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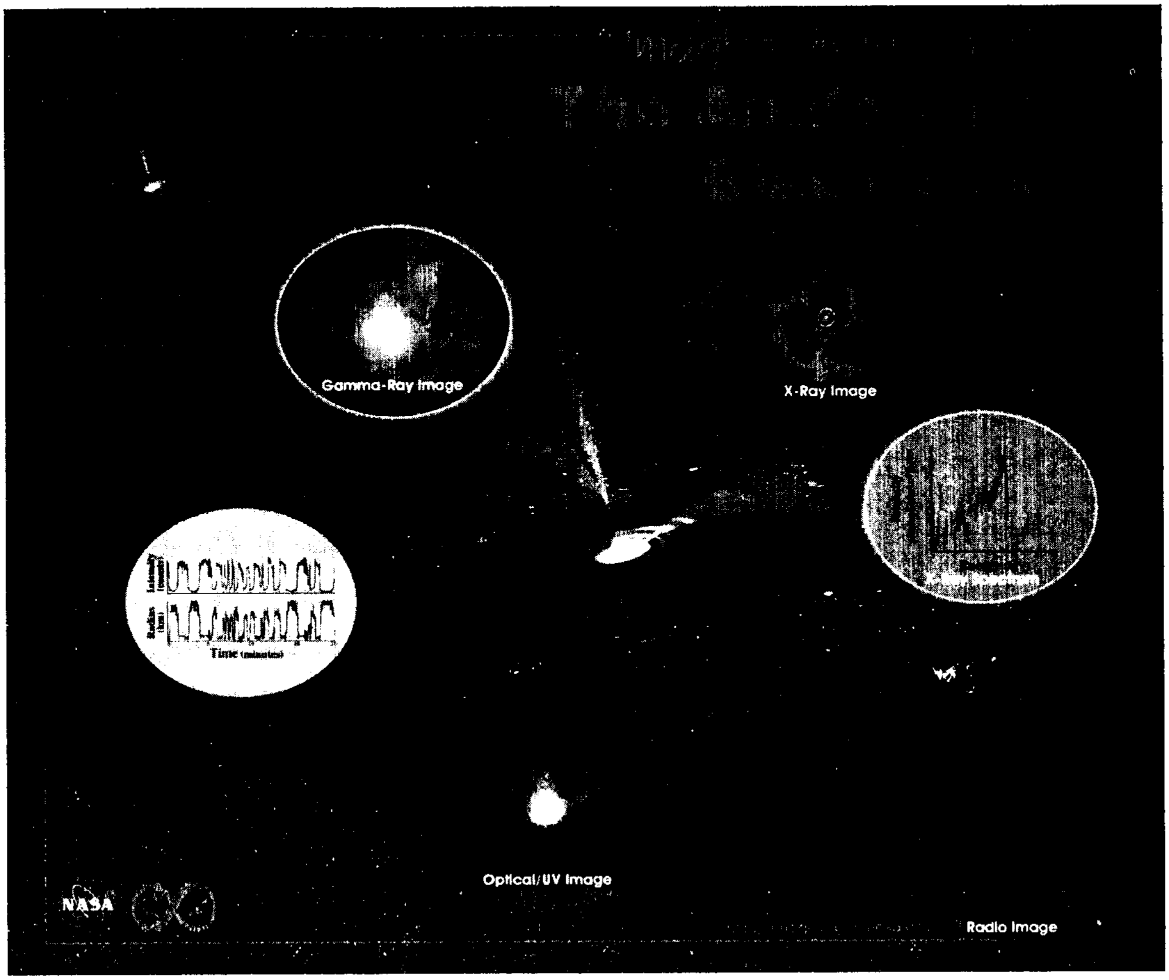
ABSTRACT

The information provided in this booklet is meant to give the necessary background information so that the science of black holes can be taught confidently to secondary students. The featured activities can be used to engage and excite students about the topic of black holes in different disciplines and in a number of ways. Activities include: (1) Model a Black Hole; (2) Tin Foil, Balloons, and Black Holes; (3) Gravity Is as Gravity Does; (4) Testing Einstein 101; (5) Crossing the Event Horizon; (6) How Much Do You Know?; (7) Inevitable Mathematics; and (8) So, You Want to Be a Black Hole? A poster and a CD-ROM accompany this guide. (WRM)



An Information & Activity Booklet

Grades 9-12

1998-1999

IMAGINE THE UNIVERSE!

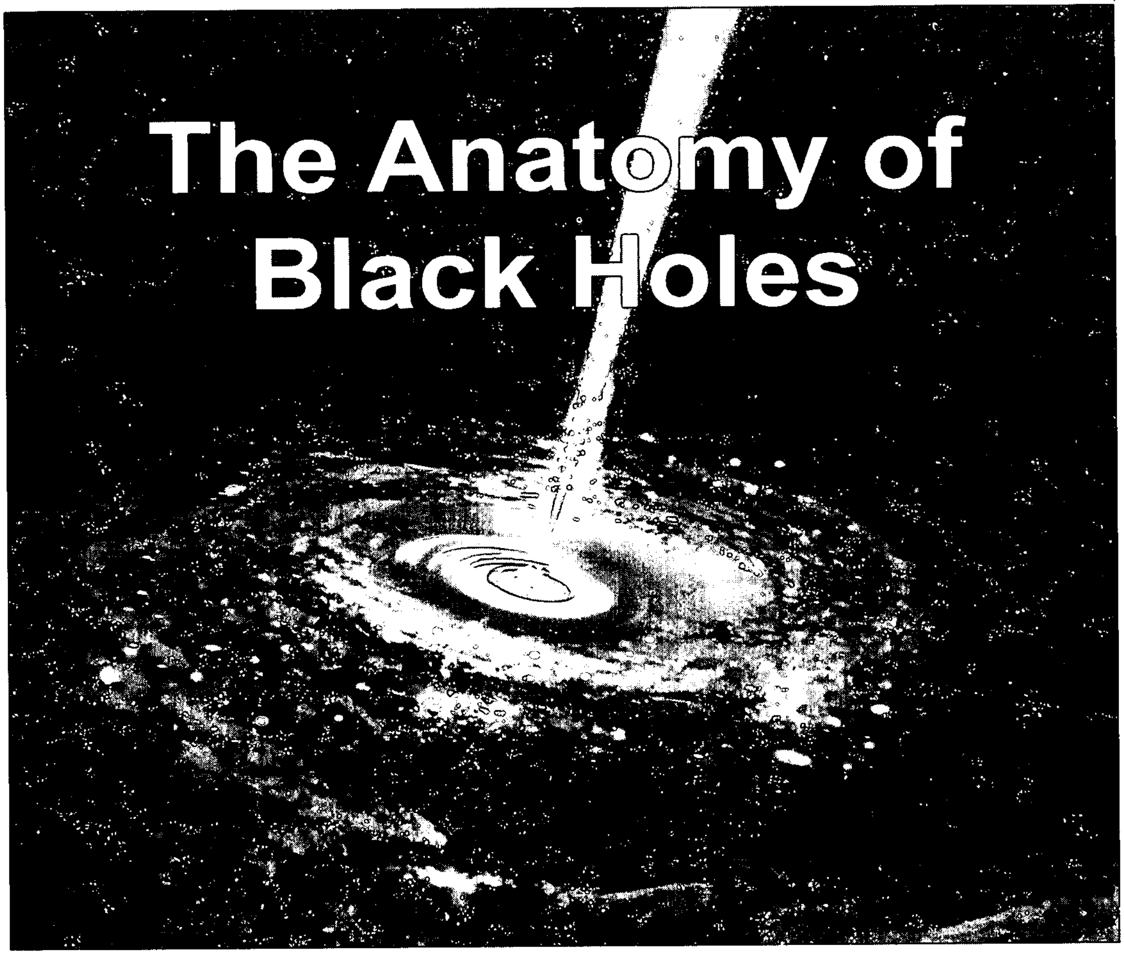
Probing the Structure & Evolution of the Cosmos

http://imagine.gsfc.nasa.gov

NP-1998(08)-040-GSFC

IMAGINE THE UNIVERSE!

Presents



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This booklet, along with its matching poster, is meant to be used in conjunction with the IMAGINE THE UNIVERSE! Web site or CD-ROM.
http://imagine.gsfc.nasa.gov/

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National Mathematics and Science Content Standards for the Activities in this Booklet

All Standards are for Grades 9-12

• Model a Black Hole

NSES

Standard A: Science as Inquiry
Standard D: Structure and Evolution of the Universe

• Tin Foil, Balloons, and Black Holes

NSES

Standard A: Science as Inquiry
Standard D: Structure and Evolution of the Universe

• Gravity Is as Gravity Does

NSES

Standard A: Science as Inquiry
Standard B: Physical Science
Standard D: Structure and Evolution of the Universe
Standard G: History and Nature of Science

NCTM

Standard 1: Problem Solving
Standard 2: Communication
Standard 3: Reasoning
Standard 4: Connections
Standard 5: Algebra
Standard 7: Statistics
Standard 8: Patterns

• Testing Einstein 101

NSES

Standard A: Science as Inquiry
Standard D: Structure and Evolution of the Universe
Standard G: History and Nature of Science

• Crossing the Event Horizon

NSES

Standard A: Science as Inquiry
Standard B: Physical Science
Standard D: Structure and Evolution of the Universe

NCTM

Standard 1: Problem Solving
Standard 2: Communication
Standard 3: Reasoning
Standard 4: Connections
Standard 5: Algebra

• How Much Do You Know?

Standard A: Science as Inquiry
Standard D: Structure and Evolution of the Universe

• Inevitable Mathematics

Standard D: Structure and Evolution of the Universe

Standard 1: Problem Solving
Standard 2: Communication
Standard 3: Reasoning
Standard 4: Connections
Standard 5: Algebra
Standard 6: Functions
Standard 8: Patterns

• So You Want to be a Black Hole?

Standard A: Science as Inquiry
Standard B: Physical Science
Standard D: Structure and Evolution of the Universe

Standard 1: Problem Solving
Standard 2: Communication
Standard 3: Reasoning
Standard 4: Connections
Standard 5: Algebra

Preface

WELCOME to the second in a series of posters and activity booklets produced in conjunction with the *Imagine the Universe!* Web site. The poster/booklet sets are intended to provide additional curriculum support materials for some of the subjects presented in the Web site. The information provided for the educator in the booklet is meant to give the necessary background information so that the topic can be taught confidently to students. The activities can be used to engage and excite students about the topic of black holes in a number of disciplines and ways. All activities can be photocopied and distributed for educational, non-commercial purposes!

For additional materials and information, visit the *Imagine the Universe!* Web site at http://imagine.gsfc.nasa.gov/. We also look forward to hearing your opinions about this poster/booklet set! Our email address is ideas@heasarc.gsfc.nasa.gov.

The Anatomy of Black Holes

I. Welcome to an Amazing Universe

Black holes exert a strong pull on both the scientific and the popular imaginations. They often prove beyond the limits of our abilities to comprehend. Indeed, they sound like a lot of nonsense from a bad movie. Nevertheless, black holes have gone from being a "purely theoretical fancy" to being the objects of cutting-edge scientific study. We have strong evidence that black holes not only exist, but may exist in the centers of *every* galaxy. We have a good theory, general relativity, that describes what happens around a black hole. It is a theory which completely overturned our commonplace notion of space and time, and nowhere do we see its amazing conclusions so strikingly as around black holes. Through a study of black holes, we will begin to piece together our picture of the fundamental physics of spacetime. And no doubt, the Universe will hold many surprises for us in our quest!

Let us begin our journey with a brief discussion of the difference between the world as we experience it in our everyday lives (the Newtonian world), and the world we must enter in order to understand the superstrong gravity which leads to a black hole (the world of Einstein). Let us consider what is experienced by a person standing on the surface of a non-rotating moon. According to the Newtonian view, the gravitational force this person is subjected to is proportional to the product of the moon's mass and the person's mass, and inversely proportional to the squared radius of the moon. Einstein's view of gravity would yield a value of the force slightly greater than Newton's value ("slightly" is a word we will define later). Let us suppose that the moon is now magically crushed. Its radius becomes smaller and smaller while its mass remains constant. According to Newton, contraction by a factor of two increases the force by a factor of four. Einstein predicts that the force increases slightly faster (there is that word again - *slightly*). So in fact, the smaller the radius of the moon, the greater the difference between the force predicted by Newton and that predicted by Einstein. According to Newton, as the size of the moon tends toward a point, gravitational force tends toward infinity. According to Einstein, infinite gravitational force occurs as the radius of the moon approaches the so-called "gravitational radius" of the body (which can be far from being point-size). The size of the gravitational radius is determined by the amount of mass: the smaller the mass, the smaller the gravitational radius. For Earth, the gravitational radius is about 1 centimeter; for the Sun, its is about 3 kilometers. Thus, we come to the heart of the difference between Newton's view of gravity and Einstein's: if the actual size of an object is much larger than its gravitational radius, the differences in the gravitational force calculated by the two theories is extremely small. (On the Earth's surface, for example, the difference is one billionth of the value of the force - a very *slight* difference indeed!). Only when the compressed radius of the object approaches its gravitational radius do the values calculated by the two theories begin to differ significantly...and the value given by Einstein's theory proves to be the correct one.

II. Introduction to Black Holes

Only in the last few decades as astronomers started looking at the Universe in radio, infrared, ultraviolet, X-ray, and gamma-ray light have we learned very much about black holes. However, the concept of a black hole has been around for over 200 years. English clergyman John Michell suggested in 1784 that some stars might be so big that light could never escape from them. A few years later, French mathematician Pierre Simon de Laplace reached the same conclusion. Michell and Laplace both based their work on the ideas about gravity put forth by Isaac Newton in 1687. Newton had said that objects on Earth fall to the ground as a result of an attraction called gravity. The more massive (heavier) an object is, the greater its pull of gravity. Thus, an apple would fall to Earth. His theory of gravity ruled unchallenged until 1915 when Einstein's general theory of relativity appeared. Instead of regarding gravity as a force, Einstein looked at it as a distortion of space itself.

Shortly after the announcement of Einstein's theory, German physicist Karl Schwarzschild discovered that the relativity equations led to the predicted existence of a dense object into which other objects could fall, but out of which no objects could ever come. (Today, thanks to American physicist John Wheeler, we call such an object a "black hole".) Schwarzschild predicted a "magic sphere" around such an object where gravity is so powerful that nothing can move outward. This distance has been named the Schwarzschild radius. It is also often referred to as the event horizon, because no information about events occurring inside this distance can ever reach us. The event horizon can be said to mark the surface of the black hole, although in truth the black hole is the singularity in the center of the event horizon sphere. Unable to withstand the pull of gravity, all material is crushed until it becomes a point of infinite density occupying virtually no space. This point is known as the singularity. Every black hole has a singularity at its center.

Ignoring the differences introduced by rotation, we can say that to be inevitably drawn into a black hole, one has to cross inside the Schwarzschild radius. At this radius, the escape speed is equal to the speed of light; therefore, once light passes through, even it cannot escape. Wonderfully, the Schwarzschild radius can be calculated using the *Newtonian* equation for escape velocity

$$V_{esc} = (2GM/R)^{1/2}.$$

For photons, or objects with no mass, we can substitute c (the speed of light) for V_{esc} and find the Schwarzschild radius, R, to be

$$R = 2GM/c^2.$$

This equation implies to us that any object with mass M can become a black hole if it can achieve a radius of R!

A. Black Holes Come in All Sizes (Masses)....

Black holes can be said to "come in all sizes", meaning that they have a wide range of masses. There are at least two different types of black holes. The types differ by their masses. We are perhaps most familiar with "stellar-size black holes"; these are the black holes which form from the death of a very massive single star. They tend to have masses in the range of a few to a few tens of solar masses. Next, there are what are called the "supermassive black holes"; these objects have the mass of a few billion to hundreds of billions of solar masses. They exist in the centers of galaxies.

• More about Stellar-mass Black Holes

The most common types of black holes have a mass of between about four and a few tens of solar masses. They are the remains of supernovae - the explosions of massive stars. To understand how such black holes can form, let us briefly review the life cycle of a massive star.

For stars some 10 or more times as massive as our Sun, fate has something very special in store when they begin to run out of hydrogen to fuse into helium. After the outer layers of the star have swollen into a red supergiant (i.e., a very big red giant), the core begins to yield to gravity and starts to shrink. As it shrinks, it grows hotter and denser, and a new series of nuclear reactions begin to occur, temporarily halting the collapse of the core. However, when the core becomes essentially just iron, it has nothing left to fuse (because the nuclear structure of iron does not permit its atoms to fuse into heavier elements) and fusion ceases. In less than a second, the star begins the final phase of its gravitational collapse. The core temperature rises to over 100 billion Kelvin as the iron atoms are crushed together. The repulsive force between the nuclei overcomes the force of gravity, and the core recoils out from the heart of the star in an explosive shock wave.

So what, if anything, remains of the core of the original star? Unlike in smaller stars, where the core becomes essentially all carbon and stable, the intense pressure inside the supergiant causes the electrons to be combined with the protons, forming neutrons. In fact, the whole core of the star becomes nothing but a dense ball of neutrons. It is possible that this core will remain intact after the supernova, and be called a neutron star. However, if the original star was very massive (say 10 or more times the mass of our Sun), even the neutrons will not be able to withstand the core collapse and a black hole will form.

Such black holes may exist all by themselves in the vast reaches of space, or may be part of a binary system of stars. There are certain conditions under which a star can start out in a binary system (the usual condition for a star), undergo a supernova explosion, and yet still remain locked into the binary system. It is possible in such systems that there will be a flow of gas from the outer layers of the normal star into the gravitational field of the black hole companion. This gas cannot simply fall onto the black hole, the orbital motion of the pair of stars will make it go into rotation and form a disk around the black hole. Friction between the disk components will heat the gas to 10,000,000 Kelvin before it reaches the event horizon, and a gas of such temperature emits X-rays.

• More about Supermassive Black Holes

In 1963, Dutch-American astronomer Maarten Schmidt was analyzing observations of a "star" named 3C 273. He had optical and radio data, and it was very confusing. He had discovered what he and his colleagues dubbed a "quasi-stellar radio object" or quasar. The average quasar is no bigger than our solar system, but is brighter than a trillion Suns. We now know that a quasar is a type of Active Galactic Nucleus (AGN) in the heart of an otherwise normal galaxy. We believe that an AGN is nothing more than a typical galaxy with a supermassive black hole in its center, creating an enormous, anomalous luminosity as it accretes nearby material. In addition, through observations, we now understand that quasars were more common at earlier times than the present, and their enormous luminosities make them excellent probes of great distances. They can provide us with fundamental information about the Universe during the time of galaxy formation and early evolution.

We now have objects called quasars, Seyferts, and blazars...all of which we believe may be galaxies with supermassive black holes in their centers. In fact, one currently popular model states that these three types of objects are all the same type of object (a regular galaxy with an active center due to accretion onto a supermassive black hole) viewed from different angles.

B. If We Can't See It, How Do We Know It's There?

The closest possible black hole to us will be a stellar-mass black hole. A stellar-mass black hole requires a massive progenitor. The nearest such star is tens of light-years away. The event horizon of such a back hole is at most a few tens of kilometers in diameter. Thus, the angular size of this hypothetical black hole is 0.00000001 seconds of arc. Bottom line: a black hole floating alone in space would be hard, if not impossible, to see. Nevertheless, there is now a great deal of observational evidence for the existence of both stellar-mass and supermassive black holes. How has this happened?

If a black hole passes through a cloud of interstellar matter, or is close to another "normal" star, the black hole can accrete matter into itself. As the matter is pulled towards the black hole, it gains kinetic energy, heats up, and is squeezed by tidal forces. As it gets hotter, its peak radiation moves progressively through the ultraviolet, X-ray, and gamma-ray wavelengths. In fact, we expect X-ray emission to occur just before the matter crosses the Schwarzschild radius, and can use this radiation to probe the most extreme environments of gravity, density, temperature, and velocity. However, it is not as simple as this may sound.

To search for X-ray emission from black hole binary systems was first suggested in 1966 by Igor Novikov and Yakov Zel'dovich - not long after the discovery of the first cosmic X-ray sources. Ever since, a "signature" in the emission properties of a source to classify it as a black hole (versus a white dwarf or neutron star) has been sought. We know that the mass calculated for the condensed star must exceed 3 solar masses in order to be considered as a black hole; we know that a characteristic "double-horn" shape will be introduced into the spectrum of a black hole due to a gravitational redshift; we know that the X-ray emission from a black hole should be highly variable in time. But are any of these methods a foolproof way of identifying black holes to the exclusion of any other type of celestial object? The answer is not yet clear. Several objects, starting with Cygnus X-1, have been tentatively identified as black holes via such methods, and while some scientists believe these absolutely are black holes, other scientists still wait for confirming evidence.

C. Journey into a Black Hole

Let us now stretch our imaginations by taking a trip into a black hole. What happens to you as you journey into a black hole depends on how massive the black hole is, but maybe not in the way you might imagine! Let us consider the forces, called tidal forces, which your body will experience as you spiral closer to the event horizon of a black hole.

Suppose that you are in a spaceship safely orbiting a 10 solar mass black hole. You decide to get closer to the event horizon, which has a radius of about 30 km. At a radial distance of around 15,000 km you already know that something strange is going on. Inside your spaceship, with your head toward the stars and your feet toward the black hole, you begin to feel a slight pull downward on your feet and upward on your head. This is the onset of the amazing tidal forces surrounding a black hole. These are the same forces as the Earth exerts on you when you stand on its surface. However, the difference between the force exerted by the Earth on your head versus your feet because one is further away from the center than the other is miniscule...less than one part in a million. For the superstrong gravitational field of black hole, however, it is not so trivial. Even at a large distance from the event horizon such as 15,000 km, the difference between the gravitational pull on your head and your feet is about 1/8 of the Earth's gravitational pull. Uncomfortable, but not painful, you continue to spiral in slowly to a distance of about 8,000 km. At this point, you experience a stretch of 4 times the Earth's gravity. Things are not fun anymore, but continue on toward 3,000 km. There is now a 15g stretching force. You cannot stand it. You give up and move your spaceship back to a comfortable distance. Whew!

Do all black holes have such strong tidal forces at such large distances from the event horizon? No, and this may sound odd, but the larger the mass of the black hole, the weaker the tidal forces will be! This seemingly paradoxical situation has a simple origin: the tidal force is proportional to the hole's mass divided by the cube of its circumference. So as the mass grows and the horizon radius grows proportionally, the near-horizon tidal force actually decreases. For a black hole weighing a million solar masses, the tidal force is 10 billion times weaker than what they are for a 10 solar mass black hole.

Thus, it is most instructive, phenomenologically, to fall into a very massive black hole like the kind you would find in the center of an active galaxy. We will try to understand what happens both from the perspective of the one who is falling (which we will call the Explorer) and from the perspective of those watching from a safe distance away (which we will call the Watchers). The journey will appear to be completely different from those two perspectives, thanks to the amazing behavior of space and time in the clutches of a black hole's gravitational pull.

As our Explorer begins to fall toward the black hole, for the first few minutes of the journey nothing will appear out of the ordinary. Clocks on board our intrepid Explorer and on board the safe-distanced Watchers are in unison. Space is not distorted and the light coming from the Explorer is normal. As our Explorer approaches the event horizon, she begins to be stretched out because gravity is pulling more strongly on her feet than on her head. Although to our Explorer time is still running along in a normal fashion, the Watchers now see her clock running slow. The strong gravity of the black hole is now distorting both space and time. The Watchers also notice that the Explorer now appears to look redder than normal, as light loses energy in its struggle with gravity to pull away from the hole. Just above the event horizon, the elongated Explorer is almost invisible. The light has become extremely red and dim as it loses most of its energy in its fight with gravity. Amazingly, the Watchers never see the Explorer fall into the black hole. Because time runs slower and slower near the hole, she never appears to cross the event horizon, but seems to hover just above it for infinite time. The experience, however, is quite different for the Explorer, who feels herself being pulled faster and faster into the black hole. As she crosses the event horizon, the black void is suddenly replaced by an unimaginable array of views. We do not know what she may see inside the black hole and, unfortunately, she can never communicate her discoveries back to the Watchers. Within a few seconds, she is swept into the singularity.

III. The Electromagnetic Spectrum as a Probe of Black Holes

All objects in our Universe emit, reflect, and absorb electromagnetic radiation in their own distinctive ways. The way an object does this provides it special characteristics which scientists can use to probe an object's composition, temperature, density, age, motion, distance, and other chemical and physical quantities. While the night sky has always served as a source of wonder and mystery, it has only been in the past few decades that we have had the tools to look at the Universe over the entire electromagnetic (EM) spectrum and see it in all of its glory. Once we were able to use space-based instruments to examine infrared, ultraviolet, X-ray, and gamma-ray emissions, we found objects which were otherwise invisible to us (e.g., black holes and neutron stars). A "view from space" is critical since radiation in these ranges cannot penetrate the Earth's atmosphere. Many objects in the heavens "light up" with wavelengths too short or too long for the human eye to see, and most objects can only be fully understood by combining observations of behavior and appearance in different regions of the EM spectrum.

We can think of electromagnetic radiation in several different ways:

• From a physical science standpoint, all electromagnetic radiation can be thought of as originating from the motions of atomic particles. Gamma-rays occur when atomic nuclei are split or fused. X-rays occur when an electron orbiting close to an atomic nucleus is pushed outward with such force that it escapes the atom; ultraviolet, when an electron is jolted from a near to a far orbit; and visible and infrared, when electrons are jolted a few orbits out. Photons in these three energy ranges (X-ray, UV, and optical) are emitted as one of the outer shell electrons loses enough energy to fall down to the replace the electron missing from the inner shell. Radio waves are generated by any electron movement; even the stream of electrons (electric current) in a common household wire creates radio waves ...albeit with wavelengths of hundreds of kilometers and very weak in amplitude.

• Electromagnetic radiation can be described in terms of a stream of photons (massless packets of energy), each traveling in a wave-like pattern, moving at the speed of light. The only difference between radio waves, visible light, and gamma-rays is the amount of energy in the photons. Radio waves have photons with low energies, microwaves have a little more energy than radio waves, infrared has still more, then visible, ultraviolet, X-rays, and gamma-rays. By the equation $E=h\nu$, energy dictates a photon's frequency and, hence, wavelength.

The value of the EM radiation we receive from the Universe can be realized by considering the following: Temperatures in the Universe today range from 10^{10} Kelvin to 2.7 Kelvin (in the cores of stars going supernova and in intergalactic space, respectively). Densities range over 45 orders of magnitude between the centers of neutron stars to the virtual emptiness of intergalactic space. Magnetic field strengths can range from the 10^{13} Gauss fields around neutron stars to the 1 Gauss fields of planets such as Earth to the 10^{-7} Gauss fields of intergalactic space. It is not possible to reproduce these enormous ranges in a laboratory on Earth and study the results of controlled experiments; we must use the Universe as our laboratory in order to see how matter and energy behave in these extreme conditions. Understanding this behavior is central to our ability to take our current models and extrapolate them successfully into "what will become of our Universe?"

As we develop better observing technologies and techniques, we can ask and answer fundamental questions, such as:

• What happens to pressure, to temperature, and to the states of matter in the intense gravity near a black hole? Black holes give us access to conditions that exist no where else in the Universe and future X-ray missions will be able to probe very close to the event horizon of a black hole. An emission line in the gravitational field of a black hole has a characteristic, identifiable shape; it is redshifted (gravitational redshift) with a peculiar double peak. Current instruments do not have enough collecting area to gather enough information on the short timescales required by the changing emission from a supermassive black hole. On timescales of an hour, we need to get enough photons for a good observation with enough resolution to be able to observe the characteristic shape of the line in order to be an effective probe.

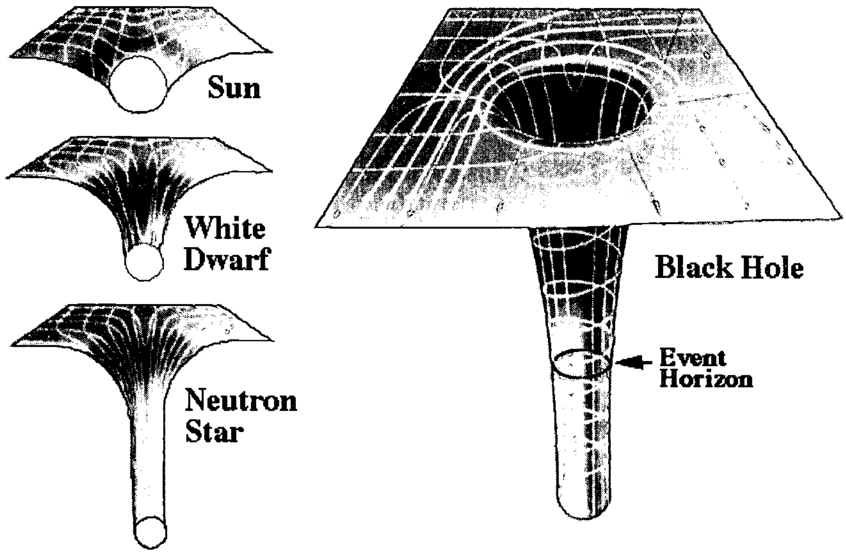
• How does matter flow in an accretion disk around a black hole? Less powerful, but closer, active galaxies will allow us to probe the outer portions of the accretion disks. Recent Very Long Baseline Interferometry (VLBI) observations have enabled us to measure the mass of the central black hole with unprecedented accuracy. Extending this technique to more distant and smaller galaxies, requiring a full-scale space-based VLBI capability, is the next step to fully understand how gas in the outer part of the disk is fed inward to the black hole.

• What causes jets? Numerous observations show that cosmic jets are a frequent natural consequence of accretion disks. These collimated beams shoot out perpendicular to the accretion disk around the compact object. First discovered by radio astronomers, they are now regularly seen at optical, X-ray, and gamma-ray wavelengths as well. Understanding how these jets are formed and what role they play in the accretion process is a major unsolved question. In particular, we need to determine if they are launched and collimated by magnetic stresses or if the pressure of the intense radiation fields (or some other phenomenon) is responsible. The jets accelerate electrons up to nearly the speed of light, producing gamma-rays which can be used as a probe of the jet environment. In addition, from high resolution X-ray spectra, we can estimate the velocity distribution of high energy electron populations and deduce magnetic field strengths.

IV. Activities and Problems Related to Black Holes

Model a Black Hole

This demonstration allows for a visual depiction of the effect of a large mass on the fabric of spacetime. In particular, what effect a black hole does or does not have on the other stars around it and how that effect depends on the mass of the black hole. Remember that Newton saw objects with increasing mass as having an increasing escape velocity; Einstein saw them as making deeper "dents" in the fabric of spacetime!



A black hole makes such a deep "dent" that it forms a bottomless well. The sides of the well are so steep that even light cannot escape once it has fallen deeper into the well than the event horizon depth.

Materials:

* Large latex balloon cut open and pulled flat, or sheet of latex
* Round bowl, roughly 4" in diameter
* Tape
* Package of small round beads (such as you might find in the cake decorating section of a grocery store)
* 1" solid ball bearing (the eraser end of a pencil can be used as a replacement)

Procedure:

1. Tape the sheet of latex (this represents space-time) tightly across the top of some round object, such as a bowl or even a coffee cup. The sheet should not be so tight that it will tear if stretched further, but should be taut enough that there are not any wrinkles!
Note: This is much easier to do with the help of a partner!

2. Scatter a few beads on the sheet of latex (this represents matter that is near the black hole). Make sure they are spread out to all parts of the sheet.

3. Gently place the ball bearing onto the sheet of latex (this represents the black hole). Try not to let it bounce! If you don't have a ball bearing, gently push down on the center of the sheet with the eraser end of a pencil.

4. Explain what happened to the matter when the black hole was put into place. Why did this occur?

5. What would happen if the ball bearing was heavier (or if you push harder on the pencil)? What physical analogy to the black hole may be made?

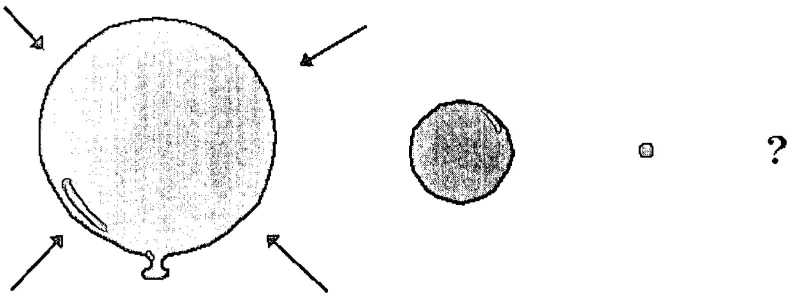
Tin Foil, Balloons, and Black Holes

Materials:

* Round, black balloon
* Several feet of tin foil
* Balance or scales (best if can measure to at least 0.1 grams)
* Vernier caliper or ruler
* Tape

Let us first conceptualize the formation of a black hole:

Blow up the balloon so that it has a diameter of about 5 inches. Tie the end so it remains inflated. Cover the outside of the balloon with tin foil so that it stays on the balloon. Be generous with the tin foil and cover the balloon thoroughly. It works best if you use long sheets and wrap around twice, rather than using several short sheets. Use tape if necessary. We will consider this to be our star, with the balloon representing the "core" and the tin foil representing the "outer layer material". Weigh the star on the scale and record this (and all future) measurement in a data table. Now squeeze your star such that the balloon bursts inside the tin foil. (Think of this as the simulation of the enormous mass of the star collapsing inward toward the core.) Now carefully crumple the tin foil into a loosely compacted ball. Weigh it again. Measure its diameter. Now crush it into a smaller ball. Weigh it and measure its diameter. Crush it into as small a ball as you can with your hands. Weigh it and measure its diameter.



What do you notice from your measurements about the weight of the crumpled ball as the size of the ball changes? What about changes in the density of the ball, where density equals mass divided by volume (for a sphere, the volume is equal to $4/3\,\pi\,r^3$)? How small would you have to make the ball of tin foil for it to achieve the average density of the Sun (1.4 g/cm^3)? What about the density of a neutron star (10^{37} g/cm^3)? How small would you have to make the ball for it to become a black hole?

Hint: Use the equation for the Schwarzschild radius! $G = 6.67 \times 10^{-11}$ $m^3/kg\text{-}sec^2$ and $c=3\times10^8$ m/sec.

Based on an idea from Jeffrey F. Lockwood, *Mercury Magazine*, Volume 27, No. 2, p. 5, 1998.

Gravity Is as Gravity Does

Gravity, whether it is holding you to the Earth's surface or swallowing light in a black hole, is the same force obeying the same laws at all places in the observable Universe.
We can measure it with this simple lab...

Measuring the Acceleration of Gravity: A Comparison of Two Methods

PURPOSE: To confirm the numerical value of g using two different experimental methods.

MATERIALS: Part A: tuning forks with frequencies between 256 - 384 Hz; adding machine tape; carbon paper; masking tape; hooked 100 g or 200 g masses; ruler or meter stick. Part B: ring stand or other device to support a pendulum; one meter of string per lab station; a pendulum bob, or hooked mass; a stop watch.

PROCEDURE - Part A

Measure a length of paper tape slightly greater than the distance from the lab bench to the floor. Make several folds in the end of the paper tape, and secure it with masking tape. Poke a hole through the reinforced end of the paper tape and insert the hook of the laboratory mass. Tape a piece of masking tape or other smoother tape to the edge of the lab bench. Cut a piece of carbon paper which is the same size as the width of the paper tape with the height of the edge of the lab bench. Stick this piece of carbon paper onto the sticky side of another piece of tape so the part of the carbon paper that makes it black is facing the edge of the lab bench. Loosely tape the carbon paper over the other piece of tape. Thread your paper tape between the carbon paper and the taped edge of the lab bench. Hold the paper tape so that the mass is hanging freely just below the edge of the lab bench. Strike the tuning fork on a rubber mallet or the heel of your hand. Touch the edge of the vibrating tuning fork to the tape that has the carbon paper on it and release the paper tape so that the hooked mass falls to the floor. The tuning fork must stay in contact with the carbon paper during the entire fall. The vibrating tuning fork should make a series of dots on the paper tape. These dots should be increasingly farther from each other. It may take several tries to acquire a suitable tape. For a good analysis, the tape needs to have at least 50 dots in a straight line. Results are better with 60 dots, because the first few dots cannot be used, nor can dots that are equidistant be used.

After a suitable tape has been obtained, students should label with an A one of the first dots that is clearly formed near the beginning of the tape. Count 10 spaces between the dots and mark the end of the tenth space with a B. Continue marking every tenth dot with a letter until the end of the tape is reached or the dots become equidistant. With a ruler or meter stick measure the distances AB, AC, AD, AE, AF, AG, etc. Record these measurements in a data table with the frequency of the tuning fork you used.

ANALYSIS

From your tape you can see that the mass falls further during each time interval. When you subtract each of the distances, AB, BC, CD, ... from the previous distance, you find that the increase in distance fallen is a constant. That is, each difference BC - AB = CD - BC = DE - CD = gt^2. This quantity is the increase in the distance fallen in each successive 10 dot interval and is an acceleration.

From your data table make a table of calculated values of AB, BC, CD, DE, etc. In the next column of your table of calculated values, place values of BC - AB, CD - BC, and so on. These values should be reasonably constant. WHY? Average these values. This represents the constant increase in distance during each time interval. To find the time, divide 10 by the frequency of the tuning fork. Each blank space between dots represents one vibration of the tuning fork, and you counted 10 spaces or 10 vibrations between letters.

To calculate g divide the average distance by the time squared. If you used cm your answer should be 980 cm/s^2. Calculate your percent error. It should be less than 10%. You might want to repeat the experiment if your percent error is greater than 12%.

List some sources of error in this experiment. What errors would be introduced by using a tuning fork whose vibrations are slower than about 100 Hz? higher than about 400 Hz?

PROCEDURE - Part B

The best pendulum to use is one whose bob is a metal sphere hung by a fine thread. However, acceptable results can be obtained with a hooked laboratory mass or a washer and any kind of string or thread.

Obtain about one meter of string and a pendulum bob. Attach the string to a suitable stand (a ring stand, for example) and then attach the string to the pendulum bob. The pendulum should be able to swing freely without hitting anything. Measure the length, L, of the pendulum from its point of attachment to the middle of the bob. Set the pendulum swinging with small swings (not more than 10 degrees from the vertical.) Time at least 20 complete round trips. Repeat the timing of 20 complete swings until you are confident that you have a reproducible result. By timing many round trips instead of just one you make the error in starting and stopping the stopwatch a smaller fraction of the total time being measured.

ANALYSIS

Divide the total time by the number of complete swings to find the time T of one swing. This time is called the period of the pendulum. Using this equation for the period of a pendulum, $T = 2\pi (L/g)^{1/2}$, calculate the value for g. If you measured L in cm, your value should be 980 cm/s^2. Calculate your percent error, it should be about 1%.

Which of your measurements do you think was the least accurate?

If you believe it was your measurement of length and you think you might be off by as much as 0.5 cm, change your value of L by 0.5 cm and recalculate the value of g. Has g changed enough to account for your error? (If g went up and your value of g was already too high, then you should have altered your measured value of L in the opposite direction. Try again!)

If your possible error in measuring is not enough to explain your difference in g (your % error), try changing your total time by a few tenths of a second - a possible error in timing. Then you must recalculate T and g.

If neither of these attempts work (nor both taken together in the appropriate direction) then you almost certainly have made an error in arithmetic or in reading your measuring instruments. In this case you should repeat the experiment. Your value for g should not differ from the accepted value more than one unit in the third digit.

QUESTIONS

1. How does the length of the pendulum affect your value of T?

2. How does the length of the pendulum affect your value of g?

3. How long is a pendulum for which T = 2 seconds? This is a useful timekeeper.

4. Which experiment gave you the lowest percent error? Explain fully.

EXTENSION

Isaac Newton made a number of contributions to our understanding of gravity and the parameters upon which it is dependent. Consider the table of information below about the Sun and planets in our solar system. Then answer the questions which follow.

Object	**Mass (kg)**	**Acceleration due to gravity (m/s^2)**
Sun	1.991×10^{30}	293.0
Mercury	3.2×10^{23}	3.72
Venus	4.88×10^{24}	8.82
Earth	5.979×10^{24}	9.80
Mars	6.42×10^{23}	3.72
Jupiter	1.901×10^{27}	24.8
Saturn	5.68×10^{26}	10.5
Uranus	8.68×10^{25}	9.01
Neptune	1.03×10^{26}	11.7
Pluto	1.15×10^{22}	0.49

1. Based on the data, what generalization seems most appropriate?

2. Are there any exceptions to the generalization?

3. If there are exceptions, how might you account for them?

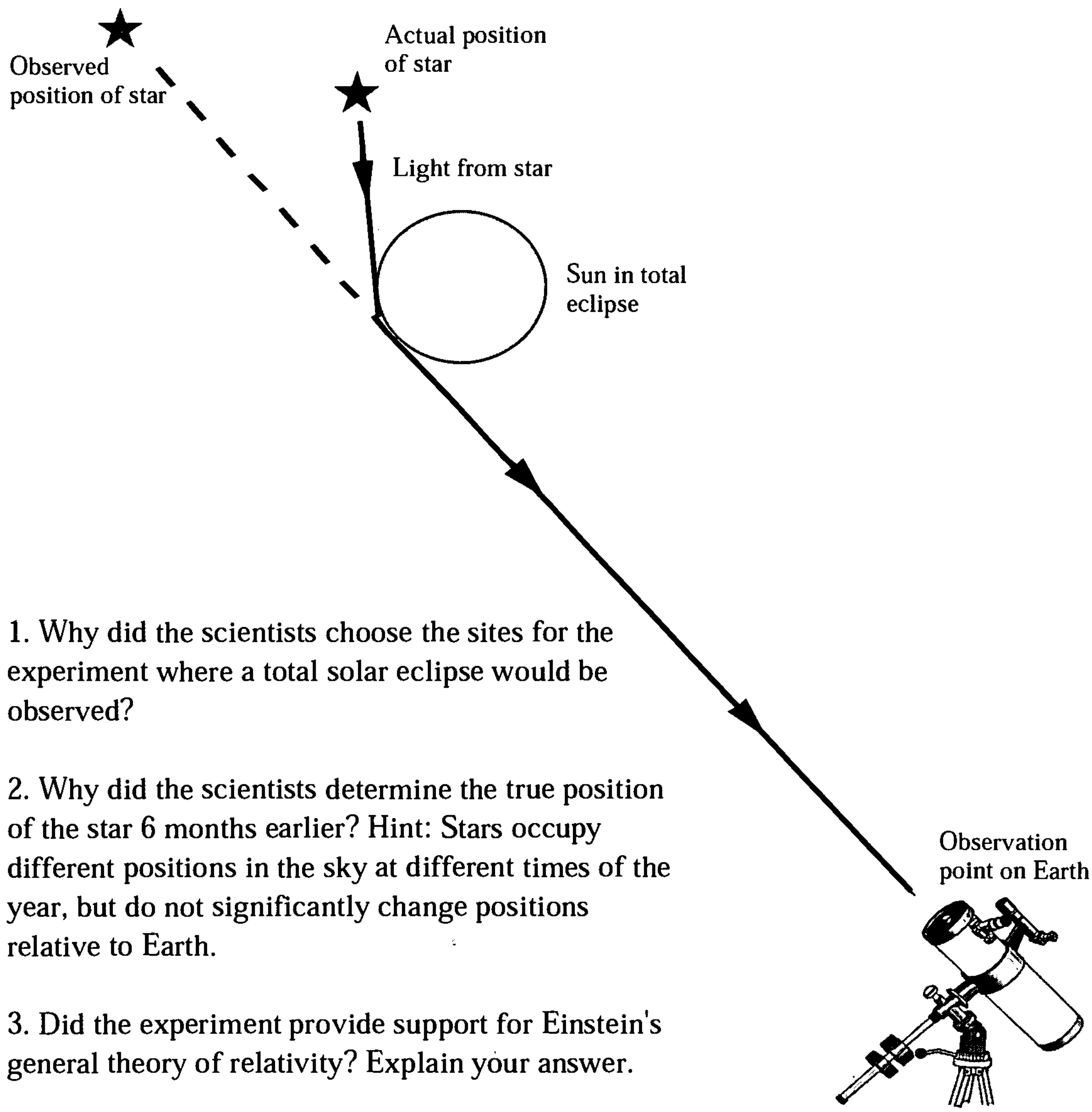
4. In what way would your weight vary, if at all, if you were to find yourself on each of the bodies in the table? Explain your answer.

5. From which body would the least energy be required to launch a projectile into space? Explain your answer.

This Extension activity is based on one found in the book *Physics Principles and Problems* by P. Zitzeitz, *et al.*

Testing Einstein 101

In 1915, Albert Einstein published an article in which he outlined his general theory of relativity. Amongst its many predictions, or predicted consequences, was that light should be deflected by a gravitational field. This idea, certainly radical at the time, seemed impossible to detect. However, scientists at the Royal Astronomical Society of London soon proposed an experiment that they believed would test Einstein's prediction. The experiment would be performed on March 29, 1919 at two separate locations: in northern Brazil and on an island off the West Coast of Africa. On that day, at those sites, a total eclipse of the Sun would be observed. The drawing below shows the position of the star as seen during the eclipse and the actual position of the star as had been established six months earlier. Study the drawing (exaggerated for clarity) and the answer the following questions.



1. Why did the scientists choose the sites for the experiment where a total solar eclipse would be observed?

2. Why did the scientists determine the true position of the star 6 months earlier? Hint: Stars occupy different positions in the sky at different times of the year, but do not significantly change positions relative to Earth.

3. Did the experiment provide support for Einstein's general theory of relativity? Explain your answer.

This activity is based on one found in *Physics Principles and Problems* by P. Zitzeitz, *et al.*

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Crossing the Event Horizon

If a black hole has no size, how do scientists talk about its surface? They don't really mean the physical surface of the black hole when they use the phrase "surface of a black hole", they mean the imaginary surface around the black hole at which the escape velocity is equal to the speed of light. In other words, if you are closer to the black hole than the distance to this surface, you cannot escape. If you are further away from the black hole than this distance, then there is still hope for you! The surface is called the event horizon, and its radius is the Schwarzschild radius. (Named for Karl Schwarzschild, an astronomer who was a member of the German army in World War I and died of illness on the Russian front in 1916. He applied the equations of general relativity to see what would happen to light near such a massive object.) It is important to keep in mind that the event horizon is not a physical boundary, but for all intents and purposes is the surface of the black hole. Once inside it, you are cut off from the rest of the Universe forever.

The relationship of the Schwarzschild radius to the black hole mass is simple:

$$R = 2GM/c^2$$

This can be easily understood by looking at the equation for the escape velocity from any spherical body such as a planet or star, namely, $v = (2GM/R)^{1/2}$, where M and R are the mass and radius of spherical object. For a black hole, the escape velocity is equal to c, the speed of light.

1. What would be the radius of a black hole with the mass of the planet Jupiter?

2. How would the period of the Earth's revolution change if the Sun suddenly collapsed into a black hole? Note that this can *never* happen!

3. Suppose the Earth were collapsed to the size of a golf ball...becoming a small black hole. What would be the revolution period of the Moon, at a distance of 381,500 km? of a spacecraft that had been hovering 300 m above a point on the surface of the Earth before its collapse? of a fly orbiting at 0.5 cm?

How Much Do You Know?

There are many popular myths concerning black holes, many of them perpetuated by Hollywood. Television and movies have portrayed them as time-traveling tunnels to another dimension, cosmic vacuum cleaners, and so on. Here is your chance to show what you know...or think you know! Decide if each of the following statements is either true or false. Explain how you came to your conclusions.

1. Black holes move around the Universe sucking up everything in sight.

2. Black holes will eventually suck in all the matter in the Universe.

Inevitable Mathematics

Scientists believe that if an object reaches a critical radius near a black hole, the object will inevitably be drawn into the singularity. In mathematics, a similar situation can occur. Some mathematical expressions and operations will result in a numerical 'black hole' no matter where you start!

A. Follow the below procedure starting with a positive integer. We show you the results for the beginning values of 5 and 7.

Start with a Number	**5**	**7**
Multiply it by 6	30	42
Add 12 to the result	42	54
Divide by 3	14	16
Subtract twice the original number	4	4

Why does this procedure always give the answer 4? Let us examine the steps. Go through the procedure again with the starting value of "B".

Start with a Number	B
Multiply it by 6	6B
Add 12 to the result	6B + 12
Divide by 3	(6B + 12) / 3 or 2B + 4
Subtract twice the original number	2B + 4 - 2B or 4

Notice that the final result is 4, regardless of the initial value. That is, all beginning numbers fall into the 'black hole' 4.

Now it is your turn. Can you create a numerical 'black hole' whose value is always 10?

B. Examine the procedure below.

Start with a Positive Integer	31
Square each digit and find the sum of the squares	$3^2 + 1^2 = 10$
Continue this process	$1^2 + 0^2 = 1$
What finally happens?	$1^2 = 1$

In this example, the beginning number falls into the numerical 'black hole' 1. Repeat the same steps with a starting value of 97. What number results?

Does starting with 81 yield the same type of numerical 'black hole' as starting with 97? Let us investigate:

$81 \rightarrow 8^2 + 1^2$ or 65, which becomes $6^2 + 5^2$ or 61. Following this through, you'll see the following pattern emerge:

$81 \rightarrow 65 \rightarrow 61 \rightarrow 37 \rightarrow 58 \rightarrow 89 \rightarrow 145 \rightarrow 42 \rightarrow 20 \rightarrow 4 \rightarrow 16 \rightarrow 37 \rightarrow 58 \ldots$

Notice that this sequence has begun to repeat and, in fact, falls into a cyclic numerical 'black hole'. The sequence eventually becomes periodic.

C. Now try 204. Does this create a new numerical 'black hole'? Justify your answer.

D. Can you describe without computation what happens if you start the procedure with 420?

So, You Want to be a Black Hole?

In theory, any object can become a black hole - as long as it can get small enough! For example, a person weighing 70 kg can become a black hole... if that person had the same mass, but was much, much smaller than the size of a hydrogen atom!

Recall the relationship of the Schwarzschild radius to the mass of the black hole:

$$R = 2GM/c^2$$

Let's use that equation to prove how small a person weighing 70 kg would have to be to become a black hole:

$R=2*(6.67X10^{-11})*70/((3X10^{8})^{2})=1.04 X 10^{-25}$ meters

Compare this the size of a hydrogen atom: $1X10^{-11}$ meters!

1. What would be the radius of the event horizon of a black hole with the mass of the planet Jupiter? how about Earth?

2. How large in mass would an object have to be in order to become a black hole with an event horizon the size of a basketball (consider the diameter of the ball to be 35 cm)?

V. Answers

Model a Black Hole

The heavy object representing the black hole will distort the latex surface (representing spacetime) and cause the small objects on the surface to be pulled in toward it... but not if you are too far away. A heavier ball bearing, however, would affect beads further out in the latex
sheet...just as a more massive black hole creates a larger distortion in spacetime, thus affecting objects further away.

Gravity is as Gravity Does

Extension:

1. Even though there are exceptions, the data tend to support the generalization that acceleration due to gravity varies directly with the mass of the object. This would be expected from this rearrangement of Newton's Universal Law of Gravitation: $g = GM/r^2$.

2. The exceptions are that Saturn and Neptune are in reverse order and so are Earth and Uranus.

3. Since acceleration due to gravity is measured at the surface of an object and since gravity increases exponentially as the distance between the surface of an object and its center decreases, an object of lesser mass but smaller radius may possesses a greater acceleration due to gravity than an object of greater mass and greater radius. When a table of planetary radii is consulted, it is found that the radius of Neptune in less than half that

of Saturn and the radius of Earth is about 1/4 that of Uranus. Based on the equation given in 2, it is reasonable to conclude that the radii of these objects account for what at first glance appear to be exceptions to the rule.

4. Your weight would change depending on the value for the acceleration due to gravity. Weight is a measure of the force that varies directly with the acceleration due to gravity, or simply $F = mg$. Thus, the larger the value of g, the greater your weight!

5. Since Pluto possesses the lowest acceleration due to gravity, thus the lowest force of attraction to its surface, less energy would be required to overcome that force than would be the case on any of the other objects.

Testing Einstein 101

1. During a total eclipse the sky would be dark and the stars could be observed. The light from some of the visible stars would pass close to the Sun.

2. If the star was visible in the sky during the day in March, six months earlier it was visible in the night sky. Since the position of stars relative to Earth remains essentially constant, determining the position of the star during the night (six months earlier) provided the scientists with valid data about the star's actual position.

3. Since the observed position of the star was more distant from the Sun's disc than its actual position, the scientists could conclude that light from the star was deflected toward the Sun by its gravitational field. Thus, the experiment supported Einstein's theory.

Crossing the Event Horizon

1. Using the Schwarzschild equation, we input the mass of Jupiter (1.9×10^{27} kg), the Gravitational constant ($G=6.67\times10^{-11}$ m^3/kg-sec^2) and the velocity of light (3×10^8 m/sec) to see that the event horizon of a Jupiter-mass black hole would occur at 2.82 meters.

2. It would not change.

3. The lunar orbit would take the same as it does now, ~ 27.3 days. The orbit of a spacecraft that had been hovering just over the surface of the Earth would be the same as the current rotation period of Earth, 24 hours. The fly would be inside of the event horizon...so we have no idea what is happening to it!

How Much Do You Know?

1. Black holes move around the Universe sucking up everything in sight.

A black hole is not a cosmic vacuum cleaner! A black hole has an "event horizon" which is the region from inside of which you can't escape. If an object crosses the event horizon, it will invariably hit the singularity. As long as the object stays safely outside of the horizon, it will not necessarily get sucked in. Far outside of the horizon, the gravitational field of a black hole is no different from the field surrounding any other object of the same mass. A black hole is not better than any other object at "sucking in" distant objects.

Consider this: if our Sun were suddenly replaced with a black hole of the same mass, the only thing that would change would be the Earth's temperature. The gravity we feel here on Earth from the "black hole Sun" would not change.

2. Black holes will eventually suck in all the matter in the Universe.

Not true. First, to be sucked into a black hole, you have to be near the event horizon. Far outside the event horizon, stars and planets and people are affected just as if the mass in the singularity was the mass of a burning star occupying the space of the event horizon. You see, as far as the gravitational pull on an object well outside the event horizon goes, it is only the amount of mass that is important, not how it is arranged.

Furthermore, it has been shown theoretically by Stephen Hawking that when virtual particles (undetectable quantum particles that carry gravity and light) enter the event horizon and get sucked into the singularity, they use up more energy than they have and so contribute negative energy (remember that this is a quantum process and not obvious to the minds of us mere humans) to the black hole. As a result, the mass of the singularity decreases and the black hole can eventually "evaporate" in this way.

What causes the creation of these virtual particles? Fluctuations of the electromagnetic and gravitational fields, especially prevalent near superstrong gravity sources, can create pairs of virtual particles (given this name because we can not detect them in any way as they exist in this form). Left to themselves, the pairs (a particle and its antiparticle) will move apart slightly, then back together to annihilate each other on a very short timescale. However, if the pair is created right along the event horizon, as they move slightly apart one can become trapped inside the event horizon and one left outside it. They cannot then get back together to annihilate. This has profound consequences:

1. Without its virtual partner, the escaping particle becomes a real particle and appears to us on Earth (watching it happen) to be radiation coming "from the black hole". This is called Hawking Radiation, and actually radiates from just outside the event horizon.

2. The particle with negative energy that was captured by the black hole will reduce the mass of the singularity. If this happens enough for a long enough period of time, the black hole will simply "evaporate" away.

Inevitable Mathematics

A. Take any number, Multiply it by 12: Add 40 to the result: Divide by 4: Subtract three times the original number.
B. 1
C. With this procedure, this number will fall into a cyclic 'black hole' like 81.
D. Again, by following through with this procedure, this number will fall into a cyclic 'black hole' like 81.

So, You Want to be a Black Hole?

In the following exercises, we need to know that:

$$G=6.67 \times 10^{-11} \text{ m}^3/\text{kg-sec}^2 \text{ and } c = 3 \times 10^8 \text{ m/sec}$$

1. Using the Schwarzschild equation, we input the mass of Jupiter (1.9×10^{27} kg) to see that the radius of a Jupiter-mass black hole would occur at 2.82 meters.

We can also input the mass of Earth (5.97×10^{24} kg) to see that the radius of an Earth-mass black hole would occur at 8.8×10^{-3} meters.

2. We would solve for M in the Schwarzschild equation to find $M = c^2 R/2G$.
If the radius of the basketball is 17.5 cm, the necessary mass to be 1.18×10^{26} kg. This is approximately the mass of Neptune.

VI. About the Poster

An artist's rendition of a supermassive black hole surrounded by a large galaxy of stars, gas, and dust, blasting powerful jets out into space serves as the background for our poster. This image was produced by the Joan Carol Design and Exhibit Group of Clinton, Maryland.

The Visible/UV image is from a *Hubble Space Telescope* observation of NGC 4261. The image is courtesy of H. Ford and L. Ferrarese (Johns Hopkins), W. Jaffe (Leiden), and NASA.

The radio image is of the nearby active galaxy Cygnus A. This image has been used with permission from National Radio Astronomy Observatory /AUI.

The X-ray spectrum is from an *ASCA* observation of the active galaxy MCG-6-30-15. This figure is from a paper entitled "Gravitationally Redshifted Emission Implying an Accretion Disk and Massive Black Hole in the Active Galaxy MCG:-6-30-15 " by Y. Tanaka *et al.*, published in *Nature*, Volume 375, p. 659, 1995.

The X-ray image is from a *Roentgen Satellite* observation of the active galaxy NGC 1275 at the center of the Perseus cluster of galaxies. The contour lines show the radio structure as given by VLA observations. The image is courtesy of the Max Planck Institute.

The X-ray light curve is from a *Rossi X-ray Timing Explorer* observation of the micro-quasar GRS 1915+105. The figure is from a paper entitled "A Unified Model for the Spectral Variability in GRS 1915+105" by T. Belloni *et al*., published in the *Astrophysical Journal*, Volume 488, p. L109, 1997.

The gamma-ray image is from a *Compton Gamma-Ray Observatory* observation of the quasar 3C279. The image is courtesy of the EGRET team, the Compton Observatory, and NASA.

The scales provided on the diagram are typical values for an active galaxy.

VII. Glossary

Accretion Disk - a swirling, heated accumulation of dust and gas in orbit around a compact object such as a neutron star or black hole. Matter from this environment continues to fall onto the disk and eventually spirals into the central object.

Active Galactic Nucleus - an extremely luminous center of an otherwise normal galaxy. In many cases, it is so bright that the surrounding galactic structure cannot be seen. Supermassive black holes are the most likely source of their power.

Cygnus X-1 - a stellar black hole candidate. Cygnus X-1 was the first X-ray source found in the constellation Cygnus.

Electromagnetic Spectrum - the range of different light or radiation. Oscillating electric and magnetic fields transfer radiant energy through space. Wavelength, energy, frequency, or temperature can classify these electromagnetic waves.

Escape Velocity - the velocity needed to escape the gravitational influence of a massive body. It depends on the distance you are away from the center of the body and the mass of the body. The closer you are, the harder it is to escape.

Event Horizon - a boundary that defines the point-of-no-return for a black hole. Once this boundary is crossed, no escape or communication with the outside world is possible.

Neutron Star - the final stage of existence for stars born three to seven times more massive than our Sun. Neutron stars are produced by supernova explosions. In these objects, material is so highly compressed that all the protons, electrons, and neutrons are piled together, breaking down the normal structure of an atom.

Nuclear Fusion - an energy-generating process that occurs where the pressure and the temperature are so enormous that lighter atoms such as hydrogen can fuse together to make heavier atoms such as helium, releasing enormous amounts of energy. Nuclear fusion occurs in the cores of stars; the energy eventually emerges from the surface and we see it as sunlight/starlight.

Singularity - a geometric point with no dimensions where the laws of physics break down. It is a theoretical point of zero volume and infinite density.

Spacetime - the combination of the three spatial dimensions (length, width, and height) with time. The four together form the 4-dimensional nature of our Universe. The effects of gravity can be regarded as a result of the curving of spacetime due to the presence of massive objects.

Speed of Light - the ultimate speed limit in the Universe: 300,000 kilometers/second.

Stellar Evolution Theory - the theory of how stars evolve from birth to death. Stars are born in huge gas and dust clouds and end as a white dwarf, neutron star, or black hole, depending on initial mass.

Supernova - a dramatic explosion marking the death of stars much more massive than our Sun. Neutron stars or stellar black holes are the objects left behind.

White Dwarf - an end-stage of life for stars with masses similar to our Sun's. A white dwarf is a stellar cinder about the size of the Earth. White dwarfs no longer have nuclear reactions taking place in their cores, but are still quite hot from their past activity. After billions of years, they will cool completely and be thought of as a black dwarf.

VIII. Related Resources

Websites

Besides the information you will find about black holes in the *Imagine the Universe!* Web site, try these other sites:

- http://starchild.gsfc.nasa.gov/docs/StarChild/universe_level1/black_holes.html
  This page explains for the grade K-4 student what black holes are and how we know they exist.

- http://starchild.gsfc.nasa.gov/docs/StarChild/universe_level2/black_holes.html
  This page contains information about black holes and how we know they exist for a grade 5-8 student, links to glossary terms and a movie about a "Journey into a Black Hole."

- http://jean-luc.ncsa.uiuc.edu/Movies/
  This Web site has virtual reality and informational movies on black holes. This site is associated with NCSA, and is for students in middle school and above.

- http://heasarc.gsfc.nasa.gov/docs/xte/learning_center/
  More about the *Rossi X-ray Timing Explorer* and some related education activities

- http://heasarc.gsfc.nasa.gov/docs/rosat/rhp_geninfo.html
  More about the *Roentgen Satellite*

- http://heasarc.gsfc.nasa.gov/docs/asca/ahp_geninfo.html
  More about the *ASCA* Satellite

- http://cossc.gsfc.nasa.gov/cossc/PR.html
  More about the *Compton Gamma-Ray Observatory*

- http://oposite.stsci.edu/pubinfo/education/amazing-space/
  More about the *Hubble Space Telescope* at their education site Amazing Space

- http://www.nrao.edu/
  More about the National Radio Astronomy Observatory

Books

• Couper, Heather and Henbest, Nigel, *Black Holes*, Dorling Kindersley Publ., 1996. A colorful introduction to the many strange behaviors and appearances of black holes. Intended for middle school to high school levels.

• Gaustad, John & Zeilik, Michael, *Astronomy: The Cosmic Perspective* - second edition, John Wiley & Sons, Inc., 1990. This text was designed for an introductory astronomy course for upper high school or undergraduate students who want a comprehensive view and understanding of modern astronomy, including black holes (see Chapters 20 & 21).

• Hawking, Stephen, T*he Illustrated A Brief History of Time*, Bantam Books, 1996. Wonderful graphics accompany this lively discussion of science, cosmology, and (of course) black holes. Some parts may be understandable on middle/high school levels, but overall it takes a great deal of abstract thinking to appreciate what is being said.

• Novikov, Igor, *Black Holes and the Universe*, Canto Edition, Cambridge University Press, 1995. A well-written, non-technical introduction to black holes and their phenomena. An interested high school student can easily enjoy this book.

• Mitton, Jacqueline & Simon, *The Young Oxford Book of Astronomy*, Oxford University Press, Inc., 1995. This book explains many concepts in astronomy from the Solar System, galaxies, and the Universe, including black holes. Intended for the middle or high school student.

• Seward, Frederick D. and Charles, Philip A., *Exploring the X-ray Universe*, Cambridge University Press, 1995. Explains X-ray astronomy and astrophysics. Intended for the undergraduate science major, or above.

• *Voyage Through the Universe: Stars*, Time-Life Books. This volume is one of a series that examines the Universe in all its aspects. General information for the upper high school student (and above), related to black holes, will be found in the 'Neutron Stars and Black Holes' chapter.

Magazine Articles

• Berstein, Jeremy, "The Reluctant Father of Black Holes", Scientific American, June 1996, vol. 274, no. 6. Discusses the details of how Einstein's equations of gravity are the foundation of the modern view of black holes. Intended for the high school student who is interested in science, and above.

• Charles, Philip A. & Wagner, R. Mark, "Black Holes in Binary Stars: Weighing the Evidence", Sky and Telescope, May 1996, vol. 91, no. 5. From this article, one can understand that by making X-ray observations, astronomers are sometimes able to detect black holes (especially when coupled to a normal star in a binary system). Intended for the high school student interested in science, or above.

• Schulkin, Bonnie, "Does a Monster Lurk Closeby?", Astronomy, September 1997, vol. 25, no. 9. Describes the possibility of a massive black hole existing at the heart of our Milky Way Galaxy. Intended for the high school student interested in science, or above.

Videos

• Mysteries of Deep Space, "Exploding Stars and Black Holes", PBS Home Video, Turner Home Entertainment (60 minutes). This is a well-told story that explains the life cycle of massive stars that will eventually die as black holes. Intended for the high-school student and above.

• "Search For Black Holes", New River Media (60 minutes). This is a video that contains interviews with all of the 'who's who' in black holes research. Some of the animations are quite clever. Intended for the high-school student and above.

• Stephen Hawking's Universe Series, "Black Holes and Beyond" (60 minutes). The animations in this video are very attractive. Intended for the high-school student and above.

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