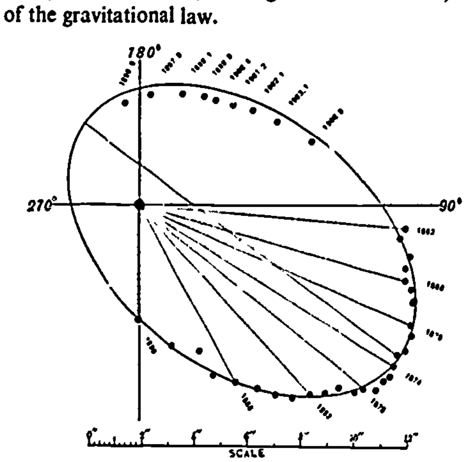


Fig. 7–7. Orbit of Sirius B with respect to Sirius A.

Fig. 7–8. A globular star cluster.

That the law of gravitation is true at even bigger distances is indicated in Fig. 7–8. If one cannot see gravitation acting here, he has no soul. This figure shows one of the most beautiful things in the sky—a globular star cluster. All of the dots are stars. Although they look as if they are packed solid toward the center, that is due to the fallibility of our instruments. Actually, the distances between even the centermost stars are very great and they very rarely collide. There are more stars in the interior than farther out, and as we move outward there are fewer and fewer. It is obvious that there is an attraction among these stars. It is clear that gravitation exists at these enormous dimensions, perhaps 100,000 times the size of the solar system. Let us now go further, and look at an *entire galaxy*, shown in Fig. 7–9. The shape of this galaxy indicates an obvious tendency for its matter to agglomerate. Of course we cannot prove that the law here is precisely inverse square, only that there is still an attraction, at this enormous dimension, that holds the whole thing together. One may say, "Well, that is all very clever but why is it not just a ball?" Because it is *spinning* and has *angular momentum* which it cannot give up as it contracts; it must contract mostly in a plane. (Incidentally, if you are looking for a good problem, the exact details of how the arms are formed and what determines the shapes of these galaxies has not been worked out.) It is, however, clear that the shape of the galaxy is due to gravitation even though the complexities of its structure have not yet allowed

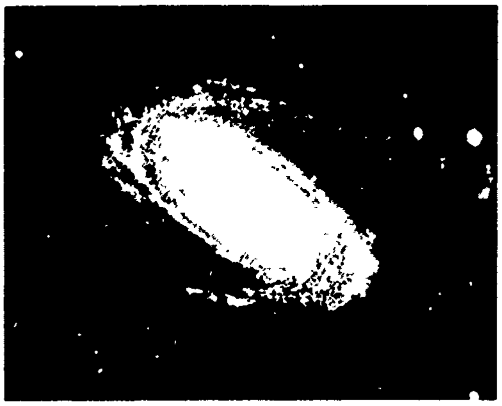


Fig. 7–9. A galaxy.

us to analyze it completely. In a galaxy we have a scale of perhaps 50,000 to 100,000 light years. The earth's distance from the sun is $8\frac{1}{3}$ light *minutes*, so you can see how large these dimensions are.

Gravity appears to exist at even bigger dimensions, as indicated by Fig. 7-10, which shows many "little" things clustered together. This is a *cluster of galaxies*, just like a star cluster. Thus galaxies attract each other at such distances that they too are agglomerated into clusters. Perhaps gravitation exists even over distances of *tens of millions* of light years; so far as we now know, gravity seems to go out forever inversely as the square of the distance.

Not only can we understand the nebulae, but from the law of gravitation we can even get some ideas about the origin of the stars. If we have a big cloud of dust and gas, as indicated in Fig. 7-11, the gravitational attractions of the pieces of dust for one another might make them form little lumps. Barely visible in the figure are "little" black spots which may be the beginning of the accumulations of dust and gases which, due to their gravitation, begin to form stars. Whether we have ever seen a star form or not is still debatable. Figure 7-12 shows the one piece of evidence which suggests that we have. At the left is a picture of a region of gas with some stars in it taken in 1947, and at the right is another picture, taken only 7 years later, which shows two new bright spots. Has gas accumulated, has gravity acted hard enough and collected it into a ball big enough that the stellar nuclear reaction starts in the interior and turns it into a star? Perhaps, and perhaps not. It is unreasonable that in only seven years we should be so lucky as to see a star change itself into visible form; it is much less probable that we should see *two!*

Fig. 7-10. A cluster of galaxies.

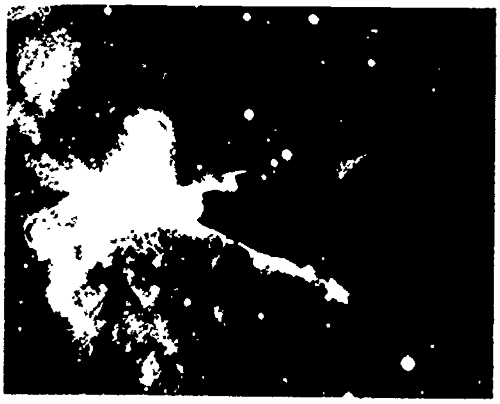


Fig. 7-11. An interstellar dust cloud.

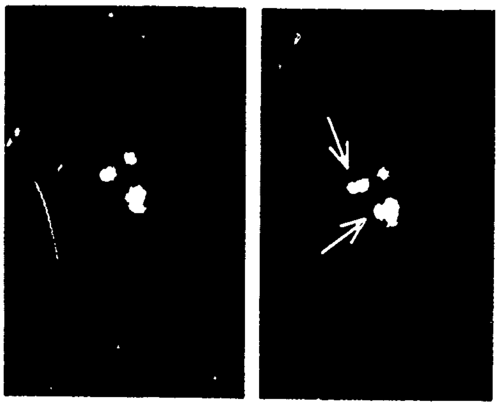


Fig. 7-12. The formation of new stars?

The earth, with all its faults, is a rather pleasant habitation for man. If things were only slightly different, our planet might not suit man nearly as well as it now does.

13 An Appreciation of the Earth

Stephen H. Dole

1964

We take our home for granted most of the time. We complain about the weather, ignore the splendor of our sunsets, the scenery, and the natural beauties of the lands and seas around us, and cease to be impressed by the diversity of living species that the Earth supports. This is natural, of course, since we are all products of the Earth and have evolved in conformity with the existing environment. It is our natural habitat, and all of it seems very commonplace and normal. Yet how different our world would be if some of the astronomical parameters were changed even slightly.

Suppose that, with everything else being the same, the Earth had started out with twice its present mass, giving a surface gravity of 1.38 times Earth normal. Would the progression of animal life from sea to land have been so rapid? While the evolution of marine life would not have been greatly changed, land forms would have to be more sturdily constructed, with a lower center of mass. Trees would tend to be shorter and to have strongly buttressed trunks. Land animals would tend to develop heavier leg bones and heavier musculature. The development of flying forms would certainly have been different, to conform with the denser air (more aerodynamic drag at a given velocity) and the higher gravity (more lifting surface necessary to support a given mass). A number of opposing forces would have changed the face of the land. Mountain-forming activity might be increased, but mountains could not thrust so high and still have the structural strength to support their own weight; raindrop and stream erosion would be magnified, but the steeper density gradient in the atmosphere would change the weather patterns; wave heights in the oceans would be lower, and spray trajectories would be shortened, resulting in less evaporation and a drier atmosphere; and cloud decks would tend to be lower. The land-sea ratio would probably be smaller. The length of the sidereal month would shorten from 27.3 to 19.4 days (if the Moon's distance remained the same). There would be differences in the Earth's magnetic field, the thickness of its crust, the size of its core, the distribution of mineral deposits in the crust, the level of radioactivity in the rocks, and the size of the ice caps on islands in the polar regions. Certainly man's counterpart (assuming that such a species would have evolved in this environment) would be quite different in appearance and have quite different cultural patterns.

Conversely, suppose that the Earth had started out with half its present mass, resulting in a surface gravity of 0.73 times Earth normal. Again the course of evolution and geological history would have changed under the influences of the lower gravity, the thinner atmosphere, the reduced erosion by falling water, and the probably increased level of background radiation due to more crustal radioactivity and solar cosmic particles. Would evolution have proceeded more rapidly? Would the progression from sea to land and the entry of animal forms into the ecological niches open to airborne species have occurred earlier? Undoubtedly animal skeletons would be lighter, and trees would be generally taller and more spindly; and again, man's counterpart, evolved on such a planet, would be different in many ways.

What if the inclination of the Earth's equator initially had been 60 degrees instead of 23.5 degrees? Seasonal weather changes would then be all but intolerable, and the only climatic region suitable for life as we know it would be in a narrow belt within about 5 degrees of the equator. The rest of the planet would be either too hot or too cold during most of the year, and with such a narrow habitable range, it is probable that life would have had difficulty getting started and, once started, would have tended to evolve but slowly.

Starting out with an inclination of 0 degrees would have influenced the course of development of the Earth's life forms in only a minor way. Seasons would be an unknown phenomenon; weather would undoubtedly be far more predictable and constant from day to day. All latitudes would enjoy a constant spring. The region within 12 degrees of the equator would become too hot for habitability but, in partial compensation, some regions closer to the poles would become more habitable than they are now.

Suppose the Earth's mean distance from the Sun were 10 per cent less than it is at present. Less than 20 per cent of the surface area (that between latitudes 45 degrees and 64 degrees) would then be habitable. Thus there would be two narrow land regions favorable to life separated by a wide and intolerably hot barrier. Land life could evolve independently in these two regions. The polar ice would not be present, so the ocean level would be higher than it is now, thus decreasing the land area.

If the Earth were 10 per cent farther away from the Sun than it is, the habitable regions would be those within 47 degrees of the equator. (The present limit of habitability is assumed to be, on an average, within 60 degrees of the equator.)

If the Earth's rotation rate were increased so as to make the day 3 hours long instead of 24 hours, the oblateness would be pronounced, and changes of gravity as a function of latitude would be a common part of a traveler's experience. Day-to-night temperature differences would become small.

On the other hand, if the Earth's rotation rate were slowed to make the day 100 hours in length, day-to-night temperature changes would be extreme; weather cycles would have a more pronounced diurnal pattern. The Sun would seem to crawl across the sky, and few life forms on land could tolerate either the heat of the long day or the cold of the long night.

The effects of reducing the eccentricity of the Earth's orbit to 0 (from its present value of 0.0167) would be scarcely noticeable. If orbital eccentricity were increased to 0.2 without altering the length of the semi-major axis (making perihelion coincide with summer solstice in the Northern Hemisphere to accentuate the effects), the habitability apparently would not be affected in any significant manner.

Increasing the mass of the Sun by 20 per cent (and moving the Earth's orbit out to 1.408 astronomical units to keep the solar constant at its present level) would increase the period of revolution to 1.54 years and decrease the Sun's apparent angular diameter to 26 minutes of arc (from its present 32 minutes of arc). Our primary would then be a class F5 star with a total main-sequence lifetime of about 5.4 billion years. If the age of the solar system were 4.5 billion years, then the Earth, under these conditions, could look forward to another billion years of history. Since neither of these numbers is known to the implied accuracy, however, a 10 per cent error in each in the wrong direction could mean that the end was very near indeed. An F5 star may well be more "active" than our Sun, thus producing a higher exosphere temperature in the planetary atmosphere; but this subject is so little understood at present that no conclusions can be drawn. Presumably, apart from the longer year, the smaller apparent size of the Sun, its more pronounced whiteness, and the "imminence" of doom, life could be much the same.

If the mass of the Sun were reduced by 20 per cent (this time decreasing the Earth's orbital dimensions to compensate), the new orbital distance would be 0.654 astronomical unit. The year's length would then become 0.59 year (215 days), and the Sun's apparent angular diameter, 41 minutes of arc. The primary would be of spectral type G8 (slightly yellower than our Sun is now) with a main-sequence lifetime in excess of 20 billion years. The ocean tides due to the primary would be about equal to those due to the Moon; thus spring tides would be somewhat higher and neap tides lower than they are at present.

What if the Moon had been located much closer to the Earth than it is, say, about 95,000 miles away instead of 239,000 miles? The tidal braking force would probably have been sufficient to halt the rotation of the Earth with respect to the Moon, and the Earth's day would equal its month, now 6.9 days in length (sidereal). Consequently, the Earth would be uninhabitable.

Moving the Moon farther away than it is would have much less profound results: the month would merely be longer and the tides lower. Beyond a radius of about 446,000 miles, the Earth can not hold a satellite on a circular orbit.

Increasing the mass of the Moon by a factor of 10 at its present distance would have an effect similar to that of reducing its distance. However, the Earth's day and month would then be equal to 26 days. Decreasing the Moon's mass would affect only the tides.

What if the properties of some of the other planets of the solar system were changed? Suppose the mass of Jupiter were increased by a factor of 1050, making it essentially a replica of the Sun. The Earth could still occupy its present orbit around the Sun, but our sky would be enriched by the presence of an extremely bright star, or second sun, of magnitude −23.7, which would supply at most only 6 per cent as much heat as the Sun. Mercury and Venus could also keep their present orbits; the remaining planets could not, although those exterior to Saturn could take up new orbits around the new center of mass.

All in all, the Earth is a wonderful planet to live on, just the way it is. Almost any change in its physical properties, position, or orientation would be for the worse. We are not likely to find a planet that suits us better, although at some future time there may be men who prefer to live on other planets. At the present time, however, the Earth is the only home we have; we would do well to conserve its treasures and to use its resources intelligently.

14 A Search for Life on Earth at Kilometer Resolution

Stephen D. Kilston, Robert R. Drummond and Carl Sagan

1965

Received July 20, 1965

A search for life on Earth at kilometer resolution, using several thousand photographs obtained by the Tiros and Nimbus meteorological satellites, has been undertaken. No sign of life can be discovered on the vast majority of these photographs. Due principally to the small contrast variations involved and the difficulty in reproducing observing conditions at satellite altitudes, no seasonal variations in the contrast of vegetation could be detected. Of several thousand Nimbus 1 photographs of essentially cloudfree terrains, one feature was found indicative of a technical civilization on Earth—a recently completed interstate highway—and another suggestive feature was discovered, possibly a jet contrail. A striking rectilinear feature was found on the Moroccan coast; however, it appears to be a natural peninsula. An orthogonal grid, discovered in a Tiros 2 photograph, is due to the activities of Canadian loggers, and is a clear sign of life. It appears that several thousand photographs, each with a resolution of a few tenths of a kilometer, are required before any sign of intelligent life can be found with reasonable reliability. An equivalent Mariner 4 system—taking 22 photographs of the Earth with a resolution of several kilometers—would not detect any sign of life on Earth, intelligent or otherwise.

Introduction

The United States spacecraft, Mariner 4, was designed to acquire a maximum of 22 photographs of the planet Mars, each containing about 2×10^5 bits, and with a ground resolution of a few kilometers. The scan pattern crossed the Martian deserts Phlegra and Zephyria—west of Amazonis—and into the dark area Mare Sirenum. Each of these regions contains a network of "canals," according to Lowell and his followers (see, e.g., Slipher, 1962). The brilliant success of the Mariner 4 photographic mission should not obscure the fact that it was designed for geological investigation and not for a remote biological reconnaissance of Mars. Speculation has appeared—and not in the popular press alone—that the Mariner 4 photographic mission represents a search for life on Mars. In order to obtain some calibration of the possibility that kilometer resolution photography may detect life on Mars, let us consider the situation reversed, and investigate the prospects of detection of life on Earth by kilometer resolution photography.

The Tiros and Nimbus Systems

Several hundred thousand photographs of the Earth are available in the 0.2- to 2.0-km resolution range, pictures obtained by the Tiros and Nimbus meteorological satellites of the National Aeronautics and Space Administration. These systems, managed by the Goddard Space Flight Center, are designed primarily for meteorological observations of the Earth's cloud cover. But since the Earth is not perpetually cloudbound, the photographs can also be used in a search for life on Earth. Through late 1964, there have been eight Tiros satellites launched. Their characteristic scientific payload is ~300 pounds. The satellite is launched into an approximately circular orbit with nominal altitudes of 400 statute miles. Tiros is equipped with a 500-line vidicon system, with three lens subsystems having 12°, 76°, and 104° fields of view. Each of the Tiros vehicles has some combination of these three lens subsystems. At the nominal altitude, the 12° lens gives a resolution of about 0.2 km; the 104° lens, about 2.0 km.

The Nimbus I meteorological satellite has a payload of ~800 pounds, and was launched into an orbit nominally ranging from 260 to 580 statute miles. Photographs from 300 miles altitude with a 36.5° field of view give a ground resolution of ~0.4 km.

The wide-angle lens of the Tiros system observes an area approximately 1000×1000 km. The perpendicular field of view of the narrow-angle lens is approximately 100×100 km. The Tiros pictures have an information content of about 1.5×10^6 bits. The Nimbus vidicon system, observing the same area, can accommodate 3.8×10^6 bits. For comparison, hand-held 35-mm cameras from manned orbiting missions yield pictures with $\sim 10^9$ bits information content. The frequency response of both Tiros and Nimbus optical frequency systems lies in the 0.45- to 0.8-micron range.

In short, there is a large body of data on satellite photographic reconnaissance of the Earth, with resolution superior to the Mariner 4 ground resolution on Mars.

A Priori Estimates of the Detectability of Life on Earth

Before representative Tiros and Nimbus photographs were actually examined, we attempted to evaluate the possible range of terrestrial surface features attributable to biological activity and detectable with kilometer resolution. We wish to emphasize from the outset that there is a great difference between photographic reconnaissance with and without ground truth. In the case of the Earth, we know, or can deduce, from observations with vastly superior resolution, the significance of features with kilometer resolution. In the case of Mars, we lack such ground truth, and our interpretation of the significance of kilometer resolution features can only be based on first principles or on terrestrial analogy. Photographic reconnaissance for indigenous life on Earth is vastly simpler than the analogous problem for Mars. Yet, if kilometer resolution biological reconnaissance of the Earth proves inconclusive, it must certainly follow that kilometer resolution reconnaissance of Mars will also be inconclusive—unless the very unlikely (Sagan, 1965*a*) case materializes that a technological civilization in substantial advance of our own exists on Mars. On the other hand, if there are some manifestations of life on Earth which are clearcut and readily interpretable at kilometer resolution, then such features might profitably be sought for on Mars.

It appeared to us that no manifestation of animal life on Earth, short of the artifacts of a technological civilization, could be discernible at kilometer resolution. The most readily detectable indication of noncultivated vegetation on the Earth would appear to be seasonal changes, e.g., of deciduous trees, in the temperate zones. Much more readily visible should be the seasonal contrast changes of cultivated crops, particularly those of high contrast with the underlying ground, such as cotton. Large fields of a single crop—for which time variations occur synchronously throughout the field—are common with wheat, corn, and cotton. Among the areas producing the largest amounts of these crops are the United States, Canada, the Soviet Union, and China. Among the times and places of particular interest in this regard are those listed in Table I (van Royen, 1954; Time, Inc., 1961).

TABLE I
TIMES AND PLACES OF EXTENSIVE CULTIVATION OF REPRESENTATIVE CROPS

Crop	Areas	Latitude	Longitude	Time of planting	Time of harvesting
Summer Wheat	North America	112°W–98°W 102°W–96°W	49°N–52°N 44°N–49°N	April–May	August
	China	114°E–120°E	33°N–40°N	April–May	September–October
Winter Wheat	North America	102°W–98°W	36°N–40°N	September 1 (north)–October 21 (south)	June 1 (south)–July 11 (north)
	China	114°E–120°E	33°N–40°N	September–October	May–June
	U. S. S. R.	40°E–65°E	50°N–54°N	August (north)–October (south)	July (south)–September (north)
Corn	United States	99°W–85°W	40°N–44°N	April–May	September–October
Cotton	United States	102°W–80°W	32°N–36°N	March 20 (south)–April 20 (north)	August (south)–January 1 (north)

It should be noted that the detection of seasonal or secular contrast variations is accompanied by some serious difficulties. Not only must several satellite observations be made of the appropriate area during the appropriate season on a cloud-free day, but also, it is important that the angle of insolation and the angle of view be reproduced in successive photographs. Because vegetation has a highly nonuniform and rough structure, the reflectivity may depend significantly on the relative angles of the Sun and the spacecraft. Since even approximate reproduction of these conditions occurs only rarely, the search for seasonal variations was not pursued in any detail. A photograph of the Texas Gulf coast near the beginning of the cotton planting season is seen in Fig. 1. The bright streak to the left is a cloud pattern; the large, dark feature near the middle of the picture is the Gulf of Mexico; and the slightly brighter area in the upper right-hand half of the picture is the Texas Gulf coast. Note the relative lack of contrast in the land area. This is a feature which is very common in photographs of the Earth, and suggests that seasonal variations in deciduous forests or cultivated crops may be very difficult to detect.

In attempting a preliminary evaluation of the detectability of intelligent life on Earth at kilometer resolution, it seemed apparent to us that the features of greatest interest were straight lines and arrays of straight lines. In the construction of communications networks and in his expressions of territoriality, considerations of economy and geometry together encourage man towards linear constructions. When the scale of construction is so large that Euclidean geometry is inapplicable, great and small circles are expected; but generally speaking, the scale of reworking the Earth's surface has not yet reached non-Euclidean proportions. Straight lines have the additional feature that they are not commonly produced in large scale by geological processes. Such natural rectilinear features as faults, rays of impact and volcanic craters, and rivers each have distinctive geometrical aspects which should lead to their recognition in photography of the Earth. On some other planet, where unfamiliar geological processes may operate, such recognition may be more difficult.

FIG. 1. Tiros 7 photograph of the Texas Gulf coast, orbit 4057, 19 March 1964.

The most obvious large-scale linear constructions of man are roads, railways, bridges, breakwaters, dikes, and great walls. Connected with transportation are two other features contemporary in nature: the condensation trails of jet aircraft, and the wakes of ships.

There are some criteria which can be used to distinguish rivers and roads. Rivers generally join each other at acute angles, forming the characteristic dendritic patterns of tributary systems. Road junctions are much more nearly at right angles. In addition, rivers rarely flow parallel to the shore or to each other for long distances. On the other hand, roads often parallel the coast, and not uncommonly, each other.

While the width of even large superhighways is smaller than the best ground resolution discussed here, this does not exclude the possibility of detecting roads and similar linear features with the Tiros and Nimbus systems. It is well known that, provided such features have high contrast with their surroundings, they are fairly easily visible even if their widths are well below the theoretical resolving power. Such rectilinear features must, however, be at least several resolution elements long.

The Great Wall of China is the only great wall with much chance of being observed. It is much larger than any other wall, averaging 8 meters in height and 5 to 10 meters' thickness at the base, sloping to 4 meters at its top (Columbia Encyclopedia, 1963). However, it is not a very straight feature, and its contrast with the surroundings is low. The Great Wall is therefore not an ideal rectilinear object for satellite photography.

Roads are longest, straightest, and widest in the United States, where transportation by automobiles is most common. Due to the relative paucity of superhighways elsewhere, the search for roads would best be carried out on photographs of the United States. A divided highway of six or eight lanes has a width between 30 and 40 meters, and this is much wider than railroad tracks. Both roads and railroads are sometimes cut through forests and other vegetation, and the resulting high-contrast swath might be visible even if the railroad or highway were not. The areas chosen for our first investigation contain certain sections of the Interstate and Defense Highways 5, 10, 35, 40, 90, and 95, and the Garden State Parkway in the Eastern United States (Portland Cement Assn., 1964).

The second class of linear objects is comprised of linear features in the water—dikes, breakwaters, and bridges. For example, the sea wall forming the boundary of the Zuider Zee, in the Netherlands, is perfectly straight for more than 25 km, and is $\sim$0.1 km wide. Bridges are usually too short to be visible—they are never very many resolution elements long, if the resolution is about 1 km—but for those which are long enough, their straightness and functional locations (connecting two peninsulas, or crossing a river or bay) are good indicators of intelligence. The widest and longest are again in the United States. They have widths of up to six lanes (about 30 meters), and lengths near 2 km. Suspension bridges might sometimes be more readily seen, because their shadows on the water would render their apparent width greater. Putting a premium on rectilinearity, we selected among the largest bridges the George Washington, the Golden Gate, the Mackinac Straits, the Verrazano Narrows, and the Lake Washington Floating Bridge (Seattle), all in the United States.

The last class of linear features includes transient indications of transportation. The largest such features are jet aircraft condensation trails and the wakes of large ships, both in water and in breaking ice. Icebreakers, however, generally follow the path of least resistance in the ice, and this is very rarely straight. In contrast, contrails and water wakes are almost always rectilinear. Especially in the case of water wakes, the angle of insolation is important, since the rectilinear feature is to be contrasted against surroundings of the same material. Both contrails and water wakes would point to intelligence, especially because they could be seen to dissipate and reappear in the same region at a later time, due to the fact that the routes of commercial shippers and airlines are fairly well fixed, and are traversed regularly.

Long, straight jet contrails should be common anywhere on the Earth, because of the world-wide air transportation system, but they would best be seen against the dark background of an ocean. The heavily traveled North Atlantic seems to provide the best opportunity for contrail detection; but the ocean is large, and the chance of spotting such a contrail on a given photograph is small. Some concentration of contrails near cities might be expected.

The wakes of ships are most concentrated near straits and channels of importance. The obvious points of concentration include such locales as New York Harbor, the Straits of Gibraltar, the Suez and Panama Canals, the Red Sea, the English Channel, the Straits of Malacca, and the Tokyo-Yokohama coastal waters.

The Observations

With the foregoing as *a priori* background, a selection was made from available Tiros and Nimbus photographs.

In the Tiros film library of the Goddard Space Flight Center, there are several hundred thousand Tiros photographs, of which only a few thousand portray with high quality land areas fairly clear of clouds. From this file, we selected photographs of areas chosen above as likely prospects for the detection of life on Earth. No clear sign of seasonal vegetation changes was detected on the selected photographs. Nimbus 1, being in operation only 26 days, produced roughly 10^4 pictures. Because of the short operational duration of this flight, no significant analysis of seasonal variations in vegetation could be attempted.

Of the Nimbus 1 photographs, a few hundred showing cloud-free areas and fine detail were selected in a random extraction of high-quality pictures made independently of any search for life on Earth. These photographs were enlarged and each examined in detail. The vast majority of the selected Tiros and Nimbus 1 photographs showed no features which seemed indicative of life on Earth. One high-resolution photograph of Tiros 2 and seven high-resolution photographs from Nimbus 1 were of interest, and are displayed and described below.

The lines of white and black dots, and the right-angle cross and T-shaped black features, are fiducial markings superposed on the camera system for orientation of the photographs. In all of these photographs, the direction of video scan is horizontal. One should therefore be wary about inter-

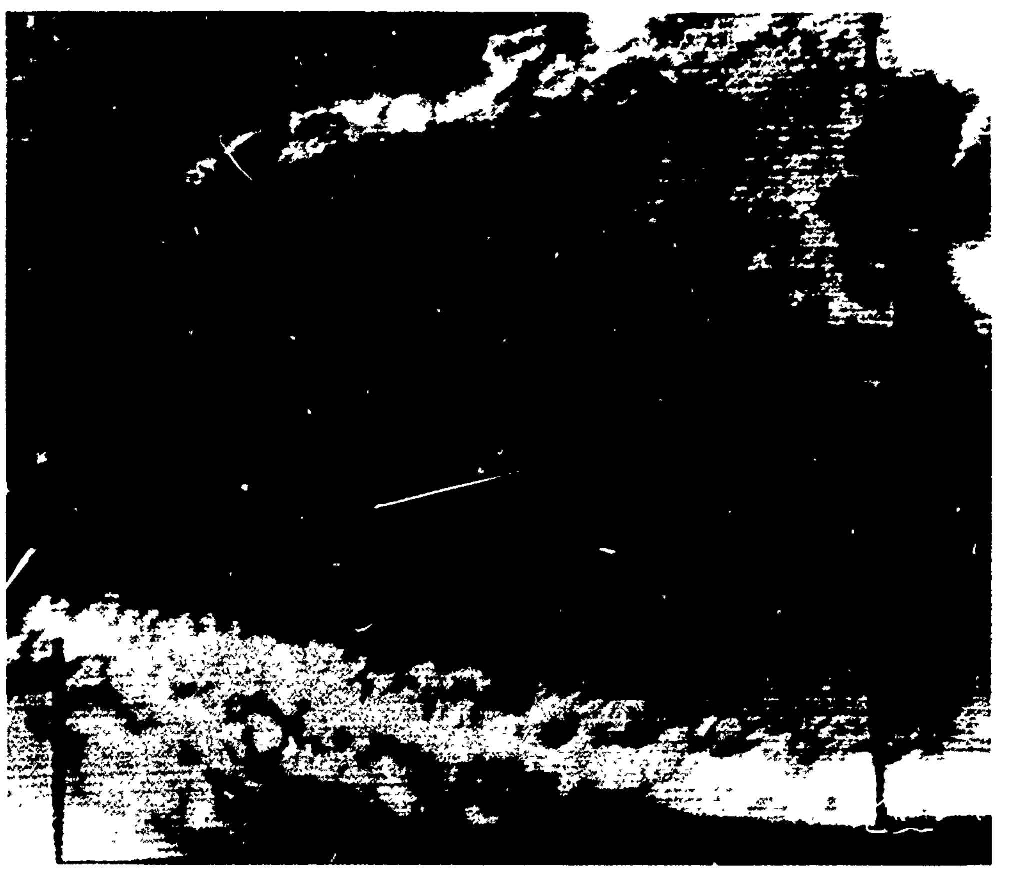


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FIG. 2. Tiros 7 photograph of the eastern seaboard of the United States, orbit 0063, 23 June 1963.

preting any rectilinear horizontal markings as a sign of life, because system noise has a tendency to align itself horizontally. The width of the scanning lines on the scale of the enlarged photographs is 0.25 mm per line. Any feature appearing smaller than this should not be considered significant.

Figure 2 is a typical Tiros photograph of a relatively cloud-free region of the Earth. It displays the Eastern seaboard of the United States from Cape Cod to Chesapeake Bay at a resolution of a few kilometers. This is one of the most heavily populated and industrialized areas in the world. It is covered with an elaborate system of railroads and superhighways, all of which are entirely invisible. A careful search was made for the bridges across, for example, Chesapeake Bay, but with negative results. There was no sign of New York City, the world's largest metropolis. At a resolution of a few kilometers and at optical frequencies, there is no sign of life near the Eastern seaboard of the United States. Similar conclusions were obtained from photographs of the regions of London, Paris, Los Angeles, Chicago, Tokyo, Calcutta, and Cairo. Figure 3 is a photograph of the Florida peninsula. The causeway to Key West, a long and isolated feature, is entirely invisible.

FIG. 3. Tiros photograph of the Florida peninsula.

FIG. 4. Nimbus 1 photograph of the northern coast of Morocco, orbit 295, September 1964.

Figure 4 is a Nimbus 1 photograph of the northern coast of Morocco. The bright features north of the coast are clouds. The Mediterranean appears very dark. An apparently perfectly straight bright line can be seen extending across an expanse of water and connecting two land areas. This rectilinear feature is 25 km long and in some places 1.5 km wide. It corresponds closely to the kind of feature which we would tend to associate with intelligent life.

However, almost certainly, this feature is not a breakwater but a natural peninsula. From Fig. 4 there seems no reason to question the connectedness of this linear feature with the western peninsula. In the upper half of Fig. 5 is a drawing of the region we are here describing, taken from the Nimbus 1 print. In the lower half of the same figure is a drawing taken from a map in Mercator projection of the same area (U. S. Army Map Service, 1955). The Nimbus 1 projection is of course somewhat different from the Mercator. It is clear that the apparent rectilinear feature is not exactly rectilinear, nor is it connected with the peninsula at

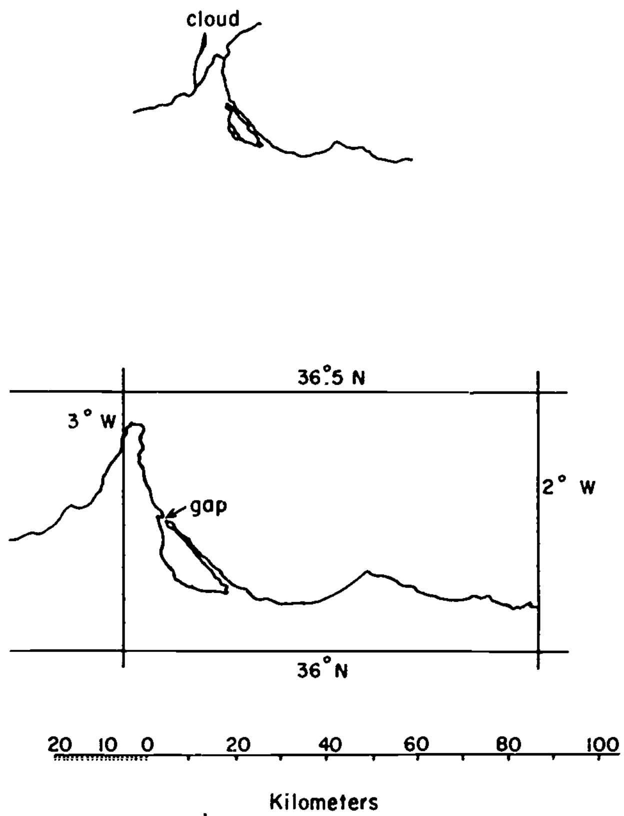

FIG. 5. Upper: Drawing of the appearance of a section of the northern coast of Morocco, from the Nimbus 1 photograph of Figure 4. Lower: Mercator projection cartography of the same region, taken from U. S. Army Map Service maps.

3° W. It is separated from the peninsula by 1.5 km of water. The discrepancy may be due to one or two bits of false data, or to the rectilinear feature actually extending to the peninsula at 3° W, but being covered over by water at the position of the gap. There is, however, a tendency, long known to students of the Martian canal problem (Antoniadi, 1930), for the human eye to connect disconnected features into rectilinear ones. This rectilinear feature in Morocco was found purely by accident from the randomly selected Nimbus photographs, and illustrates the danger of deducing the existence of intelligent life from rectilinear features on a planetary surface.

Other examples of linear features found on the Earth, but not due to intelligent activity, can be found in Fig. 6, where wave clouds over the Appalachians are shown, and in the discussion by Gifford (1964) on the seif sand dunes of the Arabian Peninsula.

Figure 7 is a Nimbus 1 photograph of the Tennessee area of the United States. Figure 8 is drawn from a tracing which attempts to reproduce all important linear details in Fig. 7. The Mississippi River, seen meandering towards the lower left corner, provides an excellent reference feature for comparison with existing maps. A map of the same area has been prepared in Fig. 9. In making tracings from such photographs, the decision as to what constitutes a continuous rectilinear feature is rather subjective; we decided not to try to depict details whose continuity might be illusory. With this constraint, the details observed were still sufficiently plentiful for some conclusions to be drawn.

FIG. 6. Tiros 7 photograph of wave clouds over the Appalachians, orbit 4363, 9 April 1964.

Figures 8 and 9 were not drawn to the same scale; even if they were, the distortions introduced by the projection effects would preclude any detailed superposition of the features of the entire region. Nevertheless, the best technique for comparison was found to be superposition of small areas. The kinks, discontinuities, and linear features were especially helpful in performing the comparisons.

Both bright and dark lines appear in this photograph, the bright lines appearing almost exclusively in the lower center and lower right regions of the photograph. Examining either the photograph or the tracing, one sees significant differences between the characteristics of the bright and those of the dark lines. Some of the bright lines are connected with the Mississippi River and Kentucky Lake on the Tennessee River (center of Fig. 7) and can be attributed to sun glint on the water surfaces. Some of the dark tributaries along the Mississippi Basin are probably not large enough to exhibit sun glint; their presence is indicated by the dark vegetation of varying widths along the banks and beds. The dark lines all appear to join the Mississippi and its tributaries at acute angles, and are clearly part of the river system. In contrast, the bright lines cross each other and are less clearly connected with the Mississippi system.

Fig. 7. Nimbus 1 photograph of Tennessee, orbit 196, 10 September 1964.

They are therefore the features of primary interest in the present context.

Since natural linear features are not expected both to be straight for extensive distances and to cross each other, at least one of the thin unbroken lines in Fig. 8 should represent a road. The line so designated is the only one which is fairly straight and which crosses more than one other linear feature.

There are three corresponding features on both the tracing of Fig. 8 and the map of Fig. 9; they are designated a, b, and c. Their correspondence leads to the conclusion that the line in question is indeed a road, namely Interstate Highway 40. The reason Interstate 40 is visible, while many other roads of comparable linearity and width are not (cf. Fig. 2) is due to the fact that this highway was, at the time it was photographed, a new one. A relatively highly reflecting surface had been made visible by cutting a swath through a forested region. The width of the swath ranged from 15 to about 50 meters, typical values for the interstate highway system. Thus, a major road has been observed, even though its width could be no more than

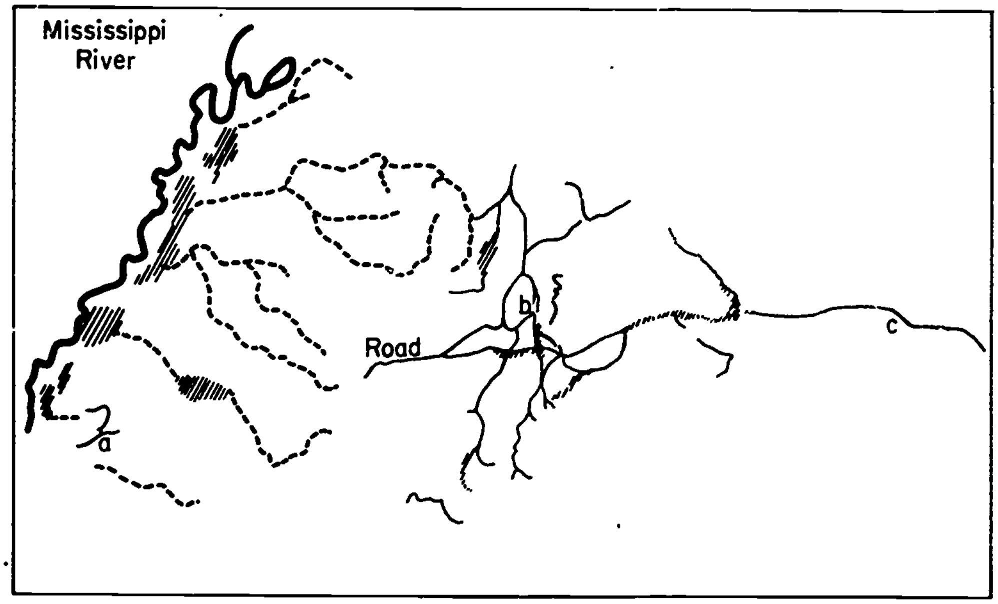

FIG. 8. A tracing of fine detail which reliably appears on the original of Fig. 7. The thick line corresponds to the Mississippi River. The dashed lines correspond to dark, approximately rectilinear features on the photograph. The thin line corresponds to bright rectilinear features on the photograph other than the Mississippi River. (The shallow sinusoid extending upwards and to the right above the feature marked b, until it ends abruptly, is a railroad.)

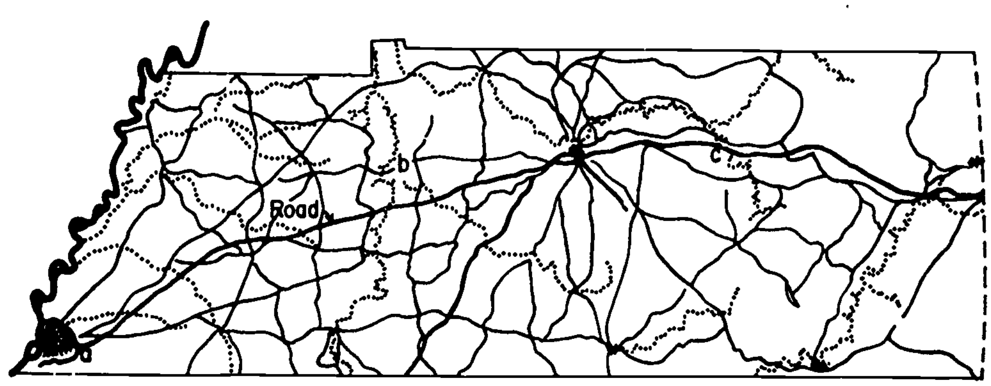

FIG. 9. Map of the area of Figs. 7 and 8. The thick line corresponds to the Mississippi River; the dotted lines, to rivers and lakes; the thin lines, to roads; and the shaded areas, to cities (Esso Oil Company, 1961; National Geographic Society, 1963; Portland Cement Assn., 1964).

10% of the 0.5-km ground resolution of Nimbus 1. The observation was possible only because of the high contrast between this rectilinear feature and its background. With Interstate Highway 40 detected, it then becomes clear that the feature to the left of the bifurcation marked a is the city of Memphis.

Figure 10 is an exception to the collection of photographs shown in the present paper, in that it represents a region that is almost entirely cloud-covered. The break in the clouds at the center of the picture is located in the Davis Straits, about midway between Godhavn, Greenland and Baffin Island, Canada. To the left of the break in the clouds, a rectilinear feature over 200 km long may be viewed. The length and recti-

FIG. 10. Nimbus 1 photograph of a primarily cloud-covered area near the Davis Straits, orbit 49, September 1964.

linearity of this feature provides a strong suggestion of intelligent origin. Closer examination shows that there are two rectilinear features, one bright and the other dark, both superposed on the cloud layer. We are looking at a bright rectilinear feature and the shadow it casts upon the cloud bank: perhaps an aircraft contrail. The photograph was taken at about local noon near 70°N latitude at approximately the autumnal equinox. With this information and the apparent distance between the feature and its shadow, it is easy to compute that the height of the feature is approximately 6 km above the cloud bank, a reasonable altitude for jet aircraft. Plotting this rectilinear feature on a globe suggests that it falls approximately on a great circle connecting California and Northern Europe. It may represent the jet contrail of a commercial over-the-pole flight. Alternatively, this feature may represent a natural jet stream cloud (White, 1965).

In the photograph of Fig. 10, the trail can be seen to have dissipated more at left than at right, indicating that the source was traveling from west to east. From an extraterrestrial vantage point, the detection of a moving rectilinear feature of approximately constant length, generated at one end and dissipated at the other, casting a shadow and traveling large distances, would provide a strong case for the existence of intelligent life on Earth.

Figures 11, 12, and 13 are Nimbus 1 photographs of, respectively, Southern California; the Fergana Basin in the Kirghiz Soviet Socialist Republic and in western Sinkiang Province; and the Island of Öland, off the southern coast of Sweden. All three figures illustrate situations where linear features were suspected, but could not be convincingly demonstrated.

The photograph of Southern California shows the region of Santa Barbara. Several roughly rectilinear features can be detected. All, however, correspond to rivers. There are no highways visible, including the very wide and straight Interstate Highway 5, and there is no trace, in a heavily cultivated area, of rectilinear fields. In the top center of Fig. 11 is a feature with somewhat regular outlines lying in the same area as the Central Valley Project of the San

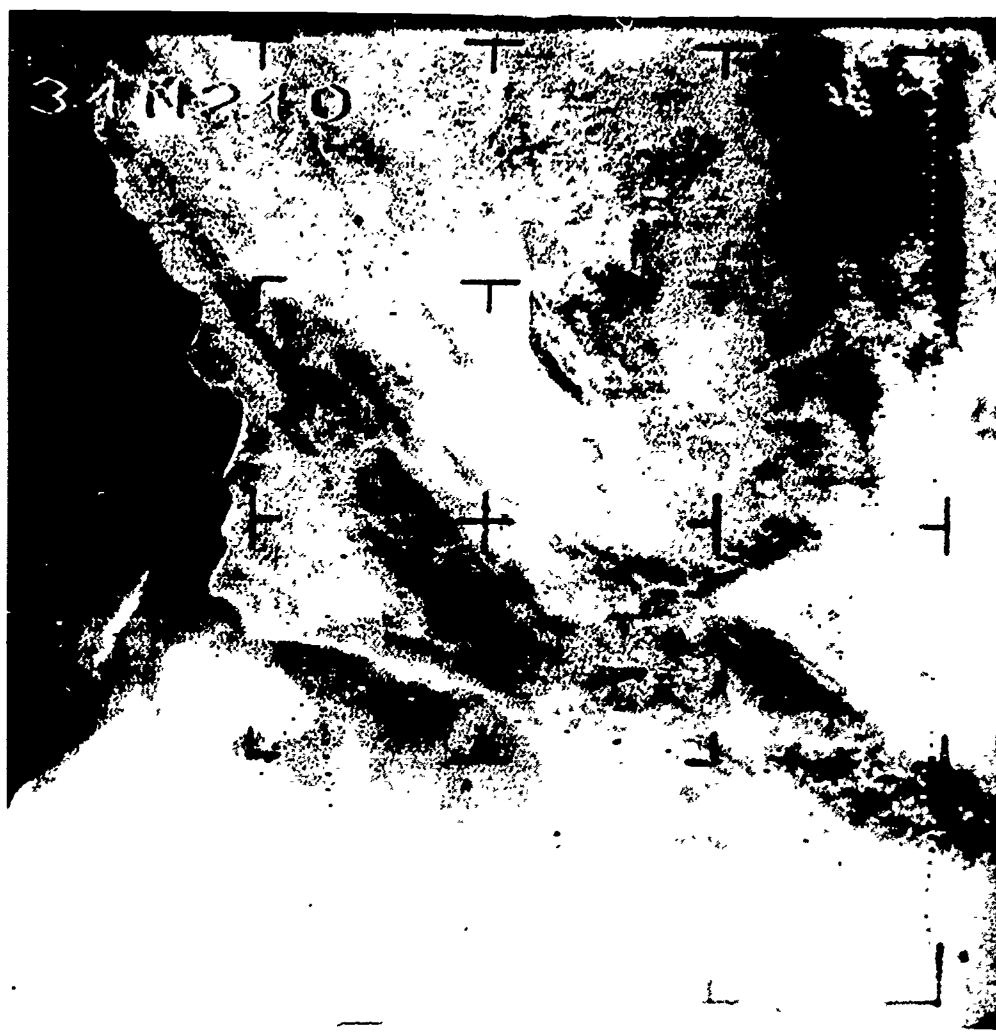

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FIG. 11. Nimbus 1 photograph of southern California, orbit 329, 19 September 1964.

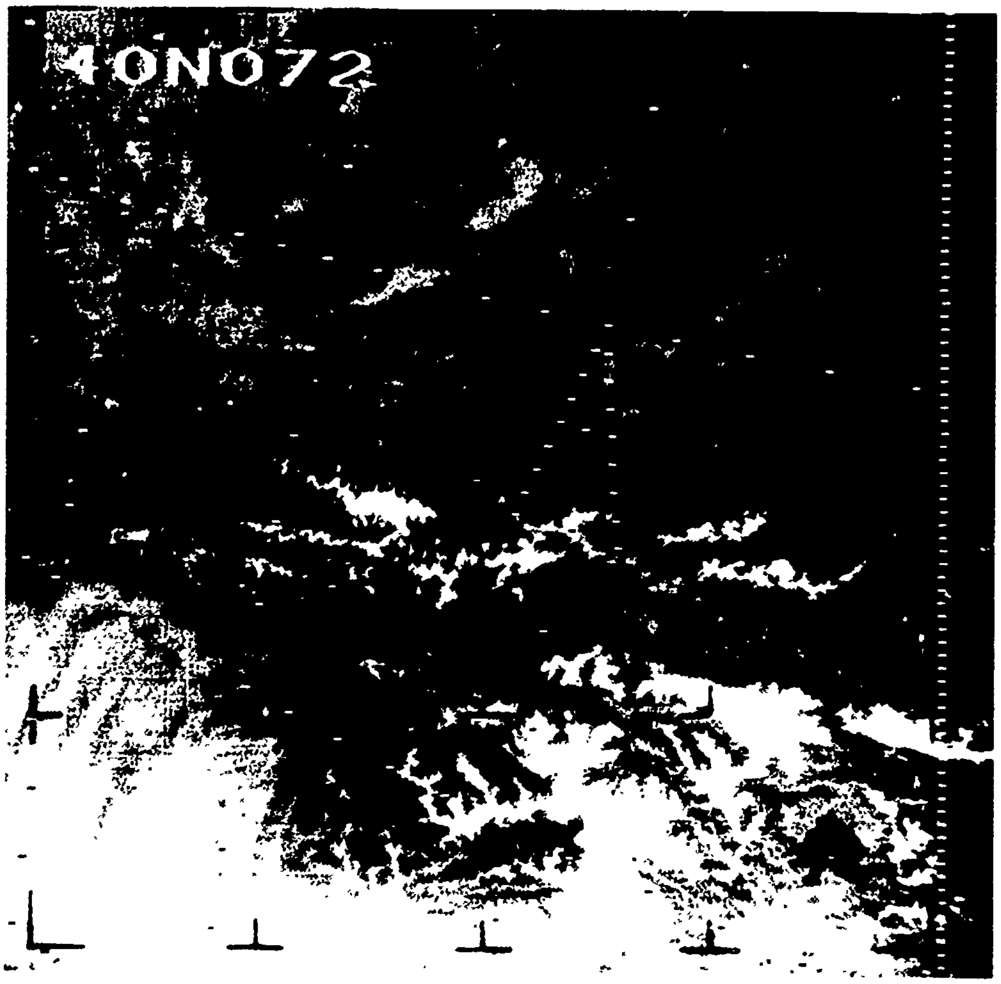

FIG. 12. Nimbus 1 photograph of the Fergana Basin, in the Kirghiz Soviet Socialist Republic and Western Sinkiang Province, China, orbit 321R, September 1964.

Joaquin Valley; but while suggestive of intelligent origin, this feature is not entirely convincing. The photograph of Fergana Basin shows, among other rectilinear features, a set of faint bright lines penetrating mountain passes in the eastern half of the photograph. However, because of the absence of convenient road maps of this region, no further investigation of these features was made.

On the island of Öland, there are some approximately rectilinear features seen which are in fact the boundaries of regions of differing contrast. There seems to be some correlation with the positions of roads and railroads on standard maps of Öland

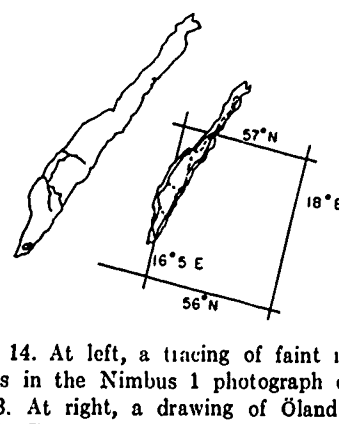

FIG. 14. At left, a tracing of faint rectilinear features in the Nimbus 1 photograph of Öland, Fig. 13. At right, a drawing of Öland redrawn after the Times *Atlas of the World*, showing roads as straight lines, and railroads as dashed lines.

FIG. 13. Nimbus 1 photograph of the Island of Öland, off southern Sweden, orbit 367, September 1964.

(cf. Fig. 14), but while suggestive, the detection of these features can at best be considered marginal.

A striking array of rectilinear markings may be seen in Fig. 15, a Tiros 2 photograph of the region near Cochrane, Ontario, Canada, obtained on April 4, 1961. This photograph, taken with the narrow-angle Tiros camera, has a ground resolution of about 0.2 km. The width of the rectilinear features is ~0.5 km. Cochrane is a lumber region, and the rectangular array represents an orthogonal grid of logging swaths. The swaths appear especially bright in this photograph because snow had recently fallen. The grid pattern is designed to allow for reforestation of the logged regions. This is surely a case where ground truth is the whole story. If we were to detect a similar rectangular array on Mars, it would certainly be premature to conclude that there are trees on Mars, that it had recently snowed, and that the trees were felled by a race of intelligent beings concerned for future reforestation. All that could be concluded would be that this is an area of unusual interest deserving further study.

As a last example of satellite photogra-

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Fig. 15. Tiros 2 photograph with the narrow-angle camera, of the region of Cochrane, Ontario, Canada, taken on 4 April 1961.

phy of the Earth, consider Fig. 16, a Nimbus 1 photograph of central France, initially selected in the hope of finding the characteristic checkerboard pattern of cultivated fields. None of these was found. Paris, which lies in the left center of the picture, on the Seine River, is entirely invisible. There is, however, one striking feature: the bright region immediately to the right of center. Examination of vegetation maps in the *Atlas de la France* shows that this feature corresponds to the only large conifer forest in France, occupying much of the province of Champagne. The spectral acceptance passband of the Nimbus 1 photometer extended into the near infrared, where the preferential reflectivity of conifers and other green plants is well

FIG. 16. Nimbus 1 photograph of central France, orbit 236, 13 September 1964.

known. However, there are many inorganic materials which have a high near-infrared reflectance, and the mere existence of a patch of high reflectivity is far from a demonstration of the existence of vegetation. In fact this same area also corresponds to the exposed Upper Cretaceous chalk formations of the Barren Champagne (Goddard Space Flight Center, 1965). The chalk formations and the conifer forest seem to be occupying the same region and a decision between these two possible sources of high reflectivity requires further study. (For further discussion of the problem of remote detection of vegetation, see Sagan, 1965*b*).

CONCLUSIONS

The remote detection of seasonal variations in the reflectivity of vegetation is difficult to perform because of the general low contrast between the vegetation and the underlying terrain. The detection of rectilinear features due to the constructions of an intelligent civilization on Earth is possible with the narrow-angle systems of the Tiros and Nimbus satellites, but such features are not evident in photographs taken with the wide-angle system of the Tiros series. The transition to detectability seems to lie somewhere around 1-km ground resolution.

If the rectilinear features have high contrast with their surroundings, they have a certain probability of detection from satellite altitudes with resolution of ~1 km. Four of the photographs seem to show strong evidence for rectilinear features of intelligent origin. These are Interstate Highway 40, in Tennessee (Fig. 7); the jet "contrail" over the Davis Straits (Fig. 10); the logging swaths near Cochrane, Canada (Fig. 15); and the "breakwater" in Northern Morocco (Fig. 4). In this small sample, the reliability of the conclusion that rectilinear markings betoken intelligence is seen to be 50% to 75%. The data is difficult to treat statistically, since the detection of even one long rectilinear feature, preferably crossing others, might be in itself convincing.

However, it is possible to make some estimate of the probability of intelligence being detected on the Earth by a given number of random observations of a quality similar to that obtained by Nimbus 1. The 200 Nimbus photographs which we examined in detail were selected from a larger group of photographs of approximately cloud-free areas, containing approximately 10 times as many photographs. Thus, out of several thousand photographs of the Earth's surface, two highly indicative objects—the "contrail" and Interstate Highway 40—were found. Also, one deceptive feature—the Moroccan "breakwater"—was identified. Thus, very crudely, we may conclude that several thousand photographs of the Earth, with a resolution of a few tenths of a kilometer, are required before any sign of intelligent life can be found with some reasonable reliability. As the resolving power improved, the number of photographs randomly distributed of the surface of the Earth required would probably decrease somewhat (Sagan, 1965b).

It is clear then, that an equivalent Mariner 4 system—taking 22 photographs of the Earth with a resolution of several kilometers—would not detect any sign of life on Earth, intelligent or otherwise. We do not expect intelligent life on Mars (Sagan, 1965a), but if there were intelligent life on Mars, comparable to that on Earth, a photographic system considerably more sophisticated than Mariner 4 would be required to detect it. Photographic reconnaissance of Mars from an orbiting spacecraft is in principle capable of providing some very significant information relevant to life on Mars providing very high resolution were obtained (Sagan, 1965b,c). The Mariner 4 photographic system can be considered the forerunner of future photographic reconnaissance experiments from spacecraft in the vicinity of Mars, experiments which might conceivably have some bearing on the question of life on Mars.

ACKNOWLEDGMENTS

We are very grateful to Messrs. Harold Oseroff and William G. Stroud, of the Goddard Space Flight Center, for invaluable assistance in obtaining access to the Tiros and Nimbus photographs; to Mr. Wm. Widger for calling our attention to the paper by White; and to Professor Fred L. Whipple for his encouragement and for several stimulating conversations.

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A dramatized account of the boyhood of the Japanese astronomer who discovered a recent comet. This same comet, Ikeya-Seki, is described also in the following article.

15 The Boy Who Redeemed His Father's Name

Terry Morris

1966

With a homemade telescope that cost only $22.32, Kaoru Ikeya searched the skies for 109 nights, until he made a discovery that brought honor to his family

As she had done many times, Mrs. Ikeya woke when her son Kaoru did and, unnoticed by him, saw him preparing for sky-watching. All the other children, stretched out beside her on the *tatami* matting, slept soundly under their quilts. Only her eldest son, mainstay of this fatherless house, refused to take his full rest before going to work the next morning. Winter nights are cold in Japan. Moving quietly, Kaoru drew on his leather windbreaker, heavy work pants, wool scarf and gloves. Carrying his bed quilt with him, he left the house to climb an outside ladder to his rooftop perch beside his telescope.

Mrs. Ikeya closed her eyes and tried to go back to sleep, but couldn't. Instead, she lay listening to the bitter wind as it swept in from the Pacific and blew across Lake Hamana, just outside the door.

No matter how bizarre his behavior might seem to others, Mrs. Ikeya felt that she owed her son understanding and acceptance. Yet when she saw him, pale, too thin, and haggard from lack of sleep, she often had to stifle a protest.

By this night of January 2, 1963, 19-year-old Kaoru Ikeya had logged a total of 335 hours and 30 minutes of observing the sky in a period of 109 nights; and there had been countless nights before he began his official log. Yet each time he peered through the eyepiece of the telescope he had made with his own hands, his pulse quickened in expectation. Kaoru had set himself a goal. More than anything else, he wanted to be the discoverer of a new comet.

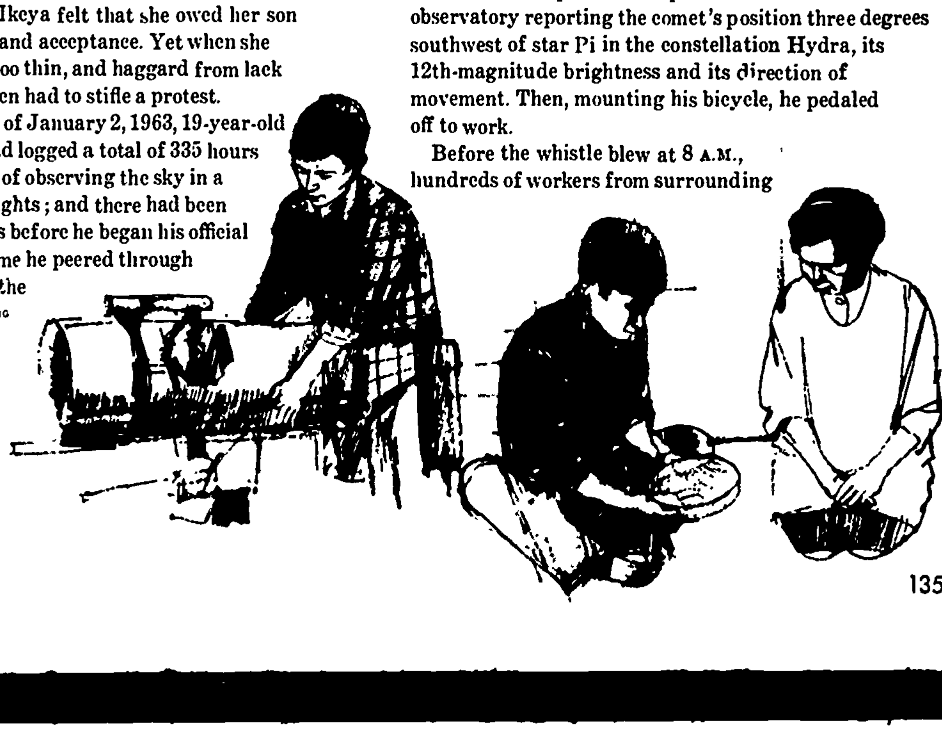
Kaoru adjusted the eyepiece and almost at once sighted in the sky a misty object he had never noticed before. He consulted his sky maps. They showed nothing in that location. Thoroughly roused, he rechecked its position meticulously, then remained glued to his telescope, half-convinced that what he was seeing must be a delusion. But the small, round, diffuse glow remained in the sky, and observing its gradual movement among the stars, Kaoru positively identified it not as a faint star cluster but a coma, the head of a comet.

But was it *his* comet? Or was he witnessing the return of a comet already recorded? Only when the Tokyo Astronomical Observatory had checked out his data would he know whether he had made a discovery.

Next morning Kaoru waited outside the telegraph office before it opened to dispatch a wire to the observatory reporting the comet's position three degrees southwest of star Pi in the constellation Hydra, its 12th-magnitude brightness and its direction of movement. Then, mounting his bicycle, he pedaled off to work.

Before the whistle blew at 8 A.M., hundreds of workers from surrounding

ILLUSTRATED BY ED YOUNG



towns had parked their bicycles within the gates of the huge plant of the Kawai Gakki Company, manufacturers of pianos. In visored cap and factory coveralls, Kaoru Ikeya, a slight figure standing five feet four inches and weighing a bit under 125 pounds, was at once absorbed into the anonymity of the assembly line, where as an ungraded, or unskilled, worker he polished the white celluloid sheaths for piano keyboards at a salary of 13,000 yen, or about $35, per month.

But Kaoru's thoughts were not on factory work. He had refused special training to upgrade himself at the piano company, and once again he was grateful that his job demanded so little of him. Polishing celluloid was mechanical; he could think of other things.

"A steady fellow," his personnel card read. "Reliable. Quiet. Middle school education only. Nonparticipant in company sports or hobby clubs. ... Lacks ambition and initiative."

Within a few days after Kaoru received his reply wire from the Tokyo Observatory, the international news services were flashing quite another profile:

"Self-taught 19-year-old amateur astronomer Kaoru Ikeya, using a reflector telescope he constructed by himself at a cost of $22.32, has discovered the New Year's first comet, officially designated Comet Ikeya 1963a and now the subject of observation and tracking by astronomers in both hemispheres."

A spate of publicity greeted Kaoru's discovery. His home was invaded by news photographers; he was led before TV cameras and radio hookups; he received more than 700 letters from amateur astronomers seeking his advice; he was awarded a gold medal by the Tokyo Observatory; and he watched in polite silence a professional actor portray him in a hackneyed, melodramatic version of his life story, an "inspirational" 40-minute movie short called

Watching the Stars, which was to be shown to the school children of Japan.

Aglow with pride at the honors heaped on her son, Mrs. Ikeya saw the film through rose-colored glasses.

But Kaoru did not share her bias. "This movie is a novel, a fiction about me," he commented wryly. "Why isn't the truth good enough?"

The truth was neither hackneyed nor melodramatic. To begin with, if his father had not moved the family from the large industrial city of Nagoya to the town of Bentenjima when Kaoru was six years old, Kaoru would probably have acquired a city boy's indifference to the sky, observing it only in bits and patches between buildings. But their house fronted on Lake Hamana, a salt-water lake fed by the Pacific, and the flat roof offered a perfect platform for observing a far-flung canopy of the heavens. As the family grew and Kaoru sought to escape from the noisy clamor of three younger brothers and a sister, he often mounted to the quiet rooftop to look at the stars.

In addition, there were Japanese holidays that had stimulated his interest in the stars. For as long as he could remember, he had joined with other boys and girls in hanging strips of colored papers bearing poems and pictures on stalks of bamboo that had been set up outdoors. These were directed to the two celestial lovers, the Weaver Star and the Cowherd Star, who, so the story goes, live on either side of the Milky Way and meet only once a year, on the night of the festival. In the middle of or in late September of each year there was also *Tsukimi*, a special holiday when all Japan makes offerings of trays of rice dumplings and clusters of seven autumn flowers to the new full moon.

By the time he was 11 years old Kaoru was highly "sky conscious." He was so enthralled with the mystery of the heavens that he had begun to look for books in his school library that would tell him more about the stars, and to trace maps and diagrams of the skies into his school notebook. Tentatively at first, then with deepening familiarity, he began to distinguish among the galaxies and constellations and to wish to see more than he could with his naked eye. What fascinated him most were comets, those ghostly celestial bodies so nebulous as to be commonly described in his books as "the nearest thing to nothing that anything can be and still be something." Kaoru made up his mind. It was a new comet that he longed to discover—a comet of his own, with its fuzzy head surrounding a bright nucleus, its long, ephemeral tail pointing away from the sun and its journey through the skies lasting from three to thousands of years.

There was still another holiday that made an impression on Kaoru during his early years. Every May 5th, on the national holiday known as Boys' Day, the Ikeya family, along with others among their neighbors who were fortunate enough to have sons, held a special celebration. On tall poles next to their houses they displayed cloth streamers in five colors made in the image of Japan's favorite fish, the river carp. Proudly the Ikeya pole flew six carp, one for each son of the house and one for each parent. Poor Fumiko, the sole daughter of the house, was given new dolls to placate her. Then Mr. Ikeya lined up his sons and exhorted them to grow up to be good citizens. In emulation of the carp's brave, vigorous struggle upstream, he said, they must aspire ever higher in their own lives.

By the time Kaoru was 12 and had had the six years of elementary school, he had determined to build his own telescope. Although his father's fish market was prospering, Kaoru was reluctant to ask him to buy one. Already there was tension between them. Instead of applying himself to learning the family's business, his father complained, Kaoru's head was "always in the stars."

Mr. Ikeya was still moored to the old, prewar attitudes. "Sound sense should show you, my son," he insisted, "that astronomy does not belong to our station in life."

How, Kaoru wondered silently, did his father's annual Boys' Day message square with this contention? How much higher could one aspire than to the stars? In contrast to his father, Kaoru was growing up in a postwar Japan heavily influenced by the Americans who occupied the country. In response to reforms enacted in the New Education Law of 1947, his teachers from first grade on rejected the old emphasis on passive, rote learning and memorizing. Instead, they encouraged questions and discussions and created projects that his father called a foolish waste of time.

The new way also widened Kaoru's horizons outside the classroom. In the spring and fall he was among the hundreds of thousands of school children who took off on excursions to parks, monuments, temples and shrines. The Get-To-Know-Japan program, under which the participants were chaperoned by teachers and billeted at hostels and inexpensive inns, was so inexpensive that by contributing pennies into the class travel fund each week, Kaoru could afford to take advantage of it.

In middle school, where he completed the nine years of compulsory education, Kaoru was a good student, ranking fifth in a class of 50 students. But he had no favorite subjects. "Except, of course, the one I thought about and worked at by myself," he says.

Astronomy was not taught in middle school, but Kaoru haunted the school library, reading texts on astronomy and studying the principles of optics, physics and chemistry involved in telescope-making. With his meager savings he also managed to buy a number of do-it-yourself manuals on how to build a telescope. He was barely 14 when, reading an astronomy journal, he came across the name of Dr. Hideo Honda, an ophthalmologist in Nagoya who held monthly meetings for amateur astronomers in his clinic.

Kaoru wrote to Dr. Honda that he was planning to construct a Newtonian reflector telescope with a 20-cm. or 8-inch mirror—the most popular and feasible for do-it-yourself amateurs. Noting that his young correspondent was only 14, Dr. Honda didn't think the boy would have either the skill or the stamina to see his project through. On the other hand, he was reluctant to discourage Kaoru.

"I think," he replied cautiously, "that you are very likely too young to make a 20-cm. mirror. Your idea presents many difficulties and I shall tell you all I know about them. But so many young men in Japan after the war are impatient, especially with regard to making observations. Although many have highpriced telescopes, they rarely observe the stars. They use their fine instruments only to watch an eclipse of the sun or some other show in the heavens. Few of them would be able to take the pains to construct their own instruments."

Kaoru reflected that Dr. Honda could not possibly understand how prepared he really was—at least to take infinite pains. He continued with his studies and gradually began to acquire the materials needed for making his telescope. It was at about this time that misfortune struck the Ikeya family.

For some time Mr. Ikeya's fish market had been failing. The reasons he ascribed to this were "price-fixing by ignorant and officious Japanese and American policy makers," but also, he pointed out, it was retribution by the gods, who were angered by the way Shinto beliefs were being shunted aside.

Discouraged and embittered, Mr. Ikeya began to lounge about the cafés, drinking sake, increasingly reluctant to face his family or five young children. Early in 1958 he resolved his dilemma by disappearing, abandoning them all.

Perhaps nowhere else in the world does a father's desertion so cruelly punish those he leaves behind as in Japan, where the concept of *on* heavily influences individual behavior. *On* refers to the obligations each person incurs through contact with others by the mere fact of his existence. The most basic form of *on* is *ko*, the obligation to one's parents for the daily care and trouble to which they are put: even by offering unwavering loyalty, obedience and reverence, no more than one ten-thousandth of this debt can ever be paid. This particular duty, *ko*, also imparts the same obligations to descendants. A Japanese proverb says: "Only after a person is himself a parent does he know how indebted he is to his own parents." It follows, then, that a significant part of *ko* is to one's own parents in giving as good or better care to one's children.

In deserting his family, Mr. Ikeya not only failed utterly in his duty as a parent but violated his most sacred *on* of filial duty to his own parents. He placed an oppressive burden of shame on them all and tarnished the family name, perhaps for generations.

"We could think of nothing else, my mother and I," Kaoru says, "but that our family was disgraced, our house destroyed."

The first and hardest impact of the disaster was on Mrs. Ikeya. Sadly Kaoru watched his mother go to work at the hotel near the Bentenjima railroad station, cooking and cleaning for strangers instead of in the seclusion of her own house and family. But, as she observed to him, at least the older children were safe in school during the day and she could keep the baby, four-year-old Yasutoshi, with her on the job. Although she was under five feet tall and even in her bulky, padded house jacket, trousers and coverall apron looked slight as a sparrow, her strength and fortitude in dealing with this family crisis were immense. What she told herself was that the money she earned, around 17,000 yen a month, or about $47, ensured food for her children.

Kaoru felt the weight of his love and duty toward his mother. But until he completed the compulsory third year of middle school he could do no more to lighten her burden than to take a part-time job, rising at five A.M. to deliver morning newspapers before school, then returning after classes to deliver the evening edition. Of course, attendance at high school was barred to him. The family could not afford either the time or the fees, which amounted to about $25 for registration and about $8 per month.

Mrs. Ikeya's and Kaoru's combined efforts were inadequate to keep up payments on their comfortable, roomy house. The bank foreclosed and permitted them to move, virtually rent-free, into a far less adequate house a few doors away.

This house provided a narrow entryway, an all-purpose eating-sleeping-living room, a tiny kitchen, a catchall cubicle and a lavatory at the back. But in common with most Japanese houses it was orderly and simple to keep clean, since shoes, which might track up the *tatami* on which families bed down at night, are never worn inside Japanese houses. In the Ikeya home the furniture consisted of a bureau, a square low table with floor cushions, Kaoru's worktable, and two rough shelves that he constructed to hold his small collection of books and manuals. No Japanese houses have central heating, and the Ikeyas relied on a large porcelain jar filled with heated charcoal briquets. Even well-to-do families have nothing more than a *hibachi*, a pit in the floor filled with charcoal.

The feature of the house that most concerned Kaoru was the flat roof, which provided as good a platform and as good a sky to view as before. On his shoulders rested the responsibility not only of replacing his father as breadwinner and head of the house, but of somehow removing from the family name the stigma his father had attached to it. More than ever he thought about his comet. What if one day he could attach the dishonored name to the tail of a new comet and write that name across the sky? New comets were generally named after their discoverers. "Comet Ikeya!" The name had a fine, proud ring to it!

In June, 1959, when he graduated from middle school, Kaoru was deeply immersed in his thoughts about telescope building, but he paused long enough to get a job at the Kawai Gakki piano factory, a few miles from home. Since degree of education is directly and, on the whole, inflexibly related to earning power in the Japanese economic scale, Kaoru was classified as an ungraded or unskilled worker at base pay.

Kaoru wasn't disturbed. "It's a simple job," he reported to his mother. "It will not bother me."

Mrs. Ikeya also was content. Although the Japanese are now more concerned with money-making and worldly success than before World War II, with its postwar Western influences, many still place greater emphasis on the reflective life and spiritual values. On the practical side of her ledger, Kaoru's base pay and regular annual raises, together with her own earnings, were enough for the necessities of life. Soon, too, Tadashi, her second son, only two years younger than Kaoru, would also become a wage earner. She didn't attempt, though, to budget the spiritual side of the ledger. She would be a poor mother indeed if she offered Kaoru anything but encouragement and the greatest freedom, within the confines imposed on him by necessity, to follow his own pursuits. Who knew? Perhaps he would even attain Buddhahood through the ordeals he imposed on himself.

Kaoru set to work grinding the high-precision surface for the main mirror that would go into his telescope. Shopping around in secondhand supply stores, he obtained the last-minute materials he needed. Bit by bit, and after trial and error, Kaoru, still thinking for himself and going it alone, completed the preliminary work, and then began the final process of assembling and mounting his telescope on the roof. In August, 1961, he was ready to begin once more to search the skies. Since starting work at the factory he had put nearly two years of off-work hours of labor into achieving his telescope, at a total out-of-pocket cost of 8,000 yen, or about $22.

In Japan, the best hours for viewing are from 3 A.M. to 5 A.M., but of course, not every sky is fit for observation. On cloudy mornings Kaoru caught up on the sleep he lost during clear mornings, when the predawn spectacles thrilled him. He logged his watches meticulously and checked back with his sky maps, but six months after he had begun to search regularly, Kaoru felt deeply discouraged. The search for a new comet seemed futile. More and more often he began to fall into a mood of profound depression.

"My son," Mrs. Ikeya said, "you are too much alone with your thoughts. Is there no one you could talk to who would give you advice?"

Perhaps she was right. Kaoru broke out of his solitude to establish communication with someone who had known not only the trials of comet-seeking but also the rewards. He wrote to the astronomer Minoru Honda, discoverer of nine comets, about his lack of success, pleading between the lines for a word of encouragement.

At first the reply seemed to him almost a rebuff. Then, pondering it, Kaoru seized eagerly on its meaning.

"To observe the skies solely to seek a new comet is a hopeless task which demands a great deal of time and hard labor," Minoru Honda wrote. "But to observe the brilliant heavens for their own sake without thought of a discovery may bring good luck to your comet-seeking. You must have humility and not be too ambitious, for, after all, you are quite young and only an amateur."

Kaoru returned to his sky watches. He tried to maintain a humbler and more relaxed attitude. He still had a great deal to learn about the heavens, and instead of searching for a comet in particular, he concentrated on the whole sky, trying to become as familiar with its plan as he was with the streets and byways of Bentenjima.

On December 31, 1962, Mrs. Ikeya counted a total of 16 months since Kaoru had begun his night vigils with his new telescope.

"Surely, Kaoru," she pleaded, "this first night of the holidays you will take your full rest. It is *Omisoka*, after all, the Grand Last Day of the year! Both of us have worked hard. We have honorably settled all our debts, and can start the new year with a clean record. Let us stay awake until midnight, listening to the temple bells, and then sleep late in the morning."

To please her, Kaoru didn't climb to the roof that night, and all through New Year's Day he remained with the family, enjoying his mother's holiday meal of *ozoni* (rice cake soup), playing her favorite game of cards, *karuta*, and then joining her for a visit to a nearby shrine to pray for good luck in 1963.

It was on the following night of January 2, 1963, while he was still in a relaxed, holiday mood, that Kaoru made his 109th search and discovered his comet.

At the Harvard Observatory, the western hemisphere's clearinghouse for astronomic information, all the data on Comet Ikeya 1963a, together with a projection of its orbit, were placed on announcement cards and sent to observatories, journals of astronomy and a network of professional and amateur astronomers around the world.

The comet changed its form and brightness nightly as it reached its maximum visibility at perihelion, or closest passage to the sun, calculated to take place on March 21st. At this point Comet Ikeya would be 59 million miles distant from the sun and some 93 million miles from the earth. Then the celestial spectacle it offered would be over until late spring, when it would become visible again in the morning sky, a considerably fainter object on the far side of the sun. Finally, traveling in an elliptical orbit out beyond the farthest planets, it would disappear, to return anywhere from 100 to 10,000 years hence.

Comet Ikeya 1963a was at first described as dim, but a few weeks after Kaoru sighted it, reports from Tokyo, the Yerkes Observatory, in Wisconsin, and the U.S. Naval Observatory's station at Flagstaff, Arizona, indicated that it was moving rapidly southward and brightening.

By February and early March, 1963, Comet Ikeya was providing an exciting spectacle for southern hemisphere watchers. In four weeks, beginning February 13th, it had traveled northward a quarter of the way around the sky and become an object visible to the naked eye.

An American physicist then working in Sydney, Australia, wrote to the journal *Sky and Telescope* of his experience with the comet:

"On February 14th I had my children in the back yard to show them 47 Tucani, a very beautiful globular cluster. My daughter Judy was looking through binoculars and remarked that what she saw was between the Magellanic Clouds. When I looked, I realized that she had not been viewing 47 at all, but a new comet—actually Ikeya's."

Kaoru kept in touch with his comet through a widening circle of fellow observers, but his most immediate source was the Tokyo Observatory and its staff members, notably Dr. Masahisa Tarao, distinguished astronomer and vice-president of the Japanese Astronomical Society, on whose behalf he presented Kaoru with the gold medal for achievement.

"We professional astronomers cannot watch the heavens all the time," Dr. Tarao said. "We need the assistance of amateurs in the observation of artificial satellites, solar explosions, meteors, comets and other phenomena of our universe. You, Kaoru Ikeya, by your patience and diligence, have added to our knowledge of the solar system."

All this while, Kaoru reported for his job at the piano factory, quietly and reliably. Only when the press requested interviews with Kaoru did the company learn of his achievement. The company's response was to initiate a collection among the workers to help Ikeya continue his work. A certificate lauding Kaoru's off-the-job zeal and dedication together with a check for about $300, a lordly sum in Japan, were presented to him at a ceremony at the plant. The company also financed the movie short about Kaoru's life, and paid him 30,000 yen, or about $80, for permission to make the film.

Kaoru made no effort to capitalize on his publicity. To have achieved a magnificent "first" in comet-hunting was all the reward he needed, and his appreciation of it deepened when he learned of other amateur astronomers such as Dr. Floyd L. Waters, of Hugo, Oklahoma, who very nearly made it, but did not quite.

"On the morning of January 26th," Dr. Waters wrote Kaoru, "at about 5 A.M., temperature 10 above zero, I discovered this object in the south. I became quite excited, wired my finding to Harvard Observatory, and found out later that day that what I had reported was the Comet Ikeya that had been discovered by a boy in Japan on January 2nd. All amateur astronomers would be very thrilled to discover a comet but of course do not have the perseverance to spend 335 hours trying to find one!"

But Comet Ikeya was not the last of Kaoru's discoveries. As if especially favored by the gods, Kaoru made a second discovery in June, 1964. Working with a new, improved telescope with a 17.5-cm. mirror, which he had made at a cost of 5,000 yen, or about $13, he discovered a second comet—Comet 1964f.

Still in the same job at the factory, Kaoru has neither sought after nor been offered the reward of advancement. For him the greatest advancement, according to his Buddhist faith, would be to find that "limitless, ever-expanding path, an eternal path to tranquillity." For the rest, his richest reward has been that in the span of his 21 years he has made partial payment on his *ko*, or prime duty to his mother and to his family, by taking a dishonored name and writing it across the skies.

The director of the Central Bureau for Astronomical Telegrams describes the excitement generated by a recent comet, and reviews current knowledge of comets.

16 The Great Comet of 1965

Owen Gingerich

1966

The Great Comet of 1965

OF ALL the memorable comets that have excited astronomers and stirred men's imaginations, not one had more impact on our concepts of the universe than the Great Comet of 1577. Discovered in November of that year, the comet stood like a bent red flame in the western sky just after sunset. The celebrated Danish astronomer Tycho Brahe was among the early observers: he caught sight of the brilliant nucleus while he was fishing, even before the sun had set. As darkness fell, a splendid twenty-two-degree tail revealed itself. Tycho's precise observations over the ten-week span before the comet faded away were to deal the deathblow to ancient cosmogonies and pave the way for modern astronomy.

In the sixteenth century nearly everyone accepted Aristotle's idea that comets were meteorological phenomena, fiery condensations in the upper atmosphere. Or, if not that, they were burning impurities on the lower fringe of the celestial ether, far below the orbit of the moon. In 1577 most astronomers still subscribed to the ancient belief that the moon and planets were carried around the earth on concentric shells of purest ether. Tycho, by comparing his careful measurements of the comet's position with data from distant observers, proved that it sped through space far beyond the moon. The Comet of 1577 completely shattered the immutable crystalline spheres, thereby contributing to the breakdown of Aristotelian physics and the acceptance of the Copernican system.

But the most renowned and most thoroughly studied of all comets is the one associated with Edmund Halley. It was the first to have a periodic orbit assigned, thus securing for comets their place as members of the solar system. Halley had matched the Comet of 1682, which he had observed, with those of 1531 and 1607. Assuming these to be different appearances of the same celestial object, he predicted another return in 1758. Although he was ridiculed for setting the date beyond his expected lifetime, the comet indeed returned, and Halley's name has been linked with it ever since.

On its latest return, in 1910, Halley's comet put on a magnificent display, reaching its climax several weeks after perihelion passage in mid-April. During the early part of May it increased until the brilliance of its head equaled the brightest stars and its tail extended sixty degrees across the sky. Later in May, the earth grazed the edge of the tail. The thin vacuous tail caused no observable effect on earth, except for such human aberrations as the spirited sale of asbestos suits. That no terrestrial consequences were detected is not surprising when we learn that 2000 cubic miles of the tail contained less material than a single cubic inch of ordinary air.

If prizes were offered for cometary distinctions, then last year's Comet Ikeya-Seki would win a medal as the most photographed of all time, and it might win again for the range of astrophysical observations carried out. As it swung around the sun, its brilliancy outshone that of the full moon, and within ten days its tail extended almost as far as the distance from the earth to the sun. The behavior of the comet was neatly explained by the "dirty snowball" theory. According to this widely accepted picture, a comet's nucleus is a huge block of frozen gases generously sprinkled with dark earthy materials. Occasionally the gravitational attraction of nearby passing stars can perturb a comet from its cosmic deep freeze in the distant fringes of the planetary system beyond Neptune; the comet then can penetrate the inner circles of the solar system, where it develops a shining gaseous shroud as its surface vaporizes under the sun's warming rays. Hence, the closer a comet approaches the sun, the more it vaporizes and the larger and brighter it becomes. Comet Ikeya-Seki passed unusually close to the sun, becoming possibly the brightest comet of the century; the resulting tail was the fourth longest ever recorded.

Today I look back with a wry smile to the Sunday morning last September when I decoded the telegram bringing the first word of the new comet. Early that morning in Benten Jima, Japan, a youthful comet hunter, Kaoru Ikeya, had discovered a fuzzy glow not charted on his sky maps. At the same time, another young amateur 250 miles away, Tsutomu Seki, had independently detected the new celestial visitor. Both men had used simple, homemade telescopes for their discovery, and both had sent urgent messages of their find to the Tokyo Astronomical Observatory.

News of the comet's appearance was quickly relayed from Tokyo to my office at the Smithsonian Astrophysical Observatory. Here the name "Comet Ikeya-Seki" was officially assigned, as well as the astronomical designation 1965 f. Throughout that day, September 19, the communications center at Smithsonian alerted observatories and astronomical groups all over the world — Flagstaff, Rio de Janeiro, Johannesburg, Prague, Peking, Canberra — in all, more than 120. Included were the twelve astrophysical observing stations of the Smithsonian Observatory, whose specially designed satellite-tracking cameras are ideal for comet photography. Within hours a confirmation of Ikeya-Seki arrived from the Woomera, Australia, station.

By Tuesday afternoon, half a dozen approximate positions were in hand, more than enough for us to try for a crude preliminary solution of the comet's orbit. Unfortunately, the positions from the observing stations were only approximate "eyeball" measurements obtained by laying the film onto a standard star chart with marked coordinates. Furthermore, the observatory's computer program had not been fully checked out. When the rough observations were used in different combinations, the computer produced two orbits in wild disagreement. Nevertheless, Professor Fred L. Whipple, director of the Smithsonian Astrophysical Observatory and author of the "dirty snowball" comet theory, noted that the second of the preliminary orbits closely resembled the path of a famous family of sun-grazing comets. The agreement was too close to be coincidence, he reasoned, and therefore the second solution must be correct.

Professor Whipple's astute suggestion provided the first hint of the excitement that was to come. Several of the previous sun-grazers had been spectacular objects. Notable among them was the Great Comet of 1843, whose seventy-degree tail stretched 200 million miles into space, setting an all-time record, and whose brilliance induced the citizenry of Cambridge to build a fifteen-inch telescope for Harvard equal to the largest in the world. And the second comet of 1882 achieved such brilliancy as it rounded the sun that it could be seen in broad daylight with the naked eye.

In the few days following the first computer solutions three "precise" positions were reported to the Central Telegram Bureau, one from Steward Observatory in Tucson, Arizona, and two from the Skalnate Pleso Observatory in Czechoslovakia. When these new positions were fed by themselves into the computer, the result indicated an ordinary comet, and not a sun-grazer at all. But our programmers noticed that something was seriously wrong. When positions from the satellite-tracking cameras were included in the calculations, the computer gave different answers. Among them was the interesting possibility that Comet Ikeya-

Seki might die by fire, plunging directly into the sun.

Then, suddenly, the mystery vanished. Six accurate positions from veteran comet observer Elizabeth Roemer at the Flagstaff, Arizona, station of the U.S. Naval Observatory established the path with great precision. One of the earlier "precise" observations had been faulty, and with its elimination, the others fell into place. Comet Ikeya-Seki was accelerating along a course that would carry it within a solar radius of the sun's surface. And since a comet's brightness depends on its closeness to the sun, there was every indication that Comet Ikeya-Seki would become a brilliant object.

Armed with predictions of Comet Ikeya-Seki's sun-grazing path, the Smithsonian staff set out to forewarn space scientists and radio astronomers whose attention does not normally encompass comets. We called a press conference to describe the magnificent view hoped for as the comet swung around perihelion, its nearest approach to the sun. First discovered in the morning sky, the comet would cross into the evening sky for only a few hours on October 21. If a tail of this comet were to appear in the evening, it would sweep across the western sky after sunset on that evening. Afterward it would reappear in the morning twilight. Such a prediction was hazardous, because although the comet's trajectory was well established, its brightness and tail length resisted astronomical forecasting since no one knew just how much material would be activated as it sped past the sun.

Had we examined more carefully the historical records of Comet 1882 II, we might have been more cautious in telling the public to look for the tail of Comet Ikeya-Seki sweeping across the western sky after sunset on October 21. Each new observation of the 1965 comet confirmed that it was a virtual twin of the Great Comet of 1882; thus, by looking at the observations from the last century, we should have guessed that the comet's enormous velocity as it rounded the sun — one million miles per hour — would dissipate the tail so widely that it could not be seen in the dark sky. On the other hand, we hardly dared publicize what the computer's brightness predictions showed: that Comet Ikeya-Seki would be visible in full daylight within a few degrees of the sun!

AND thus it happened that thousands of would-be observers in the eastern United States maintained a cold and fruitless search in the early morning hours of October 21. Thousands of others, especially in the American Southwest, had the view of a lifetime — a bright comet with its short silvery tail visible next to the sun in broad daylight. Simply by holding up their hands to block out the sunlight, they could glimpse the comet shining with the brilliance of the full moon. Hazy, milky skies blocked the naked-eye view for observers in the eastern United States and much of the rest of the world; even in New England, however, telescopes revealed the comet with a sharp edge facing the sun and the beginnings of a fuzzy tail on the other side. Professional astronomers were excited by the opportunity to photograph the object at high noon. For the first time, the daylight brilliance of a comet permitted analysis from solar coronagraphs. Airborne and rocket-borne ultraviolet detectors examined features never before studied in comets.

The spectrum observations ended eight decades of controversy. In most comets, the reflected spectrum of sunlight is seen, combined with the more interesting bright molecular spectrum from carbon and carbon compounds. The molecules are excited by the ultraviolet light from the sun, and glow in much the same way that certain minerals fluoresce under an ultraviolet lamp. But back in 1882, when spectroscopy was in its infancy, the great sun-grazing comet yielded an entirely different spectrum. Scientists at the Dunecht Observatory in Scotland thought they saw emission lines from metal atoms such as iron, titanium, or calcium, but a similar spectrum was never found in subsequent comets. Some observers expressed their disbelief in this unique record.

Astronomers did not get another chance to examine a comet so close to the sun until October 20, 1965. On that morning at the Radcliffe Observatory in South Africa, Dr. A. D. Thackeray obtained spectrograms of the nucleus of Comet Ikeya-Seki, then only 8 million miles from the sun. These showed bright lines of both iron and calcium. The telegraphic announcement, again relayed by the Central Bureau, set other spectroscopists into action. Within days, there were reports of nickel, chromium, sodium, and copper.

Though fully expected from a theoretical point of view, these observations confirmed that the impurities in comets had a chemical composition similar to that of meteors. The connection is not fortuitous; for many years astronomers recognized that those ephemeral streaks of light in the night sky, the meteors, were fragile cometary debris plunging through the earth's atmosphere. As the gases boil out of a cometary nucleus, myriads of dirty, dusty fragments are lost in space. In time, they can be distributed throughout a comet's entire orbit, and if that path comes close to the earth's own trajectory, a meteor shower results.

The Leonid meteors are a splendid example of "falling stars" closely related to a comet. A meteor swarm follows close to Comet Tempel-Tuttle. Every thirty-three years, as comet nears the earth's orbit, a particularly good display of Leonids appears around November 16. The recovery of this same comet in 1965 was followed by a November shower in which hundreds of brilliant meteors flashed through the sky within a period of a few hours. Nonetheless, the 1965 Leonids provided a sparse show compared with the hundreds of thousands seen in 1833 and 1866. In 1899, astronomers predicted yet another fireworks spectacular. The prognostication proved to be a great fiasco, for gravitational attraction from the planet Jupiter had slightly shifted the orbit of the comet and its associated meteor swarm. Ever since, astronomers have been wary of alerting the public to meteors or comets. Our enthusiasm in predicting the greatness of Comet Ikeya-Seki on October 21 was indeed risky.

Nevertheless, the daylight apparition of Comet Ikeya-Seki was but a prelude to a more spectacular show. Its surface thoroughly heated by its passage through the solar corona, the comet developed a surrounding coma of gas and dust some thousands of miles in diameter as it left the sun. As it slowed its course and receded from the hearth of our planetary system, the solar wind drove particles from that coma into a long stream preceding the comet.

As soon as Comet Ikeya-Seki could once again be seen in the early morning sky, its long twisted tail caused a sensation. Standing like a wispy searchlight beam above the eastern horizon, the tail could be traced for at least twenty-five degrees. Its maximum length corresponded to 70 million miles, ranking it as the fourth longest ever recorded. Only the great comets of 1843, 1680, and 1811 had tails stretching farther through space. (Quite a few comets have spanned greater arcs of the sky because they were much closer to the earth. Their actual lengths in space could not compare with that of the Great Comet of 1965.) At its peak brightness, Comet Ikeya-Seki was about equal to the sun-grazers of 1843 and 1882. Even after it receded from the sun, its nucleus shone brilliantly through the morning twilight. By all accounts, Comet Ikeya-Seki compared favorably with the great comets of the past. Those portentous sights, compared to giant swords by many a bygone observer, had little competition from city lights, smog, and horizon-blocking apartment buildings.

Comet Ikeya-Seki surprised most astronomers by developing a strikingly brilliant tail on its outward path from the sun, especially when compared with the poor show on its incoming trajectory. Had they looked in Book III of Newton's *Principia*, however, they would have seen another sun-grazing comet neatly diagrammed with a short, stubby tail before perihelion passage and the great flowing streamlike tail afterward. Newton spent many pages describing that Great Comet of 1680. Especially interesting to American readers is the generous sprinkling of observations reported from New England and "at the river Patuxent, near Hunting Creek, in Maryland, in the confines of Virginia."

In the new world not only astronomers were interested in the comet. From the Massachusetts pulpit of Increase Mather came the warning,

> As for the SIGN in Heaven now appearing, what Calamityes may be portended thereby? . . . As *Vespasian* the Emperour, when There was a long *hairy Comet* seen, he did but deride at it, and make a Joke of it, saying, That it concerned the Parthians that wore long hair, and not him, who was bald: but within a Year, Vespasian himself (and not the Parthian) dyed. There is no doubt to be made of it, but that God by this *Blazing-star* is speaking to other Places, and not to *New England* onely. And it may be, He is declaring to the generation of hairy Scalps, who go on still in their Trespasses, that the day of Calamity is at hand.

Superstitions concerning comets reached their highest development and received their sharpest attacks at this time. For centuries comets had been considered fearsome omens of bloody catastrophe, and Increase Mather must have been among the great majority who considered the Comet of 1680 as a symbol fraught with dark meanings. The terrors of the superstitious were compounded when a report came that a hen had laid an egg marked with a comet. Pamphlets were circulated in France and Germany with wood blocks of the comet, the hen, and the egg. Even the French Academy of Sciences felt obliged to comment:

> Last Monday night, about eight o'clock, a hen which had never before laid an egg, after having cackled in an extraordinarily loud manner, laid an egg of an uncommon size. It was not marked with a comet as many have believed, but with several stars as our engraving indicates.

In a further analysis of this comet, Newton's *Principia* reported that a remarkable comet had appeared four times at equal intervals of 575 years beginning with the month of September in the year Julius Caesar was killed. Newton and his colleague Halley believed that the Great Comet of 1680 had been the same one as seen in 1106, 531, and in 44 B.C. This conclusion was in fact false, and the Great Comet of 1680 had a much longer period. Within a few years, however, Halley correctly analyzed the periodicity of the famous comet that now bears his name.

Is Comet Ikeya-Seki periodic like Halley's? If so, can it be identified with any of the previous sun-grazers? The resemblance of Comet Ikeya-Seki to Comet 1882 II has led many people to suppose that these objects were identical. The orbits of both of these comets take the form of greatly elongated ellipses, extending away from the sun in virtually identical directions. Nevertheless, even the earliest orbit calculations scuttled the possibility that the comets were one and the same, since at least several hundred years must have passed since Comet Ikeya-Seki made a previous appearance in the inner realms of the solar system. On the other hand, it is unlikely that Comet Ikeya-Seki, Comet 1882 II, and a half dozen others would share the same celestial traffic pattern and remain unrelated. The only reasonable explanation is to suppose that some single giant comet must have fissioned into many parts hundreds of years ago.

Indeed, the Great Comet of 1882 did just that. Before perihelion passage, it showed a single nucleus; a few weeks afterward, astronomers detected four parts, which gradually separated along the line of the orbit. The periods for the individual pieces are calculated as 671, 772, 875, and 955 years. Consequently, this comet will return as *four* great comets, about a century apart.

It was, therefore, not at all unexpected when the Central Bureau was able to relay the message on November 5 that Comet Ikeya-Seki had likewise broken into pieces. The first report suggested the possibility of three fragments, but later observers were able to pinpoint only two. One of these was almost starlike, the other fuzzy and diffuse. Though first observed two weeks after perihelion passage, the breakup was probably caused by unequal heating of the icy comet as it neared the sun.

If the Great Comet of 1965 was itself merely a fragment, what a superb sight the original sun-grazer must have been. Appearances of comets with known orbits total 870, beginning with Halley's in 240 B.C., but the earliest known sun-grazer of this family is the Comet of 1668. In medieval chronicles and Chinese annals, and on cuneiform tablets, hundreds of other comets have been recorded, but the observations are inadequate for orbit determinations. Undoubtedly, that original superspectacular sun-grazer was observed, but whether it was recorded and whether such records can be found and interpreted are at present unanswerable questions.

A similar search of historical records, which holds more promise of success, is now under way at the Smithsonian Astrophysical Observatory. The comet with the shortest known period, Encke, cycles around the sun every three and a third years. Inexorably, each close approach to the sun further erodes Comet Encke. The size of its snowball has never been directly observed, but a shrewd guess based on the known excrescence of gaseous material places it in the order of a few miles. By calculating ahead, Professor Whipple has predicted the final demise of Comet Encke in the last decade of this century. By calculating backward in time, he has concluded that it might once have been a brilliant object. Its three-and-a-third-year period would bring a close approach to the earth every third revolution, so that a spectacular comet might appear in the records at ten-year intervals. In the centuries before Christ, the Chinese and Babylonian records show remarkable agreement, but the register is too sketchy, and so far, Comet Encke's appearances in antiquity have not been identified.

In addition to Encke there are nearly 100 comets whose periods are less than 200 years. Like Comet Encke, they face a slow death, giving up more of their substance on each perihelion passage. On an astronomical time scale, the solar system's corps of short-period comets would be rapidly depleted if a fresh supply were unavailable. On the other hand, there is apparently an unlimited abundance of long-period comets that spend most of their lifetime far beyond the planetary system. Astronomers now envision an extensive cloud of hundreds of thousands of comets encircling the sun at distances well beyond Pluto. Originally there may only have been a ring of cometary material lying in the same plane as the earth's orbit — the leftover flotsam from the solar system's primordial times. Perhaps the density of material was insufficient to coalesce into planetary objects, or perhaps at those great distances from the sun the snowballs were too cold to stick together easily.

Gravitational attractions from passing stars presumably threw many of the comets out of their original orbits into the present cometary cloud. These gravitational perturbations still continue, and a few comets from the cloud reach the earth's orbit every year. Their appearances are entirely unexpected, and their discoveries are fair game for professional and amateur alike. But since most professional astronomers are busily engaged in more reliable pursuits, persistent amateurs manage to catch the majority of bright long-period comets. Devotees such as Ikeya and Seki have spent literally hundreds of hours sweeping the sky with their telescopes in the hope of catching a small nebulous wisp that might be a new comet. The great sun-grazer was the third cometary find for each man. Within a week of its discovery, a British schoolteacher, G. E. D. Alcock, also found a new comet — his fourth. Alcock started his comet-finding career in 1959 by uncovering *two* new comets within a few days.

How does an amateur, or a professional, recognize a new comet when he finds one? Most new-found comets are as diffuse and formless as a squashed star, completely devoid of any tail. In this respect they resemble hundreds of faint nebulae that speckle the sky, with this difference: nebulae are fixed, but a comet will inevitably move. Consequently, a second observation made a few hours later will generally reveal a motion if the nebulous wisp is indeed a comet. However, most comet hunters compare the position of their suspected comet with a sky map that charts faint nebulae and clusters. Then the discovery is quickly reported to a nearby observatory or directly to the Central Bureau.

Today the chief reward for a comet find lies in the tradition of attaching the discoverer's name to the object, but in times past there have been other compensations. Jean Louis Pons, who discovered thirty-seven comets during the first quarter of the nineteenth century, rose from observatory doorkeeper to observatory director largely as a result of his international reputation for comet finding. And the Tennessee astronomer E. E. Barnard paid for his Nashville house with cash awards offered by a wealthy patron of astronomy for comet discoveries in the 1880s. Barnard has recorded a remarkable incident relating to the great sun-grazing comet of 1882:

> My thoughts must have run strongly on comets during that time, for one night when thoroughly worn out I set my alarm clock and lay down for a short sleep. Possibly it was the noise of the clock that set my wits to work, or perhaps it was the presence of that wonderful comet which was then gracing the morning skies, or perhaps, it was the worry over the mortgage in the hopes of finding another comet or two to wipe it out. Whatever the cause, I had a most wonderful dream. I thought I was looking at the sky which was filled with comets, long-tailed and short-tailed and with no tails at all. It was a marvelous sight, and I had just begun to gather in the crop when the alarm clock went off and the blessed vision of comets vanished. I took my telescope out in the yard and began sweeping the heavens to the southwest of the Great Comet in the search for comets. Presently I ran upon a very cometary-looking object where there was no known nebula. Looking more carefully I saw several others in the field of view. Moving the telescope about I found that there must have been ten or fifteen comets at this point within the space of a few degrees. Before dawn killed them out I located six or eight of them.

Undoubtedly Barnard's observations referred to ephemeral fragments disrupted from the Comet 1882 II then in view.

A great majority of the comets reaching the earth's orbit go back to the vast comet cloud, never to be identified again. Occasionally, however, a comet swings so close to the great planet Jupiter that its orbit is bent, and it is "captured" into a much shorter period. A "Jupiter capture" has never been directly observed, because most comets are still too faint when they reach Jupiter's orbit. Nevertheless, about a year ago, astronomers came almost as close as they ever will to witnessing the aftermath of this remarkable phenomenon.

In January, 1965, the press reported the discovery of two new comets by the Chinese, a rather unexpected claim inasmuch as it has been centuries since the Chinese discovered even one comet, not to mention two. To everyone's astonishment a pair of telegrams eventually reached our Central Bureau via England, confirming the existence of the objects. At the same time, the Chinese managed to flout the centuries-old tradition of naming comets after their discoverer. In the absence of the discoverer's name, our bureau assigned to both comets the label Tsuchinshan, which translated means "Purple Mountain Observatory."

Tsuchinshan 1 and Tsuchinshan 2 have remarkably similar orbits, whose greatest distances from the sun fall near the orbit of Jupiter. As these faint comets swung around that distant point in 1961, Jupiter was passing in close proximity. Quite possibly the gravitational attraction from Jupiter secured the capture of a long-period comet in that year, simultaneously disrupting it into the two Tsuchinshan fragments. However, it is more likely that the capture occurred at a somewhat earlier pass, a point that will eventually be established by a computer investigation. In any event, the observation of a comet pair with such a close approach to Jupiter is without precedence in the annals of comet history.

The complete roster of comets for 1965 included not only the Tsuchinshan pair, Comet Alcock, and the once-in-thirty-three-years visit of Tempel-Tuttle, but the recoveries of four other faint periodic comets and another new one, Comet Klemola, which was accidently picked up during a search for faint satellites of Saturn. Of this rich harvest, Comet Ikeya-Seki received more attention than all the others combined. Day after day, the Smithsonian observing stations around the world kept a continual photographic watch as the long twisted tail developed and faded. These thousands of frames — an all-time pictorial record — may eventually be combined in a film to illustrate in motion the details of cometary tail formation.

By now the Great Comet of 1965 has faded beyond the range of either Ikeya's or Seki's small telescope, and has apparently vanished from the larger instruments of professional astronomers as well. Perhaps in a millennium hence an unsuspecting amateur, never imagining that he has caught a sun-grazer, will find it on its next return.

"When discovered, the comet was only a white dot in the moonlit sky," Seki recently wrote to us. "I did not even dream that it would later come so close to the sun and become so famous."

The delicate modern version of the Eötvös experiment described here shows that the values of inertial mass and gravitational mass of an object are equal to within one ten-billionth of a percent. Such precision is seldom attainable in any area of science.

17 Gravity Experiments

R. H. Dicke, P. G. Roll, and J. Weber

1966

IN BRIEF: *Meaningful experiments concerning the nature of gravity are few and far between—for two reasons: gravitational forces are woefully weak, so data sufficiently precise to be meaningful are hard to come by; and the essential nature of gravity lies hidden in the theoretical labyrinth of relativity, in which it's easy to lose your way, assuming you have the courage to enter in the first place. But to the intrepid, three experimental paths are open.*

The first is in null checks of extreme precision—accuracies of 1 part in 10^{11} and a few parts in 10^{23} are involved in two such experiments discussed here—which seek to balance against each other two quantities that are expected from existing theory to be equal. The magnitude of any inequality discovered sets clear limits to theory. A second kind of experiment seeks more accurate checks than are presently available for the three famous predictions of Einstein's theory of general relativity which ties gravitation to curved space—the gravity-induced red shift, bending of light, and precession of Mercury's orbit. The third experimental approach has generated most industrial interest lately, because it seems to point to the possibilities—remote ones—of communication by gravity and of shielding against gravity. This approach assumes the existence of gravity waves analogous to electromagnetic radiation, as predicted by Einstein, and seeks to find them.—S.T.

■ There has been until recently what we might term a psychological lull in matters gravitational. Perhaps this was only to be expected after the early great labors in the long history of gravity studies. Our present ideas about it are most completely crystallized in Newton's law of universal gravitation and his three laws of motion, and in Einstein's theory of general relativity and its modern extensions (see "The Dynamics of Space-Time," page 11). Yet this lull would be easier for us to understand if the field really was "cleaned up" by these theoretical achievements. It is not, of course. In many fundamental respects gravitation still offers all the exploratory challenges of a field that's just beginning.

The feeble force called gravity

The nature of the challenge and the main barrier to possible rewards arises from the fact that gravity is the weakest force now known. The ratio of the gravitational force to the electrostatic force between a proton and an electron in an average atom is only about 5×10^{-40}. If the diminutive size of this number is hard to comprehend, here's another analogy that may help. The electrostatic force of repulsion between two electrons 5 meters apart—a scant 10^{-24} dynes—approximately equals the gravitational force exerted by the *entire* earth on one of the electrons. The extremely small magnitude of gravitational forces has led many technical people to feel that, while gravitation may be interesting from a philosophical standpoint, it's unimportant either theoretically or experimentally in work concerned with everyday phenomena. This feeling may be justified, of course. In fact, on a slightly more sophisticated level, application of the strong principle of equivalence seems at first to reinforce this point of view.

This principle tells us that the effects of gravitational forces on observations can be transformed away by making the observations in a laboratory framework that is properly accelerated. The best concrete example of this still is Einstein's original freely falling elevator in a gravity field, in which an experimenter and all his apparatus are placed. Since he and his apparatus fall with the same acceleration, gravitational effects apparently disappear from phenomena observed in the elevator. Gravitational forces, in other words, sometimes simulate inertial ones. From this it's easy to conclude that gravitation is of little or no concern.

This is probably too provincial a point of view. Our little laboratories are embedded in a large universe and thinking scientists can hardly ignore this external reality. The universal character of gravitation shows that it affects all matter, in ways we have yet fully to comprehend. For all we know now, gravitation may play a dominant role in determining ultimate particle structure. And our laboratories—freely falling or otherwise—may be tossing about on "gravitational waves" without our knowing it.

Gravitational waves represent the energy which should be radiated from a source—any source—composed of masses undergoing accelerated motion with respect to each other. Such waves—if they exist as called for in Einstein's theory of general relativity—should exert forces on objects with mass, just as elastic waves do in passing through an elastic medium, or as ocean waves do when striking the shore. An athlete exercising with dumbbells or riding a bicycle, however, would radiate away an incredibly small amount of such energy. A pair of white dwarf stars, on the other hand, with a total mass roughly equal to that of the sun, and with each star rotating at enormous speed with respect to the other in a binary or double-star system, might radiate about 2×10^{37} ergs/sec of energy as gravitational waves. This is 5000 times the amount of energy contained in the sun's optical luminosity, and far from negligible if it occurs, but in order to decide whether gravity and gravitational waves are significant or not we must learn more about them. And to do this we must subject our most profound physical theories concerning them to critical scrutiny. The moment we do we find that these theories rest upon an exceedingly small number of significant experimental measurements, and that many of these measurements are of dubious precision.

Profound theories with shaky foundations

Einstein's theory of general relativity (usually abbreviated by physicists as GTR, to distinguish it from many other relativistic theories of gravitation) is, of course, the prime example. The key idea expressed by the theory, relating gravitation to a curvature of space, is an elegant one despite the tensor language which makes it difficult for many to understand. It reduces to the more generally comprehended Newtonian form in most cases where measurements can be made. And further contributions to its tacit acceptance by most present-day physicists have come from the experimental checks of Einstein's three famous predictions made on the basis of it: the gravitational redshift of light, the gravitational bending of light, and the precession of the perihelion of the orbit of the planet Mercury. We have in GTR a widely accepted theory, elegant beyond most others, based on very little *critical* evidence.

Strategy and tactics in experimentation

How can we remedy this lack? What can the earth-bound experimenter do to investigate the nature of gravitation? Most often, in view of the extreme weakness of the force, he will need to use as his power source astronomical bodies which have sufficiently strong gravitational fields. Instead of a laboratory experiment in which all of the significant variables are under his control, some or all of the effects he seeks may be associated with planetary systems, stars, galaxies, or the universe as a whole. Two examples of this approach (to which we'll return) are the Princeton group's recent refinement of the classic Eötvös experiment, which used the sun as a source of a gravitational field, and Weber's suggested study of elastic oscillations in the earth, on the idea that they may be caused by gravitational waves coming, perhaps, from an exploding supernova.

There are roughly three categories into which experiments on gravitation may be placed. First and most important are highly precise null experiments, such as the classic experiment devised by the Hungarian nobleman and physicist Baron von Eötvös. By balancing on a torsion balance the inertial forces arising from the earth's rotation against gravitational forces due to the earth's mass (Fig. 1-1) he was able to show to a precision of a few parts in 10^9 that all materials and masses fell with the same acceleration. This was an amazing accuracy for his day, and one that two of us (Roll and Dicke) have had to work hard for several years to the total mass of an atom. Moreover, since gold and aluminum atoms differ not only in nuclear binding energy and total mass, but also in many other significant respects—such as total electron mass, electron binding energy, nuclear electrostatic energy, and energies concentrated in the electron-positron pair field surrounding the nucleus—similar arguments may be advanced to set small upper limits on any nonequivalence among *all* of these different forms of energy in their gravitational interactions.

So the Eötvös experiment establishes with considerable precision a different form of the principle of equivalence than the strong one we discussed earlier; it establishes a *weak* form which states that gravitational acceleration is the same for all important contributions to the mass-energy of a small body like an atomic nucleus.

But what of the strong version of this same principle, upon which GTR is founded? This requires that the form and numerical content of *all* physical laws be the same in all freely falling, nonrotating laboratories. The more precise null result of our Eötvös experiment verifies the *strong* principle of equivalence, too, for *strongly interacting* particles and fields such as the electro-magnetic and nuclear-force fields and their associated particles, positron-electron pairs, and pi mesons. But the experiment *fails* to verify the strong equivalence principle for interactions as weak as the universal Fermi interaction (involved in the beta decay of atomic nuclei) or the gravitational interaction itself.

Tactics of the Eötvös experiment

One of the fundamental differences between the Princeton experiment and that of Eötvös was our use of the gravitational acceleration toward the sun, balanced by the corresponding centrifugal acceleration due to revolution of the earth in orbit about the sun (Fig. 1-1, bottom). Although these accelerations are somewhat less than those which Eötvös used—his were due to the earth's mass and its rotation on its axis, remember—ours had the great advantage of appearing with a 24-hour period because, in effect, the sun moves around the earth once each day. Thus any gravitational anomalies on our torsion balance would have appeared with a sinusoidal 24-hour periodicity. By recording the rotation or torque on our balance remotely and continuously, then using a digital computer to analyze the record for a 24-hour periodicity with the proper phase, all of the extraneous effects which can produce small torques with other periods or the wrong phase could be discarded.

One additional difficulty with which Eötvös had to contend was the sensitivity of his torsion balance to gradients in the gravitational field, such as those produced by the good Baron himself sitting at the telescope. The Princeton experiment minimized such problems not only by remote observation (Fig. 1-3) but by making the torsion balance triangular in shape, with the two aluminum weights and one gold weight suspended from the corners of a triangular quartz frame. This threefold symmetry made it insensitive to nonuniformities in the gravitational field.

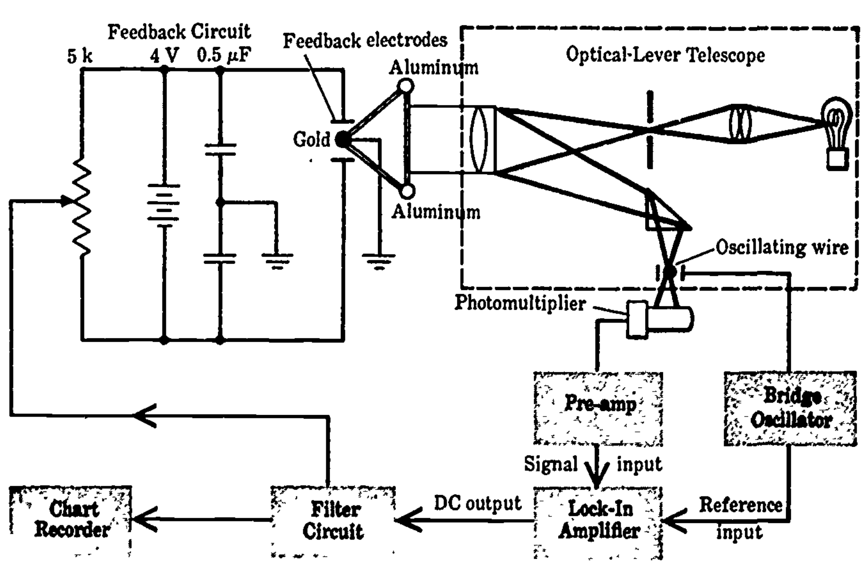


Fig. 1-3. The optical-lever system shown here was used to detect rotation of the triangular torsion balance used in Princeton version of the Eötvös experiment, shown in Fig. 1-1. Output of the detector had to be fed back to the torsion balance, through an appropriate filter network, in order to damp out long-period non-gravitational disturbances of the torsion balance caused by ground vibrations. Because balance was suspended in high-vacuum chamber (10^{-8} mm) there were no natural mechanisms to damp such extraneous oscillations in periods of time less than several months.

Our torsion balance evolved to its final form over a period of several years, and the final data were obtained between July 1962 and April 1963 in some 39 runs, lasting from 38 to 86 hours each. We could detect angular rotations of about 10^{-9} radians, corresponding to a torque of about 2.5×10^{-10} dyne cm, which in turn was 1×10^{-11} times the gravitational torque of the sun on one of the balance weights. As you may have discerned, we're rather proud of our results. They were not easy to get; but they buttress our fragile theoretical edifice a bit more firmly.

Arthur Clarke began to think seriously about space travel before almost anyone else. His conclusions, as seen in the article's very first sentence, are somewhat more pessimistic than are now fashionable.

18 Space The Unconquerable

Arthur C. Clarke

1962

Man will never conquer space. After all that has been said in the last two chapters, this statement sounds ludicrous. Yet it expresses a truth which our forefathers knew, which we have forgotten—and which our descendants must learn again, in heartbreak and loneliness.

Our age is in many ways unique, full of events and phenomena which never occurred before and can never happen again. They distort our thinking, making us believe that what is true now will be true forever, though perhaps on a larger scale. Because we have annihilated distance on this planet, we imagine that we can do it once again. The facts are far otherwise, and we will see them more clearly if we forget the present and turn our minds toward the past.

To our ancestors, the vastness of the Earth was a dominant fact controlling their thoughts and lives. In all earlier ages than ours, the world was wide indeed and no man could ever see more than a tiny fraction of its immensity. A few hundred miles—a thousand, at the most—was infinity. Great empires and cultures could flourish on the same continent, knowing nothing of each other's existence save fables and rumors faint as from a distant planet. When the pioneers and adventurers of the past left their homes in search of new lands, they said good-by forever to the places of their birth and the companions of their youth. Only a lifetime ago, parents waved farewell to their emigrating children in the virtual certainty that they would never meet again.

And now, within one incredible generation, all this has changed. Over the seas where Odysseus wandered for a decade, the Rome-Beirut *Comet* whispers its way within the hour. And above that, the closer satellites span the distance between Troy and Ithaca in less than a minute.

Psychologically as well as physically, there are no longer any remote places on Earth. When a friend leaves for what was once a far country, even if he has no intention of returning, we cannot feel that same sense of irrevocable separation that saddened our forefathers. We know that he is only hours away by jet liner, and that we have merely to reach for the telephone to hear his voice. And in a very few years, when the satellite communication network is established, we will be able to see friends on the far side of the Earth as easily as we talk to them on the other side of the town. Then the world will shrink no more, for it will have become a dimensionless point.

But the new stage that is opening up for the human drama will never shrink as the old one has done. We have abolished space here on the little Earth; we can never abolish the space that yawns between the stars. Once again, as in the days when Homer sang, we are face to face with immensity and must accept its grandeur and terror, its inspiring possibilities and its dreadful restraints. From a world that has become too small, we are moving out into one that will be forever too large, whose frontiers will recede from us always more swiftly than we can reach out toward them.

Consider first the fairly modest solar, or planetary, distances which we are now preparing to assault. The very first Lunik made a substantial impression upon them, traveling more than two hundred million miles from Earth—six times the distance to Mars. When we have harnessed nuclear energy for space flight, the solar system will contract until it is little larger than the

Earth today. The remotest of the planets will be perhaps no more than a week's travel from Earth, while Mars and Venus will be only a few hours away.

This achievement, which will be witnessed within a century, might appear to make even the solar system a comfortable, homely place, with such giant planets as Saturn and Jupiter playing much the same role in our thoughts as do Africa or Asia today. (Their qualitative differences of climate, atmosphere, and gravity, fundamental though they are, do not concern us at the moment.) To some extent this may be true, yet as soon as we pass beyond the orbit of the Moon, a mere quarter-million miles away, we will meet the first of the barriers that will sunder Earth from her scattered children.

The marvelous telephone and television network that will soon enmesh the whole world, making all men neighbors, cannot be extended into space. *It will never be possible to converse with anyone on another planet.*

Do not misunderstand this statement. Even with today's radio equipment, the problem of sending speech to the other planets is almost trivial. But the messages will take minutes—sometimes hours—on their journey, because radio and light waves travel at the same limited speed of 186,000 miles a second. Twenty years from now you will be able to listen to a friend on Mars, but the words you hear will have left his mouth at least three minutes earlier, and your reply will take a corresponding time to reach him. In such circumstances, an exchange of verbal messages is possible—but *not* a conversation. Even in the case of the nearby Moon, the two-and-a-half second time lag will be annoying. At distances of more than a million miles, it will be intolerable.

To a culture which has come to take instantaneous communication for granted, as part of the very structure of civilized life, this "time barrier" may have a profound psychological impact. It will be a perpetual reminder of universal laws and limitations against which not all our technology can ever prevail. For it seems as certain as anything can be that no signal—still less any material object—can ever travel faster than light.

The velocity of light is the ultimate speed limit, being part of the very structure of space and time. Within the narrow confines of the solar system, it will not handicap us too severely, once we have accepted the delays in communication which it involves. At the worst, these will amount to eleven hours—the time it takes a radio signal to span the orbit of Pluto, the outermost planet. Between the three inner worlds Earth, Mars, and Venus, it will never be more than twenty minutes—not enough to interfere seriously with commerce or administration, but more than sufficient to shatter those personal links of sound or vision that can give us a sense of direct contact with friends on Earth, wherever they may be.

It is when we move out beyond the confines of the solar system that we come face to face with an altogether new order of cosmic reality. Even today, many otherwise educated men—like those savages who can count to three but lump together all numbers beyond four—cannot grasp the profound distinction between *solar* and *stellar* space. The first is the space enclosing our neighboring worlds, the planets; the second is that which embraces those distant suns, the stars. *And it is literally millions of times greater.*

There is no such abrupt change of scale in terrestrial affairs. To obtain a mental picture of the distance to the nearest star, as compared with the distance to the nearest planet, you must imagine a world in which the closest object to you is only five feet away—and then there is nothing else to see until you have traveled a thousand miles.

Many conservative scientists, appalled by these cosmic gulfs, have denied that they can ever be crossed. Some people never learn; those who sixty years ago scoffed at the possibility of flight, and ten (even five!) years ago laughed at the idea of travel to the planets, are now quite sure that the stars will always be beyond our reach. And again they are wrong, for they have failed to grasp the great lesson of our age—that if something is possible in theory, and no fundamental scientific laws oppose its realization, then sooner or later it will be achieved.

One day—it may be in this century, or it may be a thousand years from now—we shall discover a really efficient means of propelling our space vehicles. Every technical device is always developed to its limit (unless it is superseded by something better) and the ultimate speed for spaceships is the velocity of light. They will never reach that goal, but they will get very close to it. And then the nearest star will be less than five years' voyaging from Earth.

Our exploring ships will spread outward from their home over an ever-expanding sphere of space. It is a sphere which will grow at almost—but never quite—the speed of light. Five years to the triple system of Alpha Centauri, ten to that strangely matched doublet Sirius A and B, eleven to the tantalizing enigma of 61 Cygni, the first star suspected of possessing a planet. These journeys are long, but they are not impossible. Man has always accepted whatever price was necessary for his explorations and discoveries, and the price of space is time.

Even voyages which may last for centuries or millenniums will one day be attempted. Suspended animation, an undoubted possibility, may be the key to interstellar travel. Self-contained cosmic arks which will be tiny traveling worlds in their own right may be another solution, for they would make possible journeys of unlimited extent, lasting generation after generation. The famous time dilation effect predicted by the theory of relativity, whereby time appears to pass more slowly for a traveler moving at almost the speed of light, may be yet a third.[1] And there are others.

With so many theoretical possibilities for interstellar flight, we can be sure that at least one will be realized in practice. Remember the history of the atomic bomb; there were three different ways in which it could be made, and no one knew which was best. So they were all tried—and they all worked.

Looking far into the future, therefore, we must picture a slow (little more than half a billion miles an hour!) expansion of human activities outward from the solar system, among the suns scattered across the region of the Galaxy in which we now find ourselves. These suns are on the average five light-years apart; in other words, we can never get from one to the next in less than five years.

To bring home what this means, let us use a down-to-earth analogy. Imagine a vast ocean, sprinkled with islands—some desert, others perhaps inhabited. On one of these islands an energetic race has just discovered the art of building ships. It is preparing to explore the ocean, but must face the fact that the very nearest island is five years' voyaging away, and that no possible improvement in the technique of shipbuilding will ever reduce this time.

In these circumstances (which are those in which we will soon find ourselves) what could the islanders achieve? After a few centuries, they might have established colonies on many of the nearby islands, and have briefly explored many others. The daughter colonies might themselves have sent out further pioneers, and so a kind of chain reaction would spread the original culture over a steadily expanding area of the ocean.

But now consider the effects of the inevitable, unavoidable time lag. There could be only the most tenuous contact between the home island and its offspring. Returning messengers could report what had happened on the nearest colony—five years ago. They could never bring information more up to date than that, and dispatches from the more distant parts of the ocean would be from still further in the past—perhaps centuries behind the times. There would never be news from the other islands, but only history.

No oceanic Alexander or Caesar could ever establish an empire beyond his own coral reef; he would be dead before his orders reached his governors. Any form of control or administration over other islands would be utterly impossible, and all parallels from our own history thus cease to have any meaning. It is for this reason that the popular science-fiction stories of interstellar empires and intrigues become pure fantasies, with no basis in reality. Try to imagine how the War of Independence would have gone if news of Bunker Hill had not arrived in England until Disraeli was Victoria's prime minister, and his urgent instructions on how to deal with the situation had reached America during President Eisenhower's second term. Stated in this way, the whole concept of interstellar administration or culture is seen to be an absurdity.

All the star-borne colonies of the future will be independent, whether they wish it or not. Their liberty will be inviolably protected by time as well as space. They must go their own way and achieve their own destiny, with no help or hindrance from Mother Earth.

At this point, we will move the discussion on to a new level and deal with an obvious objection. Can we be *sure* that the velocity of light is indeed a limiting factor? So many "impassable" barriers have been shattered in the past; perhaps this one may go the way of all the others.

We will not argue the point, or give the reasons scientists believe that light can never be outraced by any form of radiation or any material object. Instead, let us assume the contrary and see just where it gets us. We will even take the most optimistic possible case, and imagine that the speed of transportation may eventually become infinite.

Picture a time when, by the development of techniques as far beyond our present engineering as a transistor is beyond a stone ax, we can reach anywhere we please *instantaneously*, with no more effort than by dialing a number. This would indeed cut the universe down to size, and reduce its physical immensity to nothingness. What would be left?

Everything that really matters. For the universe has two aspects—its scale, and its overwhelming, mind-numbing complexity. Having abolished the first, we are now face-to-face with the second.

What we must now try to visualize is not size, but quantity. Most people today are familiar with the simple notation which scientists use to describe large numbers; it consists merely of counting zeros, so that a hundred becomes 10^2, a million, 10^6; a billion, 10^9 and so on. This useful trick enables us to work with quantities of any magnitude, and even defense budget totals look modest when expressed as $\$5.76 \times 10^9$ instead of $5,760,000,000.

The number of other suns in our own Galaxy (that is, the whirlpool of stars and cosmic dust of which our Sun is an out-of-town member, lying in one of the remoter spiral arms) is estimated at about 10^{11}—or written in full, 100,000,000,000. Our present telescopes can observe something like 10^9 other galaxies, and they show no sign of thinning out even at the extreme limit of vision. There are probably at least as many galaxies in the whole of creation as there are stars in our own Galaxy, but let us confine ourselves to those we can see. They must contain a total of about 10^{11} times 10^9 stars, or 10^{20} stars altogether.

One followed by twenty other digits is, of course, a number beyond all understanding. There is no hope of ever coming to grips with it, but there are ways of hinting at its implications.

Just now we assumed that the time might come when we could dial ourselves, by some miracle of matter transmission, effortlessly and instantly round the cosmos, as today we call a number in our local exchange. What would the cosmic telephone directory look like if its contents were restricted to suns and it made no effort to list individual planets, still less the millions of places on each planet?

The directories for such cities as London and New York are already getting somewhat out of hand, but they list only about a million—10^6—numbers. The cosmic directory would be 10^{14}

times bigger, to hold its 10^{20} numbers. It would contain more pages than all the books *that have ever been produced since the invention of the printing press.*

To continue our fantasy a little further, here is another consequence of twenty-digit telephone numbers. Think of the possibilities of cosmic chaos, if dialing 27945015423811986385 instead of 27945015243811986385 could put you at the wrong end of Creation. . . . This is no trifling example; look well and carefully at these arrays of digits, savoring their weight and meaning, remembering that we may need every one of them to count the total tally of the stars, and even more to number their planets.

Before such numbers, even spirits brave enough to face the challenge of the light-years must quail. The detailed examination of all the grains of sand on all the beaches of the world is a far smaller task than the exploration of the universe.

And so we return to our opening statement. Space can be mapped and crossed and occupied without definable limit; but it can never be conquered. When our race has reached its ultimate achievements, and the stars themselves are scattered no more widely than the seed of Adam, even then we shall still be like ants crawling on the face of the Earth. The ants have covered the world, but have they conquered it—for what do their countless colonies know of it, or of each other?

So it will be with us as we spread outward from Mother Earth, loosening the bonds of kinship and understanding, hearing faint and belated rumors at second—or third—or thousandth-hand of an ever-dwindling fraction of the entire human race. Though Earth will try to keep in touch with her children, in the end all the efforts of her archivists and historians will be defeated by time and distance, and the sheer bulk of material. For the number of distinct societies or nations, when our race is twice its present age, may be far greater than the total number of all the men who have ever lived up to the present time.

We have left the realm of comprehension in our vain effort to grasp the scale of the universe; so it must always be, sooner rather than later.

When you are next out of doors on a summer night, turn your head toward the zenith. Almost vertically above you will be shining the brightest star of the northern skies—Vega of the Lyre, twenty-six years away at the speed of light, near enough the point-of-no-return for us short-lived creatures. Past this blue-white beacon, fifty times as brilliant as our sun, we may send our minds and bodies, but never our hearts.

For no man will ever turn homeward from beyond Vega to greet again those he knew and loved on Earth.

air pressure. The air pressure itself is a scalar quantity, a number whose value at any point is independent of the coordinates used to label the point. (2) Matter could interact with a

reason we must specify six quantities to characterize the stress at each point. More exactly, the scalar, vector, and tensor fields which concern us are all in *four*-dimensional space, and

Many scientists have argued recently that intelligent life may be quite common in the universe. This work was originally written by Shklovskii, in Russian, and the "Annotations, additions, and discussions" which Sagan has added are bracketed by the symbols ▽ and △ .

19 Is There Intelligent Life Beyond the Earth?

I. S. Shklovskii and Carl Sagan

1966

▽ In the last two chapters, we have seen that the prospects for interstellar communication over distances of some tens of light years seem reasonable; over hundreds of light years, more difficult; and over thousands of light years, only possibly by civilizations in substantial advance of our own. If it seemed likely that technical civilizations existed on planets only 10 or 20 light years away, or civilizations greatly in advance of our own, at larger distances, a serious effort to establish contact might be justified. On the other hand, if we can only reasonably expect civilizations at about our level of technical advance thousands of light years away, attempts at communication would not seem profitable, at least at the present time. In the present chapter, we shall make some effort to compute the number of extant technical civilizations in the Galaxy, which will permit us to estimate the average distances between civilizations. To perform such estimates, we must select numerical values for quantities which are extremely poorly known, such as the average lifetime of a technical civilization. The reliability of our answers will reflect this uncertainty. △ The analysis will have an exclusively probabilistic character, ▽ and the reader is invited to make his own estimate of the numerical values involved, and to draw his own conclusions on the numbers of advanced technical civilizations in the Galaxy. △ However, these analyses are of undoubted methodological interest and illustrate very well the potentialities and limitations of this type of investigation.

▽ We shall be concerned with two general approaches: first, a simple discussion due essentially to Frank Drake, and then a more elaborate treatment due to the German astronomer Sebastian von Hoerner, when he was working at the National Radio Astronomy Observatory, Green Bank, West Virginia.

▽ We desire to compute the number of extant Galactic communities which have attained a technical capability substantially in advance of our own. At the present rate of technological progress, we might picture this capability as several hundred years or more beyond our own stage of development. A simple method of computing this number, *N*, was discussed extensively at a conference on intelligent extraterrestrial life, held at the National Radio Astronomy Observatory in November, 1961, and sponsored by the Space Science Board of the National Academy of Sciences. Attending this meeting were D. W. Atchley, Melvin Calvin, Giuseppe Cocconi, Frank Drake, Su-Shu Huang, John C. Lilley, Philip M. Morrison, Bernard M. Oliver, J. P. T. Pearman, Carl Sagan, and Otto Struve. While the details differ in several respects, the following discussion is in substantial agreement with the conclusions of the conference.

▽ The number of extant advanced technical civilizations possessing both the interest and the capability for interstellar communication can be expressed as permit, cannot yet be excluded.

Null experiments don't prove "nothin"

Of the various null experiments, perhaps the most important is the Eötvös experiment con- acceleration of *all* the other mass-energy contributions to the total masses of gold and aluminum. The other contributions come from neutrons, protons, electrons, electrostatic energy, and other still smaller contributors to

$$N = R_* f_p n_e f_l f_i f_c L$$

R_* is the mean rate of star formation, averaged over the lifetime of the Galaxy; f_p is the fraction of stars with planetary systems; n_e is the mean number of planets in each planetary system with environments favorable for the origin of life; f_l is the fraction of such favorable planets on which life does develop; f_i is the fraction of such inhabited planets on which intelligent life with manipulative abilities arises during the lifetime of the local sun; f_c is the fraction of planets populated by intelligent beings on which an advanced technical civilization in the sense previously defined arises, during the lifetime of the local sun; and L is the lifetime of the technical civilization. We now proceed to discuss each parameter in turn.

∇ Since stars of solar mass or less have lifetimes on the main sequence comparable to the age of the Galaxy, it is not the present rate of star formation, but the mean rate of star formation during the age of the Galaxy which concerns us here. The number of known stars in the Galaxy is $\sim 10^{11}$, most of which have masses equal to or less than that of the Sun. The age of the Galaxy is $\sim 10^{10}$ years. Consequently, a first estimate for the mean rate of star formation would be ~ 10 stars yr^{-1}. The present rate of star formation is at least an order of magnitude less than this figure, and according to the Dutch-American astronomer Maarten Schmidt, of Mt. Wilson and Palomar Observatories, the rate of star formation in early Galactic history is possibly several orders of magnitude greater. According to present views of element synthesis in stars, discussed in Chapter 8, those stars and planets formed in the early history of the Galaxy must have been extremely poor in heavy elements. Technical civilizations developed on such ancient planets would of necessity be extremely different from our own. But in the flurry of early star formation, when the Galaxy was young, heavy elements must have been generated rapidly, and later generations of stars and planets would have had adequate endowments of the heavy elements. These very early systems should be subtracted, from our estimate of R_*. On the other hand, there are probably vast numbers of undetected low-mass stars whose inclusion will tend to increase our estimate of R_*. For present purposes, we adopt $R_* \sim 10$ stars yr^{-1}.

∇ From the frequencies of dark companions of nearby stars, from the argument on stellar rotation, and from contemporary theories of the origin of the solar system [see Chapters 11–13], we have seen that planets seem to be a very common, if not invariable, accompaniment to main sequence stars. We therefore adopt $f_p \sim 1$.

∇ In Chapter 11, we saw that even many multiple star systems may have planets in sufficiently stable orbits for the origin and development of life. In our own solar system, the number of planets which are favorably situated for the origin of life at some time or another is at least one, probably two, and possibly three or more [see Chapters 16, 19, 20, and 23]. We expect main sequence stars of approximately solar spectral type—say, between F2 and K5—to have a similar distribution of planets, and for such stars, we adopt $n_e \sim 1$. However, the bulk of the main sequence stars—well over 60 percent—are M stars; as we mentioned in

Chapter 24, if the planets of these suns are distributed with just the same spacings as the planets of our Sun, even the innermost will be too far from its local sun to be heated directly to temperatures which we would consider clement for the origin and evolution of life. However, it is entirely possible that such lower-luminosity stars were less able to clear their inner solar systems of nebular material from which the planets were formed early in their history. Further, the greenhouse effect in Jovian-type planets of M stars should produce quite reasonable temperatures. We therefore tentatively adopt for main sequence stars in general $n_e \sim 1$.

∇ In Chapters 14–17, we discussed the most recent work on the origin of life on Earth, which suggests that life arose very rapidly during the early history of the Earth. We discussed the hypothesis that the production of self-replicating molecular systems is a forced process which is bound to occur because of the physics and chemistry of primitive planetary environments. Such self-replicating systems, with some minimal control of their environments and situated in a medium filled with replication precursors, satisfy all the requirements for natural selection and biological evolution. Given sufficient time and an environment which is not entirely static, the evolution of complex organisms is, in this view, inevitable. The finding of even relatively simple life forms on Mars or other planets within our solar system would tend to confirm this hypothesis. In our own solar system, the origin of life has occurred at least once, and possibly two or more times. We adopt $f_l \sim 1$.

∇ The question of the evolution of intelligence is a difficult one. This is not a field which lends itself to laboratory experimentation, and the number of intelligent species available for study on Earth is limited. In Chapter 25, we alluded to some of the difficulties of this problem. Our technical civilization has been present for only a few billionths of geological time; yet it has arrived about midway in the lifetime of our Sun on the main sequence. The evolution of intelligence and manipulative abilities has resulted from the product of a large number of individually unlikely events. On the other hand, the adaptive value of intelligence and of manipulative ability is so great—at least until technical civilizations are developed—that if it is genetically feasible, natural selection seems likely to bring it forth.

∇ The American physiologist John C. Lilley, of the Communication Research Institute, Coral Gables, Florida, has argued that the dolphins and other cetacea have surprisingly high levels of intelligence. Their brains are almost as large as those of human beings. These brains are as convoluted as our brains, and their neural anatomy is remarkably similar to that of the primates, although the most recent common ancestor of the two groups lived more than 100 million years ago. Dolphins are capable of making a large number of sounds of great complexity, which are almost certainly used for communication with other dolphins. The most recent evidence suggests that they are capable of counting, and can mimic human speech. Large numbers of anecdotes supposedly illustrating great intelligence in the dolphins have been recorded, from the time of Pliny to the present. The detailed study of dolphin behavior and serious attempts to communicate with them are just beginning and hold out the possibility that some day we will be able to communicate, at least at a low level, with another intelligent species on our planet. Dolphins have very limited manipulative abilities, and despite their apparent level of intelligence, could not have developed a technical civilization. But their intelligence and communicativeness strongly suggest that these traits are not limited to the human species. With the expectation that the Earth is not unique as the abode of creatures with intelligence and manipulative abilities, but also allowing for the fact that apparently only one such species has developed so far in its history, and this only recently, we adopt $f_i \sim 10^{-1}$.

∇ The present technical civilization of the planet Earth can be traced from Mesopotamia to Southeastern Europe, to Western and Central Europe, and then to Eastern Europe and North America. Suppose that somewhere along the tortuous path of cultural history, an event had differed. Suppose Charles Martel had not stopped the Moors at Tours in 732 A.D. Suppose Ogdai had not died at Karakorum at the moment that Subutai's Mongol armies were entering Hungary and Austria, and that the Mongol invasion had swept through the non-forested regions of western Europe. Suppose the classical writings of Greek and Roman antiquity had not been preserved through the Middle Ages in African mosques and Irish monasteries. There are a thousand "supposes." Would Chinese civilization have developed a technical civilization if entirely insulated from the West? Would Aztec civilization have developed a technical phase had there been no *conquistadores?* Recorded history, even in mythological guise, covers less than 10^{-2} of the period in which the Earth has been inhabited by hominids, and less than about 10^{-5} of geological time. The same considerations are involved here as in the determination of f_i. The development of a technical civilization has high survival value at least up to a point; but in any given case, it depends on the concatenation of many improbable events, and it has occurred only recently in terrestrial history. It is unlikely that the Earth is very extraordinary in possessing a technical civilization, among planets already inhabited by intelligent beings. As before, over stellar evolutionary timescales, we adopt $f_c \sim 10^{-1}$.

∇ The multiplication of the preceding factors gives $N = 10 \times 1 \times 1 \times 1 \times 10^{-1} \times 10^{-1} \times L = 10^{-1} \times L$. L is the mean lifetime in years of a technical civilization possessing both the interest and the capability for interstellar communication. For the evaluation of L there is—fortunately for us, but unfortunately for the discussion—not even one known terrestrial example. The present technical civilization on Earth has reached the communicative phase (in the sense of high-gain directional antennas for the reception of extraterrestrial radio signals) only within the last few years. There is a sober possibility that L for Earth will be measured in decades. On the other hand, it is possible that international political differences will be permanently settled, and that L may be measured in geological time. It is conceivable that on other worlds, the resolution of national conflicts and the establishment of planetary governments are accomplished before weapons of mass destruction become available. We can imagine two extreme alternatives for the evaluation of L: (a) a technical civilization destroys itself soon after reaching the communicative phase (L less than 10^2 years); or (b) a technical civilization learns to live with itself soon after reaching the communicative phase. If it survives more than 10^2 years, it will be unlikely to destroy itself afterwards. In the latter case, its lifetime may be measured on a stellar evolutionary timescale (L much greater than 10^8 years). Such a society will exercise self-selection on its members. The slow, otherwise inexorable genetic changes which might in one of many ways make the individuals unsuited for a technical civilization could be controlled. The technology of such a society will certainly be adequate to cope with geological changes, although its origin is sensitively dependent on geology. Even the evolution of the local sun through the red giant and white dwarf evolutionary stages may not pose insuperable problems for the survival of an extremely advanced community.

▽ It seems improbable that surrounded by large numbers of flourishing and diverse galactic communities, a given advanced planetary civilization will retreat from the communicative phase. This is one reason that L itself depends on N. Von Hoerner has suggested another reason: He feels that the means of avoiding self-destruction will be among the primary contents of initial interstellar communications. If N is large, the values of f_l, f_i, and f_c may also be larger as a result. In Chapter 15, we mentioned the possibility of the conscious introduction of life into an otherwise sterile planet by interstellar space travelers. In Chapter 33, below, we shall discuss the possibility that such interstellar space travelers might also affect the value of f_c.

▽ Our two choices for L— $< 10^2$ years, and $>> 10^8$ years—lead to two values for N: less than ten communicative civilizations in the Galaxy; or many more than 10^7. In the former case, we might be the only extant civilization; in the latter case, the Galaxy is filled with them. The value of N depends very critically on our expectation for the lifetime of an average advanced community. It seems reasonable to me that at least a few percent of the advanced technical civilizations in the Galaxy do not destroy themselves, nor lose interest in interstellar communication, nor suffer insuperable biological or geological catastrophes, and that their lifetimes, therefore, are measured on stellar evolutionary timescales. As an average for all technical civilizations, both short-lived and long-lived, I adopt $L \sim 10^7$ years. This then yields as the average number of extant advanced technical civilizations in the Galaxy

$$N \sim 10^6.$$

Thus, approximately 0.001 percent of the stars in the sky will have a planet upon which an advanced civilization resides. The most probable distance to the nearest such community is then several hundred light years. (In the Space Science Board Conference on Intelligent Extraterrestrial Life, previously mentioned, the individual values of N selected lay between 10^4 and 10^9 civilizations. The corresponding range of distances to the nearest advanced community is then between ten and several thousands of light years) △

This table lists only those stars within twenty-two light years of the earth that have probabilities for the existence of planets which could support human life. The reader with astronomical interests should scan books on astronomy for a detailed explanation of most of the terminology used in this table.

20 The Stars Within Twenty-Two Light Years That Could Have Habitable Planets

Stephen H. Dole

1964

Table 21. The Stars within 22 Light-years That Could Have Habitable Planets

Name of star	Other designations	Right ascension, RA, 1900 (hours)	Right ascension, RA, 1900 (minutes)	Declination, 1900 (degrees)	Declination, 1900 (minutes)	Apparent visual magnitude Allen	Apparent visual magnitude Boss	Parallax, π (sec) Allen	Parallax, π (sec) Boss	Spectral class, Allen	Distance (light-years), Allen	Absolute visual magnitude, M_v, Allen	Adopted mass	Probability of habitable planet, P_{HP}
α Centauri A	Rigel Kentaurus	14	32.8	−60	25	0.02[a]	0.33	0.754	0.756	G4	4.3	4.5	1.08	0.054 } 0.107
α Centauri B		14	32.8	−60	25	1.39[a]	1.70	0.754	0.760	K1	4.3	5.9	0.88	0.057 }
Lal 21185 (A)	BD + 36° 2147	10	57.9	+36	38	7.54	7.60	0.398	0.388	M2	8.2	10.51	0.37	(b)
ε Eridani		3	28.2	−9	48	4.2	3.81	0.303	0.305	K2	10.8	6.2	0.80	0.033
61 Cygni A		21	2.4	+38	15	5.2[c]	5.57	0.293	0.299	K5	11.1	7.65	0.63	(b)
61 Cygni B		21	2.4	+38	15	6.06	[illegible]	0.293	0.299	K8	11.1	8.42	0.51	(b)
ε Indi		21	55.8	−57	12	4.7	4.74	0.288	0.288	K5	11.3	7.0	0.71	(b)
Grm 34 A	BD + 43° 44	0	12.7	+43	27	8.18	8.1	0.278	0.284	M2	11.7	10.44	0.38	(b)
Lac 9352	CD − 36° 15693	22	59.4	−36	26	7.2	7.44	0.273	0.278	M1	12.0	9.4	0.47	(b)
τ Ceti		1	39.4	−16	28	3.65	3.65	0.268	0.301	G8	12.2	6.02	0.82	0.036
Lac 8760	CD − 39° 14192	21	11.4	−39	15	6.65	6.65	0.258	0.257	M0	12.6	8.7	0.54	(b)
Cin 3161	CD − 37° 15492	23	59.5	−37	51	8.6	8.57	0.219	0.222	M3	14.9	10.3	0.39	(b)
Grm 1618	BD + 50° 1725	10	5.3	+49	57	6.75	6.82	0.219	0.218	K8	14.9	8.45	0.56	(b)
CC 1290	− 49° 13515	21	26.9	−49	26	8.6	...	0.212	...	M3	15.4	10.5	0.37	(b)
Cin 18,2354	+ 68° 946	17	37.0	+68	26	9.15	9.5	0.203	0.212	M3	16.1	10.75	0.35	(b)
+15° 2620	HD 119850	13	40.7	+15	26	8.58	8.5	0.193	0.191	M1	16.9	10.0	0.42	(b)
70 Ophiuchi A		18	0.4	+2	31	4.19	4.23	0.188	0.196	K1	17.3	5.7	0.90	0.057
70 Ophiuchi B		18	0.4	+2	31	5.87	6.23	0.188	0.196	K5	17.3	7.3	0.65	(b)
η Cassiopeiae A		0	43.0	+57	17	3.54	3.64	0.181	0.182	F9	18.0	4.87	0.94	0.057
η Cassiopeiae B		0	43.0	+57	17	7.4	...	0.181	...	K6	18.0	8.7	0.58	(b)
σ Draconis		19	32.6	+69	29	4.72	4.78	0.179	0.181	G9	18.2	6.01	0.82	0.036
36 Ophiuchi A		17	9.2	−26	27	5.17	...	0.179	0.178	K2	18.2	6.4	0.77	0.023 } 0.042
36 Ophiuchi B		17	9.2	−26	27	5.20	...	0.179	0.178	K1	18.2	6.5	0.76	0.0195 }
36 Ophiuchi C		17	9.2	−26	27	6.53	...	0.179	0.178	K6	18.2	7.8	0.63	(b)
HR 7703 A	HD 191408	20	4.6	−36	21	5.24	5.34	0.175	0.178	K2	18.6	6.5	0.76	0.0195
HR 5568 A	HD 131977	14	51.6	−20	58	5.90	5.76	0.174	0.172	K4	18.8	7.1	0.70	(b)
HR 5568 B	HD 131976	14	51.6	[illegible]	58	8.08	8.87	0.174	0.172	M0	18.8	9.2	0.50	(b)
δ Pavonis		19	58.9	−66	26	3.67	3.64	0.170	0.155	G7	19.2	4.9	0.98	0.057
−21° 1377		6	6.4	−21	49	8.3	...	0.170	...	M0	19.2	9.5	0.455	(b)
+44° 2051 A	Lal 21258	11	0.5	+44	2	8.7	8.8	0.170	0.175	M0	19.2	9.9	0.43	(b)
+4° 4048 (A)		19	12.1	+5	2	9.18	..	0.168	...	M3	19.4	10.33	0.39	(b)
HD 36395	−3° 1123	5	26.4	−3	42	7.96	8.4	0.163	0.168	M1	20.0	9.06	0.51	(b)
+1° 4774	Lal 46650	23	44.0	+1	52	9.05	8.8	0.161	0.164	M2	20.2	10.18	0.40	(b)
+53° 1320		9	7.6	+53	7	7.90	...	0.161	...	K7	20.2	8.9	0.52	(b)
+53° 1321		9	7.6	+53	7	8.01	...	0.161	...	K9	20.2	9.0	0.51	(b)
−45° 13677		20	6.7	−45	28	8.4	...	0.158	...	M0	20.6	9.4	0.48	(b)
82 Eridani		3	15.9	−43	27	4.3	4.30	0.156	0.159	G5	20.9	5.3	0.91	0.057
β Hydri		0	20.5	−77	49	2.9	2.90	0.153	0.144	G1	21.3	3.8	1.23	0.037
HR 8832		23	8.5	+56	37	5.67	5.65	0.152	0.146	K3	21.4	6.69	0.74	0.011
+15° 4733		22	51.8	+16	2	8.69	...	0.150	.	M2	21.8	9.72	0.445	(b)
p Eridani A		1	36.0	−56	42	6.1	6.00	0.148	0.163	K2	22.0	7.0	0.71	(b)
p Eridani B		1	36.0	−56	42	6.1	6.03	0.148	0.163	K2	22.0	7.1	0.70	(b)
HR 753 A		2	30.6	+6	25	5.94	5.92	0.148	0.144	K3	22.0	6.79	0.725	0.004
														Net 0.434

Note: Lal—*Lalande's Star Catalogue* (1837); BD—*Bonner Durchmusterung*; Grm—*Groombridge's Catalogue of Circumpolar Stars*; Lac—*Lacaille's Catalogue* (1847); CD—*Cardoba Durchmusterung* (1886); HD—*Henry Draper Catalogue* (1918-1924); HR—*Revised Harvard Photometry* (1908).

[a] van de Kamp (1958) gives $m_{v,A} = 0.09$, $m_{v,B} = 1.38$.

[b] Very small; less than 0.001.

The existence or non-existence of unidentified flying objects has been a subject for debate in the United States and elsewhere for many years. Here an astronomer reviews our current knowledge in an impartial way.

21 U. F. O.

Carl Sagan

1967

In the United States, popular interest in unidentified flying objects began on June 24, 1947, when a group of rapidly moving, glistening objects was observed from the air in daytime, near Mount Rainier, Washington. The observer, a Seattle resident, dubbed them "flying saucers." The sighting received extensive publicity. Somewhat similar sightings have been reported ever since. The differences among these observations, however, are as striking as the observations themselves.

Investigations: Because of its national defense responsibility, the U.S. Air Force investigates reports of unidentified flying objects over the United States. The number of sightings investigated by the Air Force in the period 1947–1965 varied greatly from year to year.

UFO SIGHTINGS INVESTIGATED BY U.S. AIR FORCE

1947–1950	577	1956–1960	3,350
1951–1955	2,880	1961–1965	2,912

Source: L. J. Tacker, *Flying Saucers and the U.S. Air Force* (Princeton, 1960) and Library of Congress, *Facts About Unidentified Flying Objects* (Washington, 1966).

Evaluation of these reports is difficult. Observations frequently are sketchy, and different reports of the same phenomenon are often dissimilar, or even irreconcilable. Observers tend to exaggerate. Deliberate hoaxes, some involving double-exposure photography, have been perpetrated.

Most UFOs have been identified as belonging to one of the following categories; unconventional aircraft; aircraft under uncommon weather conditions; aircraft with unusual external light patterns; meteorological and other high-altitude balloons; artificial earth satellites; flocks of birds; reflections of searchlights or headlights off clouds; reflection of sunlight from shiny surfaces; luminescent organisms (including one case of a firefly lodged between two adjacent panes of glass in an airplane cockpit window); optical mirages and looming (a mirage in which images of objects below the horizon appear distorted); lenticular formations; ball lightning; sun dogs; meteors, including green fireballs; planets, especially Venus; bright stars; and the aurora borealis.

Radar detection of unidentified flying objects has also occurred occasionally. Many of these sightings have been explained as radar reflections from temperature inversion layers in the atmosphere and other sources of radar "angels."

Considering the difficulties involved in tracking down visual and radar sightings, it is remarkable that all but a few per cent of the reported UFOs have been identified as naturally occurring—if sometimes unusual—phenomena. It is of some interest that the UFOs which are unidentified do not fall into uniform categories such as motion, color, and lighting, but rather run through the same range of these variables as the identified UFOs. In October 1957, Sputnik I, the first earth-orbiting artificial satellite, was launched. Of 1,178 UFO sightings in that year, 701 occurred between October and December. The clear implication is that Sputnik and its attendant publicity was responsible for many UFO sightings.

Earlier, in July 1952, a set of visual and radar observations of unidentified flying objects over Washington, D.C., caused substantial public concern. Government concern was reflected in the creation in November of that year of a special panel to evalute these reports. The panel was established by the Office of Scientific Intelligence of the Central Intelligence Agency, and was headed by H. P. Robertson of the California Institute of Technology. The Robertson panel, after a thorough investigation of the UFO reports to that date, concluded that all were probably natural phenomena, wrongly interpreted.

The most reliable testimony is that of the professional astronomer. Jesse L. Greenstein of Mount Wilson and Palomar observatories pointed out that a vehicle 100 feet (30.5 meters) in diameter, at an altitude of 50 miles (80.5 km), would leave a broad track on photographic plates of the sky taken with large telescopes. This track could be differentiated easily from those of ordinary astronomical objects, such as stars, meteors, and comets. Nevertheless, it appears that such tracks or unambiguous visual observations of classical UFOs have never been made by professional astronomers.

In the Harvard Meteor Project performed in New Mexico during the period 1954–1958, extensive photographic observations were made by Super-Schmidt cameras, with a 60° field of view. In all, a surface of about 3,000 square miles (7,700 sq km) was observed to a height of about 50 miles (80 km) for a total of some 3,000 hours. Visual and photographic observations were made which could detect objects almost as faint as the faintest objects visible to the naked eye. These observations by professional astronomers were made in a locale and period characterized by extensive reports of unidentified flying objects. No unexplained objects were detected, despite the fact that rapidly moving objects were being sought in a study of meteors. Similar negative results, obtained by large numbers of astronomers, help to explain the general skepticism of astronomers toward flying saucer reports.

A series of puzzling and well-publicized flying saucer sightings in the mid-1960s again led to the appointment of a government investigating panel, this time under the aegis of the Air Force Scientific Advisory Board. It is significant that this panel was convened not at the request of the operational or intelligence arms of the Air Force, but in response to a request by the Air Force public relations office. The panel, under the chairmanship of Brian O'Brien, a member of the board, met in February 1966 and restated the general conclusions of the Robertson panel. It recommended that the Air Force make a more thoroughgoing effort to investigate selected UFO reports of particular interest, although the probability of acquiring significant scientific information (other than psychological) seemed small. The O'Brien panel suggested that the Air Force establish a group of teams at various points within the United States in order to respond rapidly to UFO reports. Each team would consist of (1) a physical scientist familiar with upper atmospheric and astronomical phenomena, (2) a clinical psychologist, and (3) a trained investigator. In October 1966 the University of Colorado was selected by the Air Force Office of Scientific Research to manage this program and to prepare a thorough analysis of the UFO problem. The National Academy of Sciences agreed to appoint a panel to review the Colorado report.

Hypotheses of extraterrestrial origin: Repeated sightings of UFOs and the persistence of the Air Force and the responsible scientific community in explaining away the sightings have suggested to some that a conspiracy exists to conceal from the public the true nature of the UFOs. Might not at least a small fraction of the unexplained few per cent of the sightings be space vehicles of intelligent extraterrestrial beings observing the earth and its inhabitants?

It now seems probable that the earth is not the only inhabited planet in the universe. There is evidence that many of the stars in the sky have planetary systems. Furthermore, research concerning the origin of life on earth suggests that the physical and chemical processes leading to the origin of life occur rapidly in the early history of the majority of planets. From the point of view of natural selection, the advantages of intelligence and technical civilization are obvious, and some scientists believe that a large number of planets within our Milky Way galaxy—perhaps as many as a million—are inhabited by technical civilizations in advance of our own.

Interstellar space flight is far beyond our present technical capabilities, but there seem to be no fundamental objections to it. It would be rash to preclude, from our present vantage point, the possibility of its development by other civilizations. But if each of, say, a million advanced technical civilizations in our galaxy launched at random an interstellar spacecraft each year (and even for an advanced civilization, such a launching would not be a trivial undertaking), and even if all of them could reach our solar system with equal facility, our solar system would, on the average, be visited only once every 100,000 years.

UFO enthusiasts have sometimes castigated the skeptic for his anthropocentrism. Actually, the assumption that earth is visited daily by interstellar spacecraft is far more anthropocentric—attaching as it does some overriding significance to our small planet. If our views on the frequency of intelligence in the galaxy are correct, there is no reason why the earth should be singled out for interstellar visits. A greater frequency of visits could be expected if there were another planet populated by a technical civilization within our solar system, but at the present time there is no evidence for the existence of one.

Related to the interstellar observer idea are the "contact" tales—contemporary reports of the landing of extraterrestrial space vehicles on earth. Unlike the UFO reports, these tales display a striking uniformity. The extraterrestrials are described as humanoid, differing from man only in some minor characteristic such as teeth, speech, or dress. The aliens—so the "contactees" report—have been observing earth and its inhabitants for many years, and express concern at "the present grave political situation." The visitors are fearful that, left to our own devices, we will destroy our civilization. The contactee is then selected as their "chosen intermediary" with the governments and inhabitants of earth, but somehow the promised political or social intervention never materializes.

Psychological factors: The psychologist Carl Jung has pointed out that the frequency and persistence of these contact tales—not one of which has been confirmed by the slightest objective evidence—must be of substantial psychological significance. What need is fulfilled by a belief that unidentified flying objects are of extraterrestrial origin? It is noteworthy that in the contact tales, the spacecraft and their crews are rarely pictured as hostile. It would be very satisfying if a race of advanced and benign creatures were devoted to our welfare.

The interest in unidentified flying objects derives, perhaps, not so much from scientific curiosity as from unfulfilled religious needs. Flying saucers serve, for some, to replace the gods that science has deposed. With their distant and exotic worlds and their pseudo-scientific overlay, the contact accounts are acceptable to many people who reject the older religious frameworks. But precisely because people desire so intensely that unidentified flying objects be of benign, intelligent, and extraterrestrial origin, honesty requires that, in evaluating the observations, we accept only the most rigorous logic and the most convincing evidence. At the present time, there is no evidence that unambiguously connects the various flying saucer sightings and contact tales with extraterrestrial intelligence.

what we will call "proto-galaxies." At some stage there will be smaller fluctuations inside a proto-galaxy, and out of these smaller fluctuations stars could form. We will call these "first-generation stars"—the first stars to form in a galaxy—and the gas they formed from might have been pure hydrogen, according to the view that the chemical elements have been built up in the stars, as discussed in Chapter IV. The "Steady-State" Theory, of course, suggests that the gas was not *pure* hydrogen but had a slight mixture of heavier elements ejected from earlier generations of stars and galaxies that had always been around in space.

In either case, the gas that formed the first generation of stars in a new galaxy would have very little of the heavier elements. It would be mostly hydrogen. From the early stages of a star's life discussed in Chapter IV, we know that the more massive a blob of matter that starts condensing, the faster it will contract under its own gravitation to form a star. During contraction, the gas becomes quite hot because of the release of gravitational energy as the gas falls in toward the center. Just as gravitational energy is released in the condensation of a star, so gravitational energy will be released in the formation of a galaxy; therefore the gas at an early stage in the proto-galaxy might be quite hot.

The Youth of a Galaxy

Because the large, hot, blue stars form rapidly, they will generally be imbedded in thinner gas that has not yet condensed into stars. The radiation from these hot stars would cause the gas they are imbedded in to shine quite brightly. Patches of glowing gas like this will show up very well in a galaxy and are seen in many irregular and spiral galaxies. This is the sort of situation we would expect in a young galaxy, and one that we see in the irregular galaxies shown in *Figures V-2* and *VII-1*. There is no pattern; an irregular galaxy is just an unorganized collec-

Figure VII-1. An irregular galaxy, NGC 4449. Such an unorganized collection of blue giant stars and blobs of glowing gas is generally considered young in age, since the blue giant stars are expected to be short lived. *Mount Wilson and Palomar Observatories*

Order Produced by Rotation

In Chapter V, it was shown that galaxies rotate about their axes. What would happen to an irregular galaxy if it rotates? Could it remain irregular? Star formation is going on, gas is contracting under its own gravitation, and the whole assemblage is rotating as well. We can expect a symmetrical and orderly structure to be produced from this formless mass of material just as a shapely vase can be made of formless clay. It is difficult to make a symmetrical object out of a lump of clay unless you have a potter's wheel to rotate the clay; then it is quite easy. So, we can understand how a galaxy could become more symmetrical-looking from its rotation. An irregular galaxy that started out with relatively few massive blue stars, and no pattern whatever in its structure, would gradually begin to take on a regular, symmetrical shape, with more of the mass collected at the center, and a generally circular outline. The cooling of the gas left over after the stars form would help this gas to contract toward the central or equatorial plane of the galaxy, and soon all of the gas and dust would lie in a thin layer or sheet in the central plane, as described in Chapter VI.

While this was happening—while the new galaxy was shrinking and speeding up its rotation, forming a more regular pattern—star formation would be going on continuously. As each generation of stars forms, the brightest members (which would be the most massive, high-temperature stars) will evolve and go through their lives most rapidly, come to the end stage, and return most of their substance to the space between the stars. But each generation will also contain some stars with a small mass. These small-mass stars, stars like our sun or smaller, with very long lifetimes, will not complete the full cycle that the hot bright stars go through—the cycle from dust to dust and gas to gas. Therefore, there should be a gradual using-up of the material of the galaxy; matter would gradually become locked up in low-mass stars whose lifetimes are so long that they take little part in the interchange between interstellar gas and stars.

Signs of a Galaxy's Age

There are also the stellar remains—skeletons, if you like—the white dwarfs left over after the massive stars have gone through their life cycle. An increasing fraction of the material of the galaxy will gradually get locked up in the form of white dwarfs; and that fraction can take no further part in the interchange between interstellar gas and stars. Thus, the gas in a galaxy will gradually get used up, until eventually there will be none left to form any new stars; in such an aged galaxy we expect only fairly cool stars of small mass, a few red giants into which such stars evolve, and some white dwarfs.

All this suggests that there are indicators of the evolutionary age of a galaxy—things which could be observed and measured from a large distance. We need features that can be measured from great distances if we are to get information about a large part of the universe, and about conditions billions of years ago—for we see the distant galaxies as they were then. We could measure, in the first place, the *color* of a galaxy. In Chapter II we saw how the colors of stars can be measured; the colors of galaxies, which are whole collections of stars, can be measured in the same way. If a galaxy has a red color it is likely to be made up mostly of old stars all of which have a reddish color—stars of a smaller mass than the sun and the red giant stars into which they would evolve. On the other hand, a young, irregular galaxy would have a bluer color because it is largely made up of hot, blue stars. Color thus would be an indicator of the evolutionary age of a galaxy.

We can also measure the *spectrum* of a galaxy, made up of the spectra of all the stars in it—an average or composite spectrum that might reveal the kinds of stars that make up a galaxy.

Another thing to measure is the *mass* of a galaxy, determined by studying how fast it is rotating (Chapter V). Having measured the mass of a galaxy, and the total light it puts out, we can determine the ratio: the mass divided by the luminosity. If we do this for a single star—the sun, for example—we get a certain value of tons mass per billion kilowatts of radiation. For a star cooler than the sun we find that the mass divided by the light is a larger number because of the way in which the luminosity depends so strongly on mass (Chapters III and IV). Stars of low mass put out relatively very little light, whereas stars of high mass are much more spendthrift of their energy. Hence the mass of a galaxy divided by its luminosity is a fairly good indication of the average kind of stars in that galaxy. Of course, it would be better if we could actually study the individual stars, but unfortunately galaxies are so far away that we can only study the brightest individual stars in a few of the nearest ones. What we need is a great deal of information about a very large number of galaxies.

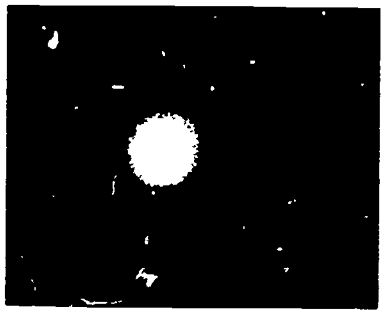
A galaxy that we might think of as being at a somewhat later stage in its life history is shown in *Figure I-10*. This spiral galaxy still has many bright patches in it which we find to be patches of hot gas lit by bright stars. These are spread all through it, just as they are spread through an irregular galaxy. But this spiral has a clearly defined center, a fairly circular outline, and characteristic spiral arms. The color of a spiral like this is a little redder than an irregular galaxy, and from its composite spectrum it seems to have a higher proportion of yellow stars like the sun than does an irregular galaxy. All of this indicates that a loose spiral galaxy is at a later stage in its life-history than an irregular one. *Figure V-1* shows a tighter spiral galaxy (M31) where things have settled down and become still more orderly. M31 looks quite tidy; it has a nice bright little center, then a smooth region, and then the spiral arms neatly wound. Even in a galaxy like M31 there are many patches of gas not yet condensed into stars, which are lit up by nearby hot stars.

Factors that May Influence the Evolution of Galaxies

Finally, the elliptical galaxies in *Figure V-4* are quite smooth. They are much brighter in the center than in their outer parts but they have no bright patches of gas, and seem to be made up entirely of stars. All the gas has been used up. Elliptical galaxies have the reddest color of all, and their composite spectra show that their stars are, on the average, low-mass stars like the sun and the red giants into which such stars evolve. What about the ratio of mass to luminosity? Unfortunately, we do not have much information yet on the masses of elliptical galaxies, but the average for a few shows that they have a much higher ratio of mass to luminosity than the spiral and irregular galaxies. This again suggests that they are at a later stage in their life-history.

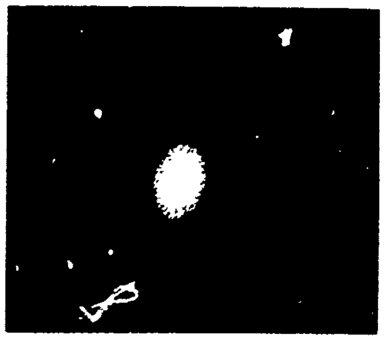
Can we now sav that an irregular galaxy will turn into a spiral galaxy and, when all the gas is used up, the spiral will turn into an elliptical galaxy? Can we say that we have an evolutionary sequence, irregular types evolving into spirals, and spirals evolving into ellipticals? Harlow Shapley, the famous Harvard astronomer, first suggested about a decade ago that this was happening. But we must keep in mind the warning example set by studies of the evolution of stars. We know that there are many different kinds of stars in the sky, but that we cannot put all these stars into one evolutionary sequence; we

Figure V-1. The Andromeda Galaxy, Messier 31, a spiral galaxy. This largest and brightest of the nearby galaxies dwarfs its two companions, M32 on the left and NGC 205 on the right, in this photograph taken with the 48-inch Schmidt telescope. M31 is estimated to be over 2 million light-years from us. It is the nearest spiral galaxy, and can just be seen with the naked eye on a clear, dark night. *Mount Wilson and Palomar Observatories*



E0 NGC 3379

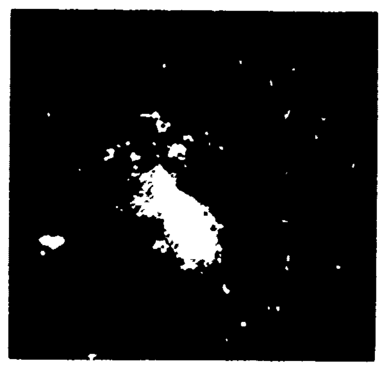
E2 NGC 221 (M32)



E5 NGC 4621 (M59)

E7 NGC 3115

NGC 3034 (M82)



NGC 4449

have seen in Chapter IV that the life-histories of stars of different masses are very different. In fact, if we want to make sense of the life-history of stars, we have to sort the stars first into groups with the same age but different masses. We cannot say that a high-temperature, massive star will evolve into a star like the sun. But in this first attempt at the life-history of a galaxy we are trying to arrange all the different kinds of galaxies in a single evolutionary sequence. Perhaps this is not right—perhaps the mass of a galaxy plays an important role in determining its life-history, just as the mass of a star is very important in its life-history.

Although we know the masses of only a few galaxies as yet, it does seem that irregular galaxies and spiral galaxies are, on the average, less massive than elliptical galaxies. How, then, could an irregular galaxy become a spiral galaxy and then an elliptical galaxy, with an *increase* in mass?

There is further evidence from the double galaxies—galaxy twins, so to speak. For instance, the irregular galaxy M82 lies quite close in space to the large spiral galaxy, M81, and may have been formed out of the same general patch of material. It ought to have the same age, just as the stars in any one cluster are likely to have the same age. Is the irregular galaxy M82 the same age as the spiral galaxy M81 near it? M82 is probably a little less massive than the spiral galaxy M81, but it is rotating, and before very long it should surely settle down to a spiral structure. Why is M82 still an irregular galaxy? What stopped it from becoming a spiral galaxy like M81?

There must be other factors, then, that determine the way in which a galaxy evolves, beside the mass it had to start with. The *magnetic field* is a possible factor, since magnetic fields are needed (Chapter VI) to explain those galaxies that are radio sources, and it is quite likely that there are magnetic fields in all galaxies, including our own. These magnetic fields are quite small in comparison to the magnetic field on the surface of the earth that causes a compass needle to point north. The magnetic field in our galaxy is only a few hundred-thousandths of this. Nevertheless, a magnetic field of this strength spread out through a whole galaxy involves a great deal of energy.

If magnetic fields are stronger in some galaxies than in others, this might have an effect upon the speed at which interstellar gas could form into stars. A strong magnetic field could delay star formation because magnetic fields tend to "freeze" a conducting gas, making it behave more like a solid, and would tend to keep apart a blob of gas that was about to contract under its own gravitation into a star. In this way the magnetic fields in a galaxy may be important in determining its life-history.

Another factor that might be important is the original *density* of the gas that contracted to form a galaxy. Suppose gas is contracting, and that, before it has achieved high average density, some fluctuations initiate star formation. This might lead to a slower over-all rate of formation than if all the gas forming a galaxy collapsed at once, reaching high density throughout before the first generation of stars formed.

The Origin of S-Zero (So) Galaxies

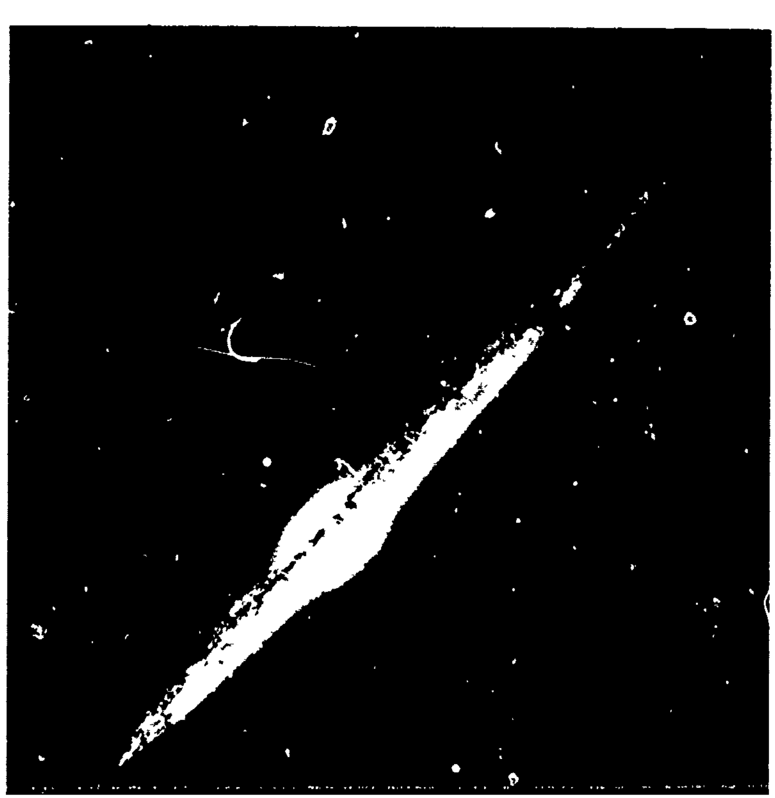
Another objection to the idea that a spiral galaxy may turn into an elliptical one is connected with *rotation*. Looking at a spiral galaxy edge-on as in *Figure I-11*, we see how flat it is. Elliptical galaxies are never that flat. Once a galaxy has become extremely flat, it is difficult to see how it can round out again, as would be necessary if a spiral galaxy were to evolve into an elliptical galaxy. However, there is a kind of galaxy that has no spiral arms and yet is more flattened than the elliptical galaxies, and these are called So galaxies (see Chapter V). There

Margaret Burbidge

1962

A fairly coherent picture has been built up of the evolution and life-history of single stars; can we make such a coherent picture of the evolution or life-history of a galaxy? At the moment our success is not as clear-cut as in the case of the life-history of a star. For example, you have seen in Chapter VI that there can be opposite points of view about the radio stars; in one interpretation two galaxies are colliding; in the other, a single galaxy is splitting into two parts. At the moment, we have no physical theory or explanation which could fit this second suggestion. In fact, the whole problem of the probable course of evolution of a galaxy is more difficult and complex than for a star. This is not to say that we shall not solve it in the comparatively near future; after all, the evolution of stars was only poorly understood ten years ago. Since then most of the story (Chapters III and IV) has been put together, and who knows what the next ten years will bring to our understanding of the evolution of galaxies.

The Life-Story of a Galaxy



almost none. In trying to trace out the life-history of a galaxy, one way to begin is to look for a time sequence between these different kinds of galaxies. Might one kind of galaxy change into another? If so, which are younger? Which are older?

From Gas to Galaxy

In Chapter V two alternative cosmological theories were described. According to the "Big-Bang" Theory the universe was created at some definite time in the past; matter was . ' en very much closer together in space. Somewhat later all the galaxies might have been formed at one time. By contrast, according to the "Steady-State" Theory, the universe has been about the same all along, and galaxies must be forming now. In either case it is likely that the material out of which the galaxies formed was originally all gas, containing no stars or dust, and spread more or less uniformly throughout space. If a gas is uniformly spread through space, it tends to "clot." If any little fluctuation takes place, one region by chance becoming a bit more dense than another, then the denser region tends to grow, attracting to itself more material by gravitational force. The clots would grow and might easily turn into galaxies.

On this basis, we shall sketch in quite general fashion what might be the life-history of a galaxy—not what can be proved, but what would be reasonable. Starting, then, with a gas spread uniformly throughout all space, fluctuations begin to form

are many galaxies of this sort in some of the giant clusters of galaxies, and it has been suggested that they were formed by chance collisions. In such a collision the stars of each galaxy just pass each other, simply because there is so much empty space between them. But the interstellar gas and dust clouds in the two galaxies *will* collide, and be separated from the stars. So collisions will sweep the gas out of spirals. S-zero galaxies, which are flat but have no interstellar clouds, might therefore be either the results of collisions between spiral galaxies, or simply aged spiral galaxies that have used up their gas and dust in forming stars.

Figure VII-2 shows an So galaxy in which a small amount of gas remains. You can see that there is a very thin line of dust through the center, the region where the spiral arms used to be. The gas that makes spiral arms is mostly gone, leaving just stars and the remnants of stars.

Winding Up of Spiral Arms

Let us now consider the spiral arms in galaxies. They are

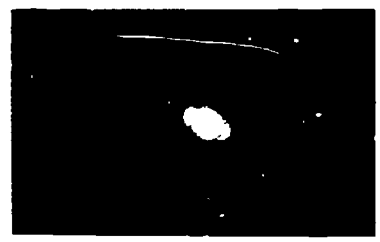
Figure VII-2. An So galaxy, NGC 5866. The S-zero (So) type of galaxy is flat like a spiral but shows no spiral arms and is often called a transition stage between spiral and elliptical types. This one has a thin line of dust in it, as a depleted spiral might.
Mount Wilson and Palomar Observatories

the opposite: why don't all galaxies have much more extended spiral arms? If the galaxies are very old they must have rotated a great many times; an average galaxy will rotate, about halfway out from its center, once in perhaps a hundred million years, and will turn a large number of times in its full life (estimated to be ten billion years). We would expect to see spiral arms completely wound up in hundreds of turns, whereas the actual spiral galaxies (*Figures I-10, V-1, V-3*) usually have arms making just one or two turns. It seems that there must be some process that renews or preserves short spiral arms; otherwise the observed rotations of galaxies would wind them out of existence. Here again, it is tempting to assume that magnetic fields stiffen the material of a galaxy and prevent a spiral arm from winding up too far. They may also play some part in the formation or renewing of spiral arms.

In addition to the ordinary spiral galaxies, as noted in Chapter V, there is the class of "barred spirals"—galaxies that have a bar across the center and two spiral arms starting from the ends of the bar (*Figure V-3*). The bar in such a galaxy rotates more or less like a solid wheel, but just beyond the end of the bar the material rotates more slowly so that the arms get trailed out. Something must "freeze" the straight bar into a rigid form so that it does not wind up into spiral arms. But *Figure VII-3* shows a different sort of barred spiral. It has a bar and two large spiral arms, but in the very center there is another little spiral, which turns out to be rotating very fast. It is hard to see how the bar could last very long without getting wound up in the central spiral. There are several other barred spirals like this, and there is a great deal to be learned before we can hope to understand them.

Figure I-10. An open spiral galaxy in Eridanus, NGC 1300. Its shape gives an impression of ro·ation, but since it takes hundreds of millions of years to turn once around, we cannot hope to detect changes in this view during one man's lifetime, or even during the whole history of astronomy. *Mount Wilson and Palomar Observatories*

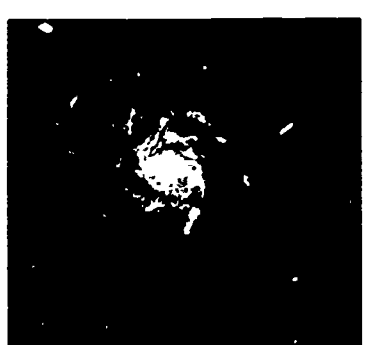
Sa NGC 4594



SBa NGC 2859

Sb NGC 2841

SBb NGC 5850



NGC 5457(M 101)

SBc NGC 7479

Figure VII-3. A barred spiral galaxy with a spiral nucleus, NGC 1097. A normal barred spiral (SB) galaxy has a straight bar between two spiral arms (*Figure V-3*). The small spiral in the center of this one raises the question of how the bar can remain straight when a part of it is more rapidly rotating at the center.

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Are Galaxies Forming Now?

Finally, do we see any galaxies that we think are really young—actually young in years? The "Steady-State" cosmological theory predicts that we should see some galaxies formed very recently; the "Big-Bang" Theory, although it does not say that there could be no young galaxies, must explain them in some special way. *Figure VII-4* shows one of the few galaxies we can claim are fairly young. It is a very odd thing—an ordinary elliptical galaxy accompanied by nearby patches of gas that must have bright, hot stars in them. A galaxy like this could not last very long in its present stage; perhaps this elliptical galaxy, moving through space, captured some left-over material —a blob of gas in which no stars had formed. As a result of the capture, this blob of gas could contract a little, until it was dense enough in some places for stars to form. That is, a young galaxy was formed in the presence of an old one.

Figure VII-5 shows two galaxies rather far away from us and located in one of the big clusters of galaxies, the Coma cluster. A long tail sticks out of the upper galaxy, and another tail from the lower one. You would think such tails must wind up; a tail cannot remain just sticking out into space from a galaxy if that galaxy is rotating at all. And these galaxies are rotating rapidly, as measured by Doppler shifts in their spectra (see Chapter II). That is, a straight, protruding tail makes it very likely that such a galaxy is very young.

Another queer thing is shown in *Figure VII-6;* it looks unlike the galaxies we are used to and yet it certainly is a galaxy. It has two strings of material and a kind of loop. One would expect such an unstable structure soon to change; hence it is also likely to be young.

In summary, it is difficult to understand in detail how one sort of galaxy can evolve into another, yet in a general way we know that it must happen. We know that the stars in a galaxy are ageing (Chapters III and IV), and that the shapes of certain galaxies (*Figures VII-5* and *VII-6*) cannot last, as the motions in each galaxy go on—motions we have measured by Doppler shifts. This reasoning leads us to think that elliptical galaxies are older than spirals and irregular galaxies. But if we go on to

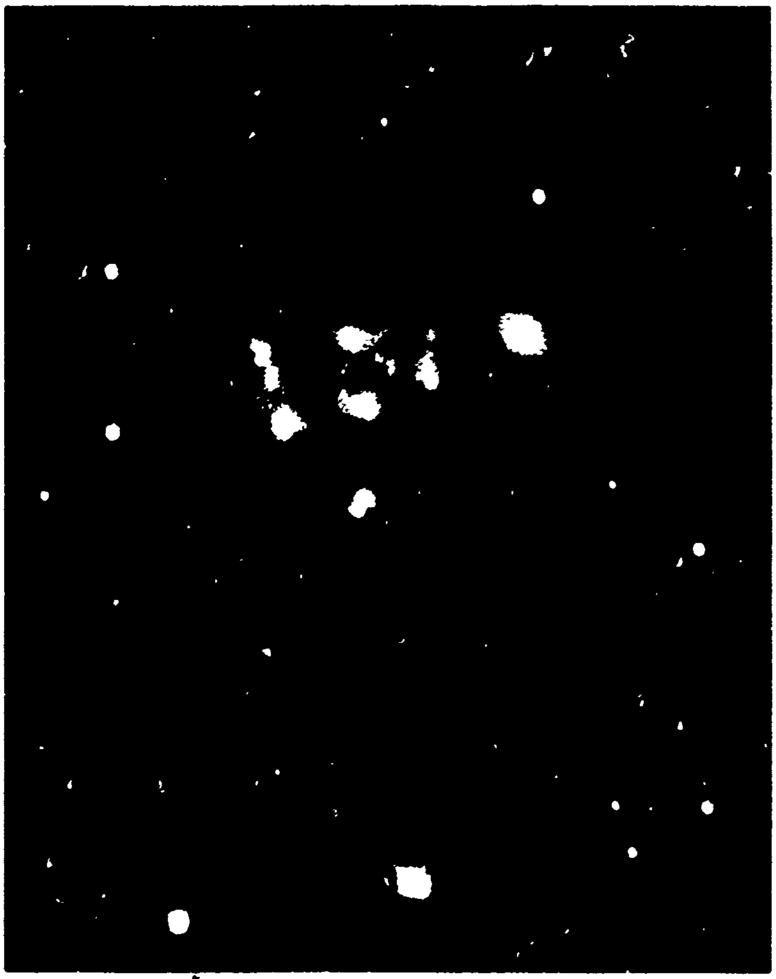


Figure VII-4. A new galaxy forming near an elliptical, NGC 2444, 2445. The bright patches to the left of the normal, presumably old, elliptical galaxy are glowing gas illuminated by young, blue giant stars. *McDonald Observatory*

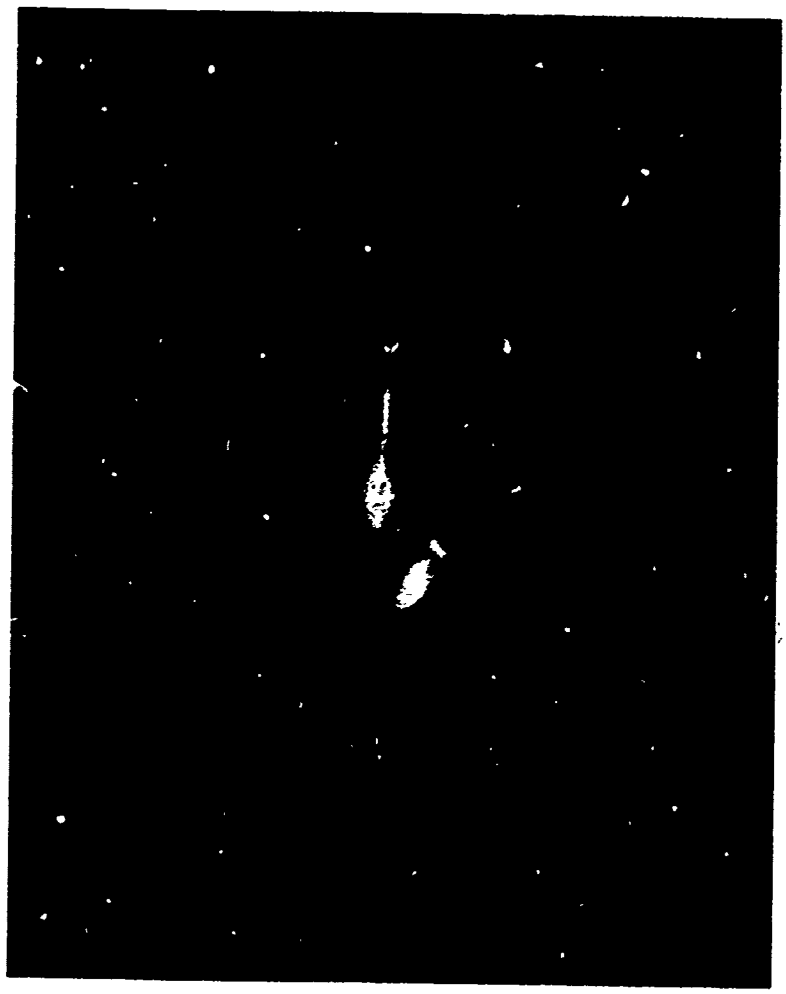


Figure VII-5. A pair of galaxies with tails, NGC 4676. The question here is how the tails can remain sticking out without "winding up" into spiral arms. The spectra show that each galaxy in this pair is rotating rapidly. *McDonald Observatory*

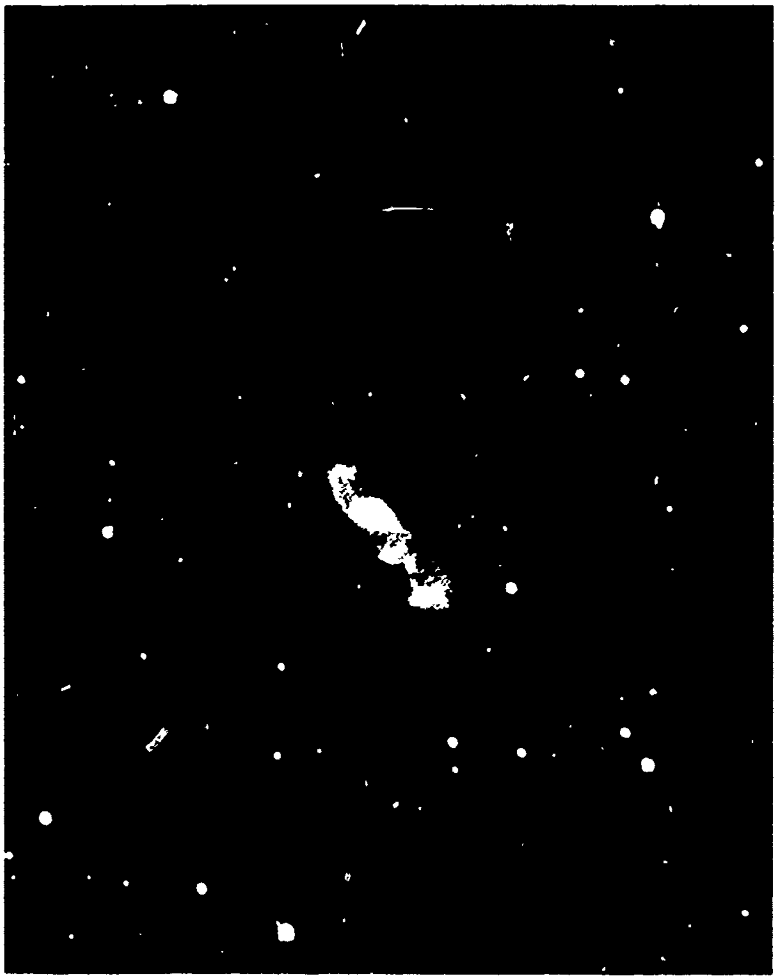


Figure VII-6. A peculiar loop-galaxy, NGC 6621, 6622. Such a shape fits into no regular class of galaxies; it is a freak that appears to be unstable and therefoic of short life in its present form.

McDonald Observatory

say that all irregular galaxies turn into spirals after 100 million years, and that all spirals turn into ellipticals after a billion years, how can we explain mixed groups or close pairs of one spiral with one elliptical? How can elliptical galaxies be heavier than spirals? (Where did the added mass come from as a galaxy aged?)

One possible explanation is that ageing does not always proceed at the same rate. Perhaps in the "young" spirals we see among "old" ellipticals, something prevented for a long time the formation and ageing of stars. Perhaps the mass of a galaxy has an effect on how rapidly it ages, so that most of the heavy ones have already become "old" ellipticals. Irregular "young" galaxies seen close to "older" spirals or elliptical galaxies suggest that, whatever the cause, evolution goes on at *different rates* in different galaxies even when they are located close to each other in space. Two close galaxies in a double may be at widely different stages in their life-histories, even though they have the same age in years. In fact, there could well be many even younger galaxies that we cannot see—dark blobs of matter in which stars have not yet formed because of magnetic fields or low density or some other peculiar condition. These ideas of the evolution of galaxies can be fitted equally well into either the "Big-Bang" Theory or the "Steady-State" Theory.

From all this you can see that we do not have an adequate theory of how galaxies evolve. More observations and much more theoretical study is needed. The subject of evolution of galaxies is a field in which we can expect great changes in the next few years.

Bondi, a noted theoretical physicist and astronomer, presents the evidence for the over-all expansion of the universe, evidence which depends greatly on the observed red shift of light from distant galaxies. The number mentioned at the end of the paper, ten billion years, is sometimes picturesquely called the "age of the universe."

23 Expansion of the Universe

Hermann Bondi

1960

The most striking feature of the universe is probably its expansion. What exactly is the evidence for this and how strong is it? In Plate I we have a picture that displays some of the evidence in striking form. A series of pictures of galaxies is shown in the left-hand column. They are all taken with the same telescope, using the same magnification. On the right-hand side we see the spectra of these galaxies. Now, first, what is a spectrum? It is well known that white light is a combination of all the colors and that it can be broken up into these colors by suitable aids; a rainbow is a familiar instance. A handier means is the use of a prism of glass or other suitable material; with its aid the whole band of colors of sunlight is spread out. If one uses a prism that spreads out the sunlight very clearly, then one notices that the colors do not form a smooth band and that in numerous places dark lines run across the spectrum. The origin of these lines is rather complicated. In the main they are due to the light from the sun shining through cooler gases of the sun's atmosphere, and these gases happen to be opaque to very particular colors, to thin lines, and so leave a part of the spectrum dark. The astronomer can use spectroscopes of great power to analyze the light of individual stars and also of individual galaxies. Naturally, particularly for the very distant galaxies, rather little light is available, and because of that, and for more technical reasons, the spectrum of a galaxy will not be nearly as clear as, say, the spectrum of the sun. Nevertheless, a few of the very prominent dark lines do show up, even in the spectra of these distant galaxies. The remarkable phenomenon that was discovered nearly forty years ago is that these lines are not where they ought to be, not where they are in the case of the sun, say, but they are displaced; they are shifted. The shift is always toward the red and is indicated in the illustrations of the spectra in Plate I. You will notice that the fainter and smaller the galaxy looks, the greater the shift of the spectrum toward the red. This is a full description of the direct observational result. A red shift of the spectrum is observed and is correlated with the apparent

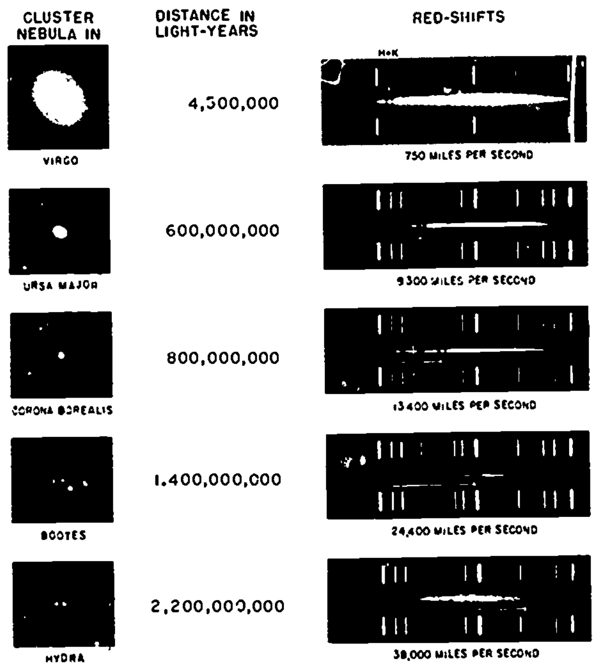


PLATE I. *The expansion of the universe is inferred from these and similar observations. The left-hand column shows galaxies at various distances photographed with the same magnification. In each photograph the galaxy appears as a diffuse object with its center in the middle of the picture, but the two most distant ones are marked by arrows for purposes of identification. The other diffuse objects in the photographs are other galaxies, the sharp ones being stars near to us. On the right are photographs of the diffuse-looking spectra of the galaxies stretching in each case from blue on the left to red on the right. The bright lines above and below each spectrum are produced in the laboratory and serve only as markers. The pair of dark lines in the spectrum of each galaxy above the tip of the arrow would be above the foot of the arrow if the source were at rest.*

brightness of the galaxy, so that the fainter the galaxy, the greater the red shift. From here on we start on a series of interpretations.

The Red Shift

First, what can be the explanation of such a red shift? In what other circumstances are red shifts observed? The answer is that, but for one rather insignificant cause, the red shift always indicates a velocity of recession. Unfamiliar as the phenomenon is in the case of light, it is commonly noticed in the case of sound. If a whistling railway train speeds past you, then you notice that, to your ears, the pitch of the whistle drops markedly as the train passes you. The reason for this is not difficult to understand. The whistle produces sound; sound is a vibration of the air in which pressure maxima and pressure minima succeed each other periodically; these travel toward your ears where they are turned into nerve impulses that enter your consciousness. While the train is approaching, each successive pressure maximum has a smaller distance to travel to reach you. Therefore, the time interval between the reception of the pressure maxima will be less than the time interval between their emission. We say that the pitch of the note is raised. Conversely, when the train is receding from you, each successive pressure maximum has farther to travel and, therefore, the pressure maxima will reach your ear at intervals of time greater than the intervals at which they were emitted. Accordingly, the pitch is lower. How great the raising or the lowering of the pitch is, depends on the ratio of the velocity of the train to the velocity of sound, which is about 1100 ft. per second.

Very much the same thing happens with light, but here an increase in the pitch becomes noticed as a shift toward the violet; a decrease in the pitch becomes noticed as a shift toward the red. Also, the crucial velocity is now not that of sound, but the very much higher velocity of light at 186,000 miles per second. A red shift, therefore, indicates a velocity of recession of the source; a velocity standing to the velocity of light in the ratio given by the magnitude of the red shift—that is, by the change in wave length divided by the wave length. The velocities so derived from the observed red shifts are shown on the right-hand side of Plate I. Such a velocity of recession is, then, the only cause of the red shift that we can infer from our terrestrial knowledge of physics. What about the other characteristic of the picture, this time the characteristic of the photographs on the left, the increasing faintness and diminishing size? We all know that an object of a given brightness will look fainter the farther away it is. There is very little else in astronomy to guide us about the distances of these galaxies which we see so very far away. Accordingly, if we interpret the faintness of the galaxies as indicators of their distances, and the red shift of the spectra as velocities of recession, then we find that the velocity of recession is proportional to the distance of the object.

Velocity of Receding Stars

We have inferred a "velocity-distance law" from the red shift-brightness relation. For a long time physicists and astronomers felt rather uneasy about these enormous velocities of recession that seemed to follow from their observations. They argued that all our interpretation was based on our local knowledge of physics, and that unknown effects might well occur in the depth of the universe that somehow falsify the picture that we receive. Nowadays, we have little patience with this type of argument. For the expansion of the universe is not merely given by the observation of the spectrum. We have also noted the remarkable uniformity of the universe, how it looks the same in all directions around us if only we look sufficiently far. If, then, we suppose that the universe is, indeed, uniform on a very large scale, we can ask the mathematical question: How can it move and yet maintain its uniformity? The answer is that it can only move in such a way that the velocity of every object is in the line of sight and proportional to its distance. This is the only type of motion that will maintain uniformity. Therefore, we are again driven to the conclusion that an expansion with a velocity of recession proportional to distance is a natural consequence of the assumption of uniformity which is also based on observation. Furthermore, if we try to form a theory of the universe, whichever way we do it, we always come up with the answer that it is almost bound to be in motion, with objects showing velocities proportional to their distances.

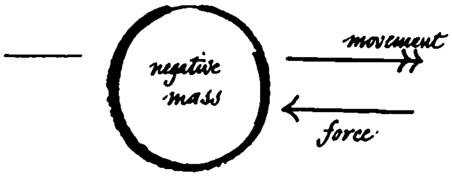
I must again stress the uniformity of the system. We are not in a privileged position on the basis of these assumptions, but in a typical one. The universe would present the same appearance to observers on any other galaxy. They would see the same effects; the same red shift-brightness relation. Though no one can be certain of anything in this field, we do see that there are different lines of argument all converging to the conclusion that the red shifts should indeed be taken as indicating velocities of recession proportional to the distance of the objects. If we divide the distance of any galaxy by its velocity of recession, we get the same number whatever galaxy we choose. That follows from the proportionality of velocity and distance. This number is a time, a time that, according to the most recent work, is about 10,000 million years. In some way or other this is the characteristic time of the universe.

Does mass, like electric charge, exist in both positive and negative forms? If so, negative mass must have the most extraordinary properties--but they could explain the immense energies of the star-like objects known as quasars.

24 Negative Mass

Banesh Hoffmann

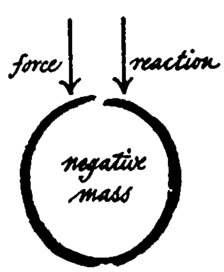
1965



ONLY A RASH MAN would assert categorically that negative mass exists. Yet he would be almost as rash if, equally categorically, he said that it does not. True, if negative mass exists it must have extraordinarily perplexing properties. For example, if we pushed a piece of negative mass towards the left with our hand, it would move perversely towards the right; and, if that were not nonsense enough, as it moved towards the right we would not feel the negative mass resisting our thrust but actually aiding it.

If the behaviour of negative mass is so seemingly nonsensical, why should one even think about it further? It has never been observed. Surely anyone who said that negative mass does not exist would be far less rash than one who thought that it might.

So it would seem. Yet the history of science should give us pause. We have learned from bitter experience that what at first seems utter nonsense can prove to be excellent science. For instance, who would have believed, at one time, that no material object can possibly move faster than light? Or that an electron is, in a sense, both a particle and a wave? Or that when two people are in relative motion each finds that the other's clock runs slow compared with his own? Yet these, and many other such unlikely statements, are now part of the legitimate currency of science.



EVEN SO, why should we seriously contemplate the idea of negative mass? The recently discovered quasi-stellar radio sources provide an answer. These objects, often referred to as quasars, pose a stark problem simply because they are, intrinsically, by far the brightest objects in the heavens. Not that they dazzle the eye. They are much too far away to do that, despite their brilliance. Indeed they are invisible to the naked eye. Though we owe their recognition in the first instance to the radio astronomers, it would be incorrect to say that the radio astronomers were the first to detect them. The quasars had often been photographed by the optical astronomers. But on the photographs they looked like faint stars of no particular interest; and with so many more glamorous celestial objects demanding their attention the optical astronomers had simply ignored them.

Whenever the radio astronomers detected a source of radio waves in the heavens they told their optical confrères who then directed their largest telescopes towards the region in question. For the most part all was neat and orderly: the optical astronomers found visible objects that were clearly the sources of the radio waves—usually galaxies of one sort or another. Sometimes they drew a blank. And just occasionally they could find nothing except a star-like object so faint that if it were indeed an ordinary star it could not have given rise to the relatively strong radio waves that had been observed.

Nevertheless, more precise radio bearings confirmed that these star-like objects were indeed the radio sources and from then on the puzzle grew until it reached massive proportions. In an expanding universe, the furthermost objects recede the fastest and this recession is evidenced by a shift of spectral lines towards the red. The quasars were found to have spectral red shifts corresponding to recession speeds as high as half the speed of light, implying that they were among the most distant known objects in the universe. This was incredible, if they were stars, since there are theoretical limits to the size and brightness of a star and no star could be bright enough to be observable at such distances. If the distances were correct, individual quasars must be emitting light at more than a million million times th rate of emission of the Sun and, indeed, something like a hundred times the rate of emission of a complete giant galaxy. Yet the quasars could not be anywhere near the size of an average galaxy which is tens of thousands of light years across: they would look larger if they were indeed that large. Another reason, less obvious, is that some of the quasars have rapid fluctuations in brightness, with periods measurable in years and even in weeks. Not only do galaxies maintain a steady brightness; there are also relativistic reasons for believing that an object whose brightness fluctuates with a period of a few years cannot be more than a few light years across.

Thus, the astronomers were faced with a major problem: how could they account for the prodigious rate at which quasars were radiating energy, and what was the source of this energy?

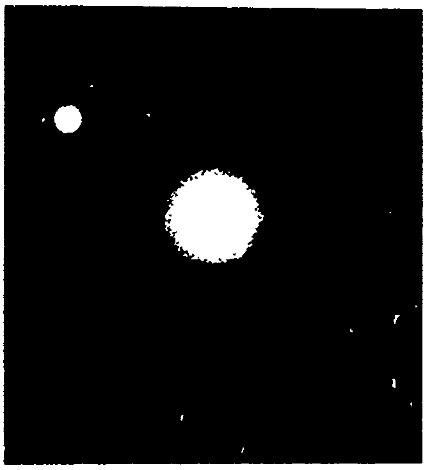
Quasi-stellar radio source 3C 147

In FEBRUARY of this year, there were 45 known quasars. By now the number is likely to be significantly larger. Several theories have been proposed to explain the nature of quasars and the source of their energy. Indeed, it is only with the recent advent of new observational techniques that the rate of discovery of quasars has significantly outstripped the rate of production of theories to account for their properties. If one tries to account for their spectacular brightness by conventional astrophysical processes, in terms of Einstein's relationship of energy to mass and the speed of light ($E=mc^2$), one is almost driven to assume it is due to a prodigious rate of supernova explosions; even then one has to postulate enormous amounts of matter.

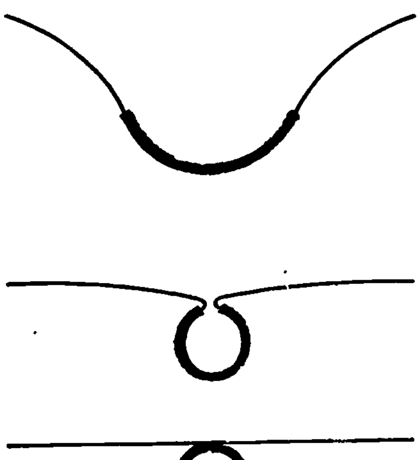
I. S. Shklovsky and G. R. Burbidge, among others, have suggested ways in which such explosions might occur frequently. Also, G. B. Field has proposed that a quasar is just an early stage in the evolution of a regular galaxy having relatively small rotational energy, the extraordinary brightness arising from the explosion of supernovae at the rate of about a hundred a year (the usual rate being one explosion every three or four hundred years in an average galaxy). Since the supernovae would explode at irregular intervals, this hypothesis could explain the fluctuating brightness but it would explain only the most rapid fluctuations and not one whose period was of the order of a decade.

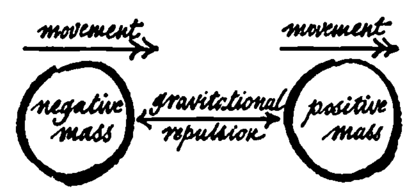
T. Gold has suggested that both the brightness and the fluctuations could come from frequent collisions of stars in a highly compact galaxy, the collisions tearing the stars open and exposing their glowing interiors.

V. L. Ginzberg, among others, has looked to gravitation as a source of energy in the quasars. A tall building seems to be a placid unenergetic thing. But if its foundations crumble it falls to the ground with devastating effect. In its upright position it has stored gravitational energy—put there by the cranes that lifted the building blocks—and when it collapses this energy is released. We do not know how matter came into existence, but it is dispersed throughout the universe and, in its dispersed state, it has gravitational energy akin to that of the upright building. As portions of matter come together locally under the influence of their mutual gravitation they transform part of their gravitational energy into energy of



Quasi-stellar radio source 3C 273





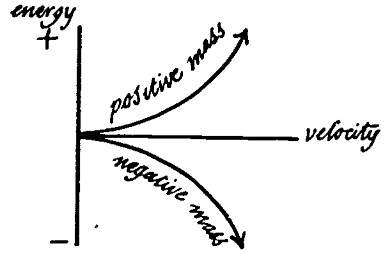
motion. Under normal conditions the celestial object built up in this way does not collapse. Its rotation tends to make it fly apart and thus counteracts the shrinking effect of gravitation. And if it does begin to collapse it usually tends to bounce back as the gravitational energy released is changed into motion. But F. Hoyle and W. A. Fowler, using the general theory of relativity, conceived of circumstances in which a gigantic 'star' might suffer a really radical gravitational collapse, becoming a relatively minuscule object of stupendous density. In the process it could give off light and radio energy at the observed quasar rate, but to do so the 'star' would have to contain an enormous amount of matter—a hundred million times that in the Sun.

Because the amounts of energy involved verge on the incredible, J. Terrell has suggested that the quasars are actually quite close, in astronomical terms, being fleeing fragments formed as a result of an explosion within our own galaxy. If so they would be much smaller and much less bright than had been supposed. But then one would have to ascribe the large red shifts of their spectral lines not to cosmological recession velocities, arising from the overall expansion of the universe, but to local recession velocities produced solely by the initial explosion. Although the amount of energy involved in this hypothesis is considerably less than that needed to account for quasars as very distant objects, it is nevertheless alarmingly large for a relatively local explosion, and to account for it Terrell feels a need to invoke a local gravitational collapse.

J. A. Wheeler has proposed yet another idea which he bases on the Einstein concept of curved space in a gravitational field. If only one could ignore rotation, a sufficiently large amount of matter would inevitably undergo radical gravitational collapse. As the matter fell together to a density of unheard of proportions, the curvature of space would increase locally until a sort of open pouch, or pocket, or blister was formed. The greater the amount of matter falling into it, the more rotund the blister would become and, as it grew more concentrated, its neck would become ever narrower. Eventually the neck would close and the blister would become a hidden cyst of space, with never an external pucker to reveal its presence. The matter that had fallen into it would be lost completely to the outside world. Not even its gravitational effect would survive. But in falling it could give up all its energy (mc^2) to the main part of the quasar, and this could be the fuel that kept the fire burning so brightly.

THERE IS YET ANOTHER possibility—if one can accept the idea of negative mass. For negative mass can act like a bank overdraft, allowing one to borrow energy for emergency purposes when high output is needed. And it has the considerable advantage over a bank overdraft that one can manage, in a sense, to avoid paying back what one has borrowed.

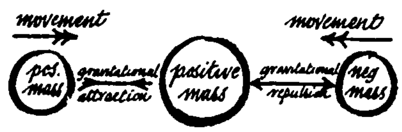
Let us, then, look more closely at the properties of negative mass, taking encouragement from the fact that neither the theory of relativity nor the quantum theory is a barrier to the existence of negative mass despite its awkward properties, and that negative mass can be excluded from those theories only by the arbitrary imposition of a ban from the outside. According to Newton, the gravitational attraction between two bodies is proportional to the product of their masses. If one of the masses is negative and the other positive, their product will be negative and therefore so, too, will the gravitational attraction between them. Since a negative attraction is a repulsion, we might expect the two masses to accelerate away from each other. But this is not the case. Negative mass does not do the expected thing. Imagine the two masses placed side by side, the positive mass to the right of the negative mass. Their mutual gravitational repulsion accelerates the positive mass towards the right, of course. But what of the repulsion that acts on the negative mass? Since it is directed towards the left, and since negative mass acts perversely, the repulsion will cause the negative mass to move towards the right, that is towards the positive mass. Thus both masses move towards the right, the negative mass chasing the positive. Enormous speeds could be built up in the course of such a chase; and it seems that we would be getting something for nothing—generating energy without doing work, and thus violating the law of conservation of energy. But in fact we would not. True, the faster the positive mass goes, the greater its energy. But the



same is not true of the negative mass. The faster it goes, the more deeply negative its energy becomes. So the negative mass can chase the positive mass and generate enormous speeds while the total amount of energy remains unchanged.

Once the perversity of negative mass is grasped, it is not difficult to see that positive mass causes both positive and negative mass to accelerate towards it gravitationally, but that negative mass gravitationally causes all mass, whether positive or negative, to accelerate away from it. Again, if two particles have electric charges that are either both positive or both negative, the particle of negative mass will still chase the particle of positive mass; but if the charges have opposite signs the particle of positive mass will do the chasing, provided that the electrical force is larger than the gravitational.

Thus, we begin to see that the idea of negative mass might help to explain the enormous brightness of the quasars. But it is not enough simply to postulate the existence of negative mass. We must be able to explain why it has not been observed and we must present a specific mechanism by which negative mass could indeed fuel the quasar furnaces.



IF NEGATIVE MASS exists we would expect all particles of positive mass to decay spontaneously into particles of negative mass, emitting radiation in the process and causing the material universe to blow up. Though this appears to be a formidable obstacle, we would be faint hearted to let it deflect us from our purpose. Indeed one needs no great courage, for theoretical physics has often been—and still is—plagued by similar theoretical catastrophes.

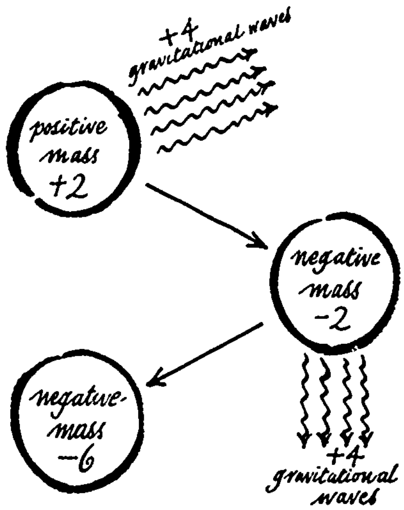
Many decay mechanisms that one could argue as conceivable seem not to occur in nature. To account for such absences, theoretical physicists impose on their theories special conservation rules which forbid decays that the theories would otherwise permit. We can introduce an analogous conservation rule that would prevent particles of positive mass from decaying into particles of negative mass.

But if we do, how are we ever going to generate particles of negative mass? Once again we take our cue from current atomic theory. Some of the conservation rules are not inviolate. We therefore make ours breakable too—but only under exceptional conditions.

Conservation rules are always related to symmetries and they are broken when the corresponding symmetries are marred. Since, according to Einstein, gravitation is a curvature of space-time, it could well warp symmetries. So we imagine that in the presence of an extremely strong gravitational field the conservation rule prohibiting the formation of negative mass can be broken; and we say that only under extreme conditions such as exist within a quasar is this likely to occur.

Next we recall that gravitation is different from all other forces, in that gravitational waves are generated by mass and themselves transport mass. (Electromagnetic waves, for example, are generated by electric charge but do not transport electric charge.) So we postulate that positive rest mass can decay into negative rest mass only if the energy is given off in the form of gravitational waves. This has two important consequences. First, gravitational waves are generated when a particle is accelerated by non-gravitational forces, and these will be particularly powerful in the hot, dense interior of a quasar. So much so that, with the requirement of an intense gravitational field, we can effectively confine the production of negative mass to such extreme circumstances as are likely to exist in the interiors of quasars.

The second consequence has to do with a curious asymmetry between positive and negative mass in Einstein's theory. Work by H. Bondi and others indicates that, irrespective of whether the matter producing the gravitational waves is positive or negative, the waves carry away only positive energy and thus only positive mass. So if a particle of, say, 6 units mass gave off gravitational waves whose energy had mass 4, it would end up with mass 2. But if a particle of mass 2 gave off gravitational waves of mass 4 it would be left with mass of −2, that is, a negative mass. It could not now give off gravitational waves of mass −4 and return to a



mass of +2. If it gave off further gravitational waves of mass 4 it would go to mass −6 and so on. The process would slow down, however, since the more deeply negative the mass became the less easily would the particle be accelerated.

THE GRAVITATIONAL waves would be carrying energy to the more peripheral parts of the quasar while building up an energy deficit in the form of negative mass. Where, though, would the deficit be stored? We might imagine that since matter of negative mass has negative density it would be far more buoyant than matter of positive mass and density. But once again the perversity of negative mass betrays our expectations. A particle of positive mass in a quasar would be pulled gravitationally towards the centre but buoyed up by the impacts of other particles. A particle of negative mass would also be accelerated gravitationally towards the centre but it would react perversely to the same impacts. It would therefore plunge towards the centre, and there it would mix with positive mass to form a growing core whose average mass was zero. Here, then, at the centre of the quasar, the deficit would reside—and accumulate. If the above theory is at all close to actuality, it is no wonder that negative mass, if it exists, has not been observed.

But we are taking too easy a way out, a way reminiscent of the White Knight in "Through the Looking Glass" who

"... was thinking of a plan
To dye one's whiskers green,
And always use so large a fan
That they could not be seen."

The presence of a growing core of zero mass would increase the natural instability of a large celestial object. If an explosion occurred, negative mass could be ejected. What would happen to it? It could not form stars of negative mass. Why not? Because for negative mass gravitation is not a cohesive but a dispersive force. As a particle of negative mass travelled through space it would be attracted towards stars, and on falling into one would plunge to its centre.

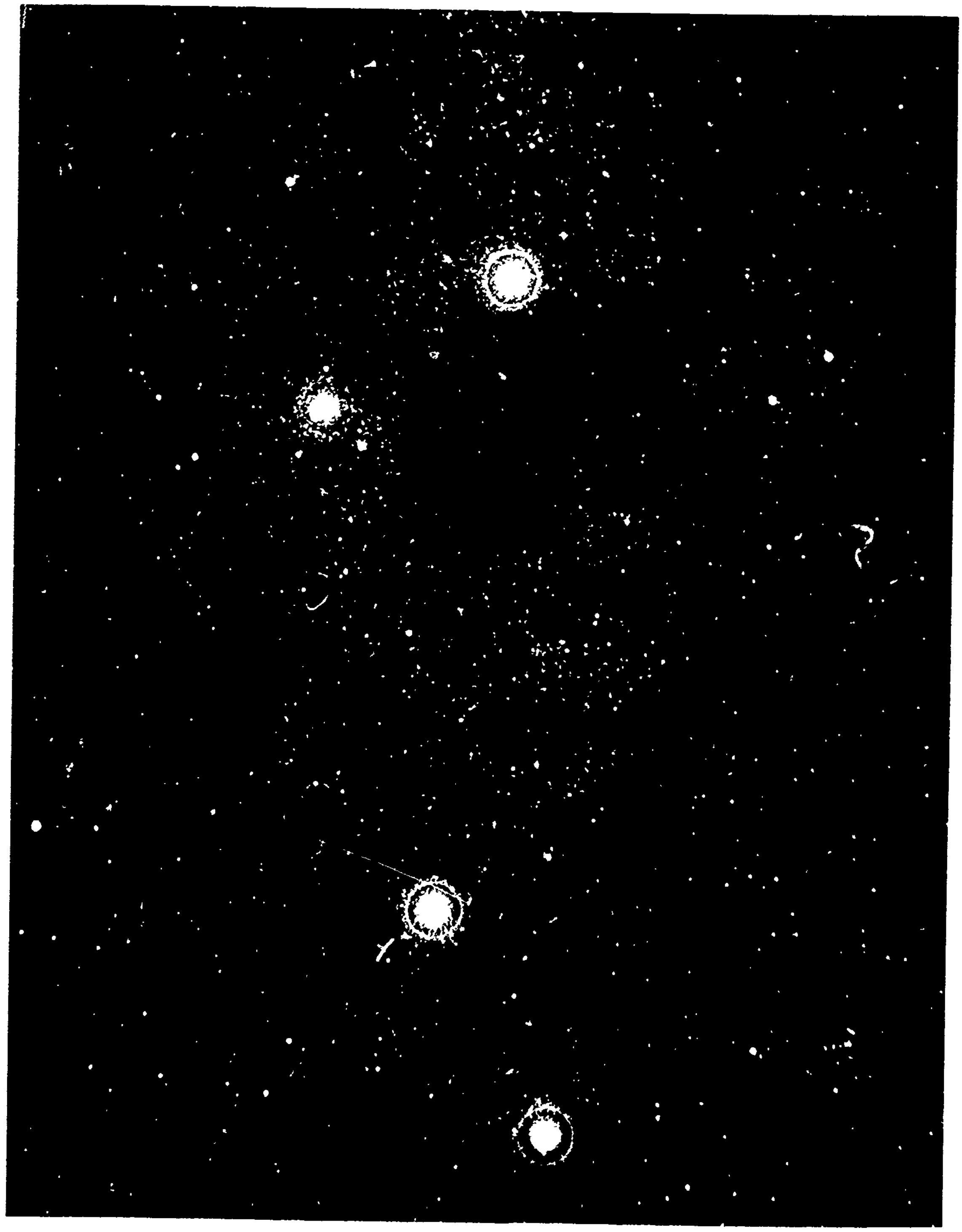
In the course of its travels, when it encountered particles of positive mass, especially if the negative and the positive particles were charged, the particle of negative mass would generate high velocities by the chasing process; and if one of these fast moving particles of positive mass entered our atmosphere it could give rise to a shower of cosmic rays of very great energy. It is not completely impossible that cosmic ray showers of puzzlingly high energy that have been observed might be due to such a cause.

What if one of the particles of negative energy entered the detection apparatus of a cosmic ray experimenter? This would be a rare event, since at best neither particles of negative mass nor cosmic ray experimenters are abundant. But if a cosmic ray experimenter ever found evidence of a particle going in one direction but pushing in the opposite direction that would indeed be a decisive event for it would show that, despite the many theoretical problems to which it would give rise, negative mass does indeed exist.

FURTHER READING

QUASI-STELLAR RADIO SOURCES by J. L. Greenstein (in *Scientific American, 209, 54, December 1963*)
THE INTERNATIONAL SYMPOSIUM ON GRAVITATIONAL COLLAPSE (*University of Chicago Press, Chicago, 1965*)
NEGATIVE MASS AS A GRAVITATIONAL SOURCE OF ENERGY IN THE QUASI-STELLAR RADIO SOURCES by B. Hoffmann (essay obtainable from *Gravity Research Foundation, New Boston, 1964*)

ACKNOWLEDGEMENTS:
Mount Wilson and Palomar Observatories (page 75, bottom, and page 76, top)



Region of the Southern Cross

25 Three Poetic Fragments About Astronomy

From Troilus and Cressida — William Shakespeare
From Hudibras — Samuel Butler
My Father's Watch — John Ciardi

from TROILUS AND CRESSIDA

The heavens themselves, the planets and this center,
Observe degree, priority and place,
Insisture, course, proportion, season, form,
Office and custom, in all line of order:
And therefore is the glorious planet Sol
In noble eminence enthroned and sphered
Amidst the other; whose medicinable eye
Corrects the ill aspects of planets evil,
And posts like the commandment of a king,
Sans check to good and bad: but when the planets
In evil mixture to disorder wander,
What plagues and what portents, what mutiny,
What raging of the sea, shaking of earth,
Commotion in the winds, frights, changes, horrors,
Divert and crack, rend and deracinate
The unity and married calm of states
Quite from their fixture! O, when degree is shaked,
Which is the ladder to all high designs,
The enterprise is sick!

William Shakespeare

from HUDIBRAS

Second Part, Canto III

The Egyptians say, The Sun has twice
Shifted his setting and his rise;
Twice has he risen in the West,
As many times set in the East;
But whether that be true, or no,
The Devil any of you know.
Some hold, the Heavens, like a Top,
Are kept by Circulation up;
And 'twere not for their wheeling round,
They'd instantly fall to the ground:
As sage Empedocles of old,
And from him Modern Authors hold.
Plato believ'd the Sun and Moon,
Below all other Planets run.
Some Mercury, some Venus seat
Above the Sun himself in height.
The learned Scaliger complain'd
'Gainst what Copernicus maintain'd,
That in Twelve hundred years, and odd,
The Sun had left his antient Road,
And nearer to the Earth, is come
'Bove Fifty thousand miles from home.

Samuel Butler

MY FATHER'S WATCH

One night I dreamed I was locked in my Father's watch
With Ptolemy and twenty-one ruby stars
Mounted on spheres and the Primum Mobile
Coiled and gleaming to the end of space
And the notched spheres eating each other's rinds
To the last tooth of time, and the case closed.

What dawns and sunsets clattered from the conveyer
Over my head and his while the ruby stars
Whirled rosettes about their golden poles.
"Man, what a show!" I cried. "Infinite order!"
Ptolemy sang. "The miracle of things
Wound endlessly to the first energy
From which all matter quickened and took place!"

"What makes it shine so bright?" I leaned across
Fast between two teeth and touched the mainspring.
At once all hell broke loose. Over our heads
Squadrons of band saws ripped at one another
And broken teeth spewed meteors of flak
From the red stars. You couldn't dream that din:
I broke and ran past something into somewhere
Beyond a glimpse of Ptolemy split open,
And woke on a numbered dial where two black swords
Spun under a crystal dome. There, looking up
In one flash as the two swords closed and came,
I saw my Father's face frown through the glass.

— *John Ciardi*

The imagination of scientists often exceeds that of the science fiction writer. The question asked is how an advanced technological civilization could capture most of the sun's energy.

26 The Dyson Sphere

I. S. Shklovskii and Carl Sagan

1966

To discuss another possible modification of the cosmos by the activities of intelligent beings, consider the following question: Is it possible that in the future—perhaps the distant future—man could so change the solar system that his activities would be visible over interstellar distances? In Chapter 11, we discussed the difficulties in the detection of planets about even the nearest stars, with present techniques. But what of the future? Is it possible that someday we shall be able to conclude, from observed characteristics, that a star is accompanied by a planet populated by an advanced technical civilization? Let us consider some of the ideas of Constantin Edwardovich Tsiolkovskii, an illustrious Russian pioneer in problems of space exploration.

Three quarters of a century ago, this remarkable man suggested a plan for the rebuilding and reorganization of the solar system. In his book *Dreams of the Earth and Sky*, published in 1895, he pointed out that the Earth receives only 5×10^{-10} of the total flux of solar radiation. He speculated that eventually mankind would make use of all the heat and light of the Sun by colonizing the entire solar system. Tsiolkovskii suggested that first the asteroids be rebuilt. The intelligent beings of the future, he predicted, would control the motion of these small planets "in the same way that we drive horses." The energy necessary to maintain the inhabitants of the asteroids would come from "solar motors." Thus, we see that over 70 years ago, Tsiolkovskii predicted the invention of the solar battery, a device which is presently used to provide energy for space vehicles.

The transformed asteroids would form a chain of space cities. The construction materials would initially come from the asteroids themselves, "the mass of which would be dismantled in a day." ▽ Tsiolkovskii's ideas on the re-engineering and relocation of the asteroids have been echoed in recent years by the American engineer Dandridge Cole, of the General Electric Corporation. △ After the asteroidal material is exhausted, Tsiolkovskii envisions the rebuilding of the Moon. He allows several hundred years for this project. Then, the Earth and the larger planets would be reorganized. According to Tsiolkovskii, the entire transformation of the solar system would require hundreds of thousands—perhaps millions—of years. This plan would provide enough heat and light to support a population of 3×10^{23} manlike beings—approximately 10^{14} more people than presently inhabit the Earth.

Although to his contemporaries the daring ideas of Tsiolkovskii seemed to be merely the daydreams of a provincial school-teacher, his brilliant foresight is readily appreciated today. The eminent American theoretical physicist Freeman J. Dyson, of the Institute for Advanced Study, Princeton, basing his theories on the achievements of contemporary science, has recently independently repeated many of Tsiolkovskii's ideas, without knowing anything of the Russian's work.

Dyson, in a most interesting article published in 1960, attempted to perform a quantitative analysis of the problem of rebuilding the solar system. He first discussed the fact that scientific and technological development takes place very rapidly, after a society has entered its technological phase. The timescale of such development is insignificant, compared with astronomical and geological timescales. Dyson concluded that the one important factor which restricts the scientific and technical development of an intelligent society is the limited available supply of matter and energy resources. At present, the material resources which can be exploited by man are limited roughly to the biosphere of the Earth, which has a mass ▽ estimated variously between 5×10^{17} and 5×10^{19} gm △—that is, less than 10^{-8} the mass of the Earth. The energy required by contemporary mankind per year is approximately equal to that which is liberated in the combustion of 1 to 2 billion tons of hard anthracite coal per year. In terms of heat, we find that contemporary man is expending an average of 3×10^{19} erg sec^{-1}. The Earth's resources of coal, oil, and other fossil fuels will be exhausted in a few centuries.

The question of our reserves of matter and energy becomes more acute when we consider the prospective long-term technological development of our society. Even if we assume that the average annual growth rate in production is only one-third of a percent (a very small figure, when compared to the annual growth rate ▽ of a few percent in modern industrial societies △), our productivity will double in about a century. In 1000 years, the rate of manufacture will increase by 20,000 times; and in 2500 years, by 10 billion times. This means that the energy requirements in 2500 years will be 3×10^{29} erg sec^{-1}, or approximately 0.01 percent of the entire luminosity of the Sun. This figure is approaching cosmic proportions. Will all of our energy resources have been exhausted by the time we achieve this level of productivity?

To answer this question, let us now consider the material resources which are conceivably available to mankind in the future. We shall—perhaps optimistically—assume that we will be able to achieve controlled thermonuclear reactions. The total amount of hydrogen in the Earth's hydrosphere is approximately 3×10^{23} grams, while the amount of deuterium is approximately 5×10^{19} grams. Deuterium would be the basic fuel of a thermonuclear reactor. The amount of energy released by reaction of all the available deuterium would be about 5×10^{38} ergs. In 2500 years, this amount of energy—still assuming an increase in production of one-third of a percent per annum—would be sufficient for only a 50-year period. Even if we assume that controlled thermonuclear fusion can eventually be fueled by ordinary hydrogen, and that 10 percent of the world's oceans can be utilized as an energy source—to burn more would probably be inexpedient—in 2500 years we would be able to provide only enough energy for another few thousand years.

Another possible energy source would be the direct utilization of solar radiation. Each second, approximately 2×10^{24} ergs of solar radiation fall upon the surface of the Earth. This is almost 100,000 times more than the current production of all forms of energy. Yet it is 100,000 times less than the estimated energy requirements for the year 4500 A.D. Thus, direct solar radiation is inadequate to support a stable and sustained increase in production of only one-third of a percent per annum, over a long period of time. From this discussion, we can conclude that the energy resources of the Earth are insufficient to fulfil the long-term requirements of a developing technological society.

Before considering this question further, let us make a slight digression. A

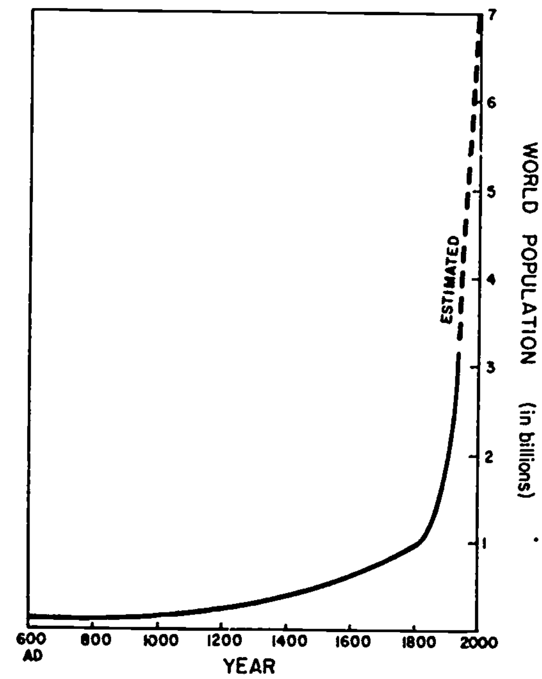


FIGURE 34–1. *Estimated past and extrapolated future rates of human population growth, planet Earth.*

:iypercritical reader may claim that the above calculations are similar to the discussions of the English clergyman Thomas Malthus. This is, however, not the case. Malthus predicted that world population growth would outstrip the development of productive forces, and that this would lead to a progressive deterioration of living conditions. His proposed solution was that the poorer classes—that is, the working classes—lower their birthrate. Malthus' views are invalid, because in an intelligent, organized society, the increase of productive forces always outstrips the increase in population. The population of a nation is related, sometimes in a complex way, to its productivity, and in fact is ultimately determined by it. Our discussion of future energy budgets bears no relation to the Malthusian doctrine. We have been discussing only the possibilities of the increase in the productive capacities of a society, which is naturally limited to the material and energy resources available.

∇ The exponential increase in the population of the Earth during historical times is indicated schematically in Fig. 34–1. The required future productive capacity of our society is dramatically illustrated—assuming no major population self-limitation occurs—by extrapolation of the curve to the future. Δ

Let us ask another question: Will there in fact *be* any appreciable increase in the future productive capability of our society? What is the basis for assuming that mankind's progress will be directly related to an increase in his productive capacity?

Perhaps development will be in terms of qualitative, not quantitative, changes. These problems are philosophical in nature and cannot be discussed in detail here. However, I would like to state that I believe it to be impossible for a society to develop without a concurrent increase in production, both qualitatively and quantitatively. If an increase in productivity were eliminated, the society would eventually die. Note that if a society were to consciously interrupt its productive development, it would have to maintain a very precise level of production. Even the slightest progressive decrease would, after thousands of years reduce the technological potential to essentially nothing. Over these timescales, any civilization which consciously resolves to maintain a constant level of productivity would be balancing on a knife-edge.

Let us now return to the subject of the material resources available to a developing society. After reaching a high state of technical development, it would seem very natural that a civilization would strive to make use of energy and materials external to the planet of origin, but within the limits of the local solar system. Our star radiates 4×10^{33} ergs of energy each second, and the masses of the Jovian planets constitute the major potential source of material. Jupiter alone has a mass of 2×10^{30} grams. It has been estimated that about 10^{44} ergs of energy would be required to completely vaporize Jupiter. This is roughly equal to the total radiation output of the Sun over a period of 800 years.

According to Dyson, the mass of Jupiter could be used to construct an immense shell which would surround the Sun, and have a radius of about 1 A.U. (150 million kilometers). ▽ How thick would the shell of a Dyson sphere be? The volume of such a sphere would be $4\pi r^2 S$, where r is the radius of the sphere, 1 A.U., and S is its thickness. The mass of the sphere is just the volume times its density, ρ, and the mass available is approximately the mass of Jupiter. Thus, $4\pi r^2 \rho S = 2 \times 10^{30}$ grams. Thus, we find that $\rho S \simeq 200$ gm cm^{-2} △ of surface area would be sufficient to make the inner shell habitable. We recall that the mass of the atmosphere above each square centimeter of the Earth's surface is close to 1000 gm. ▽ If the over-all density of the shell were 1 gm cm^{-3} or slightly less, the thickness of the shell, S, would be a few meters. △ Man today, for all practical purposes, is a two-dimensional being, since he utilizes only the surface of the Earth. It would be entirely possible for mankind in the future—say, in 2500 to 3000 years—to create an artificial biosphere on the inner surface of a Dyson sphere. After man has accomplished this magnificent achievement, he would be able to use the total energy output of the Sun. ▽ Every photon emitted by the Sun would be absorbed by the Dyson sphere, and could be utilized productively. △ The inside surface area of the Dyson sphere would be approximately 1 billion times greater than the surface area of the Earth. The sphere could sustain a population great enough to fulfil the predictions made by Tsiolkovskii three quarters of a century ago.

We shall not at this time enter into a discussion of how such a sphere would be constructed, how it would rotate, or how we would guarantee that the inhabitants would not fall into the Sun. The fact is that the sphere would have different gravitational characteristics from those of a solid body. These problems, although complex, are not the principal problems. Dyson himself gave special attention to one interesting circumstance: A number of completely independent parameters—the mass of Jupiter, the thickness of an artificial biosphere, the total energy of the solar radiation, and the period of technological development—all, in Dyson's words,

> have consistent orders of magnitude. . . . It seems, then, a reasonable expectation that barring accidents, Malthusian pressures will ultimately drive an intelligent species to adopt some such efficient exploitation of its available resources. One should expect that within a few thousand years of its entering the stage of industrial development, any intelligent species should be found occupying an artificial biosphere which completely surrounds its parent star.

Up to this point, Dyson's speculations have been essentially the same as those of Tsiolkovskii, but based upon more recent scientific knowledge. At this point, Dyson introduces an idea novel ▽ even to Tsiolkovskii △: How will a civilization living on the inner surface of a sphere surrounding its star appear from outside? Dyson says:

> If the foregoing argument is accepted, then the search for extraterrestrial intelligent beings should not be confined to the neighborhood of visible stars. The most likely habitat for such beings would be a dark object having a size comparable to the Earth's orbit, and a surface temperature of 200 to 300°K. Such a dark object would be radiating as copiously as the star which is hidden inside it, but the radiation would be in the far infrared, at about 10μ wavelength.

If this were not the case, then the radiation produced by the star inside the shell would accumulate, and produce catastrophically high temperatures.

Since an extraplanetary civilization surrounded by a Dyson sphere would be a very powerful source of infrared radiation, and since the atmosphere of the Earth is transparent to radiation between 8 and 13μ, it would be possible to search for such infrared stars with existing telescopes on the Earth's surface. ▽ The sensitivity of contemporary infrared detectors is such that with the use of large telescopes, Dyson spheres could be detected over distances of hundreds of light-years even today. However, there is not necessarily any way of distinguishing a Dyson sphere detected at $8-13\mu$ from a natural object such as a protostar, contracting towards the main sequence, and emitting infrared radiation with the same intensity. If the sky were mapped in the infrared for possible Dyson spheres, each radiation source could then be investigated by other techniques for characteristic radiation of an intelligent species—for example, at the 21 cm radio frequency. △

It is also possible that Dyson civilizations might be detected by existing optical techniques.

> Such radiation might be seen in the neighborhood of a visible star, under either of two conditions: A race of intelligent beings might be unable to exploit fully the energy radiated by their star because of an insufficiency of accessible matter, or they might live in an artificial biosphere surrounding one star of a multiple

system, in which one or more component stars are unsuitable for exploitation and would still be visible to us. It is impossible to guess the probability that either of these circumstances could arise for a particular race of extraterrestrial intelligent beings, but it is reasonable to begin the search for infrared radiation of artificial origin by looking in the direction of nearby visible stars, and especially in the direction of stars which are known to be binaries with invisible companions.

Dyson's idea is notable for the fact that it presents a specific example of how the activity of an intelligent society might change a planetary system to such an extent that the transformation would be detectable over interstellar distances. But a Dyson sphere is not the only way a civilization can utilize the available energy resources of its planetary system. There are other sources which may be even more effective than the complete utilization of local solar radiation.

First we shall consider using the mass of the large planets as a fuel for thermonuclear reactors. The Jovian planets consist primarily of hydrogen. The mass of Jupiter is 2×10^{30} gm, and the store of energy which would be released from the conversion of this quantity of hydrogen into helium would be approximately 10^{49} ergs, a vast amount of energy comparable to that released in a supernova explosion. If this energy were liberated gradually, over a long period of time—for example, at a rate of 4×10^{33} erg sec^{-1}, comparable to the present solar luminosity—it would last for nearly 300 million years, a time span most likely greater than the life of the technical civilization itself.

Perhaps a highly developed civilization could also use a fraction of its own star as an energy source. For example, it might be possible to "borrow" a few percent of the solar mass without any significant decrease in luminosity. Certainly, we do not yet know the methods for arranging such a loan, but it would probably be accomplished gradually. The conversion of, say, 5×10^{31} gm of solar hydrogen —25 times more than the mass of Jupiter—would provide some 3×10^{50} ergs, an energy supply adequate to satisfy the requirements of a technical civilization for several billion years.

It is also conceivable, but much less likely, that such utilization of the mass of a star would occur at a more rapid pace, perhaps regulated so that the lifetime of the star would correspond to the lifetime of the civilization. The spectral characteristics of such a star would slowly vary. At the time that the star finally was turned off, the civilization would cease to exist. ▽ But while we can imagine such a cosmic Götterdämmerung, it is not likely to be staged often. △

If intelligent use is made of the enormous stores of energy available in the solar system, it would not be necessary to construct a Dyson sphere about the Sun. Assume, for example, that half the mass of the Jovian planets were used to construct artificial satellites, the "space cities" of Tsiolkovskii. These cities would be established in orbits close to the Sun. We may imagine thermonuclear reactors installed in these satellites and fueled by the remaining material in the Jovian planets. This picture preserves the essential direction of the development of a technical civilization envisioned in *Dreams of the Earth and Sky*, but it adds controlled thermonuclear reactions as an energy source.

Now, given these enormous controlled energy sources, civilizations could expand their activities on a much larger scale. We shall presently consider several additional ways in which a civilization might announce its presence over interstellar distances. These methods seem fantastic. We wish to emphasize that we are not saying that such methods are actually in existence; but the probability of their existence is not zero. ▽ And what we have encompassed as "fantastic" has declined progressively with the centuries. △ The fundamental point is that the possibilities open to advanced technical civilizations are almost unlimited.

ARTISTS AND WRITERS

ISAAC ASIMOV

Isaac Asimov, born in 1920 in Petrovichi, Russia, came to the United States at the age of three. He graduated from Columbia University in 1939, and received his Ph.D. there in 1948. Since 1949 he has been in the department of Biochemistry at Boston University. Pebble in the Sky, Asimov's first book, published in 1950, started him on a prolific career of writing for the layman. For his contribution in explaining science to the public he won the James T. Grady Award of the American Chemical Society in 1965. He is also well-known as a writer of science fiction.

HERMANN BONDI

Hermann Bondi, Professor of Applied Mathematics at King's College, University of London, was born in Vienna in 1919, and received his education at Trinity College, Cambridge (B.A. 1940, M.A. 1944). He also taught and did research in the United States. Professor Bondi's interests are the composition of stars, cosmology, and geophysics.

MARGARET BURBIDGE

Margaret Burbidge often works with her husband, an astrophysicist, as a husband-and-wife team. The Burbidges met and married while she, an astronomer, was working at the University of London Observatory, and he, a physicist, was studying meson physics at the same university. They have held appointments successively at Mt. Wilson and Palomar Observatories and the University of Chicago's Yerkes Observatory at Williams Bay, Wisconsin. Currently they are in the physics department of the University of California at San Diego, and are frequent contributors to scientific journals.

SAMUEL BUTLER

Samuel Butler (1612-1680), the English satirist, was born at Strensham, Worcestershire. After the Restoration he became successively Secretary to the Earl of Carbery, Steward of Ludlow Castle, and then a full-time writer. Between 1663 and 1678 he published the three parts of his most famous work, Hudibras. Just as Cervantes in his Don Quixote satirized the fanaticism of knight errantry, Butler in his Hudibras, a burlesque heroic poem, ridiculed the fanaticism, pretentiousness, pedantry, and hypocrisy of the Puritans of his time.

JOHN CIARDI

John Ciardi, a poet and an educator, was born in Boston in 1916. His bachelor's degree is from Tufts, and he has a master's degree from the University of Michigan. He has taught at Kansas City, Harvard, and Rutgers. He is the director of the Bread Loaf Writers Conference and the poetry editor of the Saturday Review. Recipient of many awards in poetry, including the Prix de Rome, his works include Homeward to America, Other Skies, Live Another Day, I Marry You.

ARTHUR C. CLARKE

Arthur C. Clarke, British scientist and writer, is a Fellow of the Royal Astronomical Society. During World War II he served as technical officer in charge of the first aircraft ground-controlled approach project. He has won the Kalinga Prize, given by UNESCO for the popularization of science. The feasibility of many of the current space developments was perceived and outlined by Clarke in the 1930's. His science fiction novels include Childhoods End and The City and the Stars.

I. BERNARD COHEN

I. Bernard Cohen was born in Far Rockaway, New York, in 1914. At Harvard he received a B.S. in 1937 and a Ph.D. in history of science in 1947. Since then he has been on the Harvard faculty in the history of science. He has been editor of Isis, the journal of the History of Science Society, and has written many books and papers in his field, among them a number of studies of Newton's works.

HENRY S. F. COOPER, JR.

Henry S. F. Cooper, Jr., writer for the New Yorker since 1956, was educated at Phillips Academy, Andover, and at Yale University. At Yale he took a course in astronomy from Harlan Smith, and this led him to write an article about Professor Smith. This article, in part, started his writing career for the New Yorker.

JEAN BAPTIST CAMILLE COROT

Jean Baptist Camille Corot (1796-1875), one of the greatest nineteenth-century landscape painters of France, was born in Paris and studied at the Lycee de Louen. Corot was one of the first to paint out-of-doors. He traveled extensively throughout the continent. Corot's works are admired for their idyllic romanticism injected into the paintings of mountains, cathedral, and villages. His "Chartres Cathedral," "Chateau de Rosny," and "Belfry at Douai," all in the Louvre, exemplify his touch.

ROBERT H. DICKE

Robert H. Dicke, Professor of Physics at Princeton, was born in St. Louis, Missouri, in 1916, and he earned his Ph.D. at Rochester University in 1941. He was a staff member of the Radiation Laboratory at Massachusetts Institute of Technology during World War II. Dr. Dicke is widely known for his studies in gravitation, relativity, geophysics, and astrophysics.

STEPHEN H. DOLE

Stephen H. Dole is a researcher for the RAND Corporation. Born in West Orange, New Jersey in 1916, he attended Lafayette and the United States Naval Academy. Presently he is a member of the steering committee for the Group for Extraterrestrial Resources. His work has dealt with chemistry and space programs; he studies oxygen recovery, human ecology in space flight, properties of planets, and origin of planetary systems.

ROBERT RHODES DRUMMOND

Robert Rhodes Drummond, born in Little Rock, Arkansas in 1916, has spent twenty-six years in active engineering and scientific experience, mainly in aircraft structural design with the Martin Company in Baltimore, Maryland. Most recently he has been working on the NASA weather satellite program at the Goddard Space Flight Center.

RICHARD PHILLIPS FEYNMAN

Richard Phillips Feynman was born in New York in 1918, and graduated from the Massachusetts Institute of Technology in 1939. He received his doctorate in theoretical physics from Princeton in 1942, and worked at Los Alamos during the Second World War. From 1945 to 1951 he taught at Cornell, and since 1951 has been Tolman Professor of Physics at the California Institute of Technology. Professor Feynman received the Albert Einstein Award in 1954, and in 1965 was named a Foreign Member of the Royal Society. In 1966 he was awarded the Nobel Prize in Physics, which he shared with Shinchero Tomonaga and Julian Schwinger, for work in quantum field theory.

ANATOLE FRANCE

Anatole France (1844-1924) was the nom de plume of Anatole Francois Thiboult. The son of a bookseller, he began his productive literary career as a publisher's reader, "blurb" writer, and critic. Under the patronage of Madame de Calillavet, he published numerous novels, such as Le Livre de Mon Ami. His early writings were graceful. Later they grew skeptical and solipsistic, as in Les Opinions de Jerome Cognard. In 1886 France was elected to the French Academy, and in 1921 he was awarded the Nobel Prize for Literature.

GALILEO GALILEI

See Unit I, Section 2.2.

CHARLES COULSTON GILLISPIE

Charles Coulston Gillispie, born in 1918 in Harrisburg, Pennsylvania, was educated at Wesleyan, Massachusetts Institute of Technology, and Harvard. After teaching at Harvard, he went to Princeton, where he is now Professor of History. He has been president of the History of Science Society, and a Fellow of the American Academy of Arts and Sciences, and member of the Academic Internationale d'Histoire des Sciences. His books include Genesis and Geology, A Diderto Pictorial Encyclopedia, and The Edge of Objectivity.

OWEN JAY GINGERICH

Owen Jay Gingerich, born in Washington, Iowa, in 1930, is an astrophysicist and historian of astronomy at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. Among his responsibilities has been the task of directing the Central Bureau for Astronomical Telegrams, the world clearing house for comets, sponsored by the International Astronomical Union. He is interested in applying computers to the history of astronomy, and his translation from Kepler's Astronomia Nova, published for the first time in this Reader, was aided by a Latin dictionary program on an I.B.M. 7094 computer.

BANESH HOFFMANN

Banesh Hoffmann, born in Richmond, England, in 1906, attended Oxford and Princeton. He has been a member of the Institute of Advanced Study, electrical engineer at the Federal Telephone and Radio Laboratories, researcher at King's College, London, and a consultant for Westinghouse Electric Corporation's science talent search tests. He has won the distinguished teacher award at Queens College, where he is Professor of Mathematics. During the 1966-1967 year he was on the staff of Harvard Project Physics.

GERALD HOLTON

Gerald Holton received his early education in Vienna, at Oxford, and at Wesleyan University, Connecticut. He has been at Harvard University since receiving his Ph.D. degree in physics there in 1948; he is Professor of Physics, teaching courses in physics as well as in the history of science. He was the founding editor of the quarterly Daedalus. Professor Holton's experimental research is on the properties of matter under high pressure. He is a co-director of Harvard Project Physics.

FRED HOYLE

Fred Hoyle is an English theoretical astronomer, born in Yorkshire in 1915. Now Professor of Astronomy at Cambridge University, he is perhaps best known for one of the major theories on the structure of the universe, the steady state theory. Hoyle is well known for his scientific writing, and his success in elucidating recondite matters for the layman.

JOHANNES KEPLER

See Unit 2, Section 7.1.

STEPHEN D. KILSTON

Stephen D. Kilston, born in 1931, is from Freiburg, Germany. He studied physics in Germany and was a researcher at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts.

PAUL KLEE

Paul Klee (1879-1940), one of the most imaginative painters of the twentieth century, was born near Berne, Switzerland. He taught at the Bauhaus, the influential German art and design school in Weimar. Klee's style is unbounded by tradition: his figures are visually unrealistic, his space and design seem incoherent, and his colors are symbolic and emotional rather than descriptive.

ROBERT B. LEIGHTON

Robert B. Leighton, born in Detroit, Michigan in 1919, was first a student and then a faculty member at California Institute of Technology. He is a member of the International Astronomical Union, the National Academy of Science and the American Physics Society. Professor Leighton's work deals with the theory of solids, cosmic rays, high energy physics, and solar physics.

RICHARD LIPPOLD

Richard Lippold, sculptor, was born in Milwaukee in 1915. He attended the University of Chicago and graduated from the Art Institute of Chicago with a B.F.A. degree in 1937. Since graduating he has taught at the Layton School of Art in Milwaukee, the University of Michigan, Goddard College, served as head of the art section of the Trenton Junior College from 1948-52, and since 1952 has been a professor at Hunter College in New York. His works have been exhibited internationally, and frequently in the Whitney Museum in New York City. He has had several one-man shows at the Willard Gallery. In 1953 he was awarded third prize in the International Sculpture Competition, Institute of Contemporary Arts, London, and in 1958 the Creative Arts award from Brandeis University. He is a member of the National Institute of Arts and Letters.

TERRY MORRIS

Terry Morris, a free-lance magazine writer since 1951, was born in New York City. After earning her B.A. and M.A. in English, she taught English for six years in New York high schools. During World War II, her husband in the service, she wrote her experiences as an army wife in her first article, "Armytown, U.S.A." in The New Republic, which was expanded into a novel No Hiding Place (1945) at publisher Alfred A. Knopf's suggestion. Her work has appeared in many American and foreign magazines, and she has also worked for newspapers, radio, and television.

ISSAC NEWTON

See Unit 2, Section 8.1.

PABLO RUIZ PICASSO

Pablo Ruiz Picasso, the initiator (with Georges Braque) of Cubism and probably the most seminal contributor in twentieth century art, was born at Malaga, Spain in 1881. After lessons in art from his father, an artist and professor at the Academy of the Arts in Barcelona, Picasso settled in Paris. His early paintings were somber pictures, many of the life of a circus or a big city. But after 1905 he evolved toward Cubism. Picasso moved away from three-dimensional perspective and created a surrealistic two-dimensional picture. Perhaps his most famous picture is "Guernica" (at the Museum of Modern Art in New York), his reaction to the bombing of civilians in the Spanish Civil War.

PETER GUY ROLL

Peter Guy Roll was born in Detroit, Michigan, in 1933. At Yale he received his B.S., M.S., and Ph.D. He worked as Junior Scientist on the design of a nuclear reactor for the Westinghouse Atomic Power Division. After teaching and research experience at Yale, Princeton, and the University of Michigan, he became Associate Professor of Physics at the University of Minnesota. He has also been a staff physicist for the Commission on College Physics.

CARL SAGAN

Carl Sagan, born in 1921, is Assistant Professor of Astronomy at Harvard University and a staff member of the Smithsonian Astrophysical Observatory. He has made significant contributions to studies of planets, of the origin of life, and of the possibilities of extraterrestrial life. An experimenter on the Mariner 2 Venus mission, he has served on advisory committees for the National Academy of Sciences and for the National Aeronautics and Space Administration.

MATTHEW SANDS

Matthew Sands was born in Oxford, Massachusetts, in 1919. He attended Clark College, Rice Institute, and Massachusetts Institute of Technology. During World War II he worked at the Los Alamos Scientific Laboratory. He was Professor of Physics at the California Institute of Technology before joining the linear accelerator group at Stanford University. Professor Sands specializes in electronic instrumentation for nuclear physics, cosmic rays, and high-energy physics. He served as chairman of the Commission on College Physics.

GEORGES SEURAT

Georges Seurat (1859-1891) was educated at Ecole des Beaux-Arts. His most famous painting, "Un Dimanche d'Eté à la Grande Jette" (Chicago Art Institute) exemplified his characteristic technique of Pointillion painting with a very large number of small spots of strong primary colors mixed only with white. Seurat is considered to be a neo-impressionist owing to his use of orderly fundamental structures—a form antagonistic to the intuitive method of the Impressionists.

WILLIAM SHAKESPEARE (1564-1616) needs no introduction.

I. S. SHKLOVSKII

I. S. Shkovskii is a staff member of the Sternberg Astronomical Institute of the Soviet Academy of Sciences, Moscow. One of the world's leading astrophysicists, he has played a major role in Soviet space achievements and in radio astronomy. His books include Physics of the Solar Corona, Cosmic Radio Waves, and Intelligent Life in the Universe. He is a Fellow of the Royal Astronautical Society of Great Britain, and a Corresponding Member of the Soviet Academy of Sciences.

JOSEPH WEBER

Joseph Weber, now Professor of Physics at the University of Maryland, was born in Paterson, New Jersey, in 1919. He received his B.S. at the United States Naval Academy, and his Ph.D. from the Catholic University of America. He has been a fellow at the Institute of Advanced Study, a Guggenheim Fellow, and a Fellow at the Lorentz Institute of Theoretical Physics at the University of Leyden, Holland.

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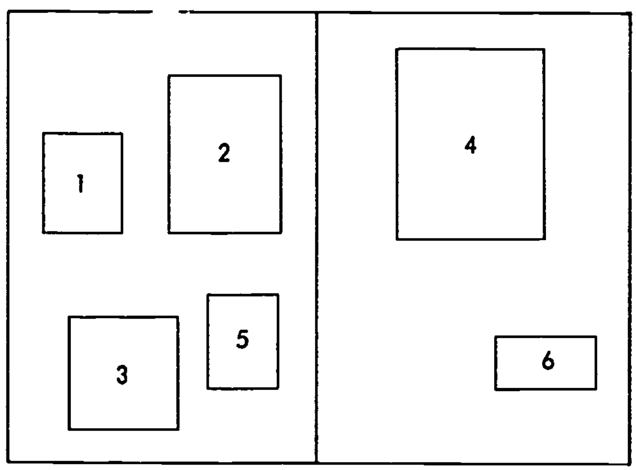

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P. 36 "Horsehead" Nebula (200-inch photograph). Mount Wilson and Palomar Observatories.

P. 84 Great Nebula in Orion (100-inch photograph). Mount Wilson and Palomar Observatories.

P. 212 Region of the Southern Cross. Photo courtesy of Dr. Owen Gingerich, Harvard College Observatory.