Black Holes in the Universe

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"Because nothing was, therefore all things are."
-Edgar Allan Poe

"A black hole is a cannibal, swallowing up everything that gets in its way."
-John G. Taylor

Black holes are among the most interesting and unuusual objects to be found in the universe. If they really exist, they might very well be the most dangerous objects in the universe as well, since they are capable of destroying anything that gets in their path, even entire planets. To understand what a black hole is, we shall take a look at where they come from.

Black holes are formed from collapsed stars, yet they themselves are not solid bodies. Rather, a black hole is a *region of* space into which matter has fallen and from which nothing, not even light, can escape. Since light cannot escape the tremendous gravitational attraction of a black hole, it would be invisible to us, hence the name "black" hole.

Our sun will probably never become a black hole--it simply isn't massive enough. Let's say, for convenience, that our sun weighs one solar mass. Stars weighing 1.4 solar masses or more end up as black holes. Let's take a hypothetical star which weighs between 1.4 and 10 solar masses, and see how it becomes a black hole.

The star starts out as a ball of hydrogen. Hydrogen, the lightest atom of all the elements, consists of a single electron orbiting a proton. Two hydrogen atoms bonded together form a molecule of hydrogen gas.

The hydrogen begins to undergo nuclear fusion at the gas ball's center when the temperature there reaches about four million degrees Celsius. The star's energy comes from this fusion of four hydrogen nuclei into one helium nucleus. A helium nucleus consists of two protons and two neutrons. In the process, a small amount of mass is converted into energy. In the case of our own sun, four million tons of its mass are converted into energy each second. Einstein's well-known mass-energy equation $E = mc^2$ can be used to show that our sun puts out 4.4 septillion horsepower.

This energy production tends to make the star expand. This expansion force is counterbalanced by a contraction force. The contraction force is due to the weight of the star's outer layers. The outer mass tends to collapse inward toward the star's gravitational center (see Fig. 1).

When all of the star's hydrogen is used up near the core, and the core is mainly composed of helium, the balance of forces is upset. The gravitational forces collapse the core because the expansion force is no longer present as the nuclear fusion of hydrogen into helium has ceased. The fusion reactions still continue in the layer around the center, and the outermost layers expand. The gravitational collapse of the core causes temperatures there to rise until it is hot enough to initiate helium fusion. Now helium, not hydrogen, is the star's fuel. The helium fusion produces even heavier elements. The star has a very hot core, but has expanded tremendously in the outer regions. Stars of this type are called Red Giants, due to their expanded size and red color.

Let's go back to our hypothetical star. For a star of the mass range we have chosen, the nuclear reactions in the core go out of control as that region collapses. An explosion occurs, and the star blows most of its mass out into space--this is what is known as a supernova. What remains of the star's matter shrinks down into a small, dense body. Protons collide with electrons to form neutrons, leaving us with a superdense star whose core is composed of solid neutrons--a neutron star. These stars have densities as high as ten million tons per cubic centimeter. This is about nine trillion times more dense than water. Why should these neutron stars be so dense?

Picture an atom as electrons orbiting a nucleus. This model isn't quite accurate, but will do for our purposes here. Now, if electrons were the size of peas and the nucleus the size of a beachball, the distance between the peas and the beachball would be about the length of a football field. From this we see that ordinary matter is mostly empty space. In the matter of a neutron star, however, there is virtually no space between the neutrons (see Fig. 2). Picture all the beachball nuclei side by side as compared with the former model of ordinary matter, and it is easy to see why solid neutrons must be so dense.

If the mass of a neutron star is greater than or equal to a certain critical mass, it cannot resist further contraction due to its tremendous gravitational force. This critical mass is estimated to be between two and three solar masses. If the star that we are talking about weighs between 1.4 and 2 solar masses, it ends its life as a neutron star. But if its mass is greater than two solar masses, further contraction occurs. The neutron star becomes what is known as a collapsar, that is, any object collapsing toward its center under gravitational attraction to become a black hole.

Our hypothetical star is now a collapsar. It is shrinking, and its radius decreases until it reaches a certain critical value called the *Schwarzschild Radius* (Rs). If our star has a certain mass M, this radius is given by the relation

$$Rs = 2GM/c^2$$

where c is the velocity of light in a vacuum and G is a constant. When the radius reaches this

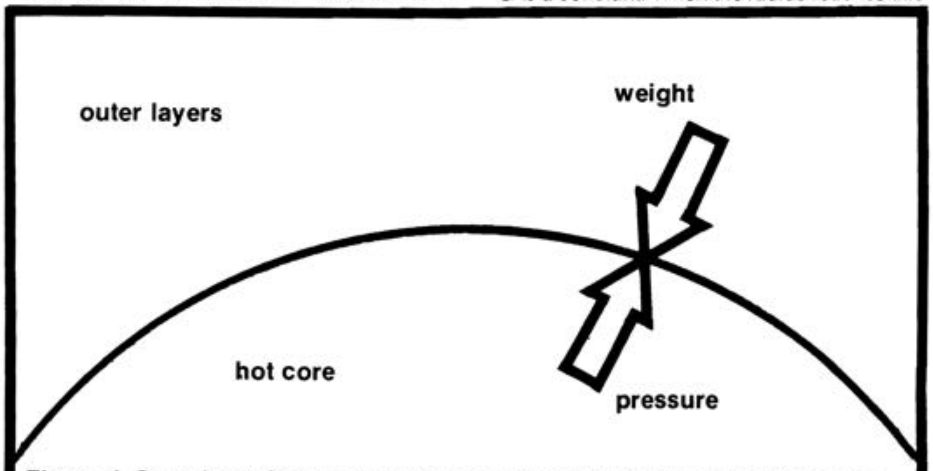
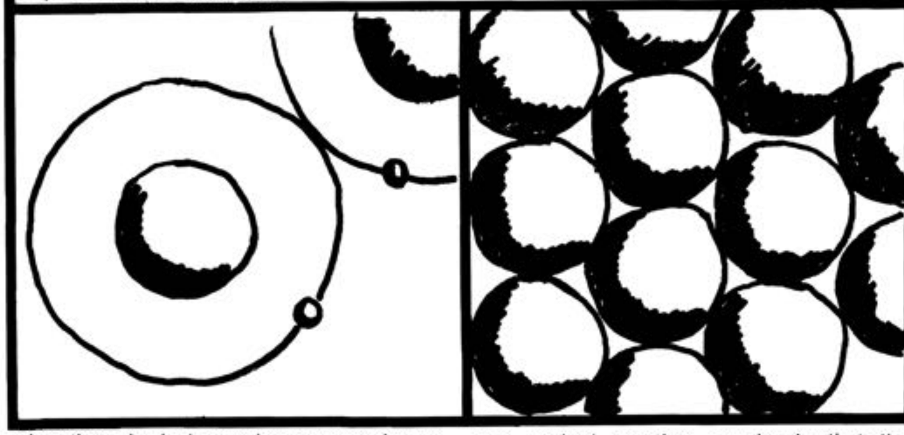


Figure 1. Stars keep from collapsing by balancing the weight of the outer layers with pressure from the interior.

Figure 2. Matter in a neutron star. In (a) we see that ordinary matter, in which nuclei are surrounded by electrons, is mostly empty space. In (b) we see that in a neutron star, the neutrons are packed closely with little space between them.



value, the spherical mass becomes so dense that even light cannot escape it. Now the gravitational field of the star is tremendous, and an event takes place which no astronomer will probably ever witness.

Suddenly, all of the star's matter is compressed to the center point. This cannot be seen because it happens too quickly to observe--the collapse takes place in a time interval on the order of millionths of a second! The density and gravitational force of the black hole are infinite at this point (which is called a singularity) and the matter of the star has literally become crushed out of existence. Surrounding the singularity is a volume of space into which matter has fallen and nothing can escape--a black hole. The radius of the black hole measured from the center is the Schwarzschild Radius. Table 1 shows the value of the Schwarzschild Radius for various objects.

If our hypothetical star had been heavier than ten solar masses, we also would have ended up with a black hole. With a star that heavy, once the core had used up its hydrogen, nothing can stop its collapse. No supernova outburst need occur; its own mass will cause it to rapidly collapse into a black hole.

Stars weighing 1.4 solar masses or less become white dwarf stars when their nuclear fuel is exhausted. The red giant collapses until it is a white dwarf, and stabilizes at that point (no further collapse taking place). While not as compact as neutron stars, white dwarf stars are still quite dense; one thimbleful of white dwarf material may weigh over a ton. White dwarfs owe their density to the fact that they are composed of what is known as degenerate matter.

In ordinary gaseous matter, the space between atoms is so much greater than the diameter of the atoms themselves that the atoms may be considered point particles for all practical purposes. They fly about at random, and the pressure exerted by the gas is due to these point particles bouncing off other particles.

In degenerate gaseous matter, the atoms are packed together so closely that the distance between the atoms is not much greater than the diameter of the atoms themselves. In this case the size of the atoms is significant and they can no longer be considered point particles. Now, electrons make up most of the volume of the atoms. The electrons resist being squeezed together in such close quarters. This resistance is called degeneracy pressure, and is the pressure the gas exerts against anything trying to compress it. This pressure holds the white dwarf up.

However, just as there was for a neutron star, there is a certain critical mass for a white dwarf beyond which it cannot resist further collapse. This is known as the Chandrasekhar Limit, and is 1.4 solar masses. If a white dwarf should incorporate more mass into its structure and exceed 1.4 solar masses in weight, it would become a collapsar and end up a black hole.

We see that there are oany situations which can, and probably do, give rise to black holes. We call a black hole's center a singularity in space. At these singular points density and gravity become infinite. In the region of a black hole the laws of physics behave contrary to ordinary experience. The laws of relativity show pronounced effects in these regions, and next we shall examine in detail the properties of these collapsed stars.

The boundary surrounding the black hole region of space is called the event horizon. Outside the event horizon an observer cannot have any knowledge of what is going on inside the event horizon, i.e. we cannot see what is going on inside a black hole if we view it from the outside. The event horizon is a barrier to communication of any kind, so an observer who has fallen inside a black hole cannot report to those outside what he is experiencing. He can't ever get back outside the event horizon to report what he's seen, since nothing can escape from a black hole. Thus, it seems that we can never directly observe what happens inside a black hole.

Suppose we decide to send an astronaut inside a black hole, anyway. The astronomer will observe him a safe distance away from the black hole through a telescope. The first thing the astronomer observes is a very pronounced redshift in the vicinity of the black hole.

What is a redshift? We noted earlier that the tremendous gravitational field of a black hole is so strong that not even light can escape from it. Light is affected by any gravitational field; only in the case of the black hole the effects are quite dramatic. Now, light loses some of its energy whenever it has to struggle against gravity. We know that energy is proportional to the frequency, so when the light loses energy, its frequency decreases.

Since frequency and wavelength are inversely proportional, this decrease in frequency causes an increase in wavelength. This "shift" toward an increase in wavelength is called a redshift because red light has a longer wavelength than any other visible color.

The redshift, a quantity denoted by the letter z, is defined as the shift in wavelength per wavelength of light emitted. For example, consider a beam of light with a wavelength of 5000 angstroms. If the light is shifted 250 angstroms, $z = 250/5000 = 0.05$.

Table 1. The Schwarzschild Radius for different objects.

Object	Weight in Pounds	Schwarzschild Radius in Feet
Hypothetical Star (ten solar masses)	4.4×10^{31}	9.7×10^{4}
Sun (one solar mass)	4.4×10^{30}	9.7×10^{3}
Earth	1.3×10^{25}	2.9×10^{-2}
Richard M. Nixon	2.0×10^{2}	4.4×10^{-26}

At the center of a black hole gravity is infinite, and so the light trying to escape loses an infinite amount of energy. Hence the redshift becomes infinite in the region of the black hole.

Let us consider the astronaut falling toward the black hole, as observed by the astronomer from a distance. Each is wearing an identical stopwatch. As he approaches the event horizon, we notice that time itself actually is slowing down for the astronaut. This is to be expected, since Einstein's theory of relativity predicts that time slows down in the region of an intense gravitational field. For each second that the astronaut's stopwatch ticks off, the astronomer's watch ticks off $1 + z$ seconds. Since the redshift z increases as one approaches the event horizon and eventually becomes infinite, the quantity $1 + z$ also becomes infinite. This means that as one second passes for the astronaut (who is right at the event horizon), an infinite amount of time passes in the universe.

In other words, time is frozen at the event horizon. The astronomer peering through his telescope would see the astronaut falling slower and slower toward the event horizon, until he seemed frozen forever at the event horizon. To the outside observer, the astronaut will never pass through the event horizon into the black hole. To our eyes, he has achieved a kind of immortality, for he will remain as he is while the universe grows old and dies.

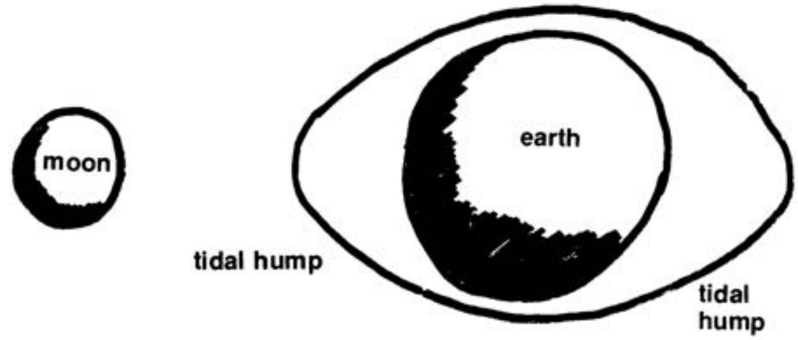
But wait a minute. How can a black hole be said to eat up all matter in its path if time is frozen at its boundary and nothing passes through it? Well, Einstein showed us that time is a subjective thing, depending on your point of view, or your reference frame, as it's called. For example, to a man standing still, a rocket ship which weighs ten tons at rest would weigh almost twenty-three tons if travelling at ninety percent the speed of light. But if the man was to fly alongside the rocketship and measure it, he would find it weighed ten tons. If he is in the same *reference frame* as the rocket, it doesn't gain any mass. In a different reference frame, it does.

By the same reasoning, the astronomer and astronaut are in different reference frames, this time the difference being due to gravitation and not velocity. Yes, to the astronomer outside the black hole's pull, it appears as if the astronaut is frozen at the event horizon. But what is it like in the astronaut's frame of reference?

As he approaches the event horizon, time runs perfectly normally from his point of view. As he falls, he sees nothing in front of him; a black hole looks like just that--a hole. At this point he might be killed or at least seriously injured by something which only affects oceans on Earth, namely, the tide.

A tidal force is exerted by a mass on a body. We know that the gravitational force decreases in strength with distance. It follows that the gravitational attraction on a body is strongest at that point on the body nearest the mass, and weakest at that point on the body farthest away from the mass. In the case of the moon acting on the Earth, this causes the water to bulge toward the moon (at the point nearest the moon) and away from the moon (at the point farthest away). This gives us two tidal humps on opposite sides of the Earth, as if the gravitational forces were "stretching" the waters, as in Fig. 3.

Figure 3. The moon pulls the ocean waters out into a hump on Earth's side nearest the moon. The moon's gravity also pulls the solid Earth out from under the water on the farside, creating a second tidal hump.



Now we are well aware of the fact that a black hole exerts a great deal more gravity on the astronaut than the moon exerts on the Earth. For a black hole of ten solar masses, the tidal force at the event horizon is about a hundred million million times greater than the tidal force one would feel standing on the Earth. The tremendous tidal force does to the astronaut something similar to what happens with the ocean.

If the astronaut approaches the hole feet first, the gravitational pull on his feet will be considerably stronger than that on his head. So strong is the force that the astronaut will be stretched out into a long cylinder; he will be torn apart on a sort of cosmic torture rack. If the astronaut isn't killed by tides at the event horizon, the infinite gravitational force at the black hole's center will surely do the trick.

But whether he does it dead or alive, the astronaut *will* pass through the event horizon. Once inside the black hole, he is pulled toward the center point where all the mass of the hole is contained. The density of matter here is infinite; this is the singularity discussed before. Here all objects lose their identity since the matter is crushed out of existence. Our astronaut is no longer an astronaut; he is merely mass that has been added to the black hole. He no longer exists in our universe. But it doesn't really matter, since once past the event horizon he was out of the picture forever.

Or was he?

Some speculation has been made to the effect that what goes into a black hole comes out somewhere else through something called a "white hole". Keep in mind that this notion, while aesthetically pleasing, may be more science fantasy than science fact.

Nature loves symmetry and order. She is supposed to make sense. The whole idea of science is to find some unity and order in nature. We believe that there are regions in space where matter is devoured, and the picture of the universe would be more symmetric if there were other regions where matter is produced. There is nothing in Einstein's Theory of General Relativity which prohibits the existence of such white holes.

These white holes would form like a collapsar in reverse, starting with a point of infinite density and ending with matter erupting outward into the universe. Thus, matter devoured by a black hole may be expelled by a white hole somewhere else in the universe. This smacks of being a sort of "space warp", where you go from one point to another instantaneously without having to travel between them.

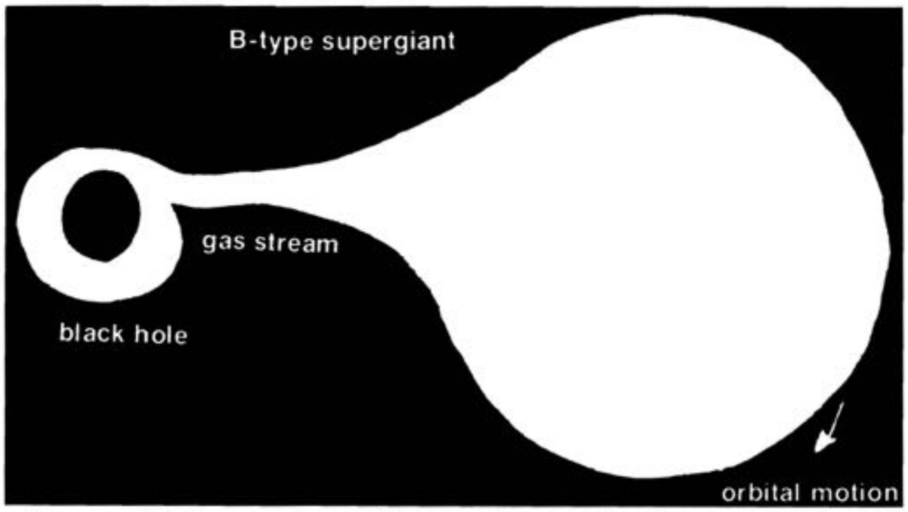
Another model of white holes pictures matter from our universe passing through a black hole, and erupting through a white hole into an alternate universe. In this picture, the black hole-white hole pair form a sort of "gateway" to another unverse. Keep in mind, however, the fact that the alternate universe is a mathematical model only. It can never be proven that it exists, since someone or something travelling through a black hole into such a universe would never be seen in our own world again.

The actual observation of a black hole in space would strongly confirm our present theories of relativistic physics. But how can we possibly detect a black hole far out in space? It is invisible, emitting no radiation whatsoever. Unless we are close enough to feel its gravity, we won't know it it's there or not.

Stars and starlike objects exist not only as single objects, but also in pairs. A system of two stars orbiting one another is called a binary star. It turns out that if one of the stars is a black hole, we should be able to detect it through its interaction with the other star.

An X-ray binary is a system in which a normal star is bound to a superdense star, as in Fig. 4. The superdense star may be a white dwarf, a neutron star, or a black hole. Matter streams from the normal star and follows a spiral path until it falls into the denser star. As the matter falls into the dense star energy is gained and converted into X-rays. This is because the matter is ionized plasma, and has an electrical charge. The X-rays are emitted into space (hence the name "X-ray" binary) and can be detected by the astronomer's instruments in orbit above the Earth.

Figure 4. A model of Cygnus X-1.



It is assumed that the superdense star has a magnetic field. For a neutron star this field is not necessarily aligned with the axis of rotation of the star. A black hole possesses axial symmetry, meaning its magnetic field *is* aligned with its rotational axis.

The X-ray signal will be a regular pulse if the magnetic field is skewed, so regular pulses indicate a neutron star. If the pulse is sharp and irregular, the magnetic field is aligned with the axis of rotation and we have a black hole. Each burst of X-rays is caused by matter spiralling toward the superdense companion star, and the bursts get narrower as the spiral orbit gets smaller.

Using this information, astronomers scanned the skies for black holes, and believe they may have found one. Remo J. Ruffini, a Princeton astronomer, believes that the star Cygnus X-1 is a black hole. Its companion is a blue supergiant, star HDE 226868. A rocket flown by the Goddard Space Flight Center accumulated data on the system which Ruffini has carefully interpreted. The data indicates that Cygnus X-1 is definitely a collapsed object, and almost certainly a black hole since the X-ray bursts were irregular in nature. Also, its mass is estimated to be at least five solar masses, and we know that any collapsed object heavier than two to three solar masses is a black hole.

Singularities in space, if found, might tell us a great deal about our own beginnings. This is becuase some theorists are now speculating that the entire universe began as a singularity in space!

Most astronomers support the Big Bang theory of the creation of the universe. This theory says that the universe began as a chunk of hot, superdense matter small enough to fit in the volume of our own solar system. The explosion of this chunk of matter (the big bang) was the start of the creation of the universe. It is possible that this creation may have been a singularity where matter poured outward; in other words, our universe was formed from a tremendous white hole.

The big bang sent matter spewing outwards at great speeds, and even now our universe is still rapidly expanding, with galaxies moving away from us a appreciable fractions of the velocity of light. This may continue until the universe ends, but many astronomers feel that this expansion may eventually come to a halt. If this happens, gravitation will cause the universe to contract. Galaxies would come together and eventually become squeezed into such a small volume that a black hole may be formed, and all the matter in the universe would be crushed out of existence.

In fact, the universe may even now be nothing but a gigantic black hole. The universe is estimated to have a radius of ten billion light years. One light year is the distance something travelling at the speed of light covers in one year. From estimates of the amount of mass in the universe, the Schwarzschild Radius of the universe has been calculated to be roughly ten billion light years. If the radius of the universe is equal to its Schwarzshild Radius, then we are all living inside the ultimate black hole, or more accurately, the ultimate collapsar. Since the volume of the universe is so large, its density is relatively low. In the continuing collapse, of course, it would eventually reach a value of infinite density at the center point.

Finding a real black hole would confirm the theory. This is justification enough for the search, since the mathematical treatment of such objects is one of the chief glories of modern science. But some are always looking for immediate practical applications of the subject in question. Are there any in the case of black holes?

Three physicists at the Lawrence Livermore Laboratory have a suggestion. They feel it would be possible to find and capture a mini-black hole. (Such miniature black holes may have been formed in the original big bang.) Once captured, we would shoot thermonuclear fuel, such as hydrogen, right at the black hole.

As the fuel falls toward the black hole, the tremendous gravitation compresses, heats, and ionizes the hydrogen. Nuclear fusion, a reaction discussed earlier, is initiated. The fuel explodes in a flash, and helium is formed. Some matter is converted into energy. The fuel mass is blown back by the explosion along with the energy away from the black hole. The energy is beamed back to Earth via microwaves where it is put to work. This system is totally nonpolluting, and has no moving parts (save the fuel itself). The idea may seem a bit wild, but the Livermore scientists are seriously urging that we search out and capture such a black hole for this purpose.

Black hole energy sources, alternate universes, space warps, and frozen time...the physics of the black hole sounds more like science fiction that modern astrophysics. But J.B.S. Haldane spoke accurately when he said: "The universe is not only queerer than we imagine, it is queerer than we *can* imagine."