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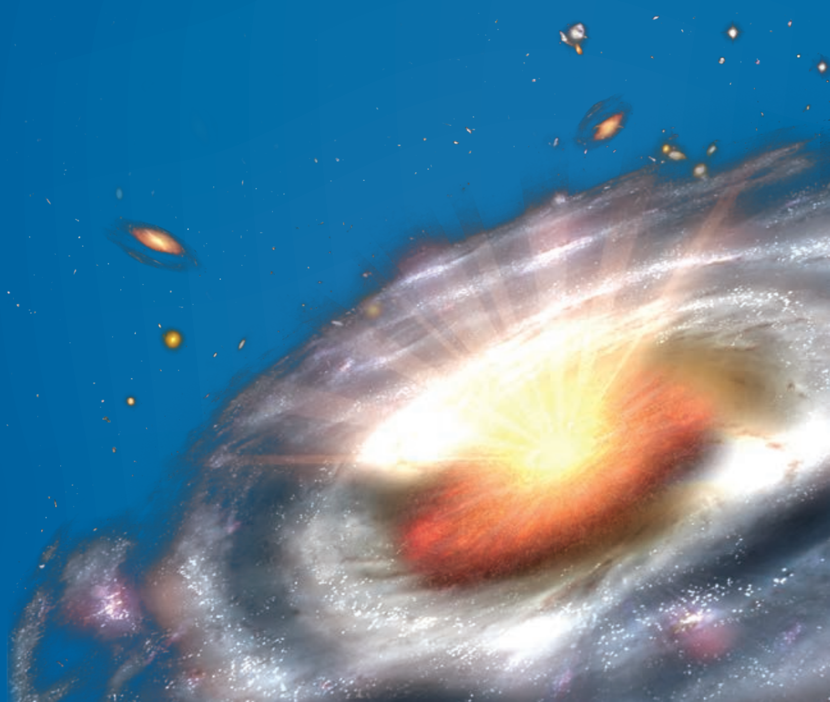
Black Holes Explained

Course Guidebook

Professor Alex Filippenko
University of California, Berkeley



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Professor Alex Filippenko received his Bachelor's degree in Physics (1979) from the University of California, Santa Barbara, and his Doctorate in Astronomy (1984) from the California Institute of Technology. He subsequently became a Miller Postdoctoral Fellow for Basic Research in Science at the University of California, Berkeley. In 1986, he joined the faculty at UC Berkeley, where he has remained through the present; he is currently the Richard and Rhoda Goldman Distinguished Professor in the Physical Sciences. A member of the International Astronomical Union, Dr. Filippenko has served as president of the Astronomical Society of the Pacific and as councilor of the American Astronomical Society. He was elected to the California Academy of Sciences in 1999 and to the National Academy of Sciences in 2009.

Dr. Filippenko is an observational astronomer who makes frequent use of the Hubble Space Telescope and the Keck 10-meter telescopes, and his primary areas of research are exploding stars (supernovae), active galaxies, black holes, gamma-ray bursts, and cosmology. He and his collaborators recognized a new class of exploding star, obtained some of the best evidence for the existence of small black holes in the Milky Way Galaxy, and found that other galaxies commonly show vigorous activity in their centers that suggests the presence of supermassive black holes. His robotic telescope at Lick Observatory in California is the world's most successful search engine for relatively nearby supernovae, having discovered about 800 of them since 1998. Dr. Filippenko also made major contributions to the discovery that the expansion rate of the Universe is speeding up with time (the accelerating Universe), propelled by some kind of mysterious dark energy. This was the top "Science Breakthrough of 1998" according to the editors of *Science* magazine, and it earned him a share of the 2007 Gruber Cosmology Prize.

Dr. Filippenko's research findings are documented in about 650 published papers and in more than 1400 abstracts and astronomical telegrams. One of the world's most highly cited astronomers, he has been recognized with several major awards, including the Newton Lacy Pierce Prize of the American Astronomical Society (1992), the Robert M. Petrie Prize of the Canadian Astronomical Society (1997), and the Richtmyer Memorial Award of the American Association of Physics Teachers (2007). Dr. Filippenko has also been a Guggenheim Foundation Fellow (2001) and a Phi Beta Kappa Visiting Scholar (2002). He has held distinguished visiting positions at numerous colleges and universities, including the Marlar Lecturer at Rice University, the Iben Lecturer at the University of Illinois, the Kaufmanis Lecturer at the University of Minnesota, the Pappalardo Lecturer at the Massachusetts Institute of Technology, the Bunyan Lecturer at Stanford University, the Salpeter Lecturer at Cornell University, and both the Spitzer Lecturer and Farnum Lecturer at Princeton University.

At the UC Berkeley campus, Dr. Filippenko has won the coveted Distinguished Teaching Award (1991) and the Donald S. Noyce Prize for Excellence in Undergraduate Teaching in the Physical Sciences (1991), each of which is generally given at most once per career. In 1995, 2001, 2003, 2004, 2006, 2008, and 2010, Dr. Filippenko was voted "Best Professor on Campus" in student polls. He also received the 2002 Distinguished Research Mentoring of Undergraduates Award. At the end of 2006, Dr. Filippenko was honored as the Doctoral and Research Universities National Professor of the Year by the Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education. In 2010, he won the Astronomical Society of the Pacific's *Richard H. Emmons* award for undergraduate teaching.

Dr. Filippenko has delivered more than 500 public lectures on astronomy and has played a prominent role in numerous science newscasts and television documentaries, such as *Mysteries of Deep Space*, *Stephen Hawking's Universe*, *Runaway Universe*, *Exploring Time*, and 5 seasons of *The Universe* on The History Channel. With Jay M. Pasachoff, Dr. Filippenko coauthored an introductory astronomy textbook, *The Cosmos: Astronomy in the New Millennium* (2001); it won the 2001 Texty Excellence Award of the Text and Academic Authors Association for the best new textbook in the physical sciences. Dr. Filippenko was also the recipient of the 2004 Carl Sagan Prize for Science Popularization from the Trustees of Wonderfest, the San Francisco Bay Area Festival of Science. In 1998, Dr. Filippenko produced a 40-lecture introductory astronomy video course with The Teaching Company, and in 2003, he recorded a 16-lecture update. These were replaced and extended in 2006 with his 96-lecture *Understanding the Universe: An Introduction to Astronomy, 2nd Edition*—the largest course produced by The Teaching Company with a single professor. ■

Table of Contents

INTRODUCTION

LECTURE GUIDES

Table of Contents

Black Holes Explained

Scope:

This is a course about black holes, regions of space in which gravity is so strong that nothing, not even light, can escape. References to black holes are abounding in popular culture; most people have heard of them, but few truly understand what they are. Far from being the figments of the fertile imaginations of theoretical physicists and science-fiction writers, black holes almost certainly exist in the Universe; the observational evidence for their presence is now quite compelling. The two main varieties are stellar-mass black holes, produced by the collapse of the core of massive stars at the end of their lives, and supermassive black holes, which form in the centers of galaxies. But although black holes themselves are real, travel through them is probably impossible, despite their use as exotic passages in some fiction books and movies. Incredibly, black holes might not really be black; modern theories combining quantum physics, thermodynamics, and general relativity suggest that they can gradually evaporate by emitting particles.

We begin with a broad overview of black holes, explaining some of the main concepts and defining terms. Newtonian plausibility arguments for the existence of “dark stars” (black holes) were first made several centuries ago, but a complete understanding requires Einstein’s general theory of relativity and the realization that matter warps both space and time. According to classical physics, matter that passes beyond the event horizon, or boundary, of a black hole collapses to form an infinitely dense singularity, and nothing ever emerges back into the outside world. Black holes are shown to be quite small, and there is virtually no chance that one will swallow Earth.

Next we consider stellar-mass black holes and their formation from certain types of massive stars. Although most massive stars end their lives by exploding as a result of the energy emitted by the final gravitational collapse of their core to a dense neutron star, in some cases the collapse proceeds further, resulting in the formation of an even denser black hole. Gamma-ray bursts, described in Lecture 3, are thought to be such “birth cries” of black holes, or (in some cases) the growth of existing stellar-mass black holes that devour a companion neutron star. Lecture 4 discusses the methods used to search for stellar-mass black holes and measure their masses, which are typically 5 to 10 solar masses but can reach as high as at least 30 Suns.

We then turn to supermassive black holes that lurk in the central regions of galaxies, starting with the monster in our own Milky Way Galaxy. This object, weighing in at about 4 million solar masses, provides the best available evidence for the existence of black holes; stars in its vicinity move so quickly around such a small volume that no explanation other than a black hole seems viable. The supermassive black holes in other galaxies can be even larger, reaching a few billion solar masses in some cases. As discussed in Lecture 6, they probably formed early in the history of the Universe and manifested themselves as luminous quasars. When two galaxies merge together, their central supermassive black holes can also coalesce into a single bigger black hole, releasing ripples in the fabric of space-time known as gravitational waves. Such waves, which are also emitted when stellar-mass black holes or neutron stars merge, are the subject of Lecture 7; they allow us to "listen" to the Universe, obtaining information that would otherwise remain hidden.

In Lecture 8 we discuss the tidal stretching that occurs near a black hole, especially in the case of the stellar-mass variety. A hypothetical journey all the way to the singularity in a supermassive black hole is described; though doomed, the traveler would experience a truly wild ride, with many weird effects visible. However, if the traveler avoids the event horizon and returns home, he will have aged less than people who remained far from the black hole, effectively jumping into the future relative to them. Lecture 9 extends the discussion to rotating and charged black holes, which mathematically seem to imply the existence of wormholes—passages to other universes or shortcuts through our Universe. Unfortunately, it is probably impossible to traverse a real wormhole.

Next we consider Stephen Hawking's theory that black holes can actually lose mass, gradually evaporating due to quantum effects and ending their existence in colossal explosions. Most physicists have reasoned that black holes are incredibly simple objects, characterized only by their mass, electric charge, and spin; if so, however, black hole evaporation seems to violate a fundamental principle of quantum physics that no information is ever permanently lost from the Universe. Lecture 11 examines this conundrum and its recent possible resolution; all of the information in a black hole actually resides in a membrane wrapped around the event horizon, analogous to a hologram, and is not destroyed by the evaporation process.

In Lecture 12, we discuss the possible production of miniature black holes in the Large Hadron Collider, and the physical implications if this were to be achieved. Contrary to common assertions, such minuscule black holes pose absolutely no threat to humans or to Earth. We end with a brief look at paths for the future of black hole research. ■

A General Introduction to Black Holes

Lecture 1

Most people have heard of black holes yet know little about them; references to black holes abound in popular culture. Simply put, they are regions in which the local gravity is so strong that nothing, not even light, can escape because the required speed exceeds that of light. Newtonian plausibility arguments for the existence of dark stars (black holes) were first made several centuries ago, although a complete understanding requires Einstein's general theory of relativity and the realization that matter warps both space and time.

Black holes are one of the most exotic, mind-boggling subjects imaginable and one of the hottest topics in astrophysics. Far from being figments of the fertile imaginations of physicists and science fiction writers, these amazing objects are real. The topic of black holes in an introductory astronomy course, including the one I recorded for The Teaching Company called *Understanding the Universe*, is normally spread across different subjects; this course offers us a tighter focus.

Black holes seem to abound in pop culture. I've seen references to black holes in many cartoons and in pop music. There are nonfiction books about black holes. They are a popular topic in science fiction books, movies, and TV series like *Futurama*. Internet jargon also features black holes.

So what is a black hole? Basically, a black hole is a region of space where gravity is so strong that nothing, not even light, can escape, so it would appear black. Black holes are important because they have extreme conditions not yet reproduced in any terrestrial laboratories.

Beginning in the early 1970s, there was growing evidence that some types of massive stars might end their lives by collapsing to form black holes. Since the 1990s, there has been even better evidence that galaxies, including our own Milky Way, have supermassive black holes at their centers.

Consider a Newtonian plausibility argument for black holes. If I toss an apple up, it comes back down because of the mutual gravitational attraction between Earth and the apple. But if I throw it sufficiently fast—at a speed exceeding the escape velocity of Earth, about 11 km/s—it will never come back down. If I squish Earth down to half of its current radius, the force of gravity will increase, as will the escape velocity; it will take more energy to throw the apple so that it doesn't come back down. If Earth is further compressed so that the escape velocity becomes the speed of light, then neither the apple nor anything else, including light, would be able to escape.

The only way to properly understand black holes is with Einstein's general theory of relativity.

In 1916, German physicist Karl Schwarzschild revived the notion of dark stars shortly after hearing about Einstein's general theory of relativity. Following Schwarzschild's mathematical formalism, the radius (r) of a black hole is directly proportional to the mass (m) of the black hole: $r = 2Gm/c^2$, where G is Newton's constant of gravitation and c is the speed of light. The Schwarzschild radius of a black hole marks its boundary. Black holes are generally quite small, with a radius of only about 3 km per solar mass. The set of points having a radius equal to the Schwarzschild radius is called the event horizon of a black hole.

The only way to properly understand black holes is with Einstein's general theory of relativity. Light is trapped inside a black hole because of severe warping of space and time within the event horizon. According to classical physics, matter inside the black hole continues collapsing to a mathematical point called a singularity. A common misconception is that black holes are cosmic vacuum cleaners, sucking up everything in space—and that Earth is in danger if even a single black hole exists in the Universe. This is not at all true.

The nonrotating black holes discussed so far are an idealization; black holes are formed by the gravitational collapse of rotating stars. The structure of a rotating black hole is considerably more` complex than that of a nonrotating black hole. There are 2 horizons in a rotating (or charged) black hole: inner and outer. The ergosphere of a black hole is a region that could be used to tap its rotational energy.

The structure of the course will be as follows: Lectures 2 and 3 explain how black holes can be formed from the titanic explosions of dying massive stars. The methods by which astronomers actually find such stellar-mass black holes are described in Lecture 4. Supermassive black holes in the centers of galaxies are the subject of Lectures 5 and 6. Lecture 7 shows how we can "listen" to merging black holes by detecting gravitational waves. The possibility of travel into and through black holes, perhaps to other universes, is discussed in Lectures 8 and 9. Lectures 10 and 11 describe how, according to quantum physics, black holes might not be completely black after all and that the devoured information may even escape from them somehow. Mini black holes and the Large Hadron Collider are discussed in the final lecture—if created, such black holes will pose no danger whatsoever to Earth or life on it. ■

Suggested Reading

Begelman and Rees, *Gravity's Fatal Attraction*.

Ferguson, *Prisons of Light*.

Gleick, *Isaac Newton*.

Pasachoff and Filippenko, *The Cosmos*.

Thorne, *Black Holes and Time Warps*.

Wolfson, *Simply Einstein*.

Questions to Consider

1. Why do you think many people find black holes to be such a fascinating subject?

2. If photons—particles of light—have no mass, Newton's law of universal gravitation ($F = GMm/d^2$) suggests that light should not be affected by gravity. So, how can an object possibly be a black hole?

3. If someone close to, but not inside, a black hole were shining a blue flashlight beam outward, how would the color that you see be affected if you are far from the black hole?

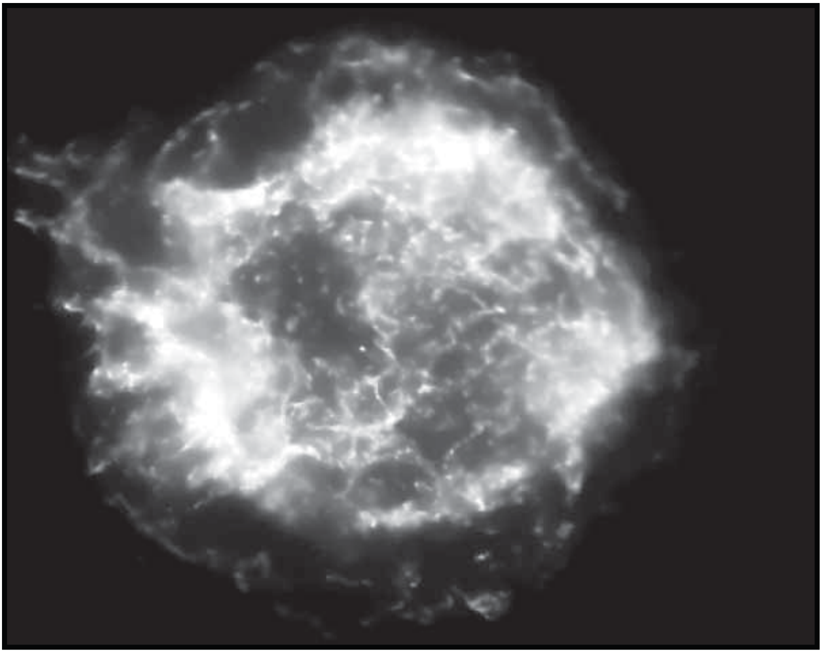
The Violent Deaths of Massive Stars

Lecture 2

Stars spend most of their lives fusing hydrogen nuclei (protons) to helium nuclei in their hot central regions, releasing energy that keeps them pressurized and prevents gravitational collapse. Relatively low-mass stars, like the Sun, eventually fuse helium into carbon and oxygen, lose their outer atmospheres during the red giant stage, and end up as white dwarfs that gradually cool and fade. But a much more massive star can undergo additional stages of nuclear fusion until its core collapses and generally forms an extremely dense neutron star, triggering a colossal explosion known as a supernova.

Black holes are not easy to form in nature. One needs to cram a lot of matter into a very small radius, and this generally implies a very high density. Normal stars are simply very distant, faint versions of the Sun. They produce energy at a relatively steady pace, converting hydrogen (H) to helium (He) in their very hot cores through a process called nuclear fusion. Four protons (H nuclei) bind together to form a helium nucleus (2 protons and 2 neutrons); 2 of the protons are converted to neutrons during the process. The He nucleus is more tightly bound and thus less massive than the 4 protons of which it was made. The mass difference between the final He nucleus and the 4 initial protons gets converted into energy according to Einstein's famous equation, $E = mc^2$. This is the energy that we see from the Sun and stars.

With this continuous source of new energy, the Sun and other low-mass stars can remain hot inside for billions of years. The outward pressure of gas balances the inward force of gravity, thus achieving mechanical balance (known as hydrostatic equilibrium). To predict the future of the Sun, we have examined many stars having many different ages, giving us the life history of a typical star. We also understand the physics of gases held together by gravity.



NASA/CXC/SAO.

This image of Cassiopeia A shows remarkable structure in the debris of a gigantic stellar explosion, as well as a probable neutron star in the center.

Massive stars (those exceeding roughly 8 solar masses) have much more violent deaths, and those are the ones that are potentially more closely related to black holes. Near the end of a massive star's life, it becomes very large, turning into a red supergiant. Eventually, the red supergiant will have an iron core surrounded by shells of progressively lighter elements, all the way to hydrogen in the outermost envelope. When the mass of the iron core reaches about 1.4 solar masses, the core can no longer hold itself up, and it collapses due to gravity. After this collapse of the iron core to a neutron star, the outer layers get ejected. Neutrinos that are released by the newly formed neutron star help explode the star.

Supernovae are extremely powerful! During a few seconds, a supernova can emit about as much energy as all of the optical light from normal stars in the entire visible parts of the Universe.

Supernovae eject the heavy elements that were formed prior to or during the explosion. Over very long periods of time, the ejected material merges with other clouds of gas. Some of these become gravitationally unstable, collapsing to form new stars and planets, enriched in heavy elements. Eventually, in at least 1 case (the planet Earth), life formed on one of these planets. Life depends on the heavy elements made by stars and supernovae.

During a few seconds, a supernova can emit about as much energy as all of the optical light from normal stars in the entire visible parts of the Universe.

Supernovae are rare. There is roughly 1 supernova per century per galaxy, so you have to look at a lot of galaxies to improve your odds of seeing one. My research team runs a robotic telescope that takes photographs of thousands of galaxies each week and then repeats the process on the same galaxies. Comparison of the old and new pictures reveals supernova candidates. Undergraduate students examine the candidates and determine which ones are likely to be genuine supernovae. Over the past decade, we have been running the world's leading search for relatively nearby exploding stars.

Supernova 1987A, the first supernova discovered in the year 1987, may have left a black hole rather than a neutron star. There also may exist a weird state of matter that allows a collapsed star to have a mass larger than the most massive "normal" neutron star, yet the collapsed star is not technically a black hole; however, this hypothesis is still quite controversial. ■

Suggested Reading

Kirshner, *The Extravagant Universe*.

Marschall, *The Supernova Story*.

Pasachoff and Filippenko, *The Cosmos*.

Wheeler, *Cosmic Catastrophes*.

Questions to Consider

1. How do you think astronomers know roughly what the future evolution of the Sun will be like?

2. How compelling do you find the arguments that we are made of stardust?

3. For those who like math: If only 10 neutrinos from SN 1987A were detected by each of 2 underground tanks containing several thousand tons of water, and if a typical human consists of 100 pounds of water, what are the odds that your body directly detected a neutrino from SN 1987A if you were alive in February 1987?

4. If 1 or 2 supernovae occur in a typical galaxy every century, how many galaxies would you need to monitor to find 20 supernovae each year?

Gamma-Ray Bursts—The Birth of Black Holes

Lecture 3

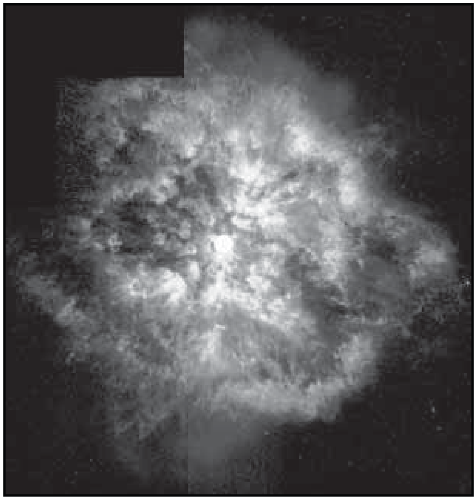
Roughly 40 years ago, the Vela spy satellites discovered short, intense bursts of high-energy electromagnetic radiation (gamma rays) coming from random positions in the sky. The distances and physical origins of these gamma-ray bursts (GRBs) were a mystery. Eventually GRB counterparts were found at other wavelengths, and the objects could be studied in more detail. We now know that most GRBs originate in galaxies billions of light years away, making them among nature's most powerful explosions.

In the 1960s and 1970s, the U.S. Air Force launched Vela spy satellites to monitor Soviet compliance with the partial Nuclear Test Ban Treaty. These satellites can detect gamma-rays—a form of electromagnetic radiation with an extremely short wavelength and high-energy photons—from nuclear blasts of bombs. They discovered intense, short bursts of gamma-rays from seemingly random places in the sky. The scientists at Los Alamos National Laboratories announced this discovery in 1973 and said that the gamma-ray bursts (GRBs) were of cosmic origin.

It is estimated that a GRB occurs somewhere in the sky roughly once per day. GRBs exhibit an incredible variety of light curves (apparent brightness of the gamma-rays versus time). There seems to be two general classes of light curves: short-duration GRBs last fewer than 2 seconds, and long-duration GRBs last more than 2 seconds. The GRBs discovered with the Vela satellites were distributed roughly uniformly in the sky, with no apparent concentration in the plane of the Milky Way Galaxy or the plane of our solar system.

In the 1990s, much progress was made with NASA's Compton Gamma-Ray Observatory. BATSE, the Burst and Transient Source Experiment, discovered thousands of GRBs. BATSE and other instruments could only tell roughly where in the sky any particular GRB was located.

A huge breakthrough in research on GRBs occurred when their afterglows were finally found at other wavelengths. A satellite called BeppoSAX obtained the first images of GRB afterglows at X-ray wavelengths. The X-ray data revealed precisely where a GRB was. Then telescopes at other wavelengths could point at the same location and see if they could detect it. Astronomers found that there was often an optical afterglow coincident with the X-ray location. One GRB optical afterglow was so bright that it could have been seen with a pair of binoculars, yet it was clearly associated with a galaxy 10 billion light years away.



Yves Grosdidier (University of Montreal and Observatoire de Strasbourg), Anthony Moffat (Universitie de Montreal), Gilles Joncas (Universite Laval), Agnes Acker (Observatoire de Strasbourg), and NASA.

A Hubble Space Telescope picture of WR124 reveals that it is surrounded by hot clumps of gas being ejected into space at speeds of more than 100,000 mph.

For many years, the only kind of GRBs for which optical counterparts had been discovered was the long-duration GRBs. It was found that these objects do not emit their gamma-rays uniformly in all directions. In the fireball model, there are two oppositely directed jets of particles that move nearly at the speed of light. The particles collide with each other, producing gamma-rays and other electromagnetic radiation. They also collide with the interstellar medium (the gas the surrounds the GRB), generating additional light.

It was found that long-duration GRBs often occur in galaxies that are actively forming many massive stars. Massive stars don’t last very long, so this association suggests that long-duration GRBs are produced by massive stars. Where massive stars form, massive stars die. Being short-lived, they do not have much time to move to other locations before dying. Astronomers suggested that long-duration GRBs are a special, particular type of core-collapse supernova. The kinds of stars that are most likely to produce long-duration GRBs are the ones that do not have much of a H or He envelope; the jets of particles have an easier time getting all the way through the star.

Now let's consider short-duration GRBs. We didn't know much about them for a long time. In 2004, a NASA satellite called Swift was launched. It could pinpoint the locations of GRBs very quickly and accurately. Astronomers using Swift found that some of these short-duration GRBs are associated with galaxies having mostly old, presumably low-mass, stars.

Where massive stars form, massive stars die.

Two neutron stars that are sufficiently close together release gravitational waves (to be discussed in Lecture 7) and spiral in toward each other. In the process of merging to form a black hole, they produce two oppositely directed jets. If we view the process along the direction toward one of the two jets, we see a short-duration GRB, the birth cry of a black hole. Some short-duration GRBs might form when a neutron star merges with a black hole, producing a pair of oppositely directed jets. Thus, short-duration GRBs appear to be associated with the birth and growth of black holes. ■

Suggested Reading

Katz, *The Biggest Bangs*.

Pasachoff and Filippenko, *The Cosmos*.

Schilling, *Flash!*

Wheeler, *Cosmic Catastrophes*.

Questions to Consider

1. Assume the Andromeda Galaxy (M31, 2.4 million light years away) is very similar to our Milky Way Galaxy. If GRBs were associated with a very extended, spherical halo of our galaxy, do you think there should be a nonuniformity across the sky in the observed distribution of GRBs, given enough data points?

2. Why was identification of the X-ray and optical afterglows of GRBs so important for the physical interpretation of GRBs?

3. If GRBs are beamed, are the energy requirements per GRB smaller than if isotropic emission (i.e., uniform across the sky) is assumed? Is the number of GRBs that we detect per galaxy affected by the beaming?

Searching for Stellar-Mass Black Holes

Lecture 4

Since black holes do not emit any light, they cannot be seen directly. However, if a black hole is in a binary system, its presence can be discerned from the observed motion of the visible star. The star's radial velocity changes periodically with time and Newton's laws can be used to determine the minimum mass of the invisible object; if that mass exceeds the 3-solar-mass limit for neutron stars, it is likely to be a black hole. We can be alerted to promising candidates if the black hole is sufficiently close to its companion star. Black holes can steal matter from their companion stars, forming accretion disks that can occasionally produce a burst of X-rays.

Is there actual evidence for the existence of stellar-mass black holes? Light doesn't escape from black holes, so one cannot see them directly. Stellar-mass black holes are very small; viewed from a big distance, many light years away, they would look tiny. Black-looking regions in the sky might simply be areas devoid of stars. We can detect black holes through their gravitational influence on other objects. They can be found in binary systems, gravitationally bound to a visible star.

First, consider a normal binary star with no black hole. The two stars orbit their common center of mass, but they might be so far away that they appear to be just a single star, even when viewed through a telescope. In a spectrum of the star, however, you can see that there are actually two sets of absorption lines produced by chemical elements in the atmospheres of the two individual stars. This is known as a spectroscopic binary star.

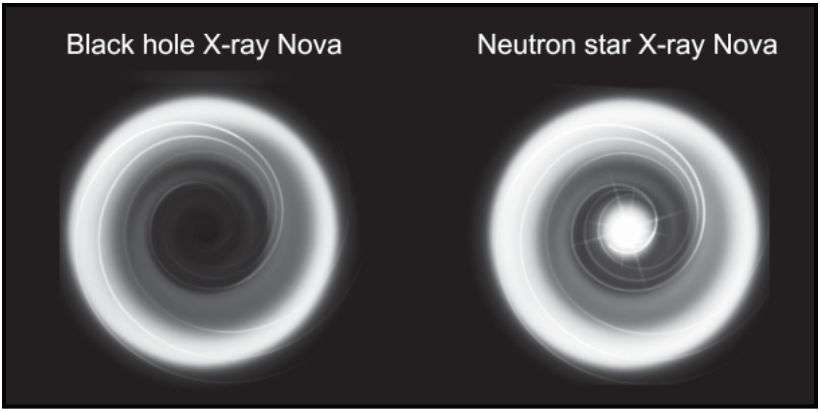
Due to the Doppler effect, the two sets of lines shift back and forth with time as the stars orbit their common center of mass. By measuring the blueshifts and redshifts, as well as the orbital period, we can in principle derive the masses of the stars. But we also need to know the inclination of the system to our line of sight; it tells us how much of the total speed the measured radial velocity represents. If we don't know the orbital inclination, we can estimate only the minimum masses of the stars.

Suppose you observe a binary star and one of the components is actually a black hole. Then you will see only a single set of absorption lines going back and forth, not two sets of absorption lines. If you measure the orbital speed and period of the visible star, it is sometimes possible to determine the mass of the invisible object from Newton's laws. But you need to know the mass of the visible star from its observed properties; otherwise, you cannot determine the mass of the invisible object. If the orbit is edge-on, then the minimum mass is the actual mass. If the orbit is inclined at some other angle, then in fact the minimum mass is not the actual mass. If the invisible object has a mass that exceeds 3 solar masses, it is probably a black hole.

If the invisible object has a mass that exceeds 3 solar masses, it is probably a black hole.

Where should we look for stellar-mass black hole candidates? A black hole or a neutron star can sometimes steal material from a closely orbiting companion star, producing X-rays from an accretion disk of hot material, and those X-rays alert us to the system. Cygnus X-1 is one such X-ray source; spectroscopic studies revealed that it consists of a massive visible star—about 30 solar masses—orbiting something invisible having a mass of about 9 solar masses. For a long time there was considerable uncertainty about the mass of the invisible object because the massive visible star complicates the analysis. Rather unambiguous evidence is provided when we have a low-mass visible star in orbit around a black hole. To get the true mass, rather than just the minimum mass, we also needed to know the orbital inclination. We now know of about 2 dozen such stellar-mass black holes.

A few stellar-mass black holes have been found in galaxies outside our own. The first of these was announced in October 2007, in the galaxy M33. The visible star is huge, with a mass of about 70 solar masses; the invisible object, presumably a black hole, has a mass of 16 solar masses. Just 2 weeks later, another group of astronomers announced that they had found a roughly 30-solar-mass stellar black hole in a galaxy called IC10.



NASA/CXC/M.Weiss.

In 2000–2001, by comparing energy from X-ray novas, researchers found that in dormancy X-ray novas with black holes emitted 1% of the energy of those with neutron stars.

How do we know that these stellar-mass black hole candidates really do have an event horizon through which material passes, never to be seen again? If there were a solid surface, as in the case of a neutron star, gas falling onto it would release energy, causing the object to glow brightly. When we compare these objects not during an outburst, we find that the ones in which we think a neutron star is present are brighter in X-rays than those that we think harbor black holes. In fact, there has been some evidence for blobs of material swirling closer and closer to the black hole, fading gradually from sight and becoming more gravitationally redshifted. There is no final burst of energy because there is no surface for the blob to hit.

We can also get information about the spin of the black hole. In some cases the spinning black hole and accretion disk in the binary system produce high-speed jets of particles, flowing outward in opposite directions at a good fraction of the speed of light. ■

Suggested Reading

Begelman and Rees, *Gravity's Fatal Attraction*.

Carroll and Ostlie, *An Introduction to Modern Astrophysics*.

Ferguson, *Prisons of Light*.

Pasachoff and Filippenko, *The Cosmos*.

Thorne, *Black Holes and Time Warps*.

Questions to Consider

1. Under what circumstances does the presence of an X-ray source associated with a spectroscopic binary star suggest to astronomers the presence of a black hole?

2. If a visible star orbits an object at least 5 times the mass of the Sun in a period of only 8 hours, can you think of anything the object could be besides a black hole?

3. Why do you think astronomers are interested in finding both the least massive and the most massive stellar-mass black holes?

4. How is it that jets of particles moving at a substantial fraction of the speed of light can be emitted by a black hole, if it is truly black?

Monster of the Milky Way and Other Galaxies

Lecture 5

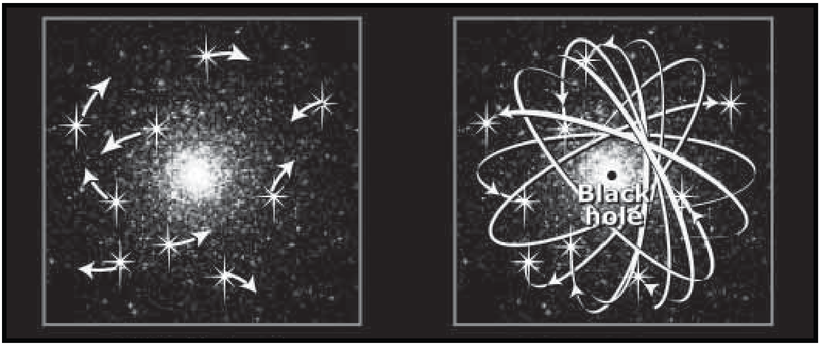
Looking along the plane of our Milky Way Galaxy, we see a large number of stars that form a faint band in the dark night sky: the Milky Way. Interstellar dust blocks our optical view of the galactic center, 27,000 light years away, but it is visible at infrared and radio wavelengths. Long-term studies of individual stars near the center show that they are moving very rapidly around an extremely small, dense, dark object—almost certainly a supermassive black hole, about 4 million times the mass of the Sun.

Our Milky Way Galaxy is a spiral galaxy, a gravitationally bound collection of hundreds of billions of stars, arranged in a flattened disk with a central bulge and stretching about 100 thousand light years from one ill-defined edge to the other. The disk consists of stars, gas, and dust from which new stars are being formed; the bulge consists mostly of old stars in a roughly spherical configuration. The halo of our galaxy contains globular star clusters, each of which consists of roughly a million stars.

Our Sun is about 1/2 to 2/3 of the way out to the edge of the thin disk or plane of our Milky Way Galaxy. On a dark, moonless night away from cities, the band of light known as the Milky Way is simply the collective light from countless stars that we see along the disk.

Studies of the orbits of stars in the very center of our galaxy reveal the presence of a supermassive black hole, about 4 million times the mass of the Sun. They are moving faster than they would if there were no black hole pulling on them.

Let's examine this conclusion's reasoning and evidence. The center of our galaxy, toward the constellation Sagittarius, cannot be seen at optical (visible) wavelengths; it is blocked by interstellar gas and dust, but the center can be seen at radio wavelengths, which are not obscured. We see a great concentration of stars in the central part of our galaxy. By measuring



NASA, Ann Rebecca Field/STScI, and R. P. van der Marel.

Stars in the central region of a galaxy containing a supermassive black hole (*above right*) move more rapidly than stars in a similar galaxy devoid of a black hole (*above left*).

the speeds of stars relatively near but not very close to the center, some astronomers suspected the presence of a black hole at the center. There are so many stars near the center that turbulence in Earth's atmosphere tends to blur them together. But with a technique called adaptive optics, we can see the stars in the middle of our galaxy much more clearly.

Reinhard Genzel of Germany (and the University of California, Berkeley) and Andrea Ghez of UCLA have been studying the galactic center for about 15 years. Their research indicates that stars near the galactic center are orbiting something that is causing them to move very fast and causing their trajectories to change. According to Newton's laws, there is one central, highly dominant mass that is causing all of these motions. The derived mass is about 4 million solar masses, within a region not larger than our solar system. By the process of elimination, the object must be a supermassive black hole. Genzel's group has obtained spectra of many of the stars in the central region, and their radial velocities confirm that a supermassive black hole is pulling on them.

At a distance of 27,000 light years from the supermassive black hole, the Sun and Earth are in a stable orbit and have no chance of being sucked in. Only the stars very close to the supermassive black hole need to worry about it.

Rapid flaring at X-ray and infrared wavelengths provides additional evidence for the supermassive black hole. Most flares are rather faint and difficult to see, but about 300 years ago we think there was a very bright flare; we have seen its X-ray echo.

There is a supermassive black hole in the center of nearly every galaxy we examine, not just in our own Milky Way Galaxy. Indeed, most galaxies have a bigger supermassive black hole than our own. One looks for rapid stellar motions in the central regions, too rapid to be produced by the collective gravitational attraction of the stars themselves. However, in these other galaxies the stars are too far away to be seen individually. Instead, we use the Doppler effect to measure the average radial motions of the whole conglomeration of stars in the middle. By measuring the widths of absorption lines in a spectrum, one can deduce that the light is being produced by a large number of stars having many different motions.

It is important to get a clear view of the galactic nucleus, to get a good detection of the supermassive black hole.

It is important to get a clear view of the galactic nucleus, to get a good detection of the supermassive black hole. The Hubble Space Telescope can obtain very clear images and spectra of the central region of a galaxy, showing that the stars are moving around very quickly. With adaptive optics, astronomers are also beginning to do this kind of research with ground-based telescopes.

One of the most massive black holes known, with 3 billion solar masses, is in M87. After the Milky Way, the next best case for a supermassive black hole in the middle of a galaxy is that of NGC 4258. Our nearest big neighbor, the Andromeda Galaxy, has a black hole of about 140 million solar masses.

The mass of the supermassive black hole seems to be correlated with the mass of the central bulge, not the size of the disk. It is not yet clear whether the black hole mass versus bulge mass correlation extends all the way down to globular star clusters. Some globular clusters may contain a black hole of up to a few tens of thousands of solar masses, but the measurements and interpretations are somewhat insecure. Perhaps even smaller black holes exist, down to a few hundred solar masses. ■

Suggested Reading

Begelman and Rees, *Gravity's Fatal Attraction*.

Ferguson, *Prisons of Light*.

Ferris, *Coming of Age in the Milky Way*.

Melia, *The Black Hole at the Center of Our Galaxy*.

———, *The Edge of Infinity*.

Pasachoff and Filippenko, *The Cosmos*.

Questions to Consider

1. Why do stars that come very close to the center of our Milky Way Galaxy provide stronger evidence for the presence of a supermassive black hole than do stars that do not approach the center so closely?

2. For those who like math: The average density of an object is its mass per unit volume. If the volume of a non-rotating black hole is proportional to the cube of its Schwarzschild radius, show that its average density is inversely proportional to the square of its mass. Are supermassive black holes denser, or less dense, than stellar-mass black holes? (Of course, all of the mass in a black hole is actually concentrated at the singularity, not spread throughout the volume.)

3. What do you think the observed correlation between the mass of the galaxy bulge and the mass of the central black hole might be telling us?

Quasars—Feasting Supermassive Black Holes

Lecture 6

In the 1960s, astronomers found that certain types of star-like objects are strong sources of radio waves, unlike normal stars. Dubbed quasars, they are distant, extremely powerful objects, sometimes spewing out long jets of particles moving with speeds close to that of light. Many quasars exhibit rapid variations in their brightness, implying that they are physically small. They are now known to be the central regions of galaxies, and their energy almost certainly comes from a supermassive black hole devouring material from an accretion disk.

After World War II astronomers developed radio telescopes with which they could scan the skies at radio wavelengths. They found some obvious radio sources, such as supernova remnants and peculiar-looking galaxies. But other regions of the sky showed nothing obvious, nothing peculiar—just a whole bunch of stars. In a few cases, astronomers eventually concluded that the source of radio waves was a star-like object, yet normal stars don't emit much radio radiation. They were dubbed "quasi-stellar radio sources" or "quasars" for short. Optical spectra of quasars were peculiar, with strong, broad emission lines at wavelengths that did not form any obvious pattern corresponding to known chemical elements.

Quasars appear star-like, smaller than galaxies, so they must be physically small. It turns out that they are tiny—much smaller than galaxies. Quasars are galaxies that have gigantic black holes at their centers, with masses of a million to a billion times that of the Sun. Quasars appear star-like because the light emitted by the accretion disk surrounding the black hole far outshines the galaxy in which the quasar is located.

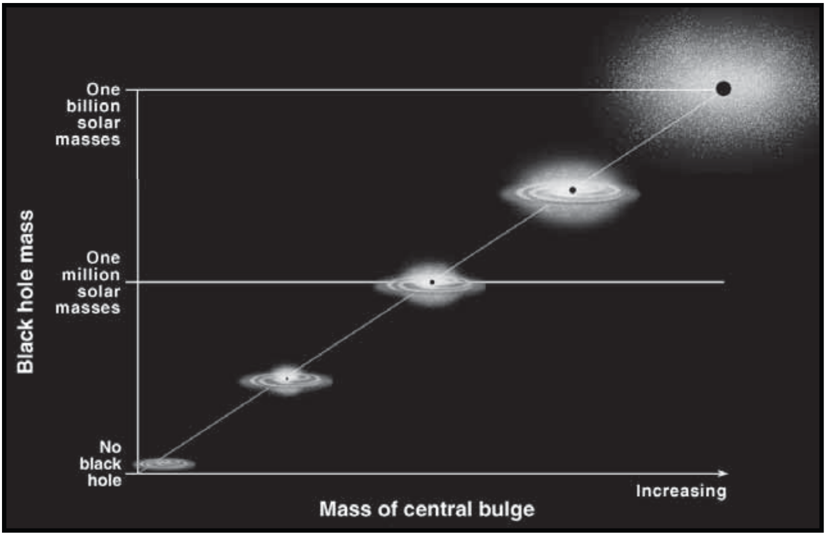
Matter near a supermassive black hole gains energy as it falls inward. Some of the matter gets channeled out in two high-speed, well-focused beams along the black hole's axis of rotation, perpendicular to the accretion disk. The accretion disk has a nozzle that helps focus the beams of particles into two high-speed jets, but the exact mechanism is not yet known.

The most luminous quasars are far away; few are nearby. They are denizens of the distant past, of the young Universe, when they were very numerous, as revealed in X-ray images that show them glowing brightly. How did they form so early? We are not certain, but probably there is a lot of dark matter—matter that you can't see but that tends to clump up. It gathers material from its surroundings very efficiently and forms a black hole.

The most luminous quasars are far away; few are nearby. They are denizens of the distant past.

Supermassive black holes may have grown from intermediate-mass black holes having only a few hundred to a few tens of thousands of solar masses. The growth of the supermassive black holes regulated the star-formation rate, to some extent. This process may be an important part of the explanation for the strong correlation between the supermassive black hole mass and bulge mass discussed in Lecture 5. Jets and energetic winds from accretion disks may have also contributed to the demise of the luminous quasar. We also see many examples of less luminous versions of quasars in nearby galaxies, known as active galaxies, or active galactic nuclei. A supermassive black hole is present in nearly each galaxy.

We expect the supermassive black holes in active galaxies to be spinning. As material in the accretion disk gets closer to the nucleus, its spin rate should increase. When it falls into the black hole, the black hole's spin increases. Jets are a consequence of the spin of the accretion disk and black hole.



K. Cordes & S. Brown (STScI).

Correlation between black hole mass and bulge mass.

Evidence for spin has now been seen in the form of very luminous gas. The spin energy of the black hole is being tapped, due to the dragging of space around it. Also, X-ray observations of the shapes of emission lines shows that that gas is spinning very rapidly, and it should transfer its spin to the black hole. Some of the black holes spin at nearly the maximum possible rate; with a bit more spin, their event horizons would merge together, revealing a naked singularity. ■

Suggested Reading

Begelman and Rees, *Gravity's Fatal Attraction*.

Carroll and Ostlie, *An Introduction to Modern Astrophysics*.

Ferguson, *Prisons of Light*.

Ferris, *The Red Limit*.

Melia, *The Edge of Infinity*.

Pasachoff and Filippenko, *The Cosmos*.

Questions to Consider

1. Outline the argument used to infer that the physical size of quasars is very small.

2. Suppose no nearby galaxies exhibit evidence for the presence of supermassive black holes in their centers. Would this be a problem for the hypothesis of what powers quasars?

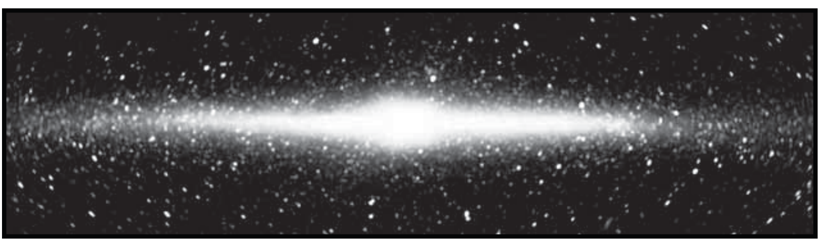
3. Why doesn't gas generally fall directly into a black hole, instead forming an accretion disk?

Gravitational Waves—Ripples in Space-Time

Lecture 7

When pairs of galaxies merge, their supermassive black holes can also coalesce and grow. Binary stellar-mass black holes and neutron stars can also merge. In all cases, ripples in the fabric of space-time called gravitational waves should be emitted. Several ambitious instruments have been built to observe gravitational waves from merging neutron stars and black holes. With such detectors, we will be able to effectively "listen" to physical processes in the Universe, and draw conclusions about their characteristics.

Galaxies can cannibalize each other by merging together. Certainly long ago, when galaxies were closer together, small galaxies with intermediate-mass black holes merged over time and their black holes coalesced as well. In the far future, perhaps roughly 5 billion years from now, our Milky Way Galaxy and the Andromeda Galaxy will merge into one giant galaxy. When gas-rich big galaxies merge, the colliding clouds of gas produce large numbers of new, massive stars, causing the galaxy to light up brightly. Eventually the supermassive black holes can also merge, but this takes a long time because their separations are large. With so many galaxies in the Universe, how do we find the rare ones that are in the process of merging? The key to success may come from observations of gravitational waves.



COBE DIRBE/NASA.

The Milky Way Galaxy, which contains a supermassive black hole at its center.

If two objects revolve around one another, the curvature, or warping, of space around them is not static; gravitational waves are produced that carry energy outward. The two objects approach each other as energy is lost, eventually merging to form a single object. The merging of binary supermassive black holes, neutron stars, stellar-mass black holes, or black hole/neutron star pairs should produce strong gravitational waves. Currently, binary pulsars provide the best indirect evidence for the emission of gravitational waves.

A major goal of astrophysics is to detect gravitational waves directly. This would verify a major prediction of general relativity and would provide a brand new window on the Universe: gravitational waves, instead of electromagnetic radiation. Although cosmic rays—high-energy charged particles—neutrinos, and meteorites provide additional information, it remains true that most of what astronomers have learned about the Universe so far has come from studies of electromagnetic radiation.

Gravitational waves provide a brand new way to study the Universe. In fact, we can "listen" to the Universe by detecting them.

Gravitational waves provide a brand new way to study the Universe. In fact, we can "listen" to the Universe by detecting them, even if we can't see them with electromagnetic radiation. Highly asymmetric gravitational wave emission can sometimes lead to the ejection of a supermassive black hole after merging. A possible example was recently announced, but other explanations for the data are not ruled out.

How do we directly detect gravitational waves? They have a distinct signature: an alternate stretching and squeezing along two perpendicular directions. However, they are generally very weak: Over a distance of 1 meter, we expect variations of a *millionth* of a proton diameter. Human ears can amplify a signal by a factor of a million due to the collective response of many cells. Perhaps we can do something similar with gravitational waves?

Joseph Weber first attempted this in the 1960s with a cylindrical aluminum bar, 2 meters in length. He tuned it to the expected frequency of incoming waves, hoping to amplify the effect. Weber didn't detect any gravitational waves, but his efforts were pioneering.

Modern techniques are based on interferometers, giant systems with large arms over which you might detect a small variation in length. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is an important stepping stone, though no waves have yet been detected. The technique involves two laser beams perpendicular to each other, arranged in such a way as to cause completely destructive interference. If a gravitational wave passes by, the light beams might not perfectly cancel each other because the relative lengths of the beams change. There are now about half a dozen such systems world-wide; any real signal would have to be detected at many locations if it is to be believed. They are useful for mergers of binary neutron stars or stellar-mass black holes, which produce high-frequency signals. Merging supermassive black holes might be detected in the future by LISA, the Laser Interferometer Space Antenna, which we hope will be built by 2018 or 2020. ■

Suggested Reading

Cristensen, Fosbury, and Kornmesser, *Hubble*.

Drake, *Galileo*.

Greene, *The Fabric of the Cosmos*.

LIGO. http://www.ligo.caltech.edu.

Pasachoff and Filippenko, *The Cosmos*.

Sounds of gravitational waves. http://www.black-holes.org/explore1.html.

Thorne, *Black Holes and Time Warps*.

Will, *Was Einstein Right?*

Questions to Consider

1. Given that we feel the effects of gravity every day, why do you think gravitational waves are so difficult to detect?

2. Do you consider the opening of the gravitational-wave window on the Universe to be a smaller or larger leap than going from optical light to radio waves (or from optical light to any other form of electromagnetic radiation)?

3. For those who like math: If the surface area of the event horizon of a black hole can never decrease (it remains the same, or increases with time), calculate the minimum final mass of the black hole formed by the merging of 2 non-rotating black holes each having 10 solar masses. The mass difference—that is, the sum of the initial masses minus the final mass—can be radiated in the form of gravitational waves. Calculate the efficiency of this process.

4. In an interferometer designed to detect gravitational waves, why do you think it is advantageous for the laser beams to bounce back and forth many times along each of the 2 arms?

The Wildest Ride in the Universe

Lecture 8

Near a stellar-mass black hole, a human would be stretched and torn apart by tidal forces, but these are much weaker outside a supermassive black hole. If someone were to travel safely into a black hole, he would see a highly distorted view of the sky because of the extreme curvature of space-time. Computer simulations show that he would experience a truly wild ride, with many weird effects visible. Viewing him from a distance outside the black hole, we would see his clock slow down, grinding to a halt as he approaches the event horizon.

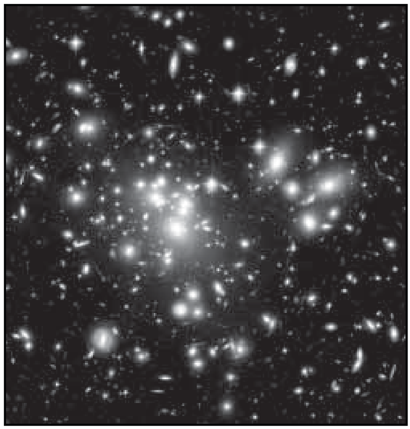
It is very hard to get an intuitive feeling for what black holes are like. Various scenarios have appeared in science fiction books and movies, and also in cartoons, where people get torn apart—and in fact, this would indeed occur near a stellar-mass black hole.

If you were to fall without any rocket power toward a black hole, you would get stretched and squeezed by tidal forces, especially in the case of a low-mass black hole. This process is informally known as "spaghettification," even among physicists and astronomers. If a neutron star spirals into toward a black hole it gets ripped apart tidally, possibly producing a short-duration gamma-ray burst. The tidal forces near a supermassive black hole are much smaller than those near a stellar-mass black hole; however, stars are so large that they would still get ripped apart, and there exists observational evidence for such stellar disruptions.

If you were to travel safely toward a black hole, you would see a highly distorted view of the sky because of the extreme curvature of space-time. There would be much gravitational lensing, which occurs when a massive foreground object bends and distorts the light from background object. For example, astronomers have found many distant galaxies gravitationally lensed by closer clusters of galaxies.

Let's imagine traveling toward a non-rotating black hole; we choose a supermassive one so as not to get spaghettified. Crossing the event horizon would lead to certain death at the singularity, but computer simulations show that you would experience a truly wild ride, with many weird effects visible, especially if a coordinate grid were painted on the horizon. Exactly what you would see depends on whether you're in free-fall or are firing rockets.

Andrew Hamilton, from the University of Colorado, has constructed a great web site. He took the equations of general relativity, and tried to simulate what you would see while falling into a black hole in a very realistic way. A clock shows the time in seconds before reaching the singularity. He chose the supermassive black hole in the center of the Milky Way Galaxy, and assumed a mass of 5 million solar masses. The true mass is probably closer to 4 or 4.5 million solar masses, so the times he gives need to be adjusted a little, but there are no qualitative differences. (The background for his animations is Axel Mellinger's beautiful Milky Way panorama, made from a whole bunch of optical photographs stitched together.)



NASA, N. Benitez (JHU), T. Broadhurst (Racah Institute of Physics/The Hebrew University), H. Ford (JHU), M. Clampin (STScl), G. Hartig (STScl), G. Illingworth (UCO/Lick Observatory), the ACS Science Team, and ESA.

The Hubble Space Telescope photographed the massive cluster of galaxies Abell 1689, revealing many faint, very distant, gravitationally lensed background galaxies.

Hamilton paints a red grid on the black hole's event horizon. There wouldn't be such a grid in reality, but it is useful to see the distortions of space in the animations. For example, the grid shows that you can see both the north and south poles of the event horizon simultaneously, due to the extreme curvature of space. Freely falling into the black hole, one experiences a truly wild ride, with a plethora of amazing and weird effects being visible. For example, when you reach the event horizon and pass through it, you see two coordinate grids because there are effectively two event horizons; this will be further explained in the next lecture.

If, instead of being in free-fall, you lower yourself toward the event horizon slowly and you look in the opposite direction (away from the black hole), you would see the whole Universe being crammed into a smaller and smaller area, tending toward infinite brightness in a flash when you reach the horizon. Back in free-fall, on your way to the singularity you would be spaghettified, and when you hit the singularity everything would be crammed into a single point and there would be total darkness.

Viewing this traveler from a distance outside the black hole, we would see his clock slow down, grinding to a halt as he approaches the horizon; from our perspective, neither the traveler nor anything else ever crosses the horizon, instead forming a thin membrane around it. Moreover, the light that he emits would become progressively more redshifted. However, if the traveler avoids the event horizon and returns home, he will have aged less than people who remained far from the black hole, effectively jumping into the future relative to them.

Suppose Luke Skywalker were to throw his mortal enemy, Darth Vader, toward a black hole. Luke would see Darth Vader's clock slow down due to gravitational time dilation. But Vader would see his own clocks ticking normally. To Luke it would appear that Vader *never* falls in. Time comes to a halt as seen from Luke's perspective when Vader reaches the event horizon. Indeed, nothing ever falls into a black hole from the perspective of outside observers, because of infinite time dilation.

Because of this effect, decades ago some physicists and astronomers referred to black holes as "frozen stars."

Because of this effect, decades ago some physicists and astronomers referred to black holes as "frozen stars": a collapsing star appears to stop getting smaller, when it is just a little larger than the event horizon. The term "black hole" was coined by John Wheeler in 1967 because it was more visually descriptive of what a black hole really is; it resonated with people more. Though a star falling into a black hole doesn't cross the horizon from our perspective, it does fade from view because few of the photons actually reach us and those that do are gravitationally redshifted. But from Vader's perspective, he definitely does fall in, and he hits the singularity a very short time later.

Suppose Vader turns on his rockets near the event horizon, stops himself, and then comes back to fight Luke again. Vader will have aged much less than Luke did. Vader spent time near the event horizon where all clocks (physical, biological, etc.) run slowly. This is a way of jumping into the future without aging very much.

We have seen some observational evidence of gas falling into a black hole, showing some of these effects. A blob in the accretion disk around the black hole Cygnus X-1 is falling in. As it gets closer and closer to the event horizon, it fades from view and becomes gravitationally redshifted. If that blob were Darth Vader, he would see blueshifted high-energy light from Luke and the rest of the outside world. ■

Suggested Reading

Begelman and Rees, *Gravity's Fatal Attraction*.

Hamilton, http://casa.colorado.edu/~ajsh/schw.shtml.

———, http://jilawww.colorado.edu/~ajsh/insidebh/index.html.

Hawking, *The Universe in a Nutshell*.

Kaufmann, *Black Holes and Warped Spacetime*.

Nemiroff, http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html.

Pasachoff and Filippenko, *The Cosmos*.

Pickover, *Black Holes*.

Thorne, *Black Holes and Time Warps*.

Questions to Consider

1. Explain why the tidal stretching ("spaghettification") is smaller near a supermassive black hole than near a stellar-mass black hole.

2. Given that in a non-rotating black hole, the singularity takes up all of space at a particular time, rather than a point in space over an infinite period of time, does it make sense to think that space and time have, to a certain extent, reversed roles inside a black hole?

3. If you were given the chance, would you travel close to a black hole and then return to Earth, having aged very little compared with your friends and family? Would you, effectively, want to permanently jump to the future (and, if so, by what amount of time)?

Shortcuts through the Universe and Beyond?

Lecture 9

Mathematically, black holes seem to connect our Universe with others, or to provide amazing shortcuts within our Universe. In the case of a non-rotating black hole, such a "wormhole" is definitely not traversable. In the case of rotating or charged black holes, there are two event horizons, and it appears to be possible, in principle, to traverse them and end up in another universe. However, recent studies predict that a tremendous amount of energy is concentrated at the inner event horizon; one would get vaporized near that location, and in fact the wormhole itself is destroyed. If a journey through the ring singularity of a rotating black hole were possible, one would see many bizarre effects.

The equations of Albert Einstein's general theory of relativity suggest that black holes are connected to passages through space-time known as wormholes. In principle, it might be possible to use them as shortcuts to a different distant location in our Universe, or as gateways to other universes, or maybe even to travel backward in time. This concept has been used in many science fiction books and movies. So let's explore black holes in more detail, to show you what really happens.

Let's begin with non-rotating black holes, known as "Schwarzschild black holes," after Karl Schwarzschild. Mathematically, space-time can be thought of as flowing inward toward the black hole.

To further explore the structure of black holes, I need to carefully define what is meant by curved space. If one puts an intrinsically curved 2-dimensional surface on a flat sheet of paper, there will always be some distortions. The spatial geometry of a black hole can be represented with an embedding diagram showing only 2 of the 3 dimensions. Embedding diagrams have limitations; in many ways space-time diagrams are better. These are usually arranged in such a way that light travels along 45 degree lines. Positive "x" is to the right, and time goes vertically upward.

A specific type of space-time diagram that is especially suitable for the analysis of black holes is generally known as a Penrose diagram. The Penrose diagram can be extended to show the other Universe, which cannot be reached without exceeding the speed of light. The Penrose diagram also shows the mathematical presence of a "white hole," the time reversal of a black hole. Instead of objects falling into it and never being able to get out, objects come out of a white hole and are never able to get back in. But white holes have never been found in the Universe; perhaps they do not exist.

Now we consider rotating black holes, known as "Kerr black holes," after relativist Roy Kerr. A rotating black hole is mathematically much more complicated than a non-rotating black hole. There are two horizons (inner and outer), and also a ring singularity. The Penrose diagram shows that the singularity is now a vertical (rather than horizontal) line, so it can in principle be avoided. The Penrose diagram also shows a never-ending sequence of other parallel universes into which one may seemingly travel. You could also conceivably travel into what we call the "antiverse" by going through the ring singularity. However, the wormhole can be traversed only if we ignore some important physical effects.

White holes have never been found in the Universe; perhaps they do not exist.

Recently, it has been calculated that a large amount of mass and energy builds up at the inner horizon. Material is streaming into and out of the inner horizon, and collisions occur, heating gas tremendously; everything gets roasted at the inner horizon. This so-called "mass inflation instability" doesn't even let the wormhole form; it gets closed, and is thus not traversable.

Charged black holes—known as "Reissner-Nordstrom black holes"—theoretically have many of the same properties as rotating black holes. The angular coordinates differ from rotating black holes, but they aren't shown in the Penrose diagram. The idealized kind of charged black holes that never swallow anything are open and traversable. The catch is that if you try to traverse them, then you create mass inflation instabilities and the wormhole ceases to exist. Also, we don't expect charged black holes to occur in nature because they would neutralize themselves.

Suppose traversable wormholes do exist. It would be fun to simulate what one would see while falling into one and going through it. Andrew Hamilton does this on his website. But if traversable wormholes really did exist, they might allow travel backward in time to our Universe. When Carl Sagan was writing *Contact*, he actually had to use idealized wormholes because travel through a real one wouldn't have been possible. Maybe there are ways of doing it, but we really don't know how. ■

Suggested Reading

Hamilton, http://casa.colorado.edu/~ajsh/schw.shtml.

———, http://jilawww.colorado.edu/~ajsh/insidebh/index.html.

Hawking, *The Universe in a Nutshell*.

Kaufmann, *Black Holes and Warped Spacetime*.

Pickover, *Black Holes*.

Thorne, *Black Holes and Time Warps*.

Questions to Consider

1. Why do you think travel through black holes and wormholes has been such a popular concept in science fiction books, movies, and cartoons?

2. Do you think the repulsive "dark energy" that permeates space, and currently accelerates the expansion of the Universe, might someday be harnessed to keep the throat of a wormhole open for travel?

3. What sorts of problems could be produced by the violation of causality—that is, if you could travel through a wormhole and return before your departure?

Stephen Hawking and Black Hole Evaporation

Lecture 10

According to classical general relativity, black holes are completely black, emitting no light. But in 1975, Stephen Hawking came up with an interesting result believed to be generic to quantum theories of gravity: Black holes can "evaporate" via a quantum tunneling process! This conclusion is based in part on the strong apparent mathematical connections between black hole physics and thermodynamics.

General relativity is an amazingly successful theory, and it predicts that black holes are completely black. But might this be false if quantum effects are taken into account? The basic idea behind quantum physics is that particles do not have definite properties such as position, speed, and energy until one actually measures them. What if one applies quantum physics to black holes?

When general relativity and quantum physics are used to describe a large amount of mass in a small volume, there is violent conflict. The holy grail of modern theoretical physics is to unify its two great pillars. We have some candidate theories, but nothing conclusive. However, the celebrated Cambridge physicist Stephen Hawking came up with an interesting result believed to be generic to such theories: Black holes can evaporate, due to the presence of quantum fluctuations!

Here is the basic argument behind Hawking's theory. (Just get the general idea; don't worry about the details.) Black holes are very simple; they have "no hair." No details other than mass, charge, and angular momentum (the amount of spin) can be discerned from the outside.

Entropy is a measure of the amount of disorder in a system. It is proportional to the natural logarithm of the number of macroscopically similar states. The second law of thermodynamics states that in any natural process, the entropy of a closed system—one from which nothing escapes—always increases or, at best, stays constant. At first sight, a black hole, having "no hair," seems to have very little, if any, entropy. So what happened to the entropy of the material that went into the black hole? Is this a violation of the second law?

In 1972, physicist Jacob Bekenstein suggested that a black hole has entropy, and it is associated with the surface area of its smooth-looking event horizon. As one throws more matter or energy into a black hole, the surface area of the event horizon increases, and so does its entropy. The "second law of black hole dynamics," that the surface area of the event horizon can never decrease, sounds like the second law of thermodynamics, especially if entropy is associated with the event horizon. Bekenstein suggested that a black hole is physically a thermal body having a temperature (a measure of how much things jiggle around). But in this case a black hole should radiate light, since thermal bodies of nonzero temperature radiate, or "shine." This violates classical physics, so Bekenstein abandoned the idea.

As one throws more matter or energy into a black hole, the surface area of the event horizon increases, and so does its entropy.

Hawking realized that black holes might be able to radiate energy, if quantum mechanics is taken into account. The black hole's effective temperature is inversely proportional to its mass. The evaporation process can be understood by considering the production of virtual pairs of particles and antiparticles near the event horizon, according to the Heisenberg uncertainty principle; some of the particles and antiparticles escape when their partners go into the black hole with negative energy as seen from the outside. The black hole evaporates progressively faster as its mass decreases through evaporation, ending with an explosion dominated by gamma rays. Miniature black holes that might have been created shortly after the big bang could now be exploding, but none has ever been detected. ■

Suggested Reading

Adams and Laughlin, *The Five Ages of the Universe*.

Ferguson, *Prisons of Light*.

Feynman, Dyson, and Leighton, *Classic Feynman*.

Hawking, *A Briefer History of Time*.

Pasachoff and Filippenko, *The Cosmos*.

Shu, *The Physical Universe*.

Thorne, *Black Holes and Time Warps*.

Questions to Consider

1. Are you surprised to learn that black holes aren't completely black, after all?

2. For those who like math: If the luminosity (energy emitted per second) per unit of surface area of a thermal emitter is proportional to the fourth power of its temperature, to what power of mass is the total luminosity of an evaporating black hole proportional?

3. Which of the observed or inferred aspects of gamma-ray bursts do you think are inconsistent with evaporation of mini black holes as an explanation?

Black Holes and the Holographic Universe

Lecture 11

After a black hole evaporates due to the Hawking process, all that remains are thermally emitted particles, and they tell us only the temperature of the black hole. But such a conclusion violates the basic principle of quantum physics that no information is ever truly lost from the Universe; it only gets scrambled or hidden. Recently, this long-standing puzzle may have been resolved. It appears that information does emerge out of a black hole during its evaporation, but the details are subtle and still not fully understood. One way to view this conclusion is through the holographic principle: the information inside a black hole is actually contained on its surface.

Given the "no-hair theorem" discussed in Lecture 10, it appears that information is permanently lost from the Universe when it goes into a black hole. As viewed from the outside, the only discernable properties of a black hole are its mass, angular momentum, and electric charge, regardless of what objects it swallowed. After the black hole evaporates, all that remains are thermally emitted photons, and they carry information only about the object's temperature. This conclusion seems to violate a basic principle of quantum physics that no information is every truly lost from the Universe; it only gets scrambled or hidden.

Recently, this long-standing information paradox may have been resolved. Leonard Susskind and Gerard 't Hooft argue that information is not destroyed; it must be carried by the Hawking radiation, though the exact mechanism might be complex. In 2004, Stephen Hawking changed his mind and agreed that information is not lost, but Kip Thorne is unconvinced. This is frontier research, with no unanimous agreement, though most experts believe that information is preserved.

Information is a set of data that completely describes a system, distinguishing it from all others. Computers use the binary system, 1s and 0s. A bit is a single unit of information; it cannot be reduced in size. The total information of a large object consists of all the bits of information that would be needed to completely describe it. If it were possible for information to be destroyed, rather than just scrambled or hidden, the laws of physics would look different if one were to reverse the arrow of time – yet they are thought to be same. Though this is counterintuitive, even in quantum mechanics (which basically says that the world is probabilistic) the information about a system is conserved, not lost.

It turns out that black holes have the most entropy possible in a given volume. All of the information that went into a black hole gets scrambled, though not destroyed; entropy is hidden or scrambled information. When the black hole evaporates, the information seems to have disappeared from the Universe. What happened to it?

One way to view this conclusion is through the holographic principle: All of the information inside a black hole is actually contained on its surface, a thin membrane just outside the event horizon that resembles a hologram. This is the membrane paradigm introduced in Lecture 8. Recall that from the perspective of an outside observer, nothing ever crosses the event horizon of a black hole, due to infinite time dilation. The material accumulates on a very thin membrane just outside the event horizon; this is sometimes called a stretched horizon. Since all of the information in a black hole can be thought of as being on the thin, 2-dimensional membrane on the event horizon, this is kind of like a hologram. A hologram is a 2-dimensional plate of glass, or other recording device, which when illuminated, shows a realistic 3-dimensional image. By shining light on a sequence of holograms, one can even make a 3-dimensional movie.

In this case, the membrane has a thickness of only 1 Planck length (about 10^{-33} cm), 20 orders of magnitude smaller than a proton! According to the membrane paradigm, the information was never inside the black hole; thus, it can in principle escape. To an outside observer, the membrane is very hot and emits particles that somehow carry the original information. Quantum mechanics is saved! However, the information has been scrambled; it has high entropy.

Since a black hole stores the maximum possible information in a given volume, it must be the case that when the information density is high, the total information grows in proportion to surface area rather than volume. This is unlike normal substances such as bricks; normally, two bricks have twice the information content, and twice the volume, of one brick. Since that information can be described by a 2-dimensional hologram, one can conclude that any smaller amount of information in a given volume can also be described by a 2D hologram at the boundary of the volume. Mathematically, the contents of the entire visible Universe might be described by information plastered in Planck areas at its visible edge! But the location of the horizon is changing with time as the Universe expands. Moreover, it depends on the observer's particular position. So there is almost certainly no physical hologram at the horizon, like some giant machine clanking away. Rather, it's thought to be a mathematical correspondence that leads to these amazing conceptual insights.

Mathematically, the contents of the entire visible Universe might be described by information plastered in Planck areas at its visible edge.

If the Universe really is a hologram, it should look fuzzy, because there are more Planck volumes within the Universe than there are Planck areas at its horizon. There is intriguing, but still highly tentative and speculative, observational evidence that this is indeed the case. ■

Suggested Reading

Susskind, *The Black Hole War*.

———, *The Holographic Universe*.

Thorne, *Black Holes and Time Warps*.

Wolf, *Taking the Quantum Leap*.

Questions to Consider

1. Normally, when we hear the word "information," we think of an organized set of data that clearly conveys the nature of the subject. A glass of water throughout which ink is uniformly spread is not considered to contain much information. Contrast this with the definition adopted in this lecture.

2. How might it be that the thermal spectrum emitted by a black hole through Hawking radiation is able to convey information about the matter that fell into the black hole?

3. If a 2-dimensional hologram reveals the 3-dimensional structure of an object only when light from a third dimension shines on it, can the hologram really be thought of as having only 2 dimensions?

Black Holes and the Large Hadron Collider

Lecture 12

Production of miniature black holes in a particle accelerator might imply the existence of additional dimensions as predicted by some modern theories: gravity would be stronger over short distances than previously expected and the Schwarzschild radius would be larger, making it easier to compress material enough to create a black hole.

Sometimes black holes kind of get bad publicity; people are afraid of them. But black holes are generally quite safe; only at a close distance is the gravitational force very strong. No known black holes are sufficiently nearby to pose a threat to our existence; the nearest stellar-mass black hole is probably over 100 light years away.

Recently in the news, mini black holes have been portrayed as a possible threat to our existence. In particular, rumors have spread that the Large Hadron Collider (LHC) might produce a miniature black hole that will devour Earth and its inhabitants!

What is the Large Hadron Collider? First, some terminology. Hadrons are particles that consist of more-fundamental particles called "quarks" bound together by a strong nuclear force. The most familiar ones are the protons and neutrons, more generally called nucleons because this is what the nuclei of atoms consist of. Leptons are the other major kind of particle; they do not consist of quarks, and they feel the weak nuclear force. Electrons and neutrinos are leptons.

The LHC is a giant underground particle accelerator at CERN, the European Organization for Nuclear Research, near Geneva, Switzerland. It consists of a circular evacuated ring, 27 km in circumference, that is lined with supercooled, superconducting magnets. In it, protons are accelerated to 99.9999991% of the speed of light; this is the most powerful particle accelerator humans have ever built. Bundles of protons go in two opposite directions through the tubes, and in some places they collide with each other at tremendous energies. At the collision points, a zoo of particles gets created, and they are measured with detectors. The hope is to create particles that have never been seen before, but perhaps existed very early in the history of the Universe, when it was extremely hot and dense.

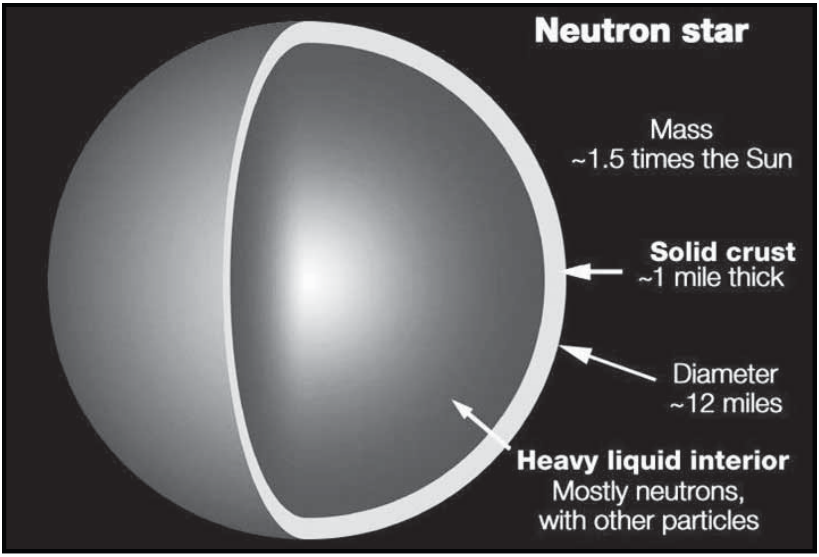
Perhaps the best-known goal of the LHC is to create the so-called "Higgs boson," sometimes informally called the "God particle." It is thought to be associated with a field, the "Higgs field," which ends up giving various particles their different masses. Particles moving through the Higgs field encounter different amounts of resistance, and this translates into different particle masses.

Another major goal of the LHC is to find some candidates for the so-called "dark matter" in the Universe. This matter exists, it exerts a gravitational pull in galaxies and clusters of galaxies, but we can't see it. It accounts for nearly a quarter of the contents of the Universe. It is thought to consist of weakly interacting massive particles (WIMPs) left over from the big bang.

If Hawking's evaporation theory is incorrect, then the black holes probably can't form in the first place.

More generally, the LHC is designed to help physicists develop and test theories that unify the fundamental forces and particles of nature. The thorniest issue right now within this goal of unification is the incredible weakness of gravity, compared with the other fundamental forces. One of the most promising recent ideas for explaining the weakness of gravity is that there are additional macroscopically large dimensions, not just our familiar three dimensions of x, y, and z. The presence of additional relatively large dimensions in which gravity partly resides might allow the formation of mini black holes—having 1000 to 10,000 proton masses—in LHC collisions.

The production rate of mini black holes might be as high as 1 per second, something like 100 thousand per day. Should we fear them? No. Minuscule black holes would quickly evaporate by the Hawking process, so they would last only about 10 billionths of a billionth of a billionth of a second (10^{-26} sec) and wouldn't eat anything at all.



D. Dooling (D2 Associates and NASA/MSFC).

The existence of old, dense neutron stars suggests that mini black holes are either nonexistent or do not devour stars.

If Hawking's evaporation theory is incorrect, then the black holes probably can't form in the first place. Even if such black holes were to form and survive, Earth would not get eaten for an exceptionally long time, much longer than the remaining lifetime of the Sun. Their Schwarzschild radius would be about 1/1000 of a proton radius—using the appropriate formula incorporating extra dimensions. So, the black hole probably wouldn't eat most of the nucleons that it encounters. Most of the black holes would have such high speeds that they would immediately escape from Earth. Those few that remain in Earth eat it at a negligible rate. Even if we allow all of the black holes to remain in Earth, and make generous assumptions about their production rate, Earth gets eaten so slowly that the Sun will die long, long before any effects would be noticed.

Collisions of extremely energetic cosmic rays with Earth have not produced black holes that devoured it. Old white dwarfs and neutron stars have been found, and mini black holes have not devoured them, yet they are much denser than Earth and hence easier to eat.

Let's conclude with some speculations about the future of black hole research. The detection of gravitational waves from merging black holes should be incredibly exciting, opening a brand new window through which to view the Universe. By monitoring the gravitational wave signal in detail, we will also determine whether black holes really are as simple as we think.

With radio telescopes spread across many continents, we hope to examine the immediate environment of the supermassive black hole in the center of our Milky Way Galaxy. This will allow us to test various specific predictions of general relativity in a strong gravitational field.

We wish to better understand how quasars and their supermassive black holes are able to form within the first billion years after the big bang. Also, how do relativistic jets from quasars, as well as the winds from their accretion disks, affect their growth? If we find intermediate-mass black holes, we will be one step along the way to understanding the growth of the supermassive ones.

Additional examples of stellar-mass black holes will allow us to better constrain what kinds of stars turn into black holes at the end of their lives and to find more direct evidence of event horizons. We hope to soon more accurately measure black hole spin, and find definitive evidence for frame dragging.

Mini black holes have still not been found, yet they are an important frontier. They might be produced when the highest-energy cosmic rays collide with molecules in Earth's atmosphere. If the LHC produces mini-black holes that evaporate, studies of their decay should help constrain fundamental theories of the Universe. Progress in quantum theories of gravity, such as string theory, should help us understand the nature of the black hole singularity and space-time itself.

In summary, observational studies of real black holes, as well as theoretical investigations, allow humans to explore the most extreme limits of physics, ever deepening our understanding of the fundamental laws of nature according to which the Universe operates. ■

Suggested Reading

Barrau and Grain, *The Case for Mini Black Holes*.

Collins, *Large Hadron Collider*.

Davies, *Superforce*.

Greene, *The Elegant Universe*.

Kaku, *Hyperspace*.

Randall, *Warped Passages*.

Weinberg, *Dreams of a Final Theory*.

Questions to Consider

1. Do you think enormous, complicated scientific machines like the LHC, which cost about $10 billion, are worth the money?

2. Suppose a black hole having the mass of Earth, and a Schwarzschild radius of about 1 cm, were to get stuck in the center of Earth. Would we need to worry about the destruction of Earth?

3. Which questions about black holes do you find most fascinating? What would you like astronomers and physicists to concentrate on during the next decade, in their studies of black holes?

Timeline

1665 .... Isaac Newton develops laws of motion and universal gravitation; invents calculus. His work is finally published in 1687, in *The Principia*.

1783 .... John Mitchell writes Henry Cavendish about the possibility of "dark stars."

1796 .... Pierre-Simon Laplace independently proposes the possibility of invisible stars.

1801 .... Thomas Young shows that light acts as a wave, beginning a century-long loss of interest in dark stars.

1808 .... Laplace removes discussion of invisible stars from thirf edition of his *The System of the World*.

1873 .... Maxwell's theory of electromagnetism establishes the wave formulation of light.

1905 .... Albert Einstein's publishes his special theory of relativity, as well as the photoelectric effect demonstrating the particle nature of light.

1915 .... Einstein publishes his general theory of relativity, which explains gravity.

1916 .... Karl Schwarzschild finds the first exact solution to Einstein's equations for spherical, non-rotating objects, including black holes.

1920 .... Hans Reissner and Gunnar Nordström work out mathematics of charged black holes.

1933 .... Fritz Zwicky and Walter Baade propose the existence of neutron stars, a year after discovery of the neutron.

1935 .... Albert Einstein and Nathan Rosen propose a passageway from a black hole to a white hole ("Einstein-Rosen bridge"), possibly bypassing the singularity.

1939 .... J. Robert Oppenheimer and Hartland Snyder argue that a sufficiently massive star would collapse to the size of the Schwarzschild radius; J. Robert Oppenheimer and others find that the maximum mass for a neutron star is only around 3 solar masses.

1957 .... John Wheeler coins the term "wormhole" for the Einstein-Rosen bridge.

1958 .... David Finkelstein shows that the event horizon is a one-way membrane; nothing can pass outward through it.

1960 .... Kruskal-Szekeres extension of the Schwarzschild solution for a black hole.

1963 .... Roy P. Kerr develops space-time equations for spinning stars, soon applied to rotating black holes; Maarten Schmidt uses redshifts to identify quasars as extremely remote and luminous objects.

1964	Donald Lynden-Bell and Martin Rees propose that a quasar is powered by the accretion of matter onto a supermassive black hole.
1965	Joseph Weber develops simple gravitational wave detector.
1967	John Wheeler coins the term “black hole”; Anthony Hewish and Jocelyn Bell discover the first pulsars (spinning neutron stars).
1969	Donald Lynden-Bell and Martin Rees suggest that a supermassive black hole might be at the center of the Milky Way Galaxy; Roger Penrose proposes that “naked singularities” do not exist; this idea becomes known as cosmic censorship.
1970	Roger Penrose and Stephen Hawking prove that a black hole collapses to a singularity.
1971	The first observational evidence for black holes is found in the binary system Cygnus X-1/HDE 226868, 6000 light-years away.
1972	Jacob Bekenstein proposes that entropy is associated with the surface area of a black hole’s event horizon; 4 laws of black hole mechanics, analogous to the laws of thermodynamics, are proposed by James Bardeen, Brandon Carter, and Stephen Hawking.

1973.. Gamma-ray bursts discovered; John Wheeler declares that “black holes have no hair”; the “no hair” theorem states that black holes have only mass, electric charge, and angular momentum or spin.

1974.. Stephen Hawking argues that black holes are thermodynamic objects that radiate energy.

1978.. Evidence is found for a supermassive object, probably a black hole, in the center of the giant elliptical galaxy M87 (NGC 4486), 60 million light-years away.

1989.. Excellent evidence for the presence of a stellar-mass black hole is found in the binary system V404 Cygni.

1994.. Hubble Space Telescope confirms previous suspicions that a supermassive black hole, about 3 billion Suns, resides in galaxy M87.

1995.. Very strong evidence for a supermassive black hole of 36 million solar masses is found in the galaxy NGC 4258 (M106), about 23 million light-years away.

1996.. Gamma-ray burst X-ray afterglows found by BeppoSAX satellite, leading to ground-based detections at other wavelengths (optical, radio, etc.).

1996–2000	A team led by Reinhard Genzel, and somewhat later one led by Andrea Ghez, provides strong evidence for the presence of a supermassive black hole at the center of the Milky Way Galaxy, confirming previous, more tenuous suggestions based on less compelling data.
1999	First evidence for intermediate-mass black holes of 100 to 10,000 solar masses; first evidence for the tidal disruption of a star by a supermassive black hole in the center of a non-active galaxy.
2000–2009	Independent teams led by Reinhard Genzel and Andrea Ghez strengthen the case for a 4 million solar mass black hole at the center of the Milky Way Galaxy.
2002	Strong evidence for a 20,000 solar mass black hole in the globular cluster G1 orbiting the Andromeda Galaxy.
2003	First observation of rapid infrared flares at the center of the Milky Way Galaxy, probably from the inner accretion disk around the supermassive black hole.
2007	First observed stellar-mass black hole outside the Milky Way and its immediate neighbors: 16 solar masses orbiting a 70 solar mass blue star in galaxy M33, 2.5 million light-years away, announced October 17.

2009.. Evidence found for an intermediate-mass black hole of 500 solar masses located 290 million light years from Earth.

Glossary

absorption line: A wavelength, or small range of wavelengths, at which the brightness of a spectrum is less than it is at neighboring wavelengths.

accelerating Universe: The model of the Universe based on recent observations that its expansion is speeding up with time.

accretion: The transfer of matter to the surface of a star or a black hole. When the transferred matter goes into orbit around the object, an accretion disk is formed.

active galaxy: A galaxy whose nucleus emits large quantities of electromagnetic radiation that does not appear to be produced by stars; radio galaxies are one example of active galaxies.

adaptive optics: Optical systems providing rapid corrections to counteract atmospheric blurring.

angstrom (Å): A unit of length commonly used for visible wavelengths of light; 1 Å = 10^{-8} cm.

angular momentum: A measure of the amount of spin of an object; dependent on the object's rotation rate, mass, and mass distribution.

antiparticle: A particle whose charge (if not neutral) and certain other properties are opposite those of a corresponding particle of the same mass; an encounter between a particle and its antiparticle results in mutual annihilation as well as the production of high-energy photons.

antiverse: Another Universe, on the other side of the singularity associated with either a rotating black hole or a charged one.

apparent brightness: The amount of energy received from an object per second, per square centimeter of collecting area. It is related to luminosity and distance through the equation $b = L/(4\pi d^2)$, the inverse-square law of light.

astronomical unit (AU): The average distance between the Sun and Earth (1.5×10^8 km).

Big Bang: The birth of the Universe in a very hot, dense state 13.7 billion years ago, followed by the expansion of space.

binary pulsar: A pulsar in a binary system. Often, this term is used for systems in which the pulsar's companion is another neutron star.

binary star: Two stars gravitationally bound to and orbiting each other.

bipolar outflow: A phenomenon in which streams of matter are ejected from the poles of a rotating object.

blackbody: An object that absorbs all radiation that hits it; none is transmitted or reflected. It emits radiation due to thermal (random) motions of its constituent particles, with a spectrum that depends only on the temperature of the object.

black hole: A region of space in which the gravitational field is so strong that nothing, not even light, can escape. Predicted by Einstein's general theory of relativity.

centrifugal force: The fictitious outward force felt by an object in a rotating frame of reference.

Chandrasekhar limit: The maximum stable mass of a white dwarf or the iron core of a massive star, above which degeneracy pressure is unable to provide sufficient support; about 1.4 solar masses.

collapsar model: Model proposed for some types of gamma-ray bursts, wherein a rotating, massive star collapses and forms two highly focused beams (jets) of particles and light.

core: In a main-sequence star, roughly the central 10% by mass. In an evolved star this usually refers to the degenerate central region.

corona: The very hot, tenuous, outermost region of the Sun, seen during a total solar eclipse.

cosmic censorship: The notion that nature abhors naked singularities, and does not let them exist.

cosmic rays: High-energy protons and other charged particles, probably formed by supernovae and other violent processes.

cosmology: The study of the overall structure and evolution of the Universe.

dark energy: Energy with negative pressure, causing the current expansion of the Universe to accelerate.

dark matter: Invisible matter that dominates the mass of the Universe. We have never seen dark matter, but we can infer its presence from its gravitational effects on ordinary matter.

degenerate gas: A peculiar state of matter at high densities in which, according to the laws of quantum physics, the particles move very rapidly in well-defined energy levels and exert tremendous pressure.

Doppler shift: The change in wavelength or frequency produced when a source of waves and the observer move relative to each other. Blueshifts (to shorter wavelengths) and redshifts (to longer wavelengths) are associated with approach and recession, respectively.

$E = mc^2$: Einstein's famous formula for the equivalence of mass and energy.

eclipse: The passage of one celestial body into the shadow of another or the obscuration of one celestial body by another body passing in front of it.

electromagnetic force: One of the four fundamental forces of nature; it holds electrons in atoms.

electromagnetic radiation: Self-propagating, oscillating electric and magnetic fields. From shortest to longest wavelengths: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

electron: Low-mass, negatively charged fundamental particle that normally "orbits" an atomic nucleus.

electroweak force: The unification of the electromagnetic and weak nuclear forces.

ellipse: A set of points (curve) such that the sum of the distances to two given points (foci) is constant.

elliptical galaxy: One of the two major classes of galaxies proposed by Edwin Hubble; has a roughly spherical or elliptical distribution of generally older stars, less gas and dust, and less rotation than its spiral counterpart.

emission line: A wavelength (or small range of wavelengths) at which the brightness of a spectrum is more than it is at neighboring wavelengths.

ergosphere: A region surrounding a rotating black hole from which work can be extracted; the rotational energy is tapped by utilizing the dragging of space-time.

escape velocity: The minimum speed an object must have to escape the gravitational pull of another object.

event horizon: The boundary of a black hole from within which nothing can escape.

extinction: The obscuration of starlight by interstellar gas and dust.

fusion: The formation of heavier nuclei from lighter nuclei.

galactic cannibalism: The swallowing of one galaxy by another.

galaxy: A large gravitationally bound system of hundreds of millions and up to a trillion stars, typically 5000 to 200,000 light years in diameter.

Galilean satellites: The four large moons of Jupiter—Io, Europa, Ganymede, and Callisto.

gamma-ray burst (GRB): A brief burst of gamma rays in the sky, now known to generally come from exceedingly powerful, distant objects.

gamma rays: Electromagnetic radiation with wavelengths shorter than about 0.1 Å.

general theory of relativity: Einstein's comprehensive theory of mass (energy), space, and time; it states that mass and energy produce a curvature of space-time that we associate with the force of gravity.

globular cluster: A bound, dense, spherically symmetric collection of stars formed at the same time.

grand unified theory (GUT): A theory that unifies the strong nuclear ("color") and electroweak forces into a single interaction.

gravitational lens: In the gravitational lens phenomenon, a massive body changes the path of light passing near it so as to make a distorted image of the object.

gravitational redshift: A redshift of light caused by the presence of mass.

gravitational waves: Waves thought to be a consequence of changing distributions of mass.

gravity: The weakest of nature's fundamental forces but the dominant force over large distances because it is cumulative; all matter and energy contribute, regardless of charge.

hadron: a particle that consist of more-fundamental particles called "quarks" bound together by the strong nuclear force. Protons and neutrons are the most familiar hadrons.

halo: The region that extends far above and below the plane of a galaxy.

Hawking radiation: According to Stephen Hawking, the thermal radiation emitted by black holes because of quantum effects.

Heisenberg uncertainty principle: One form: In any measurement, the product of the uncertainties in energy and time is greater than or equal to Planck's constant divided by 2π. Another form: In any measurement, the product of the uncertainties in position and momentum is greater than or equal to Planck's constant divided by 2π.

Higgs boson: Sometimes informally called the "God particle." Thought to be associated with a the "Higgs field," which ends up giving various particles their different masses.

Hubble's law: The linear relation between the current distance and recession speed of a distant object: $v = H_0d$. The constant of proportionality, H_0, is called Hubble's constant.

infinity: All numbers, or an infinite distance or time.

interference: The property of radiation, explainable by the wave theory, in which waves in phase can add (constructive interference) and waves out of phase can subtract (destructive interference).

interferometer: Two or more telescopes used together to produce high-resolution images. Also, two or more laser beams arranged in such a way as to allow, in principle, the detection of gravitational waves.

intermediate-mass black hole: A black hole having a mass of a few hundred to a few tens of thousands of solar masses (that is, between stellar-mass and supermassive black holes). Some dense star clusters may have such black holes.

interstellar medium: The space between the stars, filled to some extent with gas and dust.

inverse-square law: Decreasing with the square of increasing distance. For example, the brightness of a star is proportional to the inverse-square of distance, as is the gravitational force between two objects.

ionized: Having lost at least one electron. Atoms become ionized primarily by the absorption of energetic photons and by collisions with other particles.

isotopes: Atomic nuclei having the same number of protons but different numbers of neutrons.

isotropic: Having properties that are the same in all directions—that is, no preferred alignment.

Kelvin: The size of 1 degree on the Kelvin (absolute) temperature scale, in which absolute zero is 0 K, water freezes at 273 K, and water boils at 373 K. To convert from the Kelvin scale to the Celsius scale, subtract 273 from the Kelvin-scale value. To convert from the Kelvin scale to the Fahrenheit: (F) = (9/5)C + 32.

Kerr black hole: A rotating black hole.

Large Hadron Collider: The world's most powerful particle accelerator, near Geneva, Switzerland on the French border. Though first turned on in 2008, it experienced a hardware problem; operations resumed near the end of 2009.

Large Magellanic Cloud: A dwarf companion galaxy of our Milky Way Galaxy, about 170,000 light years away; best seen from Earth's Southern Hemisphere.

large-scale structure: The network of clusters, voids, and other shapes seen on the largest scales of the Universe.

lepton: A fundamental particle that does not consist of quarks and feels the weak nuclear force. Electrons and neutrinos are the most familiar examples.

light curve: A plot of an object's brightness as a function of time.

light year: The distance light travels through a vacuum in 1 year; about 10 trillion kilometers, or about 6 trillion miles.

lighthouse model: The explanation of a pulsar as a spinning neutron star whose beam we see as it comes around and points toward us.

lookback time: The duration over which light from an object has been traveling to reach us.

luminosity: Power; the total energy emitted by an object per unit of time; intrinsic brightness.

magnetar: Spinning neutron star with an extraordinarily powerful magnetic field that occasionally releases a burst of gamma rays when the crust of the star undergoes a sudden restructuring (a "star quake").

main sequence: The phase of stellar evolution, lasting about 90% of a star's life, during which the star fuses hydrogen to helium in its core.

merging: The interaction of two galaxies in space, with a single galaxy as a result.

Milky Way: The band of light across the sky coming from the stars and gas in the plane of the Milky Way Galaxy.

mini black hole: Hypothetical miniature black hole, having less than about 1 billionth of Earth's mass. Such black holes might have formed shortly after the Big Bang, or perhaps in extremely high-energy collisions.

multiverse: The set of parallel universes that may exist, with our observable Universe as only one part.

nebula: A region containing an above-average density of interstellar gas and dust.

nebular hypothesis: Theory of the formation of our solar system, asserting that spinning clouds of interstellar matter gradually contracted and allowed for the formation of the Sun and the planets.

neutrino: A nearly massless, uncharged fundamental particle that interacts exceedingly weakly with matter. There are three types: electron, muon, and tau neutrinos.

neutron: Massive, uncharged particle that is normally part of an atomic nucleus.

neutron star: The compact endpoint in stellar evolution in which typically 1.4 solar masses of material is compressed into a small sphere supported by neutron degeneracy pressure.

nova: A star that suddenly brightens, then fades back to its original intensity; caused by the accretion of stellar matter from a companion star.

nuclear fusion: Reactions in which low-mass atomic nuclei combine to form a more massive nucleus.

nucleosynthesis: The creation of elements through nuclear reactions, generally nuclear fusion.

parallel Universe: In the context of black holes, one of the many alternate universes that mathematically appear to be connected to our Universe via wormholes.

parsec: A unit of distance equal to about 3.26 light years (3.086×10^{13} km).

particle physics: The study of the elementary constituents of nature.

Pauli exclusion principle: Wolfgang Pauli's explanation for the arrangement of electrons in an atom. The quantum mechanical principle states that no two electrons can be in the same "quantum state" in an atom at the same time.

photon: A quantum, or package, of electromagnetic radiation that travels at the speed of light. From highest to lowest energies: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

photon sphere: A region of space surrounding a black hole at which the curvature of space is so great that it causes light to orbit in circles.

photosphere: The visible surface of the Sun or another star from which light escapes into space.

Planck length: A fundamental unit of length, about 10^{-33} cm.

Planck's constant: The fundamental constant of quantum physics, *h*; a very small quantity.

planet: A body that primarily orbits a star—so that moons don't count; is large enough to be roughly spherical—typically, larger than about 600 km in diameter; gravitationally dominates its region of space, has largely cleared away other debris; and has never undergone nuclear fusion.

planetary nebula: A shell of gas, expelled by a red-giant star near the end of its life (but before the white-dwarf stage), that glows because it is ionized by ultraviolet radiation from the star's remaining core.

planetary system: A collection of planets and smaller bodies orbiting a star (e.g., our solar system).

positron: The antiparticle of an electron.

progenitor: In the case of supernovas, stars that eventually explode.

proton: Massive, positively charged particle that is normally part of an atomic nucleus. The number of protons in the nucleus determines the chemical element.

protostar: A star still in the process of forming in a cloud of gas and dust, collapsing nearly in free fall.

pulsar: An astronomical object detected through pulses of radiation, usually radio waves, having a short, extremely well-defined period; thought to be a rotating neutron star with a very strong magnetic field.

quantum fluctuations: The spontaneous, but short-lived, quantum creation of particles out of nothing.

quantum mechanics: A 20^{th}-century theory that successfully describes the behavior of matter on very small scales and radiation.

quark: A fundamental particle with fractional charge; protons and neutrons (and other hadrons) consist of quarks.

quasar (QSO): A star-like, extremely luminous object, typically billions of light years away; now thought to be the nucleus of a galaxy with a supermassive black hole that is accreting matter from its vicinity.

radial velocity: The speed of an object along the line of sight to the observer.

red giant: The evolutionary phase following the main sequence of a relatively low-mass star, such as the Sun; the star grows in size and luminosity but has a cooler surface.

redshift: Defined to be $z = (\lambda - \lambda_0)/\lambda_0$, where λ_0 is the rest wavelength of a given spectral line and λ is its longer, observed wavelength. The wavelength shift may be caused by recession of the source through space, by the expansion of space, or by the propagation of light out of a gravitational field.

Reissner-Nordstrom black hole: A charged black hole.

relativistic: Having a speed that is such a large fraction of the speed of light that the special theory of relativity must be applied.

resolution: The clarity of detail produced by a given optical system, such as a telescope.

rest mass: The mass of an object that is at rest with respect to the observer. The effective mass increases with speed.

rest wavelength: The wavelength radiation would have if its emitter were not moving with respect to the observer.

rotation curve: A graph of the speed of rotation versus distance from the center of a rotating object, such as a galaxy.

Schwarzschild black hole: A non-rotating black hole.

Schwarzschild radius: The radius to which a given mass must be compressed to form a non-rotating black hole. Also, the radius of the event horizon of a non-rotating black hole.

second law of thermodynamics: In any closed system, entropy never decreases; it always increases or remains constant.

singularity: A mathematical point of zero volume associated with infinite values for physical parameters, such as density.

solar mass: The mass of the Sun, 1.99×10^{33} grams, about 330,000 times the mass of Earth.

space-time: The 4-dimensional fabric of the Universe whose points are events having specific locations in space (3 dimensions) and time (1 dimension).

special theory of relativity: Einstein's 1905 theory of relative motion, gravity excluded.

spectroscopic binary stars: Binary stars detected by examining the periodically varying Doppler shift in their absorption lines.

spectrum: A plot of the brightness of electromagnetic radiation from an object as a function of wavelength or frequency.

spiral galaxy: One of the two major classes of galaxies defined by Edwin Hubble; made up of a roughly spherical central "bulge" containing older stars, surrounded by a thin disk in which spiral arms are present.

star cluster: A gravitationally bound group of stars that formed from the same nebula.

stellar-mass black hole: A black hole that forms from the gravitational collapse of a massive star. Typically has a mass of 3 to 12 solar masses.

string (superstring) theory: A possible unification of quantum theory and general relativity in which fundamental particles are different vibration modes of tiny, 1-dimensional "strings," instead of being localized at single points.

stripped-envelope stars: Stars that have lost their hydrogen and helium envelopes, either through stellar winds or through transferring of gas to a companion star; thought to be the progenitors for gamma-ray bursts.

strong nuclear force: The strongest force, it binds protons and neutrons together in a nucleus. Actually, it is the residue of the even stronger color force that binds quarks together in a proton or neutron.

supergiant: The evolutionary phase following the main sequence of a massive star; the star becomes more luminous and larger. If its size increases by a very large factor, it becomes cool.

supermassive black hole: A very massive black hole in the center of a galaxy. Typically has a mass of roughly a million to a few billion solar masses.

supernova: The violent explosion of a star at the end of its life. Hydrogen is present or absent in the spectra of Type II or Type I supernovae, respectively.

supernova remnant: The cloud of chemically enriched gases ejected into space by a supernova.

symmetric: Forces that are symmetric act identically. They act differently when the symmetry is broken.

terrestrial planets: Rocky, earth-like planets. In our solar system: Mercury, Venus, Earth, and Mars.

tidal force: The difference between the gravitational force exerted by one body on the near and far sides of another body.

time dilation: According to relativity theory, the slowing of time perceived by an observer watching another object moving rapidly or located in a strong gravitational field.

transverse velocity: The speed of an object across the plane of the sky—perpendicular to the line of sight.

Universe: All that there is within the space and time dimensions accessible to us, as well as regions beyond (but still physically connected to) those that we can see.

variable star: A star whose apparent brightness changes with time.

virtual particle: A particle that flits into existence out of nothing and, shortly thereafter, disappears again.

wavelength: The distance over which a wave goes through a complete oscillation; the distance between two consecutive crests or two consecutive troughs.

weak nuclear force: Governs the decay of a neutron into a proton, electron, and antineutrino.

weight: The force of the gravitational pull on a mass.

white dwarf: The evolutionary endpoint of stars that have an initial mass less than about 8 solar masses. All that remains is the degenerate core of He or C–O (in some cases, O–Ne–Mg).

white hole: The time reversal of a black hole; matter and energy can only come out of it, not go in.

WIMPs: Weakly interacting massive particles; theorized to make up much of the dark matter of the Universe.

wormhole: A hypothetical connection between two universes or different parts of our Universe.

year: Earth's orbital period around the Sun.

zenith: The point on the celestial sphere that is directly above the observer.

Biographical Notes

Chandrasekhar, Subrahmanyan (1910–1995). Indian-born American astrophysicist. Awarded the Nobel Prize in Physics in 1983 for his work on the physical understanding of stars, especially the upper mass limit of white dwarfs, which he calculated while on a voyage from India to England in order to attend graduate school. The Chandra X-ray Observatory is named after him.

Eddington, Sir Arthur (1882–1944). Eminent British astrophysicist; studied the physical structure of stars and was an expert on Einstein's general theory of relativity. Through his observations of a total solar eclipse in 1919, he helped confirm this theory, making Einstein an overnight worldwide sensation.

Einstein, Albert (1879–1955). German-American theoretical physicist, the most important physicist since Newton. Developed the special and general theories of relativity, proposed that light consists of photons, and worked out the theory of Brownian motion (the irregular, zigzag motion of particles suspended in a fluid is due to collisions with molecules). Responsible for $E = mc^2$, the world's most famous physics equation.

Feynman, Richard (1918–1988). American theoretical physicist, one of the greatest of the 20th century. Developed the theory of quantum electrodynamics, specifically forms of computation using "Feynman diagrams" that greatly simplified many problems; won the 1965 Nobel Prize in Physics for this research. Very well known for popularizing physics through books and lectures, and for having an extremely intuitive feel for the workings of nature.

Finkelstein, David (b. 1929). American theoretical physicist, known in the field of general relativity for having introduced a new coordinate system in the study of non-rotating black holes that elucidated the nature of the locus of points at radius $r = 2GM/c^2$. In 1958, he showed that this "event horizon" was not a physical singularity, but rather behaves like a 1-way membrane: Light and particles can pass through it only to smaller radii.

Galileo Galilei (1564–1642). Italian mathematician, astronomer, and physicist; was the first to systematically study the heavens with a telescope. Discovered the phases of Venus and the 4 bright moons of Jupiter, providing strong evidence against the geocentric model for the Solar System. After being sentenced by the Inquisition to perpetual house arrest, he published his earlier studies of the motions of falling bodies, laying the experimental groundwork for Newton's laws of motion.

Hawking, Stephen (b. 1942). English theoretical physicist, best known for his remarkable theoretical work while physically incapacitated by Lou Gehrig's disease (ALS). His prediction that black holes can evaporate through quantum tunneling is an important step in attempts to unify quantum physics and gravity (general relativity). He is Lucasian Professor of Mathematics at Cambridge University, as was Newton.

Hubble, Edwin (1889–1953). American astronomer, after whom the Hubble Space Telescope is named. He proved that "spiral nebulae" are galaxies far outside our own Milky Way and discovered the expansion of the Universe ("Hubble's law") by recognizing that the redshifts of galaxies are proportional to their current distances. He also proposed a widely used morphological classification scheme for galaxies.

Kerr, Roy (b. 1934). New Zealand mathematician; best known for having been the first to solve (in 1963) Einstein's equations of general relativity for a rotating, uncharged black hole (or any other rotating, massive, uncharged object). Prior to that, an exact solution has been found only for non-rotating black holes.

Laplace, Pierre-Simon (1749–1827). French mathematician and astronomer; developed a number of extremely useful mathematical tools, in part applicable to celestial mechanics, and postulated the "nebular hypothesis" for the formation of the Solar System. Independently of John Mitchell, he reasoned (in 1796) that some stars might be so massive that nothing, not even light, could escape; such "dark stars" are known today as black holes.

Maxwell, James (1831–1879). Scottish physicist; showed that visible light is only one form of electromagnetic radiation, whose speed can be derived from a set of four equations that describe all of electricity and magnetism. Also investigated heat and the kinetic theory of gases.

Mitchell, John (1724–1793). English geologist and natural philosopher whose 1783 letter to Henry Cavendish first postulated the idea of "dark stars," which are so massive that nothing, not even light, can escape from them. Though based on a Newtonian argument rather than general relativity, this conclusion presaged the modern notion of black holes.

Newton, Isaac (1642–1727). English mathematician and physicist of monumental stature. Developed three laws of motion and the law of universal gravitation, all published in *The Principia* (1687). Invented the reflecting telescope, determined that white light consists of all colors of the rainbow, and invented calculus. At age 27, became Lucasian Professor of Mathematics at Cambridge University. Became Warden of the Mint in 1696; knighted in 1705.

Oppenheimer, J. Robert (1904–1967). American theoretical physicist and, having been the scientific director of the Manhattan Project during World War II, is now known as the "Farther of the Atomic Bomb." A brilliant theorist, he worked in many areas and inspired a generation of physicists at the University of California, Berkeley and elsewhere. In 1939, he calculated that a sufficiently massive star collapses to form a black hole.

Page, Don. Canadian theoretical physicist at the University of Alberta; works on quantum theory, general relativity, and cosmology. In 1980, published a paper questioning Stephen Hawking's assertion that information about the matter that previously fell into a black hole is necessarily lost from the Universe after the black hole has evaporated away. Made a bet with Hawking for $1, which Hawking conceded in 2007.

Penrose, Roger (b. 1931). English theoretical physicist and mathematician; has worked extensively on general relativity and cosmology. Predicted the formation of a singularity when a star collapses to form a black hole, and conjectured that naked singularities—not surrounded by an event horizon—do not exist. Developed diagrams that are very useful for studying the nature of black holes and possible paths of particles falling into them.

Preskill, John (b. 1953). American theoretical physicist currently at the California Institute of Technology. Has made several bets with Caltech colleague Kip Thorne and with Stephen Hawking; in particular, he disagreed with Hawking's assertion that information is permanently lost from the Universe when a black hole evaporates. Received an encyclopedia of baseball when Hawking conceded the bet.

Sagan, Carl (1934–1996). American astronomer who is one of the 20th century's great popularizers of science, especially astronomy. Among his scientific accomplishments, he demonstrated that Venus suffers from an enormous greenhouse effect. *Cosmos*, his 13-episode public-television astronomy series, has been seen by more than 500 million people. Authored a number of books, including the non-fictional *Contact* which features travel through a wormhole.

Schmidt, Maarten (b. 1929). Dutch astronomer who has worked for decades at the California Institute of Technology. In 1963, he used the Palomar Observatory 200-inch telescope to obtain an optical spectrum of the bright quasar 3C 273; he realized that 3C 273 was exceedingly distant and hence intrinsically very luminous. This led to the idea (by others) that quasars are powered by accretion of matter onto a supermassive black hole.

Schwarzschild, Karl (1873–1916). German theoretical physicist, best known for having obtained, while fighting on the Russian front in World War I, the first exact solution for Einstein's brand-new equations of general relativity, specifically for the case of a spherical, non-rotating, massive object. The solution shows that if the object is smaller than a certain radius, now known as the Schwarzschild radius $2GM/c^2$, then no light can escape; we now call this a black hole.

Susskind, Leonard (b. 1940). American theoretical physicist, now at Stanford University. One of the founding fathers of string theory, he has also worked on the thorny problem of apparent information loss when a black hole evaporates, showing that information probably is not lost, contrary to Stephen Hawking's assertions. This work also helped reveal a deep mathematical connection between reality and 2-dimensional holograms.

't Hooft, Gerard (b. 1946). Dutch theoretical physicist and Nobel laureate; developed quantum theory of electroweak interactions. Together with Leonard Susskind, questioned Hawking's conclusion that quantum physics breaks down when considering the evaporation of black holes; this work led to the holographic principle of the Universe, an idea having great potential.

Thorne, Kip (b. 1940). American theoretical physicist, most noted for his work on general relativity; relativistic astrophysics; gravitational waves; black holes, including the membrane paradigm; and the possibility of time travel through wormholes, in part inspired by a request from Carl Sagan while writing *Contact*. He has made a number of famous bets with Stephen Hawking and other physicists.

Wheeler, John Archibald (1911–2008). American theoretical physicist, who during a long career at Princeton University supervised and inspired a very large number of now-famous students in general relativity and other topics. He worked extensively on curved space-time and black holes and was responsible for the terms "black hole" (1967) and "wormhole" (1957), and also for the phrase "a black hole has no hair."

Zwicky, Fritz (1898–1974). Swiss-American astronomer; proposed that supernovae result from the collapse of the cores of massive stars, producing neutron stars and energetic particles. Compiled an extensive atlas of galaxy clusters and showed that many such clusters must contain dark matter in order to be gravitationally bound.

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———. *The Fabric of the Cosmos: Space, Time, and the Texture of Reality*. New York: Vintage: 2005. Somewhat similar to *The Elegant Universe*, but with an emphasis on relativity and cosmology rather than on string theory.

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Professor Recommended Websites

Andrew Hamilton's website on travel into black holes; University of Colorado: http://casa.colorado.edu/~ajsh/schw.shtml

Andrew Hamilton's other website on travel into black holes; University of Colorado: http://jilawww.colorado.edu/~ajsh/insidebh/index.html

Astronomical Society of the Pacific home page: http://astrosociety.org

Astronomy magazine home page: http://www.astronomy.com

Astronomy Picture of the Day: http://antwrp.gsfc.nasa.gov/apod/

Department of Astronomy, University of California, Berkeley: http://astro.berkeley.edu

Introduction to string theory: http://superstringtheory.com

Large Hadron Collider home page: http://lhc.web.cern.ch/lhc

Large Hadron Rap: http://www.youtube.com/watch?v=j50ZssEojtM

LIGO home page: http://www.ligo.caltech.edu

Photographs and press releases from the Chandra X-ray Observatory: http://chandra.harvard.edu/photo

Photographs and press releases from the Hubble Space Telescope: http://hubblesite.org/newscenter

Questions about astronomy are answered: http://www.astronomycafe.net

Robert Nemiroff's website on travel into a black hole; Michigan Tech: http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html

Sky & Telescope magazine: http://www.skyandtelescope.com

Sounds of gravitational waves: http://www.black-holes.org/explore1.html