Black Holes: Gravity's Relentless Pull

Black holes are out there. But what are they? The mass of the earth creates the gravity that pulls things to the ground. With enough power, we can escape that gravity and leave the earth behind. But if you can take the earth and squeeze it to the size of a marble, the gravity in the surface would be much greater- not even a beam of light could escape. We call this a black hole. Fortunately, neither the earth nor the sun will ever become a black hole but black holes do exist

Introduction

Black holes are places where ordinary gravity has become so extreme that it overwhelms all other forces in the Universe. Once inside, nothing can escape a black hole's gravity — not even light.

Yet we know that black holes exist. We know how they are born, where they occur, and why they exist in different sizes. We even know what would happen if you fell into one. Our discoveries have revealed one of the strangest objects in the Universe, and there's still much we don't know.

The nearest black hole is many light years away, so we don't have to worry about threats to the Earth. This is as close as you'll ever get to one.

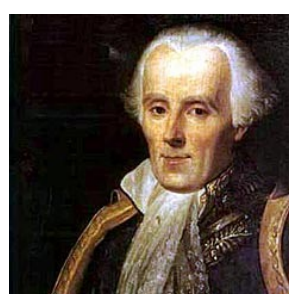
What is a Black Hole?

A black hole is an object that is so compact (in other words, has enough mass in a small enough volume) that its gravitational force is strong enough to prevent light or anything else from escaping.

The existence of black holes was first proposed in the 18th century, based on the known laws of gravity. The more massive an object, or the smaller its size, the larger the gravitational force felt on its surface. John Michell and Pierre-Simon Laplace both independently argued that if an object were either extremely massive or extremely small, it might not be possible at all to escape its gravity. Even light could be forever captured.

The name "black hole" was introduced by John Archibald Wheeler in 1967. It stuck, and has even become a common term for any type of mysterious bottomless pit. Physicists and mathematicians have found that space and time near black holes have many unusual properties. Because of this, black holes have become a favorite topic for science fiction writers. However, black holes are not fiction. They form whenever massive but otherwise normal stars die. We cannot see black holes, but we can detect material falling into black holes and being attracted by black holes. In this way, astronomers have identified and measured the mass of many black holes in the Universe through careful observations of the sky. We now know that our Universe is quite literally filled with billions of black holes.

->American physicist John Archibald Wheeler (1911-) first introduced the term black hole and led many important studies into their properties.



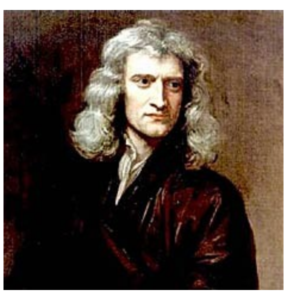
French scientist Pierre-Simon Laplace (1749-1827) was one of the first to discuss the possible existence of black holes.<-

Do Black Holes Obey the Laws of Gravity?

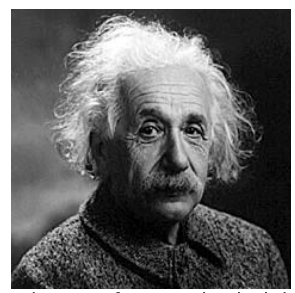
Black holes obey all laws of physics, including the laws of gravity. Their remarkable properties are in fact a direct consequence of gravity.

In 1687, Isaac Newton showed that all objects in the Universe attract each other through gravity. Gravity is actually one of the weakest forces known to physics. In our daily life, other forces from electricity, magnetism, or pressure often exert a stronger influence. However, gravity shapes our Universe because it makes itself felt over large distances. For example, Newton showed that his laws of gravity can explain the observed motions of the moons and planets in the Solar System.

Albert Einstein refined our knowledge of gravity through his theory of general relativity. He first showed, based on the fact that light moves at a fixed speed (671 million miles per hour), that space and time must be connected. Then in 1915, he showed that massive objects distort the four-dimensional space-time continuum, and that it is this distortion that we perceive as gravity. Einstein's predictions have now been tested and verified through many different experiments. For relatively weak gravitational fields, such as those here on Earth, the predictions of Einstein's and Newton's theories are nearly identical. But for very strong gravitational fields, such as those encountered near black holes, Einstein's theory predicts many fascinating new phenomena.



->British scientist Sir Isaac Newton (1643-1727) formulated the laws of gravity, supposedly after pondering why an apple falls from a tree.



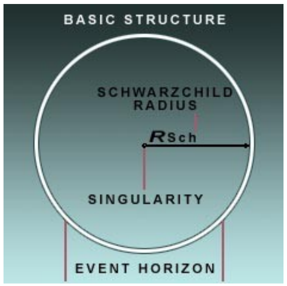
German-Swiss-American physicist Albert Einstein (1879-1955) expanded Newton's work by formulating the theory of general relativity.<-

How big is a black hole?

All matter in a black hole is squeezed into a region of infinitely small volume, called the central singularity. The event horizon is an imaginary sphere that measures how close to the singularity you can safely get. Once you have passed the event horizon, it becomes impossible to escape: you will be drawn in by the black hole's gravitational pull and squashed into the singularity.

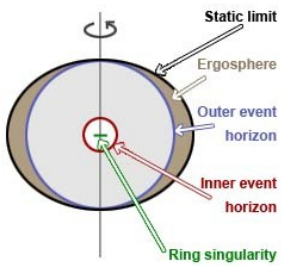
The size of the event horizon (called the Schwarzschild radius, after the German physicist who discovered it while fighting in the first World War) is proportional to the mass of the black hole. Astronomers have found black holes with event horizons ranging from 6 miles to the size of our solar system. But in principle, black holes can exist with even smaller or larger horizons. By comparison, the Schwarzschild radius of the Earth is about the size of a marble. This is how much you would have to compress the Earth to turn it into a black hole. A black hole doesn't have to be very massive, but it does need to be very compact!

Some black holes spin around an axis, and their situation is more complicated. The surrounding space is then dragged around, creating a cosmic whirlpool. The singularity is an infinitely thin ring instead of a point. The event horizon is composed of two, instead of one, imaginary spheres. And there is a region called the ergosphere, bounded by the static limit, where you are forced to rotate in the same sense as the black hole although you can still escape.



->In a non-rotating black hole, a central point singularity is surrounded by an imaginary sphere called the event horizon. Its size is called the Schwarzschild radius.

German physicist Karl Schwarzschild (1873-1916) first discovered the solutions of the equations of general relativity that describe non-rotating black holes.<-



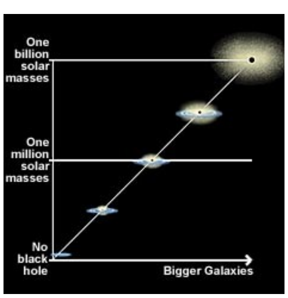
->In a spinning black hole, a central ring singularity is surrounded by two event horizons, the ergosphere and the static limit.

What types of black holes are there?

Black holes often look very different from each other. But this is because of variety in what happens in their surroundings. The black holes themselves are all identical, except for three characteristic properties: the mass of the black hole (how much stuff it is made of), its spin (whether and how fast it rotates around an axis), and its electric charge. Amazingly, black holes completely erase all of the other complex properties of the objects that they swallow.

Astronomers can measure the mass of black holes by studying the material that orbits around them. So far, we have found two types of black holes: stellar-mass (just a few times heavier than our Sun) or supermassive (about as heavy as a small galaxy). But black holes might exist in other mass ranges as well. For example, recent observations suggest there may be black holes with masses between stellar-mass and supermassive black holes.

Black holes can spin around an axis, although the rotation speed cannot exceed some limit. Astronomers think that many black hole in the Universe probably do spin, because the objects from which black holes form (stars for example) generally rotate as well. Observations are starting to shed some light on this issue, but no consensus has so far emerged. Black holes could also be electrically charged. However, they would then rapidly neutralize that charge by attracting and swallowing material of opposite polarity. So astronomers believe that all black holes in the Universe are uncharged.



->Supermassive black holes live in the centers of galaxies. Bigger galaxies generally have bigger black holes.

New-Zealand mathematician Roy Kerr (1934-) first discovered the solutions of the equations of general relativity that describe spinning black holes.<-

Can we safely orbit a black hole?

It is possible to be near a black hole without falling into it, provided you move rapidly. This is similar to what happens in the solar system: Earth does not fall into the Sun because we move around it at a speed of some 67 thousand miles per hour. But the orbits near a black hole can have various interesting shapes, whereas those in the solar system are always elliptical (and almost circular).

Suppose that you are near a black hole and launch a spaceship to study it up close. If you start too slow, you will spiral into the black hole. If you start too fast, you will fly into the far off distance. At intermediate speeds you will orbit the black hole in a complicated pattern. There is exactly one launch speed that will put you on a circular orbit. This provides a stable vantage point if you start far from the black hole, but it is like playing Russian roulette if you start too close. In that case, even the smallest movement on your ship will drastically change your orbit. You might drift away from the black hole, but if you are unlucky you will spiral into it.

Can a black hole bend light rays?

Imagine that you are in orbit around a black hole at a safe distance outside the event horizon. What would the sky look like? Normally you would just see the background stars steadily sliding by, due to your own orbital motion. But the gravitational force of a black hole changes things considerably.

Light rays that pass close to the black hole get caught and cannot escape. Therefore, the region around the black hole is a dark disk. Light rays that pass a little further away don't get caught but do get bent by the black hole's gravity. This makes the starfield appear distorted, as in a funhouse mirror. It also produces multiple images. You would see two duplicate images of the same star on opposite sides of the black hole, because light rays passing the black hole on either side get bent toward you. In fact, there are infinitely many images of each star, corresponding to light rays that circle the black hole several times before coming toward you.

Einstein's theory of general relativity predicts that every object bends light rays through its gravity. This is called gravitational lensing. For our Sun this effect is very weak, but it has been measured. For more massive and distant objects in the Universe much stronger lensing has been seen. However, it has not yet been possible to observe this effect near a black hole, or to directly photograph the dark disk surrounding a black hole. However, this may become possible in the foreseeable future.

->Simulated view towards a black hole. The background stars are shown with realistic colors. Close to the black hole, they all blend together into a white haze.

Albert Einstein's prediction that gravity would bend starlight as it passed the Sun was verified during a total solar eclipse over Brazil in 1919.->

->The four blue dots (known as the "Einstein Cross") are images of the same distant quasar. Its light is bent by the gravity of a foreground galaxy.

The gravity of this galaxy cluster (called Abell 2218) bends the light from more distant galaxies behind it, creating thin arcs of light.->

What happens when black holes collide?

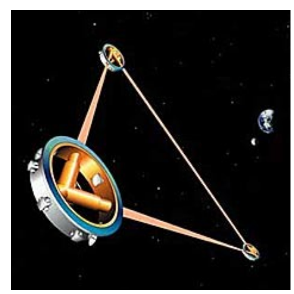
It is possible for two black holes to collide. Once they come so close that they cannot escape each other's gravity, they will merge to become one bigger black hole. Such an event would be extremely violent. Even when simulating this event on powerful computers, we cannot fully understand it. However, we do know that a black hole merger would produce tremendous energy and send massive ripples through the space-time fabric of the Universe. These ripples are called gravitational waves.

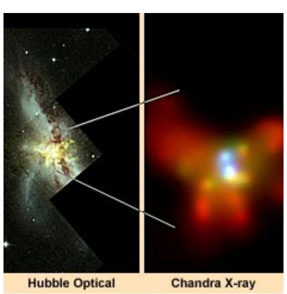
Nobody has witnessed a collision of black holes yet. However, there are many black holes in the Universe and it is not preposterous to assume that they might collide. In fact, we know of galaxies in which two supermassive black holes move dangerously close to each other. Theoretical models predict that these black holes will spiral toward each other until they eventually collide.

Gravitational waves have never been directly observed. However, they are a fundamental prediction of Einstein's theory of general relativity. Detecting them would provide an important test of our understanding of gravity. It would also provide important new insights into the physics of black holes. Large instruments capable of detecting gravitational waves from outer space have been built in recent years. Even more powerful instruments are under construction. The moment they detect their first gravitational wave, you are sure to hear about it!

->One of the two LIGO gravitational wave observatories (Hanford, WA, USA). In two 2.5 mile long pipes laser beams are used to search for gravitational waves.

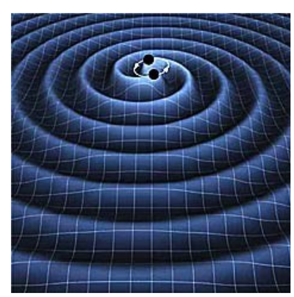
The LISA observatory will consist of three satellites in orbit around the Sun. Laser beams between the satellites may detect gravitational waves.->





->The galaxy NGC 6240 hosts two supermassive black holes near its center (blue dots on the right) that may one day collide with each other.

Two colliding black holes send ripples through the space-time fabric of the Universe that are called gravitational waves.->



What is inside a black hole?

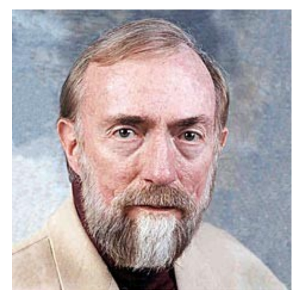
We cannot glimpse what lies inside the event horizon of a black hole because light or material from there can never reach us. Even if we could send an explorer into the black hole, she could never communicate back to us.

Current theories predict that all the matter in a black hole is piled up in a single point at the center, but we do not understand how this central singularity works. To properly understand the black hole center requires a fusion of the theory of gravity with the theory that describes the behavior of matter on the smallest scales, called quantum mechanics. This unifying theory has already been given a name, quantum gravity, but how it works is still unknown. This is one of the most important unsolved problems in physics. Studies of black holes may one day provide the key to unlock this mystery.

Einstein's theory of general relativity allows unusual characteristics for black holes. For example, the central singularity might form a bridge to another Universe. This is similar to a so-called wormhole (a mysterious solution of Einstein's equations that has no event horizon). Bridges and wormholes might allow travel to other Universes or even time travel. But without observational and experimental data, this is mostly speculation. We do not know whether bridges or wormholes exist in the Universe, or could even have formed in principle. By contrast, black holes have been observed to exist and we understand how they form.

->A wormhole can provide a short-cut connection between two distant points in the curved space-time of the Universe, as this diagram shows.

American physicist Kip Thorne (1940-) researched the hypothetical possibilities of time travel using wormholes.->



What happens when I fall into a black hole?

Let's assume that you start outside the event horizon of the black hole. As you look toward it, you see a circle of perfect darkness. Around the black hole, you see the familiar stars of the night sky. But their pattern is strangely distorted, as the light from distant stars gets bent by the black hole's gravity.

As you fall toward the black hole, you move faster and faster, accelerated by its gravity. Your feet feel a stronger gravitational pull than your head, because they are closer to the black hole. As a result, your body is stretched apart. For small black holes, this stretching is so strong that your body is completely torn apart before you reach the event horizon.

If you fall into a supermassive black hole, your body remains intact, even as you cross the event horizon. But soon thereafter you reach the central singularity, where you are squashed into a single point of infinite density. You have become one with the black hole. Unfortunately, you are unable to write home about the experience.

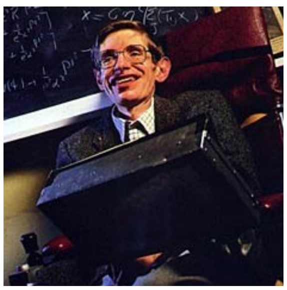
Do black holes live forever?

Since nothing can escape from the gravitational force of a black hole, it was long thought that black holes are impossible to destroy. But we now know that black holes actually evaporate, slowly returning their energy to the Universe. The well-known physicist and author Stephen

Hawking proved this in 1974 by using the laws of quantum mechanics to study the region close to a black hole horizon.

The quantum theory describes the behavior of matter on the smallest scales. It predicts that tiny particles and light are continuously created and destroyed on sub-atomic scales. Some of the light thus created actually has a very small chance of escaping before it is destroyed. To an outsider, it is as though the event horizon glows. The energy carried away by the glow decreases the black hole's mass until it is completely gone.

This surprising new insight showed that there is still much to learn about black holes. However, Hawking's glow is completely irrelevant for any of the black holes known to exist in the Universe. For them, the temperature of the glow is almost zero and the energy loss is negligible. The time needed for the black holes to lose much of their mass is unimaginably long. However, if much smaller black holes ever existed in the Universe, then Hawking's findings would have been catastrophic. A black hole as massive as a cruise ship would disappear in a bright flash in less than a second.



->British physicist Stephen Hawking (1942-), almost incapacitated by a rare nerve disease, discovered that black holes do not live forever.

Quantum mechanics dictates that matter on the smallest scales often behaves more like waves than like particles. Much modern technology relies on this.->

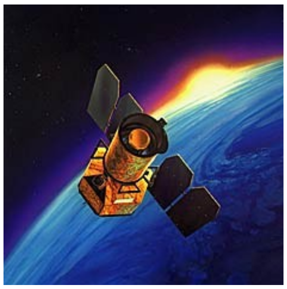
What instruments do astronomers use to find black holes?

When our eyes look at the heavens we see the visible light from stars and other objects in the Universe. Thousands of years ago astronomers in Greece and other ancient cultures already built a detailed understanding of the night sky. Many names and concepts then developed are still in use today. However, our human eyes are actually not very sensitive and modern astronomers use sophisticated telescopes to study the Universe.

The telescopes used by astronomers do not just study visible light. While visible light is the type of 'electromagnetic radiation' that our eyes can see, there are many other types of such radiation. Different types of radiation are characterized by different wavelengths. If the wavelength is much shorter than that of visible light we speak about X-rays. We encounter X-rays often in our daily lives, for example at the hospital or during security screening. If the wavelength is much larger than that of visible light we speak about radio waves. We encounter radio waves often in our daily lives, for example in radios and cell phones.

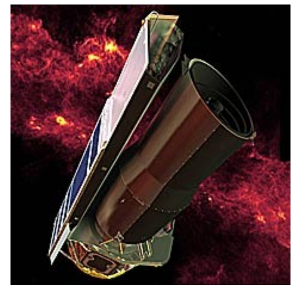
The black holes in the Universe do not emit any detectable type of light. However, astronomers can still find them and learn a lot about them. They do this by measuring the visible light, X-rays and radio waves emitted by material in the immediate environment of a black hole. For example, when a normal star orbits around a black hole we can measure the speed of the star by studying the visible light that it emits. Knowledge of this speed can be combined with the laws of gravity to prove that the star is in fact orbiting a black hole, instead of something else. It also yields the mass of the black hole. Alternatively, when gas orbits around a black hole it tends to get very hot because of friction. It then starts emitting X-rays and radio waves. So black holes can also often be found and studied by looking for bright sources of X-rays and radio waves in the sky.

There are many other types of electromagnetic radiation as well. Radiation that has even smaller wavelengths (and even higher energies) than X-rays is called gamma-rays. Radiation with wavelengths between those of X-rays and visible light is called ultraviolet light. We encounter ultraviolet light in our daily lives for example in fluorescent lamps. Ultraviolet telescopes allow astronomers to study things such as the composition of the gas that exists between stars. Electromagnetic radiation with wavelengths between those of radio waves and visible light is called infrared light. We encounter infrared light in our daily lives for example in heat lamps and night-vision cameras. Infrared telescopes allow astronomers to study things such the formation of stars.



->Artist impression of the GALEX satellite, which can make images of the ultraviolet light from astronomical objects.

Artist impression of the Spitzer Space Telescope, which can image and analyze infrared light from objects in the Universe.->



How are black holes born?

A black hole is born when an object becomes unable to withstand the compressing force of its own gravity. Many objects (including our Earth and Sun) will never become black holes. Their gravity is not sufficient to overpower the atomic and nuclear forces of their interiors, which resist compression. But in more massive objects, gravity ultimately wins.

Stellar-mass black holes are born with a bang. They form when a very massive star (at least 25 times heavier than our Sun) runs out of nuclear fuel. The star then explodes as a supernova. What remains is a black hole, usually only a few times heavier than our Sun since the explosion has blown much of the stellar material away.

We know less about the birth of supermassive black holes, which are much heavier than stellar-mass black holes and live in the centers of galaxies. One possibility is that supernova explosions of massive stars in the early Universe formed stellar-mass black holes that, over billions of years, grew supermassive. A single stellar-mass black hole can grow rapidly by consuming nearby stars and gas, often in plentiful supply near the galaxy center. The black hole may also grow through mergers with other black holes that drift to the galactic center during collisions with other galaxies. Astronomers are actively investigating these and other scenarios through observations and computer simulations.

->The Large Hadron Collider is a 17-mile long particle accelerator in Switzerland that may reach energies high enough to create miniscule black holes.

Stellar-mass black holes are created when massive stars explode as supernovae. The image shows a supernova remnant in the constellation Cassiopeia.->

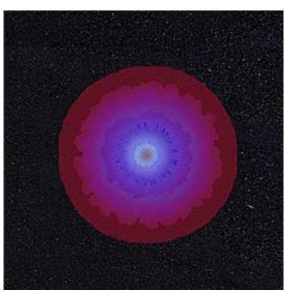
->Collisions of galaxies contribute to the growth of supermassive black holes. The image show the ''Antennae,'' a pair of colliding galaxies.

How can a star become a black hole?

A star shines because its center is so hot and dense that hydrogen nuclei fuse together, creating tremendous energy. It lives for millions or billions of years while the inward pull from its own gravity is balanced by the outward pressure from nuclear fusion. Its life ends when the nuclear fuel has been used up. First the star swells, brightens and cools to become a red giant. Then it collapses into a compact stellar remnant, much smaller than our Sun but of similar mass.

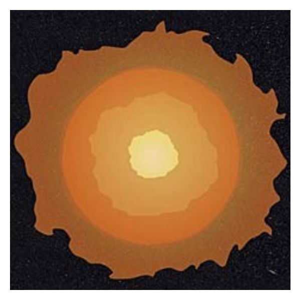
Stars less than eight times heavier than the Sun die relatively peacefully. The outer layers are shed in a stellar wind, making the star temporarily visible as a planetary nebulae. The remnant is about the size of the Earth and is called a white dwarf. Heavier stars die in a spectacular supernova explosion. If the star was moderately heavy, the remnant is a neutron star: a dense ball of neutral elementary particles, squeezed into a space little more than 10 miles across. Extremely heavy stars (more than 25 times heavier than the Sun) have no means to withstand their own gravity as they die. They collapse completely to a black hole.

We can see examples of the life cycle of stars all around us in the sky. Our own Sun is a fairly typical medium-sized middle-aged star. The star Betelgeuse is a well-known red giant. Planetary nebulae and supernova remnants can both be spectacular sights, even through a small telescope. Good examples are NGC 7027 and the Crab nebula, respectively. Albireo is an example of a binary star system in which two stars orbit around each other. More than half of all stars live in such systems. If one of the stars in such a binary system evolves into a black hole, then the system can sometimes be observed as a bright X-ray source. In our own Milky Way galaxy this is the case for example in Cygnus X-1. More examples can seen in other nearby galaxies, such as in M33.



->When low-mass stars die they slowly shed their outer layers. These layers can glow for thousands of years. The star is then confusingly called a planetary nebula.

High-mass stars die in a spectacular supernova explosion that lasts only seconds. The explosion blows most of the star apart.->



Stars of different mass leave different compact remnants when they die, either a white dwarf (left), a neutron star (middle) or a black hole (right).

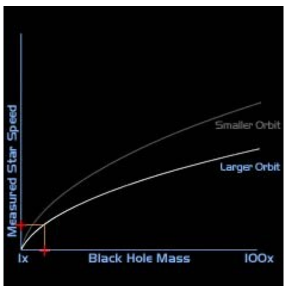
How do astronomers find the mass of a black hole?

Black holes often have stars or gas orbiting around them. It is then possible to measure the mass of the black hole, just by measuring the speed of the orbiting material.

Consider the case in which a star and a black hole orbit around their mutual center of gravity. Although we can't see the black hole, we can see the star. With accurate observations, we can measure the speed of the star as well as the size of the orbit. Once these have been measured, the laws of gravity tell us exactly what the black hole mass is.

For example, let's assume that a star like our Sun orbits a black hole. Suppose that we measure the speed of the star to be 117 miles per second, and that we measure the diameter of its orbit to be similar to the distance of the planet Mercury from our Sun. This implies that the star orbits the black hole once every 12 days. The laws of gravity then tell us that the black hole must be 10 times more massive than our Sun.

The supermassive black holes in the centers of galaxies can often be measured using this method. For example, the mass of the black hole in the center of our Milky Way galaxy was calculated by measuring the speeds of individual stars that orbit around it. This showed that the black hole is three million times more massive than our Sun. And the mass of the black hole in the center of the nearby Andromeda galaxy has been calculated by measuring the average speeds of all the stars that orbit around it. This showed that Andromeda's black hole is 30 million times more massive than our Sun.



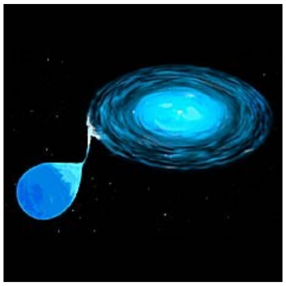
->The laws of gravity tell us the mass of the black hole, provided that we can measure the speed of the star and the size of its orbit.

How do black holes grow?

Black holes grow in mass by capturing nearby material. Anything that enters the event horizon cannot escape the black hole's gravity. So objects that do not keep a safe distance get swallowed.

Despite their reputation, black holes will not actually suck in objects from large distances. A black hole can only capture objects that come very close to it. They're more like Venus' Flytraps than cosmic vacuum cleaners. For example, imagine replacing the Sun by a black hole of the same mass. Permanent darkness would fall on Earth, but the planets would continue to revolve around the black hole at the same distance and speed as they do now. None of the planets would be sucked into the black hole. Our Earth would be in danger only if it came within some 10 miles of the black hole, much less than the actual distance of Earth from the Sun (a comforting 93 million miles).

The diet of known black holes consists mostly of gas and dust, which fill the otherwise empty space throughout the Universe. Black holes can also consume material torn from nearby stars. In fact, the most massive black holes can swallow stars whole. Black holes can also grow by colliding and merging with other black holes. This growth process is what can reveal the presence of a black hole. As gas falls toward a black hole, it is heated to high temperatures, generating powerful radio waves and X-rays that can be studied by astronomers.

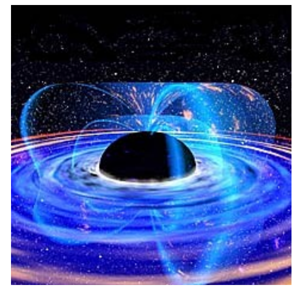


->Stellar-mass black holes can grow by pulling gas of a companion star that orbits around it.

A disk of dust and gas in the galaxy NGC 7052. Supermassive black holes can grow by consuming gas and dust from such disks.->

->Gas that falls into a black hole settles into a so-called accretion disk. Friction and magnetic fields in the disk cause the gas to heat and emit X-rays.

Magnetic fields near a spinning black hole can propel electrons outward in a jet along the rotation axis. The electrons produce bright radio waves.->



How many black holes are there?

There are so many black holes in the Universe that it is impossible to count them. It's like asking how many grains of sand are on the beach. Fortunately, the Universe is enormous and none of its known black holes are close enough to pose any danger to Earth.

Stellar-mass black holes form from the most massive stars when their lives end in supernova explosions. The Milky Way galaxy contains some 100 billion stars. Roughly one out of every thousand stars that form is massive enough to become a black hole. Therefore, our galaxy must harbor some 100 million stellar-mass black holes. Most of these are invisible to us, and only about a dozen have been identified. The nearest one is some 1,600 lightyears from Earth. In the region of the Universe visible from Earth, there are perhaps 100 billion galaxies. Each one has about 100 million stellar-mass black holes. And somewhere out there, a new stellar-mass black hole is born in a supernova every second.

Supermassive black holes are a million to a billion times more massive than our Sun and are found in the centers of galaxies. Most galaxies, and maybe all of them, harbor such a black hole. So in our region of the Universe, there are some 100 billion supermassive black holes. The nearest one resides in the center of our Milky Way galaxy, 28 thousand lightyears away. The most distant we know of lives in a quasar galaxy billions of lightyears away.