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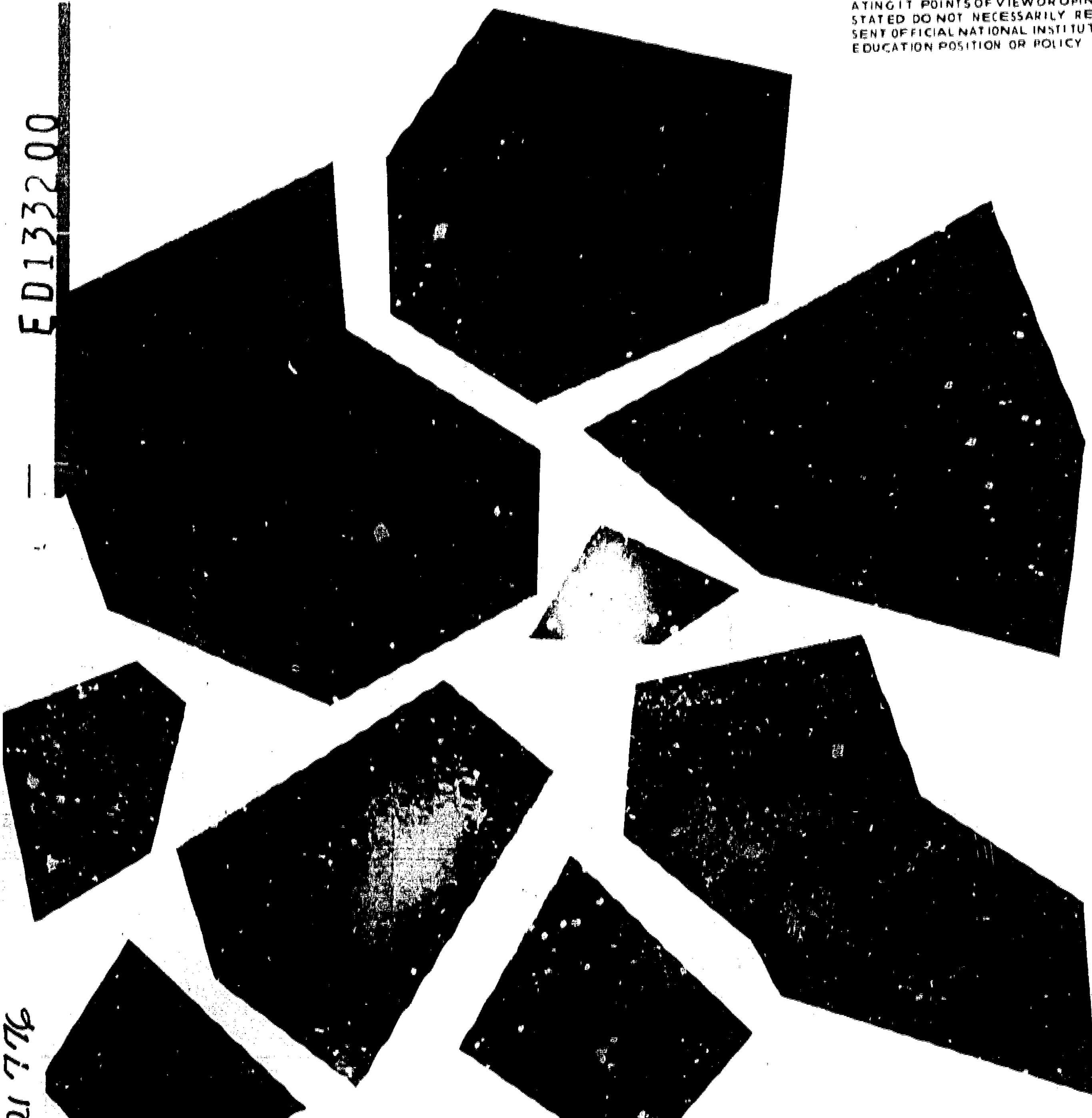
ABSTRACT

This booklet is part of an American Astronomical Society curriculum project designed to provide teaching materials to teachers of secondary school chemistry, physics, and earth science. The following topics concerning supernovae are included: the outburst as observed and according to theory, the stellar remnant, the nebular remnant, and a summary of some of the unsolved puzzles. Suggested student projects are given, with several levels of difficulty, so that the teacher may choose material appropriate for the particular class. (MH)

The Supernova



NASA
National Aeronautics and
Space Administration

THE SUPERNOVA

A Stellar Spectacle

A curriculum project of the American Astronomical Society,

prepared with the cooperation of the

National Aeronautics and Space Administration and the National Science Foundation

by

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National Aeronautics and Space Administration
Washington, DC 20546 September 1976

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PREFACE

In the past half century astronomers have provided mankind with a new view of the universe, with glimpses of the nature of infinity and eternity that beggar the imagination. Particularly, in the past decade, NASA's orbiting spacecraft as well as ground-based astronomy have brought to man's attention heavenly bodies, sources of energy, stellar and galactic phenomena, about the nature of which the world's scientists can only surmise.

Esoteric as these new discoveries may be, astronomers look to the anticipated Space Telescope to provide improved understanding of these phenomena as well as of the new secrets of the cosmos which they expect it to unveil. This instrument, which can observe objects up to 30 to 100 times fainter than those accessible to the most powerful Earth-based telescopes using similar techniques, will extend the use of various astronomical methods to much greater distances. It is not impossible that observations with this telescope will provide glimpses of some of the earliest galaxies which were formed, and there is a remoter possibility that it will tell us something about the edge of the universe.

The researches of the past 10 years, plus the possibility of even more fundamental discoveries in the next decade, are fascinating laymen and firing the imagination of youth. NASA's inquiries into public interest in the space program show that a major source of such interest is stellar and galactic astronomy. NASA's enabling Act, the Space Act of 1958, lists a primary purpose of NASA, "the expansion of human knowledge of phenomena in the atmosphere and space"; the Act requires of NASA that "it provide for the widest practicable and appropriate dissemination of information concerning its activities and the results of those activities."

In the light of the above, NASA is publishing for science teachers, particularly teachers of secondary school chemistry, physics, and Earth science, the following four booklets prepared by the American Astronomical Society (AAS) with the cooperation of NASA:

> *The Supernova, A Stellar Spectacle,* by Dr. W. C. Straka, Department of Physics, Jackson State University, Jackson, Mississippi.
>
> *Extragalactic Astronomy, The Universe Beyond our Galaxy,* by Dr. Kenneth C. Jacobs, Department of Astronomy, University of Virginia, Charlottesville, Virginia.
>
> *Chemistry Between the Stars,* by Dr. Richard H. Gammon, National Radio Astronomy Observatory, Charlottesville, Virginia.

Atoms in Astronomy, by Dr. Paul A. Blanchard, Theoretical Studies Group, NASA Goddard Space Flight Center, Greenbelt, Maryland.

The National Science Foundation has cooperated in this project by funding for the AAS a High School Astronomy Education Workshop in June 1974 at the University of Richmond in order to give the manuscripts a thorough pedagogic review in terms of curricular relevance and classroom use. The resulting publications provide exciting accounts of recent discoveries in the cosmos, and of the nature of the scientific thought and techniques by which scientists are trying to understand these discoveries.

NASA expresses its appreciation to the authors and to the members of the AAS Task Group on Education in Astronomy (TGEA), whose enthusiasm and energy carried the project to completion, particularly to Dr. Gerrit L. Verschuur, Director of the Fiske Planetarium, University of Colorado, who served as Director of the project; Dr. Donat G. Wentzel, Astronomy Program, University of Maryland, initiator of the project; Dr. Paul H. Knappenberger, Jr., Director, the Science Museum of Virginia and Chairman of the TGEA, who served as Workshop Director, and Herman M. Gurin, Executive Officer of the American Astronomical Society. To those who were enrolled in the Workshop and to others whose judgments and suggestions helped give the manuscripts the necessary scientific and curricular validity, NASA is grateful.

Appreciation is also expressed to the National Science Foundation for its support of the Workshop, to the University of Richmond for its cordial and efficient service as host to the Workshop, and to the NASA Goddard Space Flight Center for its assistance in making possible the publication of this project.

Technical Monitor for the project was Dr. Nancy W. Boggess, Staff Astronomer, Astrophysics Division, Office of Space Science, NASA. Coordinators of the project were Dr. Nancy G. Roman, Chief, Astronomy/Relativity, Office of Space Science, NASA, and Dr. Frederick B. Tuttle, Director, Educational Programs Division, Office of Public Affairs, NASA. Assisting until his retirement in June 1974, was Mr. Myrl H. Ahrendt, Instructional Materials Officer, Educational Programs Division.

September 1976

National Aeronautics and Space Administration
Washington, DC

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8

STATEMENT OF PURPOSE

The purpose of this brochure is to discuss the most spectacular event in the life of a star, the supernova, related objects and their importance in astronomy and science in general. The only thing in the universe more spectacular than this explosive flareup of the star in its death throes is the quasar (which some astronomers think may be closely related). Not only are supernovae thought to mark the end of a star, but they may also be the mechanism through which the elements created in the nuclear reactor that is the core of a star are dispersed and mixed into the raw materials of interstellar space--the material from which the new generation of stars will be formed. In the process of the explosion, the heaviest of the elements are also formed. It is from these elements from the interiors of the stars that the planets and life itself are made.

Some of the most fascinating and puzzling objects in the universe are also associated with supernovae. Among these are the pulsars and X-ray objects, the neutron stars and black holes, the Crab Nebula and the vast networks of filaments, and perhaps even gamma-ray bursts and gravity-wave events.

The general organization of the brochure is indicated by the table of contents: the outburst as observed and according to theory, the stellar remnant, the nebular remnant, and a summary of some of the unsolved puzzles. Some suggested discussion topics and student projects are given, with several levels of difficulty, so that the teacher may choose material appropriate for the particular class.

W. C. Straka

9

CONTENTS

CHAPTER I

INTRODUCTION

> One evening, when I was contemplating as usual the celestial vault, whose aspect was so familiar to me, I saw, with inexpressible astonishment, near the zenith, in Cassiopeia, a radiant star of extraordinary magnitude. Struck with surprise, I could hardly believe my eyes...
>
> –Tycho Brahe, November 1572

Every year, one or two stars flare more brightly than they have appeared in the sky before. Most of these can only be seen through the telescope, but every few generations one of these novae, for so Tycho called his new star, shines more brightly than any other star in the sky, perhaps brightly enough to be seen in broad daylight. The name *nova* is a Latin word meaning *new.* Yet these "new" stars last only a short time, fading from sight in perhaps a year. The ancient Chinese astronomers called these newly appeared but temporary objects "guest stars," a more accurate term. Sometimes long after the star has faded astronomers can detect through the telescope a cloud of debris at the location of a nova looking as if it had come from a huge explosion.

Until the 20th century, all novae were thought to be the same or nearly the same. Then Edwin Hubble showed that the great nebula in Andromeda must be another galaxy like our own Milky Way. As a result, astronomers realized that the nova discovered in the Andromeda nebula in 1885, S Andromedae, must have been much bigger than any other. Such gigantic novae came to be called *supernovae.*

Ordinary novae are found in telescopic observations several times a year. Occasionally one may become visible to the unaided eye. In reality, these "new stars" are not new at all. Instead they are the flareup of a very old star, the last grand fling of the star before it dies. Some may flare up several times, but these recurrent novae are less bright than the others. Since the brightness that a star appears to have is determined by its actual intrinsic brightness, the distance of the star from Earth, and any dust or gas that lies between the star and the Earth (producing a dimming called *interstellar absorption*), many novae probably remain hidden from us by a combination of their remoteness and the dust and gas clouds (which are called *nebulae*).

While an ordinary nova may brighten by as much as 10 000 times, a supernova may flare to a billion times its original luminosity. This extreme brightness, combined with the fact that supernovae are rare (only six have been recorded in our galaxy in the past 2000 years, and a seventh has been deduced), leads us to the conclusion that a supernova must be a very different kind of thing from an ordinary nova. Astronomers now recognize that, while both the nova and supernova are explosions of stars, the ordinary nova explosion is only in the outer layers of the star. The supernova, on the other hand, is an explosion in the interior regions, with spectacular effects on the outer layers as well.

After the nova or supernova fades, astronomers have sometimes detected clouds of debris expanding outward. This agrees with the idea that an explosion has taken place. The supernova is found to expel much more material than the ordinary nova, again suggesting that the causes, as well as the end results, may be basically different.

As the astronomer looks about the sky, he can also detect many nebulae that have the appearance of explosions. For example, the Crab Nebula in the constellation of Taurus (fig. 1) has that appearance. The Cygnus Loop (fig. 2), also called the Veil Nebula, is an intricate network of filaments arranged in a circle. It also appears to have come from an explosive event near its center.

The supernova, as is obvious from the preceding paragraphs, is one of the most spectacular and important events in the universe. It is the most spectacular thing that happens in the life of a star. As will be seen in the rest of this brochure, the supernova affects almost everything of interest to the astronomer. Chapter II will discuss what is known about the explosion and what is left of the star afterward; chapter III will discuss the cloud of debris that is thrown off in the outburst; and chapter IV will list some of the astronomical puzzles and mysteries still surrounding supernovae.

In addition to the part they play in the life of the universe, supernovae have played an important part in the development of scientific thought. Like many other celestial events, these stars which suddenly become bright were regarded with superstition by ancient and pre-Renaissance people and were considered to have astrological significance. For example, according to Sung Dynasty records, the report of the head astronomer of the court in 1054 says:

> Prostrating myself, I have observed the appearance of a guest star; on the star there was a slightly iridescent yellow color. Respectfully, according to the dispositions for Emperors, I have prognosticated, and the result said: The guest star does not infringe upon Aldebaran; this shows that the Plentiful One is Lord, and that the country has great worth. I request that this be given to the Bureau of Historiography to be preserved.
>
> (Translated by J.J.L. Duyvenbak, quoted in Gorenstein and Tucker, *Scientific American*, July 1971, p. 77.)

Such records of brightness, color, and location are valuable to both the astronomer and the historian. But care must be taken, since astrologers predict only good things. Indeed, they had good reason to do so, since in many ancient cultures bearers of bad tidings were often executed. There is evidence that the Chinese astronomer may have altered the color of the star, for example, from the yellow-orange predicting sickness to iridescent yellow, the Oriental royal color.

When Tycho recorded his observations of the supernova of 1572, he also recorded that the people of his island of Hven feared that this was a sign of impending plague, famine, or other disaster.

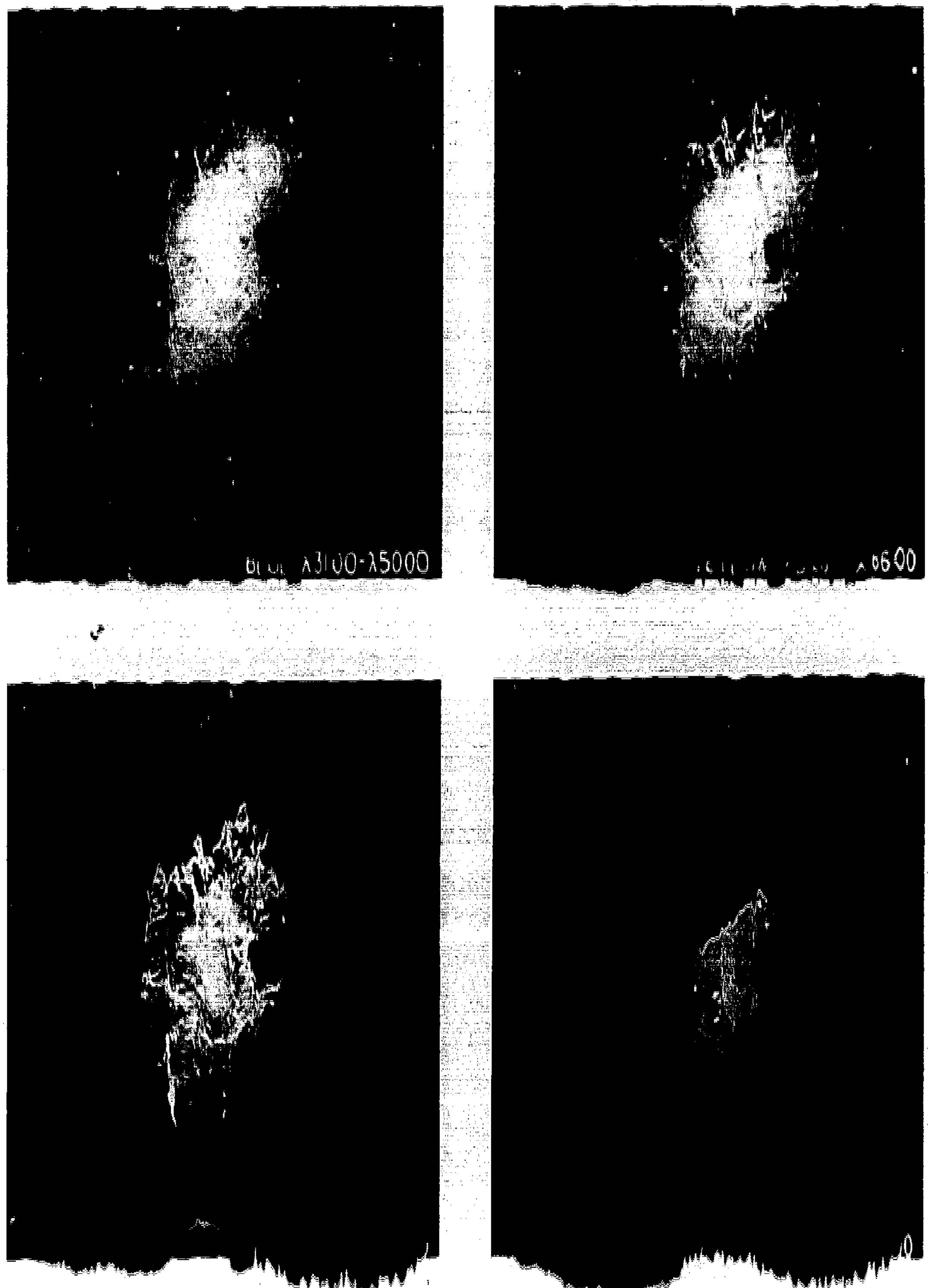

Figure 1. The Crab Nebula (Messier 1) of 4 wavelengths. This object in Taurus is the remnant of the supernova of 1054. (Hale Observatories photograph)

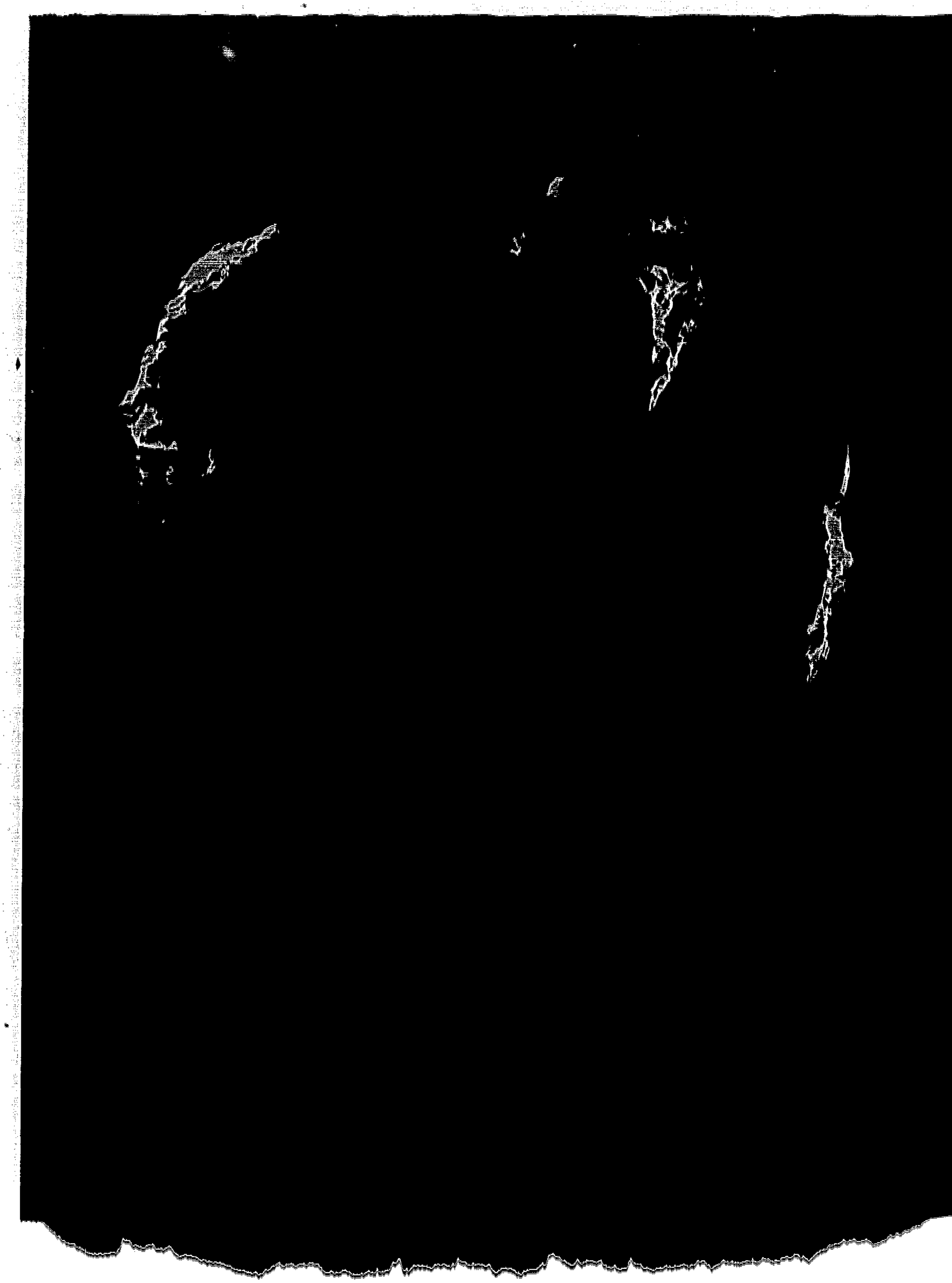

Figure 2. The Cygnus Loop. The remnant of a supernova which happened 30 000 to 40 000 years ago. A possible X-ray pulsar has been found near the center of the Loop. (Hale Observatories photograph)

Before the Renaissance, the heavens were thought to be unchanging and immutable. The Sun, Moon, and planets moved against the background of the stars, but in a fairly predictable manner. Comets and meteors were thought to be in the atmosphere and thus part of the imperfect Earth. The observation of Tycho and of Johannes Kepler (better known for his laws of planetary motion) of new temporary stars helped to change this. Not only did the Sun, Moon, and planets move, but the "unchanging" stars could change!

More recently, a supernova played an important but negative role in the progress of our ever-growing view of the universe. In 1885, the nova known as S Andromedae was discovered in the Great Nebula in Andromeda (also known as M31). At the time, it was thought that the whole universe was contained in the Milky Way galaxy. The great philosopher Immanuel Kant had proposed in 1755 that there might be other galaxies like our own ("island universes"), but there was no evidence to support his theory.

The idea that S Andromedae was an ordinary nova hindered acceptance of the theory of "island universes." If S Andromedae were a normal nova, then it, and thus the Great Nebula in Andromeda, would still be within the boundaries of the Milky Way. Thus, the Great Nebula and the other nebulae like it (the spiral nebulae) would just be nearby clouds of material and not "island universes." These theories sparked a debate that was not resolved until the 1920's. The resolution, by Edwin Hubble, proved that there were indeed other galaxies and that S Andromedae was a previously unrecognized and spectacular object, the supernova.

Even now there are many things about supernovae that are unexplained. Throughout this brochure we shall look at some of the attempts at explanation and indicate where some of the unknown puzzles lie.

> There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.
>
> —Hamlet, I, v, 166

> The miracle occurs not in contradiction to Nature, but in contradiction to what we know about Nature.
>
> —St. Augustine

CHAPTER II

THE STAR

A. Observations

One of the major problems in astronomy is the wide gulf between the observations of supernovae and the theories that have been tried. The theories can explain some of the details, but no theory has yet been able to explain completely what is happening.

An important beginning step is to know how many supernovae occur. Is it something that happens to a few stars only or is it something that happens to every star?

Ordinary novae happen several times each year, but only six supernovae have been seen from Earth in our own galaxy during all of recorded history. Table 1 summarizes some of the information known about these six.

Table 1
Supernovae Observed by Naked Eye

Date (A.D.)	Constellation	Apparent Brightness	Galactic Longitude (degrees)	Distance (kpc)	Observers
185	Centaurus	Brighter than Venus (-6)	312	2.5	Chinese
369	Cassiopeia	Brighter than Mars or Jupiter (-3)	108	10.	Chinese
1006	Lupus	Brighter than Venus (-5)	328	3.3	Chinese Japanese Korean European Arabian
1054	Taurus (Crab Nebula)	Brighter than Venus (-5)	185	2.	Chinese Southwestern Indian (no European or Arabian)
1572	Cassiopeia	Nearly as bright as Venus (1-4)	120	5.	Tycho and Many others
1604	Ophiuchus	Between Sirius and Jupiter (-2)	5	6.	Kepler Galileo Many others

The column labeled "apparent brightness" gives the brightness of the supernova at its maximum value, as seen by the observers. The objects to which the brightness is compared are among the brightest in the sky—the planets Venus, Mars, and Jupiter at their brightest and the brightest star in the night sky, Sirius. The number in parentheses is the apparent magnitude on a scale used by astronomers and may be used in classes where the teacher has discussed the astronomical magnitude scale.

The table shows that all of the supernovae seen were very bright. Also, they were all fairly close to the Earth. By comparison, the center of our Milky Way galaxy is about 8 to 10 kpc away from us (1 kpc is about 3×10^{18}m). The galactic longitude is measured from the direction to the galactic center. All of these supernovae, in other words, took place in our part of the galaxy.

These two facts tell us that a supernova had to be very bright for astronomers to notice it in the days before there were telescopes. Also, supernovae that take place very far away from us in our own galaxy are not seen.

It is interesting to note that the supernova of 1006 was recorded by Arabian and European astronomers, as well as those in the Far East, while the one in 1054 (first recorded on July fourth of that year) was not. On the other hand, the supernova of 1054 is recorded in the rock carvings of Indians in the western part of North America (fig. 3). These Indians have no written history.

Tycho recorded enough information in his book *De Stella Nova* about the supernova of 1572 that astronomers can draw an accurate graph of the brightness of the star as it progressed from June 1572 until it faded out early in 1574. He also included descriptions of the color.

Kepler, the discoverer of the laws of planetary motion, and Galileo, who first applied the telescope to astronomy, both recorded the supernova of 1604, beginning in October. An interesting comparison of cultures may be found in the quite accurate records of this supernova kept by Chinese astronomers.

In addition to the six that are recorded in the historical and prehistorical records, a supernova also occurred in the constellation of Cassiopeia in about 1670. Unfortunately, there are no records of this event. We know about it today because radio astronomers discovered the debris as one of the most powerful radio sources in the sky. This debris is located at a galactic longitude of 110° and an estimated distance of 2.8 kpc.

In order to find out more about these rare objects, astronomers obviously must find more supernovae. The only possible way, unless we are very lucky and one happens close by, is to look at other galaxies. We already mentioned the supernova that happened in 1885 in M31 (Andromeda).

Fritz Zwicky began a search for supernovae in other galaxies in the 1930's. Many photographs of other galaxies are taken each year. Then the new photographs are carefully compared with older ones to see if there are any stars that have become brighter. This project has been very successful, leading to the discovery of several supernovae each year. One of the brightest is shown in figure 4.

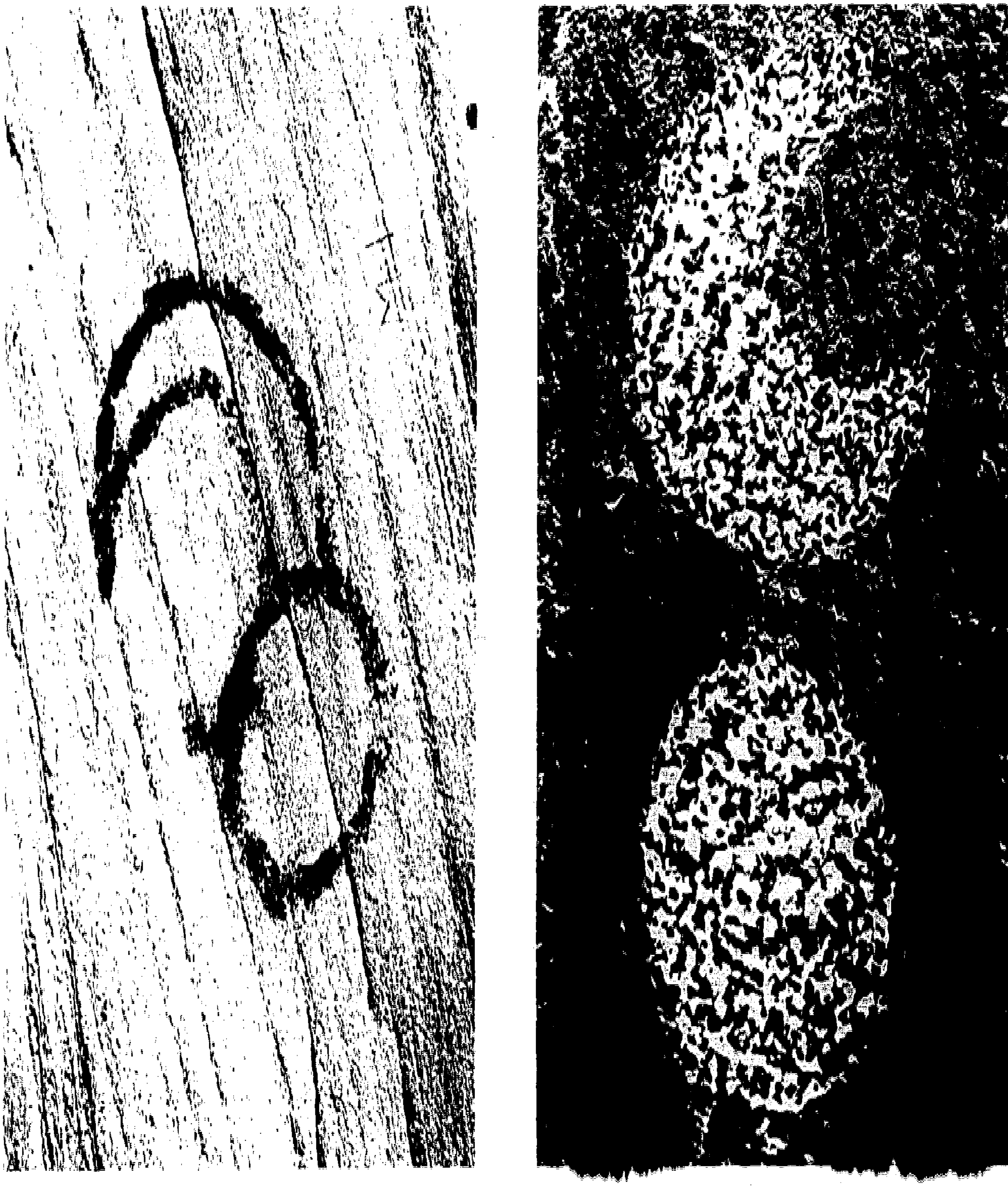

Figure 3. Rock drawings in Arizona, believed to depict the supernova of 1054.
(left, William C. Miller; right, R. C. Euler)

21  22

Figure 4. One of the brightest supernovae found in another galaxy. This object, at the lower right of the galaxy, was found by a systematic search at the Hale Observatories. (Hale Observatories photograph)

Even though this has been very successful, such a search requires many hours of hard work. Several other projects have been proposed to make this work easier and faster. These projects would make use of computers to aid in finding likely galaxies and in making the necessary before and after comparisons. A television camera would be hooked to the telescope to make the image more readily visible to the eye without the necessity of developing the photographic plates. The most sophisticated proposal would have had the computer take over all the tasks, including pointing the telescope, studying the television image, and making the necessary comparisons. None of these projects is in the operating stage at present.

Historical records tell us that there is one supernova every 270 years or so in our galaxy, but we find that there are many more supernovae in other galaxies, perhaps as many as one every 20 or 25 years. This leads us to an apparent puzzle. Why are there fewer supernovae in the Milky Way than in other galaxies? Is our galaxy unique, or is there some reason why we cannot see a large number of the supernovae that do occur? If the estimate of one every 25 years in other galaxies is correct, then we are seeing only 10 percent of the supernovae in the Milky Way. We will discuss this puzzle in chapter IV.

The next thing we can find from a study of the supernovae that have been found in our own and other galaxies is where they occur.

As seen from the Earth, our Milky Way, a typical spiral galaxy, appears as a hazy band of light around the sky. We are located in the disc, inside or at the edge of a spiral arm, and about 8 to 10 kpc from the center. Because we are in the midst of all the stars, gas, and dust, our vision is somewhat obscured (see projects at end of brochure). It is similar to being in the middle of a thick forest; we may not be able to see a house that is 100 m away, but we can look into the sky and see the Sun, which is 150 million km away. So too in our galaxy we cannot see the center which is perhaps 10 kpc away, but in another direction we can see other galaxies that are 50 000 kpc away.

The supernovae we have found in historical records are all located near the band that marks the Milky Way in the sky. Many of the supernovae in other spiral galaxies have been found in or near the main discs of the galaxies, too. This tells us that the kinds of stars that become supernovae are mostly the types of stars found in the discs of spiral galaxies. A very few supernovae have been found in the spiral arms themselves. These are likely, then, to come from the types of stars found in the spiral arms.

Observations of how the brightness of the light rises and falls during the supernova outburst have led to the conclusion that there are at least two distinct types of supernovae. These are simply called supernovae of Type I and supernovae of Type II. Figures 5 and 6 show graphs of the rise and fall of the light of the two types. The important difference to note is that after about 50 days the Type I supernova fades fairly slowly, while the Type II pauses briefly, then fades rapidly. Type I supernovae are found throughout the discs of spiral galaxies, while Type II are found in the spiral arms. The supernovae found so far in elliptical galaxies are all Type I.

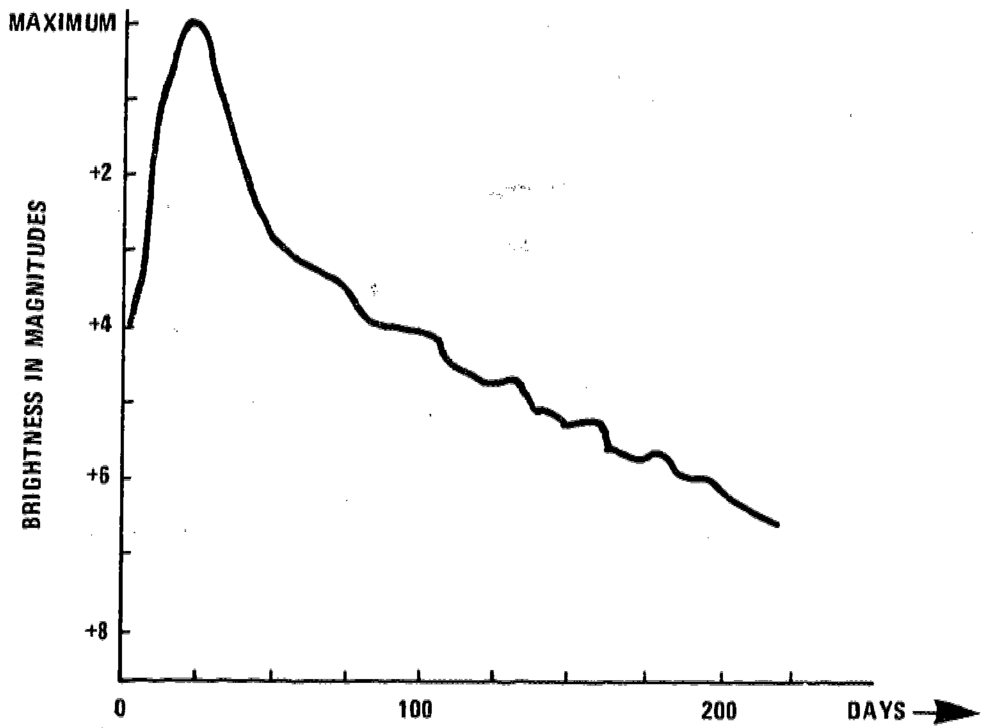

Figure 5. Type I supernova compiled from various sources.

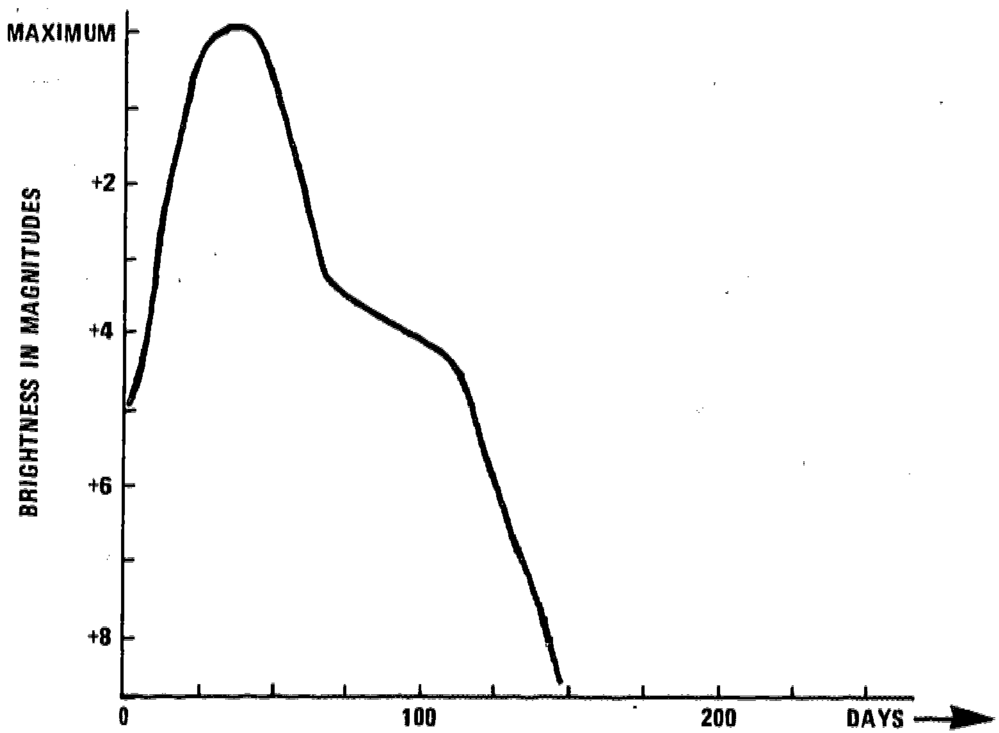

Figure 6. Type II supernova compiled from various sources.

There is also a difference in the maximum brightness reached for each of the two types of supernovae. Type I reaches a maximum brightness 3×10^9 times that of the Sun. Type II reaches 9×10^8 times the Sun's luminosity. Obviously, if the Sun should become a supernova, the Earth would be vaporized. (However, the Sun isn't the kind of star that becomes a supernova.)

The supernova will not appear that bright to us because distance diminishes the apparent brightness, and there is often dust and gas in the way to block our part of the light. But the supernova can sometimes outshine, for a brief moment, all the other stars in the galaxy put together (fig. 4).

It is important to look at the supernova's color and at what its spectrum is like at different times, since the color can tell the astronomer something about the temperature and the spectrum will tell him the speed of the expanding materials, the chemicals present, their quantities, etc., when properly interpreted. (The spectrum is also used to tell which type the supernova is during the early stages of the outburst.)

The color of supernovae tends to be yellow to red, indicating a fairly low temperature for an astronomical object, perhaps 4000 to 6000 K. Of course, this is just the temperature of the outside of the expanding material (we cannot see the inside), and it is not the temperature of the star before the outburst. Unfortunately, no one has yet observed a star before it becomes a supernova. Some have been seen a few days before the maximum brightness was reached, but then the explosion was already underway.

The low temperature means that most of the radiation coming from the supernova is visible light, with only a small proportion in the infrared, ultraviolet, and X-ray parts of the spectrum. Even though it is only a small fraction of the total light coming from the star, the amount of X-ray is probably millions or billions of times greater than the amount of X-ray coming from the Sun. Observations from some of the present and planned NASA satellites and space probes will give us those answers,

The spectrum of a supernova is extremely complex and hard to interpret. There are broad and narrow emission bands at the same time. There are also many complex dark features. Some features can be identified as being caused by hydrogen, helium, oxygen, and some other elements, with major differences between Types I and II.

The Doppler shift (see Glossary) of the lines in the spectrum of the supernova shows that the rate at which the gas is expanding is truly explosive—about 8000 km/s for Type II supernovae. This is many times greater than the escape velocity from the star. The width of the broad emission bands indicates that the different parts of the gas are moving in many directions at once, with a wide range of velocities. This disordered motion is referred to as *turbulence*.

The spectrum of a supernova does not remain the same, but shows many changes during the year or so that it is observed. The astronomers who attempt to devise the theories to explain what is happening seem to have an impossible task, but some progress has been made, as we shall see below.

After the explosion is over and the material that has been thrown off has spread out into space, what is left over? Supernovae in other galaxies are so far away that even the largest telescopes do not allow astronomers to see what is left a few years or decades after the explosion. But we can consider which types of objects known to the astronomer might be the remains of the star. The first type of object suggested is called a *white dwarf.* The first white dwarf to be observed was the companion to Sirius. These stars are a white color, indicating a high temperature, perhaps 10 000 K; yet they are very faint. Usually something very hot glows very brightly. These stars must then be very small.

The typical white dwarf is just as massive as any other star, ranging from one-half to one and one-half times as massive as the Sun, which is an average star. The Sun's mass is 2×10^{30} kg, about 300 000 times more massive than the Earth. But the white dwarf has a tiny radius, about the same as that of a planet, so all of the matter is squeezed very tightly together. If we could obtain a teaspoon of white dwarf material, we would find that it would weigh a ton. The electrons have been stripped off of the atoms, and the nuclei and electrons have been crowded as closely together as possible. When matter is in this compacted condition, we say that it is degenerate.

The second possibility is an object referred to as a *pulsar*. When these were first discovered by the radio astronomers in 1967, they showed up as a series of pulses at very regular intervals. The startled radio astronomers at first thought that they had picked up a radio beacon from some other civilization in the galaxy, and the pulsars were first called LGM's (Little Green Men). But very quickly the astronomers realized that artificial radio stations couldn't produce signals like a pulsar; it had to be a natural phenomenon.

Many years before, some theoreticians had proposed another kind of degenerate matter that might be called super-degenerate. In this kind of matter, the material is so tightly squeezed that the electrons are forced into the protons. The negative and positive charges cancel each other, and a neutron is formed. These neutrons are then squeezed as closely together as possible. The star that results is called a *neutron star.* Such a star might explain the pulsar. The matter is so dense that if we could exchange the teaspoon of sample white dwarf for a sample teaspoon of neutron star, we would find that it weighed 10^6 tons.

Pulsars are found by the regular pulses they send out in the radio part of the spectrum. Attempts have been made to find if they also pulse in other parts of the spectrum. Although they are very faint and thus difficult to observe, two have been found to pulse in the visible part of the spectrum. By means of rockets and satellites sent above the Earth's atmosphere, these two plus one other have been found to have X-ray pulses as well.

There are a hundred or so pulsars known. The first one identified was in the Crab Nebula. The star that turned out to be the pulsar had been picked out previously by studying the way in which the nebula was expanding and tracing the expansion backwards.

Pulsation is very rapid. The fastest pulsar is the one in the Crab Nebula, which pulses about 30 times a second. Figure 7 shows the pulsar when it is shining and when it is not

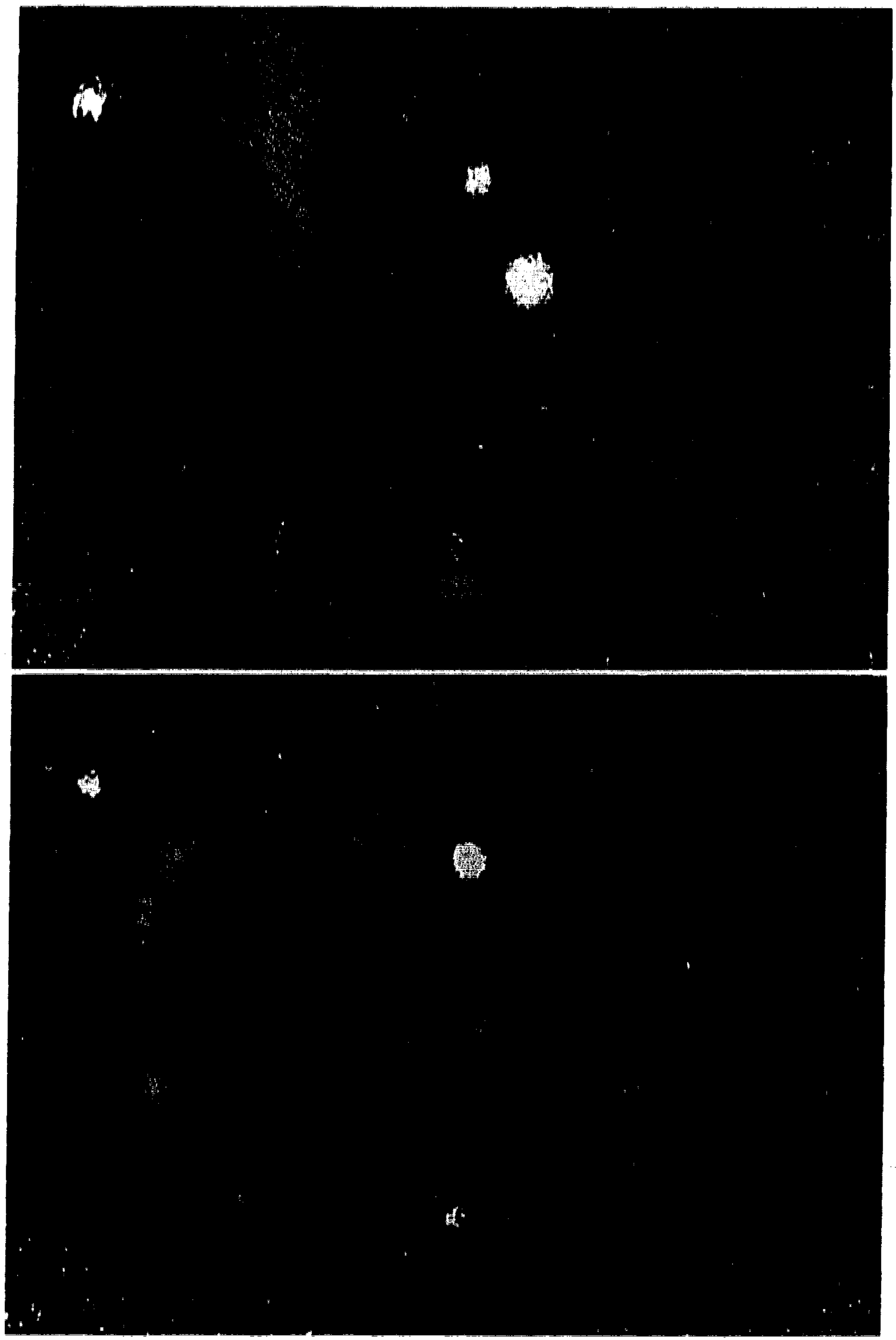

Figure 7. The pulsar in the Crab Nebula, M-1. The top picture shows the pulsar during a pulse. The lower picture is between pulses. (Lick Observatory photograph)

shining. In figure 1, the pulsar is the lower one of the pair of stars near the center of the nebula.

Pulsars are concentrated toward the disc of our galaxy. Because radio waves can go through the dust and gas clouds, we are able to see that they are concentrated toward the center of the galaxy just as the stars are.

Another possibility of what might be the remains of a star is found among a number of objects that are seen with NASA satellites that look at the X-ray part of the spectrum. Uhuru, one of the most famous of these NASA satellites, has found several of these objects. It is thought by some astronomers that some X-ray sources might be a type of object known as a *black hole* (discussed in a subsequent subsection).

One X-ray source, Hercules X-1, is associated with a variable-brightness binary star, HZ Herculis. It seems likely that Her X-1 and HZ Her are the remains of a supernova outburst in a binary star system which stayed together. However, in this case, the X-ray source appears to be due to a neutron star rather than a black hole.

There seem to be a number of "runaway" stars around the galaxy that could be the remains of binary stars that did not stay together after the supernova explosion. Suppose we look at what would happen to a binary star if one of the two companions lost part of its mass suddenly. If it loses too much mass, the gravity of the two is no longer enough to hold them together. Both of the stars "run away" from their original location. There are even a few pulsars that seem to be runaway stars (such as the one known as PSR1133+16, which travels at 300 km/s), giving support to this idea.

Some other observations that relate to supernovae are the gamma-ray bursts observed by some of NASA's satellites, gravity waves, and cosmic rays. These will not be discussed here, but the teacher may wish to refer to articles in *Scientific American*, *Sky and Telescope*, *Astronomy*, or other periodicals.

B. Theories Concerning the Outburst

It is not yet known why a supernova occurs. There have been several theories in the past that proposed that the nuclear reactions in the center of a star might suddenly increase in an uncontrolled manner. This would lead to the release of a huge amount of energy that could result in an explosion of the entire star.

A normal star's energy is supplied by the conversion of hydrogen into helium. If it were not for this nuclear reaction, the star would just cool off. The Sun, for example, would cool off in 2×10^7 years, but hydrogen fusion (into the heavier helium) will keep the Sun hot for from 5 to 10×10^9 years.

When all the hydrogen in the center of the star is converted to helium, changes take place to permit the fusion of helium atoms to form carbon. When all the helium available in the star's core is exhausted, it appears likely that a sort of "energy crisis" occurs, leading to the supernova explosion.

The *carbon detonation model* suggests that when the fusion of carbon into still heavier elements begins, the nuclear reactions proceed catastrophically, precipitating an explosion in the core of the star. The explosion throws the outer layers of the star into space, producing the outburst we see as the supernova.

This *neutron star formation* model was originally developed to explain how a neutron star might form. When the nuclear reactions converting carbon into heavier elements begin, a large number of particles called neutrinos are produced. These neutrinos carry away so much energy so rapidly, according to this theory, that the core of the star collapses in on itself. This rapid inward collapse is called an *im*plosion. As the electrons are forced into the nuclei of the atoms, forming neutrons (and thus the neutron star), a huge amount of energy is produced. This energy can only be used up by expelling the outer parts of the star. This expulsion is the violent explosion that we see as the supernova.

The basic difference between these two theories is that the carbon detonation model has an immediate explosion produced by the violent starting of the carbon reactions, while the neutron star formation model has a sudden loss of neutrinos, leading to an implosion that results in the violent expulsion of the outside of the star.

A third theory of how supernovae happen is that two stars, for example, white dwarfs, might collide. This collision would produce the explosion, and the force of the impact would produce the neutron star. The problem with this theory is that collisions between stars are very rare; there might be only one such collision in the whole life of our galaxy. But we know that at least seven supernovae have happened in the last 2000 years.

A recent suggestion is that the two stars, a white dwarf and a red giant (a very late stage in a star's life just before the white dwarf stage) might be found as a binary pair. By a process similar to the Moon's producing tides on Earth, the white dwarf might be dragged closer and closer to the red giant until the white dwarf actually falls in, thus producing the necessary collision.

All three of these theories have support, but none is completely satisfactory. More research will have to be carried out to determine, for example, the differences between Type I and Type II supernovae.

One result of supernovae in all three theories is the formation of the heavier elements. The process of forming the heavier elements and their various isotopes is referred to as *nucleosynthesis.* Some nucleosynthesis takes place in the normal nuclear reactions in the stars. The fusion of hydrogen to form helium has already been mentioned, as has the formation of carbon from the fusion of helium. But formation of some of the heavier elements requires energies much greater than can be found in the cores of normal stars—energies that can only be found during the supernova explosion.

Thus, supernova explosions affect the chemistry of the universe in two ways: by creating the heaviest of the elements and by stirring the elements formed both in the stars and in the outburst itself into the materials that will form the new stars, planets, and, perhaps, life.

C. Theories Concerning the Leftover Star

Although the white dwarf may be the result of an ordinary nova, it seems very unlikely that a supernova could produce one. This conclusion is reached because the explosion of a supernova is much too violent and there are too many white dwarfs. The number of white dwarfs is, however, just right for the number of ordinary novae.

The neutron star seems a much better candidate for the aftermath of a supernova. The extremely high density of the neutron star could only be produced by something as energetic as a supernova. But how does a neutron star produce the pulses that we see in the pulsar?

There have been many theories suggested for the exact way in which a pulsar works. The best ones make use of a magnetic field. Many stars, including the Sun and the most massive stars, have magnetic fields. When the star's core collapses to form the neutron star, it also concentrates the magnetic field, maybe by as much as a billion times.

If the star was spinning before the explosion (and most stars do spin), it will be spinning afterward as well. But, just as a figure skater speeds up her spin by drawing her arms in close, the star will speed up its spin as it collapses to form the neutron star. (This is called conserving angular momentum.) The star will be spinning several times a second. If the magnetic field is tilted slightly compared to the spin, the direction of the field will sweep around through space. Charged particles, such as electrons, will be accelerated by the magnetic field. In being accelerated, the electrons will radiate radio waves, visible light, and all the other parts of the spectrum.

Figure 8 shows the tilted magnetic field and the cone of radiation produced. As the cone sweeps past the Earth, we will see a flash. Thus, the pulsar can be thought of as somewhat like a lighthouse, with its beam of light periodically sweeping past the observer (if he is in the right location).

The black hole is the most exotic of the possibilities. There is much argument among scientists over whether or not they can exist. No black hole has yet been observed, and astronomers aren't certain what to look for. (Some astronomers think that an X-ray source in Cygnus, Cyg X-1, might be a black hole.)

According to Einstein's general theory of relativity, gravity is really a warping and bending of space. It is possible to have a region of space completely warped and curved in on itself. Black holes cannot be understood by using the law of gravity found by Newton. The black hole has such strong gravity that it even traps light, hence its name. No light can escape a black hole, and any ray of light that comes too close will be trapped as well.

If a neutron star has more than twice the mass of the Sun, then it must continue collapsing into a black hole. Einstein's theory predicts, in fact, that any resistance to the collapse will itself create more gravity that will inevitably crush the star to an infinite density. A region forms in space-time, which has zero volume and infinitely strong gravity at its boundary. Anything, whether it be matter or light, that ventures too close to the black hole is swept in. This point of no return is about 15 km from the center of the black hole, as seen by the observer on the outside.

Theory predicts that matter falling into a black hole should give off a large number of X-rays. Thus, some X-ray sources could be black holes. It might be possible to identify them with some certainty if they are part of binary star systems.

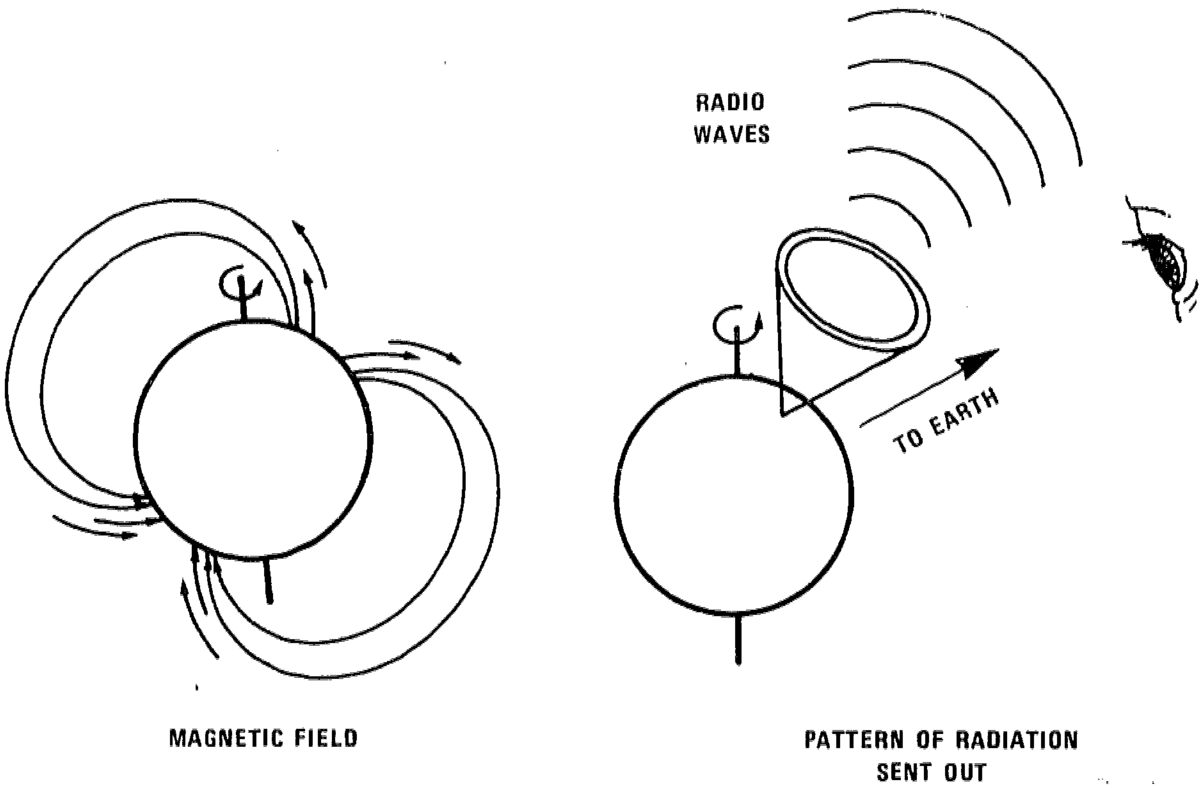

Figure 8. A model of a pulsar. In this model, the radiation is sent out in a cone-shaped distribution. A pulse is heard each time the cone sweeps past the direction to the Earth.

31

CHAPTER III

THE SHELL EXPELLED

A. Observations

Around the sky are a number of nebulae that appear to have come from some violent event. Some of these may be the debris thrown out by the supernova explosions. Perhaps not all of them are the debris itself, but a shock wave spreading through space as a ripple spreads across the surface of a pool when a pebble is dropped in.

A couple of dozen such remnants have been identified. In four cases the nebula is at the same location as a known supernova. These supernovae were the ones that occurred in 1006 (Lupus), 1054 (Crab Nebula), 1572 (Tycho's), and 1604 (Kepler's).

The Crab Nebula in the constellation of Taurus was discovered by John Bevis in 1731. It was discovered independently by the "comet hunter" Charles Messier in 1758. Annoyed by this and other nebulae that look like comets when seen through a telescope, Messier compiled a catalog of just over 100 objects to avoid. The Crab Nebula became the first object on his list, and is now called Messier 1 or M-1 (the Andromeda galaxy is the 31st object, and is called M31).

The other three supernova remnants that have been identified were all found by the radio astronomers. So far, the only one of these three visible is Kepler's supernova. There are also other nebulae that look as if they were produced by explosions, but which are not associated with the historical supernovae. One of the most beautiful objects in the sky is the network of fine filaments arranged in a circular form in the constellation Cygnus. This nebulosity is known as the Cygnus Loop, or the Veil Nebula (fig. 2).

There are a number of other objects that are similar in appearance to the Cygnus Loop. A large nebula in Auriga which has only a catalog number, Shajn 147 (fig. 9), consists of an intricate network of filigree spread across 5 degrees of the sky. Another remnant, found in Gemini, is shown in figure 10.

Photographs taken of some of these objects over a period of years show them to be growing in size. Careful measurements have allowed astronomers to trace the motions back to the center of the nebula in a few cases. This gives the age of the nebula and, thus, the date of the supernova. Most of them happened 10,000 or more years ago.

A somewhat different evidence of a past supernova is found in the immense Gum Nebula (named for Colin Gum, the astronomer who discovered it). This object is an extremely extensive network of nebulosity, appearing to stretch 40 degrees across the sky in the southern part of the Milky Way. It spills over into a number of different constellations, but is centered on Vela and Puppis, the sail and deck of the ship Argo. Some astronomers feel that parts of the nebula may extend over as much as 90 degrees of the sky! This nebula appears large because it is close by. Near the center of this complex object is a fine filamentary nebula that is very much like the Cygnus Loop or Shajn 147.

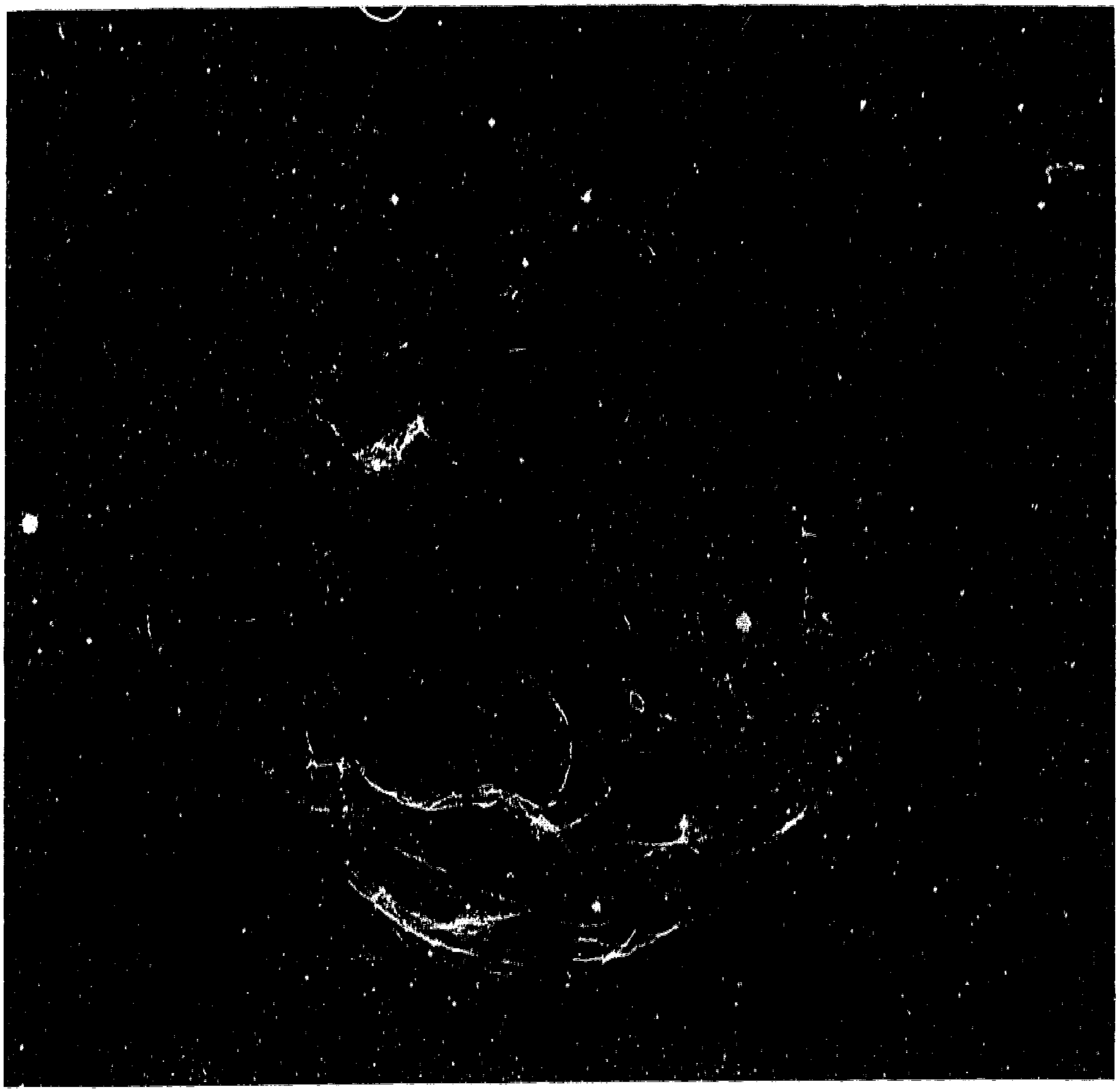

Figure 9. Shajn 147, a supernova remnant in Auriga. (Hale Observatories photograph)

Figure 10. A supernova remnant in Gemini. (Hale Observatories photograph)

So important is this region that a whole conference was devoted to discussing it in May 1971 at NASA's Goddard Space Flight Center in Greenbelt, Maryland. A report, profusely illustrated with pictures, may be found in the August 1971 issue of *Sky and Telescope* magazine.

Astronomers have looked at the filaments with the spectroscope to see if they could determine their composition. In the Cygnus Loop, hydrogen and the other elements occur in the normal proportions found in other parts of our galaxy. But in Cas A, the supernova of about 1670, elements like sulfur are very abundant. Yet hydrogen, the most common element in the rest of the universe, is missing. In the Crab Nebula, there is twice as much helium as is normal in the rest of the galaxy.

Generally, the larger, older nebulae show the same chemical composition as the universe as a whole. The younger ones show an excess of the very elements that are supposed to be made in the nuclear reactions in the stars. We conclude that the young nebulae show the material thrown out of the star by the explosion. In the older nebulae, the debris has been thoroughly mixed into the surroundings.

B. Theories

The nebulae resulting from supernovae look like violent explosions and are composed of intricate networks of filaments. The spectroscope shows that the matter in these filaments is much denser and at higher temperatures than is normal for interstellar space. Photographs taken of the Crab Nebula with a polarizing filter show that magnetic fields must be explained by any theory that is to be accepted (fig. 11).

Popular articles and science fiction stories refer to space as a vacuum. There is really a large amount of matter there, although space is a better vacuum than we can produce here on Earth. If we were to study a sample volume of space, say a cube 1 cm on a side, we would find one atom in it on the average. In some regions, there may be 100 atoms in our 1-cm cube. For comparison, the Earth's atmosphere at sea level has about 10^{19} molecules in each 1-cm cube.

According to present theories, the supernova remnant will go through several distinct stages. The first stage is that the debris is thrown off the star, forcing its way into the matter in space surrounding the star. This expelled shell is traveling much faster than the escape velocity of the star (speeds of 8000 km/s have been measured).

At first, the shell expands almost unhindered, but soon it sweeps up material equal to its original mass. (This stage is reached a few hundred years after the supernova.) The debris then begins to slow down, much as a swimmer diving into the water is slowed. A shock wave is created and continues to shoot outward (sonic booms and the crack of a rifle are shock waves). Next, the original debris disperses, while the shock wave continues outward.

So far, the loss of energy through radiation has had only a small effect. But the energy lost cannot be recovered, so eventually this radiation becomes very important. After 20 or 30 thousand years, this loss of heat and light causes a rapid collapse of the

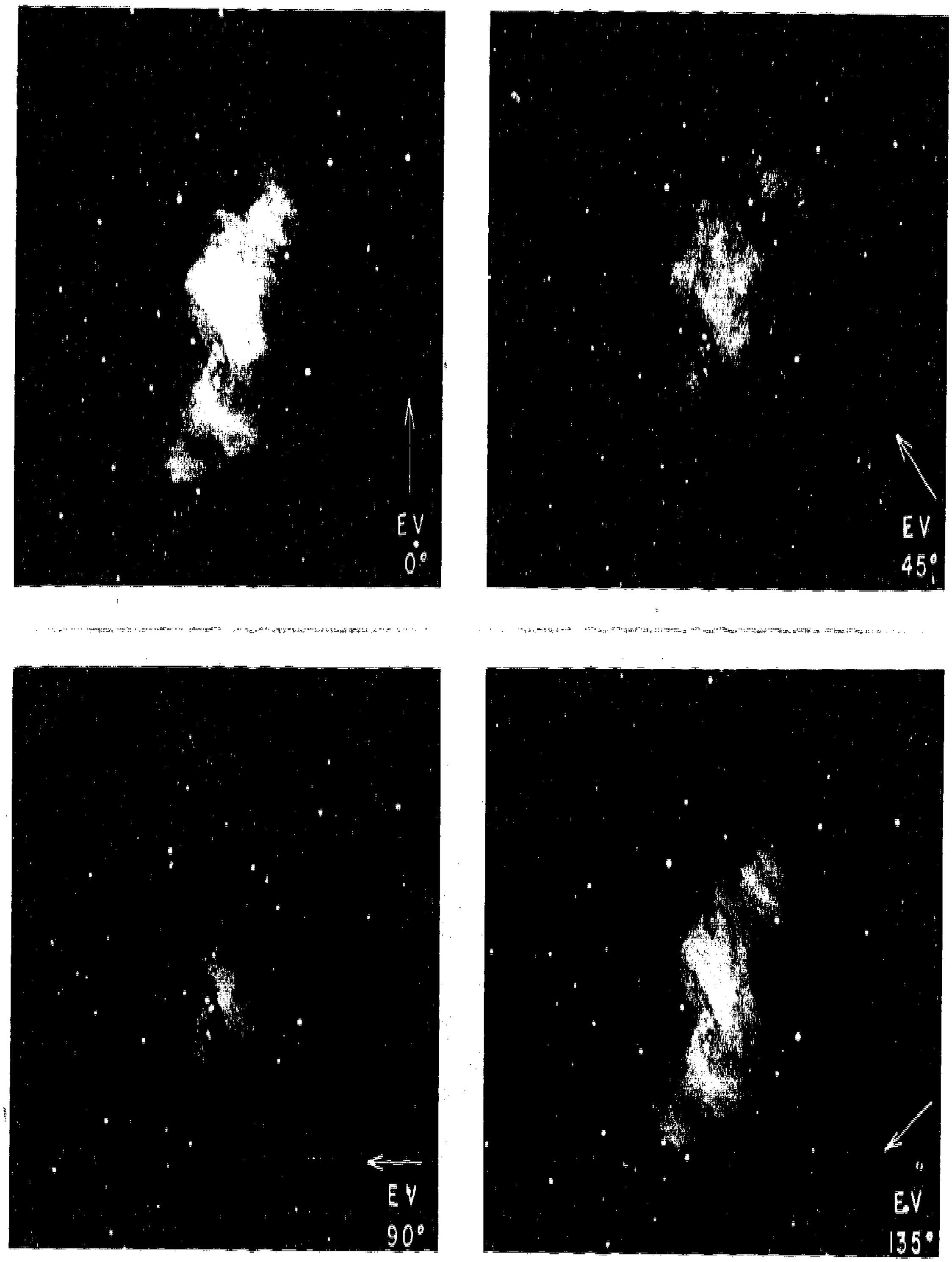

Figure 11. The Crab Nebula photographed through polarizing filters. The arrow shows the orientation of the filter. This provides evidence of a magnetic field. (Hale Observatories photograph)

shock wave. The material at the outer edge suddenly becomes hundreds of times more dense. The temperature drops from a million degrees to almost nothing.

The next stage has this newly formed, cold, dense shell continuing to move outward, carried only by its momentum (there is no longer heat to push it outward). It sweeps up the interstellar matter before it like a snowplow. As it gathers more mass, the shell slows down.

Finally, when the speed has slowed to about 10 or 20 km/s, the shell just dissipates and the hole created in the interstellar medium slowly fills back in.

Complex computer programs using this theory have been written. The computer is another tool for the astronomer, just like the telescope. It speeds up the task of doing the arithmetic (although the computer only does what it is told).

But is the theory successful? The computer calculations say that young supernova remnants should show the original debris thrown off the star. Medium-aged remnants should show sharp shock fronts surrounding hot regions. Old remnants should show cold dense shells.

We saw that two young supernova remnants, the Crab Nebula and Cas A, show large amounts of the chemicals that come from the interiors of stars. The older remnants, such as Shajn 147 and the Cygnus Loop, show compositions like the rest of interstellar space. Old nebulae are found to have high densities in the filaments, but the temperatures are not as low as predicted. Some of the young remnants have high densities in the shells. Cas A doesn't show a complete shell, but many blobs of material. The Crab doesn't look spherical, and yet this was a basic assumption—that a spherical shell was thrown off the star.

Another deficiency is that the computer calculations don't include magnetic fields. We know from the observations mentioned before that there are magnetic fields in the Crab Nebula, among others.

The last fault with the theories to be mentioned here is that they do not explain the filaments. None of the remnants known looks like the soap bubbles predicted by the theories. Some attempts have been made to explain these filaments. One theory suggests that the filaments may be formed when the clouds of gas and dust that are known to be scattered throughout space are compressed by the shock wave or shell.

> When a man has no ideas at all he starts working with a computing machine.
>
> —P. Debye

C. Side Effects

One of the major problems of astronomy has been to explain how stars (and planets) are formed. The various theories say that, once the contraction of a cloud of material begins, gravity will continue the contraction to form a star. The problem has been how to get the contraction started in the first place.

Perhaps the supernova remnant nebula can help to solve this problem. We have seen that the supernova remnant forms a high-density region at its outer edge. Furthermore, the dense region is cold. This may be just what is needed to start the contraction to form a star. We might also note that the amount of matter in such a supernova remnant nebula is enough to form several thousand stars. In one sense, then, the death of one star in a supernova may result in the birth of hundreds or even thousands of new stars. The supernova is, in a way, both the beginning and the end of a star's life.

Dust grains and molecules may also form in these cool dense shells. (See the brochure in this series titled *Chemistry Between the Stars,* by R. H. Gammon.)

The heaviest elements can only be formed during the supernova outburst. These elements and those formed during the normal course of a star's life (carbon, nitrogen, and oxygen) will be distributed into space by the shell of debris thrown off the star. We have already mentioned that the remnants of the Crab Nebula and Cas A have been observed to have large amounts of these very elements.

The most common elements in the universe are hydrogen, helium, and the C-N-O group (carbon, nitrogen, and oxygen). The biologists and chemists tell us that the basic elements of life are carbon, nitrogen, oxygen, and hydrogen. Hydrogen is all around and was present from the beginning, but the rest were formed in the stars. Thus, we and all life on Earth may be the products of supernovae.

CHAPTER IV

PUZZLES AND PARTIAL ANSWERS

There are many puzzles that remain to be explained. In some cases, we may never know the answer. In other cases, the answer will be so obvious that we may ask why no one thought of it before.

We have seen several cases in which the theory was incomplete, sometimes only because the models were simple ones. By adding the complications later, many of the theories can be improved. But other observations remain unexplained.

A. Detection

Several puzzles exist concerning the detection of supernovae and their remnants. One puzzle is why the supernova of 1054, which was so well described in China and Japan, was not seen in Europe and Arabia. European and Arabian astronomers had seen the supernova of 1006, which seems to have been of the same brightness.

One suggestion is that the Europeans were so convinced that the heavens were immutable (unchanging) that such a change was ignored or dismissed. This does not explain, however, why the Arabian astronomers did not see it.

Another suggestion is that perhaps there was bad weather during that year; but there is no record of any such bad weather over the whole of Europe, and the Arab countries are noted for their clear skies.

Another supernova that was not seen was the outburst of Cassiopeia A. By 1670, there were a number of large telescopes. Two supernovae had been observed during the century preceding (1572 and 1604). Many other astronomical events were recorded. Yet no record has been found anywhere on Earth of this supernova. Why was it not seen?

Interstellar clouds would dim the supernova, and it might have gotten only as bright as the planet Jupiter. If so, then some astronomers estimate a 50 percent chance of the star's being missed.

In more recent time, almost all of the known pulsars have been detected only as radio pulsars. Only in one case has pulsation definitely been detected optically, with one more possible case. In both of these (the Crab Nebula pulsar and the one in Hercules (HZ Herculis)), X-ray pulsations have also been detected. There is one case in which an X-ray pulsar has been detected where no radio pulsar is known to exist—in the center of the Cygnus Loop.

If the theories are correct, there should be an optical pulsar for each radio pulsar. Why do we not see them? In many cases, peculiar blue stars have been seen at the radio location, but they do not pulsate. Perhaps the theory is wrong. Perhaps there is something we don't know.

Another puzzle is the lack of supernovae in our own Milky Way galaxy. This has already been mentioned. We find that other galaxies have from two to five supernovae each century. Yet we know of only seven in our galaxy in the last 2000 years. Why so few?

One possible answer is this. If we draw a map of our galaxy and put the known supernovae on it (table in ch. II), they all lie in our part of the galaxy (see the suggested projects). The gas and dust clouds may prevent us from seeing the others.

B. Coincidence

If all the various things we believe to have come from supernovae really do, then there should be a number of coincidences among them. For example, the remnant nebulae, pulsars (or neutron stars), and black holes are all supposed to result from supernovae. Thus, they should be close to one another in space.

Stellar associations are found in the parts of the spiral arms with the highest concentrations of gas and dust. They are groupings of the youngest, hottest, brightest, most metal-rich stars in the galaxy. These are not stable groupings. The stars scatter soon after they are formed. Since the supernovae of Type II are thought to come from the most massive, metal-rich stars, then pulsars, X-ray stars, and supernova remnants should be found close to or in such associations. However, there are none to be found, except for the Vela pulsar.

One clue to this lack of relics of supernovae is that associations disperse rapidly. Another clue is the runaway stars mentioned earlier. The more massive stars are almost all binary. Perhaps when the supernova occurs, the two stars fly apart so rapidly that the pulsar or X-ray star (the neutron star or the black hole) will quickly leave the association.

The next puzzle is that, except for two definite cases and one possibility, there are no X-ray sources in the centers of supernova remnants. The two cases are the pulsar in the Crab Nebula and the Vela pulsar. The possible case is the object at the center of the Cygnus Loop. If neutron stars produce X-rays and black holes are seen as X-ray stars, why are there no more than these? Again, a possible, but unlikely, answer is the runaway stars.

A curious puzzle has been found by the radio astronomers while looking at supernova remnant nebulae. If these nebulae really come from supernovae and pulsars are also the result of supernovae, then pulsars should be found at the centers of supernova remnants. Also, supernova remnant nebulae should be found around pulsars. Yet, in only two cases is there a pulsar in a supernova remnant. These two are the Crab Nebula and the Vela pulsar in the Gum Nebula. Some X-ray astronomers may have found an X-ray pulsar in the Cygnus Loop, but this has not been confirmed by other astronomers. All the other hundred pulsars are not near such nebulae, and the nebulae known are not near pulsars.

CHAPTER V

SUMMARY

In this brochure we have examined a few of the aspects of one of the most spectacular phenomena in the universe. We have seen that it consists of many different things. There is a flareup of the star itself; a shell of material expelled into space; and a shock wave spreading through the interstellar medium.

Each of these is a violent occurrence. The star flares to a billion times brighter than the Sun, so that no system of planets surrounding it could survive. If such a supernova were to occur in the nearest star to the Sun, Alpha Centauri, it would be a hundred times brighter than the full Moon in the night sky, or one-sixteenth as bright as the Sun itself. More important, the amount of X-ray and ultraviolet light bombarding our atmosphere would put the shielding layer of the ionosphere to a severe test.

At the same time, the supernova is important to the universe. By its occurrence, the elements created in the nuclear furnace in the cores of stars are mixed into the raw material from which new stars, planets, and life itself are formed. In the violence of the explosion, the heaviest of the elements, including most of those on which our civilization depends, are created. The shock wave provides the initial squeeze needed to form those new stars and planets on which new life may form.

In supernovae and their remnants, science is confronted with many great puzzles. There are several conflicting theories to explain many of the phenomena. There are observations that seem to contradict one another. The resolution of these apparent conflicts will eventually do much to advance science.

SOURCES OF FURTHER INFORMATION

In addition to the references given in the text and the suggested exercises, the following sources may prove useful.

Resource Letter EMAA-1: Educational Materials in Astronomy and Astrophysics, R. Berendzen and D. DeVorkin. *American Journal of Physics*, v. 41, p. 783, 1973. Available as a reprint for 50 cents and return envelope from Arnold A. Strassenburg, Executive Office, American Association of Physics Teachers, Drawer AW, Stony Brook, N.Y. 11790.

Photographs and slides:

(Hale Observatories)

California Institute of Technology Bookstore
1201 East California Boulevard
Pasadena, California 91109

(Lick Observatory)

Lick Observatory
University of California, Santa Cruz
Santa Cruz, California 95060

A tiny sample of the many texts available:

Abell, *Exploration of the Universe*, Holt, Rinehart, and Winston (several editions).

Baker and Frederick, *Astronomy*, Van Nostrand (several editions).

Brandt and Maran, *New Horizons in Astronomy*, Freeman, 1972.

Goldsmith, *From the Black Hole to the Infinite Universe*, Holden Day, 1974.

Wyatt, *Principles of Astronomy*, Allyn and Bacon (several editions).

Magazines (in many schools and public libraries):

Astronomy
Science News
Scientific American
Sky and Telescope

SUGGESTED DISCUSSION TOPICS AND PROJECTS

Chapter I

1. Many ancient people (particularly in Europe) believed that the heavens were immutable. The effect of supernovae discoveries on this belief can be discussed and can be fitted into a larger study of how Man's view of his universe has expanded (see M. Munitz, *Theories of the Universe*).

2. Discuss the scientific method.

Chapter II

1. Prepare a map of the locations of supernovae in the Milky Way galaxy. If possible, obtain polar graph paper. Otherwise, a compass, protractor, centimeter ruler, and pencil may be used. At the center of the paper, mark a point to be labeled "Sun." Find the line marked "0°" on the graph paper or draw a vertical line downward from the point marked "Sun." This is the direction to the center of the galaxy. Mark a distance of 10 cm along this line from the "Sun" and label this point "Galactic Center." Your scale is now 1 cm = 1 kpc. With the compass, draw a circle centered on the "Galactic Center" of radius 10 cm (passing through the Sun). This represents the Sun's orbit around the Galaxy. Mark the positions of the supernovae listed in table 1 (ch. II) in the following manner. The supernova of 185 A.D. is at 312° galactic longitude. Measure this angle counterclockwise with the protractor centered on the Sun (or find the line marked 312° on the graph paper). Measure from the Sun a distance of 2.5 cm, corresponding to the 2.5-kpc distance. Label this point "185 A.D." Do the same for the other supernovae plus Cassiopeia A (given in the text). Are the supernovae in the same part of the galaxy as the Sun?

2. An evening session pointing out bright stars and planets will give the students an idea of the brightness of the supernovae. Pointing out constellations will show the locations.

3. A map of pulsars as seen from Earth is included in a 1968 Anthony Hewish article on pulsars published in *Scientific American*. A similar map is in *Sky and Telescope*, July 1970. Discuss the concentration of the pulsars to the band of the Milky Way. Are most of the stars also in the Milky Way band? The concentration of supernovae to the Milky Way band is discussed in the text.

4. Some articles on X-ray stars are in *Sky and Telescope*, April 1973, and *Scientific American*, July 1972. A popular discussion of white dwarfs and neutron stars is in *Sky and Telescope*, January 1971. An article titled "The Death of a Star" may be found in the *World Book Encyclopedia Science Year, 1968*, p. 70. An article on black holes, "Gravitational Collapse," appears in *Scientific American*, November 1967.

Other relevant articles that may be used for class reports appeared in *Sky and Telescope*, November and December 1970 and January and February 1971.

5. The teacher can discuss nuclear reactions on a level appropriate to the class. Descriptions may be found in many general science books and introductory physical science texts. Formation of the elements in stars should be emphasized in physics classes.

6. For physics classes, the rate of spin of a neutron star, as evidenced by the pulsar period, can be used as an illustration of angular momentum. The Sun's rotation period is about 25 days, at the present radius of 700 000 km. Calculate the period if the Sun were to collapse to the 700-km radius typical of the neutron star (it is close to the period of the Crab pulsar).

7. To demonstrate absorption, fill a rectangular aquarium or other tank with transparent sides with water. The length should be at least twice the width. Mix a dark dye, such as black ink, into the water until it appears moderately dark (but not so dark you cannot see through it). With the lights in the room turned out, shine a flashlight through the tank along the short side, then the long way. Compare the brightness of the flashlight in each case with the unobscured flashlight. If a photographic or other light meter is available, measure the difference in brightness. If an aquarium is not available, clear water glasses will do. Make sure the water is darkened to the same degree in each glass. Discuss how this illustrates the effect of dust clouds in space on starlight and the brightness of supernovae and their remnants.

Chapter III

1. Slides and pictures from Hale and Lick Observatories may be used to trace out networks of filaments and generally examine supernova remnants. (Are the filaments connected with each other?) Hale slides of interest include catalog numbers 7 (Crab Nebula, color S-22), 56, 57, 102, 111, 64, 108, 109 (color S-20), and 159. Lick catalog numbers include N3a, N3b, N3c, N5 (color X17), N5a, S17, and S30. See also the resource letter by Berendzen and DeVorkin. An article on "Supernova Remnants" may be found in *Scientific American*, July 1971.

2. Teachers of physics classes can give a problem of conservation of momentum based on an expanding supernova shell colliding inelastically with interstellar gas. Have students find the speed of several radii. A typical shell is one solar mass with an initial speed of 8000 km/s. Interstellar matter has a density of about 1 hydrogen atom per cubic centimeter.

3. At various times starting in late 1945, photographs of nuclear explosions (atom and hydrogen bomb tests) have appeared in *Life* and other magazines. Find some of these showing the explosion step by step before the cloud forms. Compare these pictures to the photographs of supernova remnants in this brochure and the Hale and Lick slides (see number 1 above).

Chapter IV

These topics should be discussed in more detail. For example, is Europe's weather likely to have been bad all during 1054? Is it reasonable that our galaxy would have fewer supernovae (or otherwise be so unique) than any other galaxy, including galaxies that look the same? How fast would a runaway pulsar have to go to get outside the expanding shell (physics classes can work a problem based on the orbital speed obtained from Kepler's third law)? Could the pulsar's beam be pointing in another direction?

GLOSSARY

atom– smallest particle of an element, consists of a nucleus and electrons in orbit about the nucleus.

black hole– object with extremely high surface gravity. Gravity is high enough to trap light and crush matter beyond recognition.

disc (of galaxy)– flat disc-shaped region of galaxy containing most of stars, on which spiral pattern is superimposed.

Doppler shift– change in wavelength of light or sound caused by motion toward (blue shift) or away from (red shift) observer.

electron– negatively charged subatomic particle that normally moves about the nucleus of the atom.

galactic longitude– longitude of a star or other object in the sky measured in degrees (like longitude on Earth). The "equator" is the plane of the Milky Way. The starting point (0°) like the Greenwich meridian is the direction toward the center of the galaxy as seen from Earth.

galaxy– large grouping of stars, typically 10^6 to 10^{11} stars.

interstellar matter– gas and dust in the galaxy between the stars.

kpc– kiloparsec

Milky Way– our own galaxy, a spiral galaxy.

nebula– cloud of interstellar gas or dust. Sometimes a galaxy.

neutrino– a neutral particle smaller than a neutron, having a mass approaching zero.

neutron– a subatomic particle with no charge and the same mass as a proton. Part of the nucleus.

neutron star– a star of extremely high density composed entirely of neutrons.

nucleus– (of atom) heavy part of an atom, made of neutrons and protons, with a positive charge. The electrons go around the nucleus.
(of galaxy) central concentration of stars, gas, and dust in a galaxy.

parsec– 3×10^{15} m.

proton– a subatomic particle with a positive charge, about 1800 times heavier than the electron.

pulsar– a pulsating radio source. Probably a rotating neutron star.

quasar— any of a number of starlike objects that emit immense quantities of energy and that appear to be extremely distant from the Earth.

solar mass— 2×10^{30} kg.

spiral arms— the part of a spiral galaxy where the gas, dust, and young stars are concentrated, distributed in a spiral pattern throughout the galaxy.

white dwarf— a star that is very dense and small, having exhausted all of its nuclear fuel.

50

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