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Black Holes

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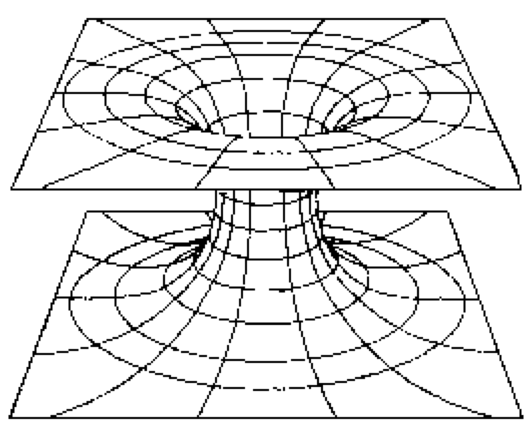
Gravity is the midwife and the undertaker of the stars. It gathers clumps of gas and dust from the interstellar clouds, compresses them and, if they are sufficiently massive, ignites thermonuclear reactions in their cores. Then, for millions or billions of years, they produce energy, heat and pressure which can balance the inward pull of gravity. The star is stable, like the Sun. When the star's energy sources are finally exhausted, however, gravity shrinks the star unhindered. Stars like the Sun contract to become white dwarfs -- a million times denser than water, and supported by quantum forces between electrons. If the mass of the collapsing star is more than 1.44 solar masses, gravity overwhelms the quantum forces, and the star collapses further to become a neutron star, millions of times denser than a white dwarf, and supported by quantum forces between neutrons. The energy released in this collapse blows away the outer layers of the star, producing a supernova. If the mass of the collapsing star is more than three solar masses, however, no force can prevent it from collapsing completely to become a black hole.

What is a black hole?



A black hole is a region of space in which the pull of gravity is so strong that nothing can escape. It is a "hole'' in the sense that things can fall into it, but not get out. It is "black'' in the sense that not even light can escape. Another way to say it, is that a black hole is an object for which the escape velocity (the velocity required to break free from an object) is greater than the speed of light -- the ultimate "speed limit'' in the universe.

In 1783, British amateur astronomer, Rev. John Mitchell, realized that Newton's laws of gravity and motion implied that the more massive an object, the greater the escape velocity. If you could somehow make something 500 times bigger than the Sun, but with the same density, he reasoned, even light couldn't move fast enough to escape from it and it would never be seen. But it took

Einstein's general theory of relativity, the modern theory of gravity, for astronomers and physicists to understand the true nature and characteristics of black holes.

The boundary of a black hole is called the *event horizon*, because any event which takes place within is forever hidden to anyone watching from outside. Astronomer Karl Schwarzschild showed that the radius of the event horizon in kilometers is 3 times its mass expressed in units of solar masses; this radius is called the Schwarzschild radius. The event horizon is the one-way filter in the black hole: anything can enter, but nothing can leave.

A black hole is a very simple object: it has only three properties mass, spin and electrical charge. Because of the way in which black holes form, their electrical charge is probably zero, which makes them simpler yet. The form of the matter in a black hole is not known, partly because it is hidden from the outer universe, and partly because the matter would, in theory, continue to collapse until it had a radius of zero, a point mathematicians call a singularity, of infinite density -- something with which we have no experience here on Earth.

Black holes are theorized to come in three different sizes: small ("mini''), medium, and large ("supermassive''). There is good evidence that medium-sized black holes form as the corpses of massive stars which collapse at the end of their lives, and that supermassive black holes exist in the cores of many galaxies -- perhaps including our own.

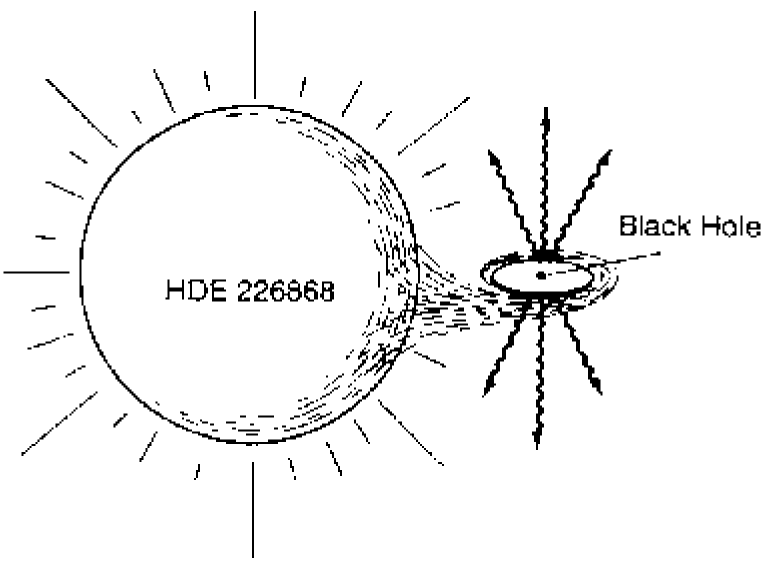
Mini Black Holes

A black hole with a mass less than three solar masses would not form on its own; its gravity is too weak to cause it to completely collapse in on itself. Enormous outside pressure would be necessary to create a "mini-black hole.'' In 1971, astrophysicist Stephen Hawking theorized that, in the dense turbulence of the Big Bang from which the universe emerged, such enormous outside pressures existed and many mini-black holes formed. These would be as massive as mountains, but as small as the protons of which atoms are made. They would have another bizarre property: as a result of the laws of quantum mechanics which govern very small particles in the universe, they would spontaneously radiate energy and, after billions of years, eventually evaporate in a final violent explosion. Thus, mini-black holes may not be entirely "black" -- an intriguing possibility. No observational evidence of mini-black holes exists but, in principle, there could be such objects scattered throughout the universe, perhaps even near our solar system.

Black Holes

How can you "see'' a black hole?

You might wonder how a black hole could be found if nothing including light can escape from it. Black holes have mass, which causes a gravitational force, which effects objects near them. This gravitational force would be very strong near the black hole, and could have noticeable effects on its environment. Material falling into the black hole would gain energy from the gravitational field, and would be crushed and heated as it tried to squeeze into the black hole's tiny throat, causing it to emit x-rays. The first example of a black hole was discovered by just such a gravitational effect on a companion star.



An artist's conception of the Cygnus X-1 system. HDE 226868 is a massive blue supergiant star; its companion is believed to be a black hole, surrounded by an accretion disc of gases from HDE 226868 which are spiraling into the black hole. The star and the black hole are in orbit around each other. The black hole's existence was deduced from the orbital motion of the star, and from the X-rays produced by the gas in the accretion disc which is heated as it falls toward the black hole. (Courtesy William J. Kaufmann III, Universe, W.H. Freeman & Company, 1991. Used with permission.)

Cygnus X-1 was the name given to a source of x-rays in the constellation Cygnus, discovered in 1962 with a primitive x-ray telescope flown on a rocket. By 1971, the location of the x-ray source in the sky had been measured more precisely, using rocket and satellite observations. A key breakthrough came in March 1971, when a new source of radio waves was discovered in Cygnus, near the position of the x-ray source. The radio signal varied at the exact same time when the strength of the x-rays changed strong evidence that the radio and x-ray sources were the same object.

A faint star called HDE 226868 appears at the position of this radio source. Astronomers studying the light of HDE 226868 have found two important facts: (1) HDE 226868 is a blue supergiant star -- a massive, normal star near the end of its life; and (2) the star is orbiting another massive object in a 5.6-day orbit.

From the gravitational force needed to keep HDE 226868 in orbit, the mass of the companion can be determined -- it is about 10 solar masses. But there is no sign of any visible light from the companion -- and something in the object produces x-rays. The explanation or "model'' which best fits these facts is that the companion is a black hole of about 10 solar masses -- the corpse of a massive star which was once the companion of HDE 226868. The x-rays are produced as gas from the atmosphere of the blue supergiant star falls into the collapsed object and is heated. The collapsed object cannot be a white dwarf or neutron star, because these objects can't have masses greater than 1.44 and three solar masses, respectively. We may never be able to "prove'' this theory of Cygnus X-1 by "seeing'' the black hole, but the circumstantial evidence is strong. Three other objects -- LMC X-3 in the Large Magellanic Cloud galaxy, and A0620-00 and V404 Cygni in our galaxy -- are also believed to have black holes as one of their components.

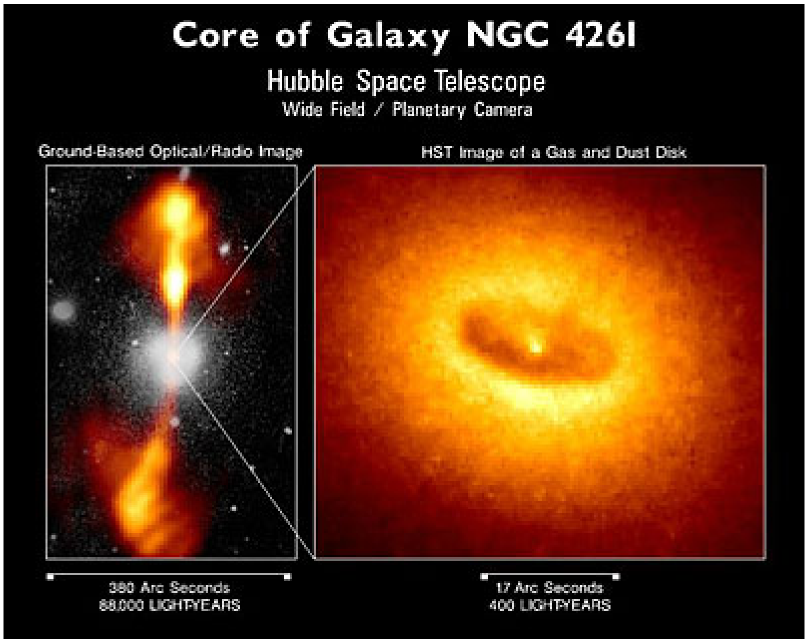
Supermassive black holes

A quarter of a century ago, astronomers discovered distant objects rare, distant objects which were producing extraordinarily large power in an extraordinarily small volume -- the power of a trillion Suns in a volume not much larger than the solar system. They called these objects quasi-stellar radio sources -- quasars, for short -- because they looked like stars, and produced large amounts of radio waves as well as light. Astronomers also realized that, although quasars were rare, there were many other objects -- apparently galaxies of stars -- which showed less extreme versions of the same phenomenon: very large power from a very small volume. These objects shared another remarkable property: jets of high-energy particles emitted from their cores. These properties were so difficult to explain, using the physical knowledge of the time, that some astronomers even questioned whether that knowledge was correct!

In the years since, astronomers realized that there is an explanation for these active galactic nuclei which is consistent with observations and with theory -- even though this explanation boggles the mind: at the core of these galaxies is a supermassive black hole, with the mass of millions or billions of Suns. The size of its event horizon would be about the same as the size of the solar system. The observed power output could be explained if only one solar mass of material were to fall into the black hole each year -- an amount of material which could easily come from the "winds'' of gas produced by stars near the core. The jets of particles in active galactic nuclei are produced by material spiraling into a disk around the black hole, and being squashed out the top and bottom of the disk as it tries to enter the black hole. This explanation for the "engine'' in an active galactic nucleus has been strongly supported by images obtained by the *Hubble Space Telescope* (see image below).

How does a supermassive black hole form? Some theories hold that the first generation of stars included a large proportion of very massive stars, all of which formed black holes which somehow merged. Other theories hold that a single "seed'' black hole accreted stars and gas, growing more and more massive with time.

There is evidence that these supermassive black holes exist in many galaxies, including our own Milky Way, and our nearest neighbor galaxy, the Andromeda galaxy (also known as M31). There is also evidence that they form early in the life of the galaxy: we see quasars so far away that their light, traveling at 300,000 kilometers/sec, must have left these objects shortly after they formed. Supermassive black holes may therefore be a normal part of the process of birth and evolution of galaxies.



A composite image of the active galaxy NGC 4261, showing jets of radio-emitting particles spurting from the core of the galaxy. On the right: a false-color image from the Hubble Space Telescope, showing a dark, doughnut-shaped structure surrounding a possible supermassive black hole, believed to be the "central engine" of the galaxy. (Photo credit: Walter Jaffe, Leiden Observatory; Holland Ford, STScI, NASA)

Black holes and science fiction

A concept as bizarre as a black hole naturally attracts the interest and creativity of science fiction writers. A favorite theme is the use of a black hole as a path to elsewhere or else when in the universe. Mathematically, a pair of black holes could form a "bridge'' between two locations in the universe, but it is not clear how such a bridge could form or survive. A black hole, such as one formed as a stellar corpse, would be rather inconvenient for space travel, because the matter falling into it would be crushed and incinerated by tidal forces as it entered the black hole. A supermassive black hole would have less extreme tidal forces, but the nearest one is thought to be at the center of our galaxy -- and therefore inconveniently distant! A rotating black hole has more interesting possibilities, because there exists a region called the ergosphere, just outside the event horizon, which has the following property -- objects can enter and exit from the ergosphere (if they could stand the tidal forces). A spaceship full of trash could enter the ergosphere, dump its load into the black hole, and come out with more energy than it entered with -- thus solving the energy crisis arid the pollution problem simultaneously (at least in theory)!

Black Holes

Activity #1: Shrinking

Purpose:

To demonstrate how a black hole might be formed.

Materials:

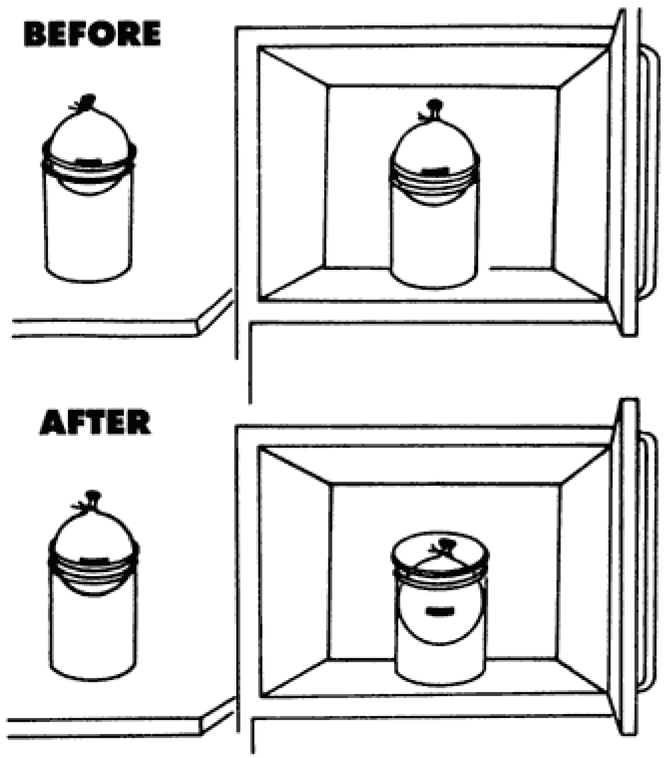
two balloons (small, round size) two large-mouthed glass jars refrigerator marking pen

Procedure:

1. Prepare two separate jars, with balloons inflated inside each one.
2. Hold each balloon so that its mouth is above the edge of the jar, and the remaining part of the balloon is inside the jar.
3. Inflate the balloons inside the jars.
4. Tie the openings of the balloons closed.
5. Mark the balloons just above the top edge of the jars with the marking pen.
6. Place one Jar in the freezer for 30 minutes, and place the second jar on a table so that it remains at room temperature.
7. After 30 minutes, remove the jar from the freezer.
8. Observe the position of the mark on both balloons.

Results:

The balloon at room temperature remains unchanged, but chilling the balloon in the freezer causes it to shrink and sink into the jar.

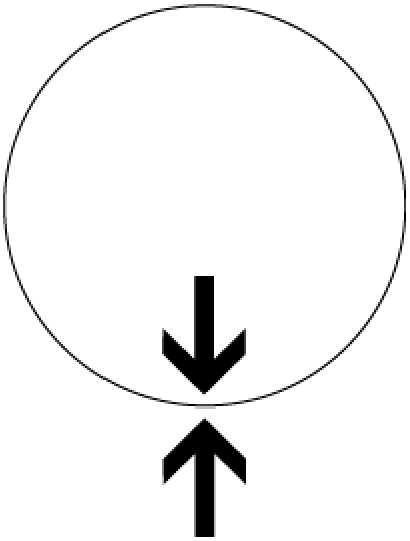


At room temperature, the mark on both balloons remains the same. But after one is refrigerated and shrinks, the marks are at different levels.

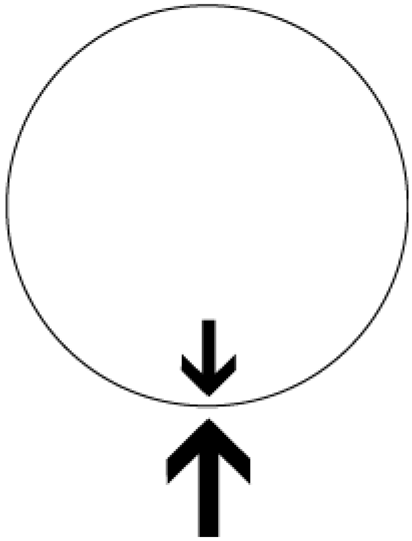
Explanation:

Gas inside the balloon pushes out, and outside air and the elastic surface of the balloon pushes in. The size of the balloon remains the same as long as the outward gas pressure and the inward elastic pressure are equal. This was the case with the balloon which remained at room temperature.

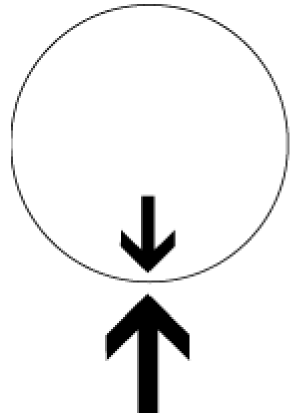
The balloon in the freezer shrank when the, inside gas pressure decreased, gas pressure is proportional to the gas temperature. If the inside gas pressure continued to decrease, the inward force of the elastic surface of the balloon would cause the balloon to become smaller and smaller. It is the balance between the outside air pressure and the elastic surface pushing in, and the gas pressure inside pushing out, which can demonstrate the formation of a black hole. The nuclear reactions at the center of a star produce an outward gas pressure. As long as the outward pressure balances the inward pull of gravity, the star remains stable in size. When the nuclear reactions stop, the balance is upset, and gravity pulls the star's materials toward its center. If the mass of the star, and therefore its gravity, is large enough, then nothing can prevent the shrinking from continuing until the star is so small that it was invisible. It becomes a black hole.



1) At room temperature, the pressure of gas inside the balloon pushing out balances the pressure of air outside the balloon pushing in.



2) As the balloon cools in the refrigerator, the pressure inside decreases. The pressure is determined, in part, by how fast the gas molecules move. As the temperature cools, the molecules slow down, resulting in a decreased pressure inside the balloon. Without enough pressure to resist the inward push of the outside air, the balloon shrinks.



3) The balloon stops shrinking when the pressure inside once again balances the outside pressure. Even though the gas molecules inside are moving slower (due to lower temperature), they are moving within a smaller volume, and so the inside pressure starts to increase as the balloon continues to shrink. Once the two pressures are equal, the shrinking stops.

Black Holes

Activity #2: A Scale Model of a Black Hole

The radius of the event horizon of a black hole with the mass of the Sun would be about 3 kilometers, about the same size as your city, town or village. If the Earth could be compressed into a black hole, the radius of its event horizon would be 1/330,000 of this, because the mass of the Earth is 1/330,000 times the mass of the Sun. Have your students calculate the radius of its event horizon [about 1 centimeter] and suggest a common object which could be used to represent it in this full-sized model [a golf ball]. It can also be instructive to construct a scale model of the Cygnus X- 1 binary system, in order to appreciate the relative size of the normal star and the black hole. The scale of this model is 1 cm to 100,000 km.

Object	**Actual Diameter (kilometers)**	**Scale Diameter (centimeters)**
Blue supergiant HDE 226868	30,000,000	300
Accretion disk in Cygnus X-1	20,000,000	200
Bulge in accretion disk	700,000	7
X-Ray emitting region	20,000	0.2
Black hole event horizon	60	0.0006
Sun	1,400,000	14

On a larger scale in which the black hole is the size of a penny, the Sun would be the size of your schoolyard, and the blue supergiant HDE 226868 would be the size of a city.

Black hole myths

MYTH: All stars collapse to become black holes upon their death.
TRUTH: Only rare, massive stars (one in millions!) end up this way.

MYTH: A black hole in space would devour everything in our galaxy.
TRUTH: There is so much space between the stars that a black hole would not affect any objects except those very close to it.

MYTH: The black hole in the Cygnus X-1 system is devouring the blue supergiant.
TRUTH: Less than a thousandth of the mass of the blue supergiant will fall into the black hole before it too dies, a million or so years from now.

MYTH: Matter which falls into a black hole reappears somewhere else in the universe.
TRUTH: The matter remains in the black hole; in fact, it is the matter in a black hole which causes the gravitational force which allows us to discover these objects.

MYTH: The gravity of a black hole is different from the gravity of a normal object.
TRUTH: If the Sun were to suddenly turn into a black hole (which it won't, by the way, because its gravity is too weak for it to completely collapse in on itself, the Earth and planets would continue to move in the normal way. However, the Earth would have lost its source of heat and light!

MYTH: Black holes are very dense.
TRUTH: Small and medium black holes are very dense, but a supermassive black hole with a 100 million solar masses, for example would have a density the same as water. [You can work this out from the mass of the black hole and the radius of its event horizon; this assumes that all of the matter is distributed within the entire event horizon, not just in the singularity.]

For Further Reading About Black Holes

- *Black Holes,* an information packet prepared by the A.S.P., containing reprints of articles, and a reading list.
- Kaufmann, W.: *Black Holes and Warped Spacetime.* 1979, W.H. Freeman & Sons. A brief, non-technical overview.
- Parker, B.: "In and Around Black Holes'' in *Astronomy,* Oct. 1986, p. 6. A non-technical article describing the fascinating properties of black holes.
- Shipman, H.: *Black Holes, Quasars and the Universe,* 1980, Houghton Mifflin. A somewhat more advanced book, giving an excellent account of how modern astronomical research is done.
- Thorne, K.: "The Search for Black Holes'' in *Scientific American,* Dec. 1974, p 32. A superb, classic semi-technical article.

Science Fiction With Interesting and Accurate Treatment of Black Holes:

- Niven, L.: *A Hole in Space,* 1974 Ballantine
- Niven, L.: *Neutron Star,* 1968 Ballantine
- Pournelle, J.: *Anthology of Black Holes,* 1978 Fawcett