
Print

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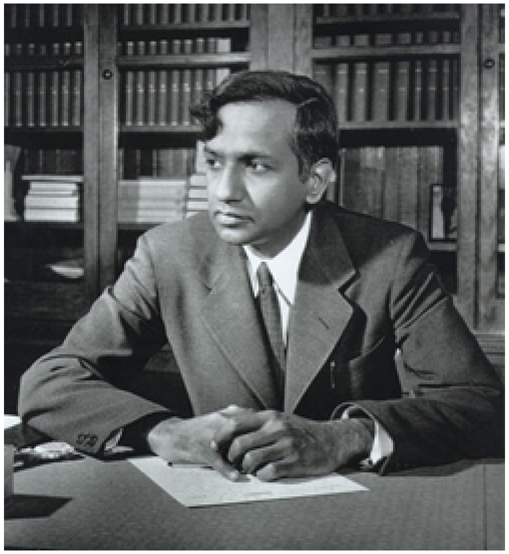
Black holes make great B-movies, like the 1979 film *The Black Hole*. (I consider it a classic despite the fact that it's terrible.) They also make for great conversations. Every astronomer can tell stories of parties at which, upon revealing their occupation, they were asked about black holes. The truth of the matter is that we are naturally drawn towards the unknown and the bizarre.

Many fascinating concepts, like that of being invisible, are out of the realm of physics and into that of fantasy. With black holes, similarly tantalizing ideas such as returning to the past, traveling to other parts of the universe, or even between universes, are as real as the electricity that brightens our evenings, the rockets that propel us to the Moon, or the Sun that warms us.



Chandrasekhar, a professor at the University of Chicago, was recognized for his groundbreaking studies of the structure and evolution of stars with the 1983 Nobel Prize in Physics. ©Library of Congress

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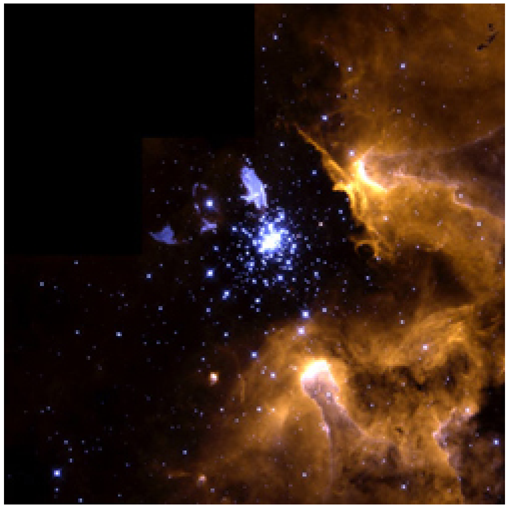
From a Figment of Our Imagination to Physical Reality

In 1783, the English geologist John Michell (1724-1793) used Newtonian mechanics to deduce that if a star's radius were small enough and its mass high enough, then any body trying to escape that star's gravitational pull would need to move faster than light. If even light could not escape, then this star would be dark. Mitchell did not know how one could make a *dark star*, as he called them, but credit should be given to him for taking simple physical laws and using them to think out of the box.

Two hundred years were to pass before physicists returned to the problem of the effect of gravity on light. In 1916, the concept of dark stars was revived when the German astrophysicist Karl Schwarzschild (1873-1969) found a solution to Einstein's field equations that described the gravitational field around a star. (The field equations describe how mass acts on space—by bending it— and how space acts on mass— by changing its course. We will discuss the field equations in more detail in Week 6.) Schwarzschild realized that if a star contracts below a certain radius, called today the *Schwarzschild radius*, the surrounding space-time would be so curved that light emitted from the stellar surface would return to it. In a sense, Schwarzschild's idea is not that dissimilar from the one of Michell and the French physicist Pierre-Simon Laplace (1749-1827), who elaborated Michell's initial ideas. For Laplace and Newtonian mechanics, however, space-time is absolute and the speed of light variable, while for Schwarzschild and general relativity, light's speed is constant, but space-time around the contracting mass is variable.

By 1916 general relativity had accumulated much support and many fans (although a confirmation would only come in 1919). Yet the solution to the field equations, which predicted the shape of space-time around a super-compressed star, was disliked by many because many physical principles appeared to break down in the cores of such objects. Among the detractors was Einstein himself. He knew that the principle of a black hole was right, but he did not believe that nature would allow a stellar collapse that would result in one.

In 1935, a young Indian physicist, Subrahmanyan Chandrasekhar (1910-1995), presented a new and daring result. While investigating the stability of white dwarf stars, Chandrasekhar realized that for masses larger than about 1.4 Msun (one solar mass is the mass of the sun, 1.989 x 1030 kg) a star would not be able to support itself against the force of gravity. *Chandrasekhar's limit*, as the mass is known today, is the first step of a collapse that can lead to a black hole.



The galactic nebula NGC 3603, through the eyes of the Hubble Space Telescope, shows the various stages in the life cycle of stars. ©Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington), You-Hua Chu (University of Illinois Urbana-Champaign), and NASA

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Theoretical Foundation

Stars struggle all their life to resist collapse under their exceptional weight. During a star's life, the nuclear fusion reactions in the star's interior produce enough energy to balance its gravity. However, eventually this fuel runs out, and collapse is inevitable. But every timestars contract, something always comes to their rescue to halt the collapse. In the case of solar-like stars, the rescuing agent is *electron pressure*, electrons fighting for their right to occupy a reasonable amount of space. The more massive the star, the more it contracts, forcing its electrons to occupy the same state. But the natural stubbornness of electrons puts pressure on the star not to contract too much. However, there is a limit to electron pressure. If the contracting star is more massive than 1.4 Msun, or Chandrasekhar's limit, electron pressure is not "strong" enough to halt the collapse. The star will continue to collapse until its particles are so compressed and dense that if we weighed a teaspoonful of this material under Earth's gravity, it would weigh 100 million tons! A new equilibrium point is reached once the star has collapsed to the size of Manhattan, and its material is packed so densely that the neutrons in the atoms are as close as they can be. Now it is the neutron's time to fight for space and keep the star from further collapse. Fittingly, we call these stars *neutron* stars.

The next logical question about neutron stars must be: is there a mass above which not even neutron pressure can halt the collapse? It turns out that the answer is Yes, since even neutrons are not that strong. When a contracting star is more massive than a few solar masses, neutrons will not do. The star will continue to contract, ending up compressed into a point of zero radius and infinite density. The star has disappeared into a "singularity," or what we call a *black hole*.

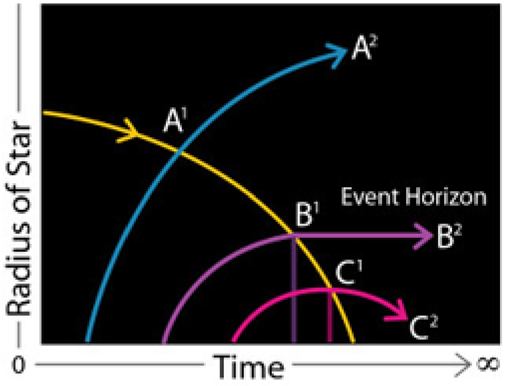

Figure 1

A collapsing star shrinks over time and its surface gravity increases. Once the radius shrinks below the event horizon (B^1, C^1) a ray of light cannot escape (B^2, C^2). ©AMNH

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At a certain point in the collapse, the star becomes so small that the escape velocity from its surface is greater than the speed of light. Hence, even light cannot escape. In the diagram [**Figure 1**], we plot time on the x-axis and space on the y-axis. The surface of the collapsing star can therefore be described by the thin yellow curve. A light ray emitted from the surface of the star will escape only when the stellar radius is larger than the Schwarzschild radius. We call the sphere whose radius equals the Schwarzschild radius the *event horizon*. Once the star has collapsed below this radius, any light emitted from its surface cannot leave.

Recall that, in Einstein's General Theory of Relativity, mass bends space-time around it. Light rays from distant stars bend as they pass near the Sun on their journey to Earth. This phenomenon, confirmed by Eddington during the solar eclipse of 1919, is due to the fact that space around the Sun is bent. We can imagine space being like the folds of a drape or the strokes of a brush. Light rays will follow those curved paths. The more massive an object is, the more curved the space around it becomes. So light leaving a very massive star will not travel straight into space, but will curve its path on its way out. A black hole is so massive that the light ray emitted from it will curve all the way back and never succeed in leaving it.

This model depicts Cygnus X-1, a binary star system where one member has become a black hole. The gas from the visible blue supergiant star is flowing towards the invisible black hole gathering around it in a bright disk. ©John Blondin, Michael Owen

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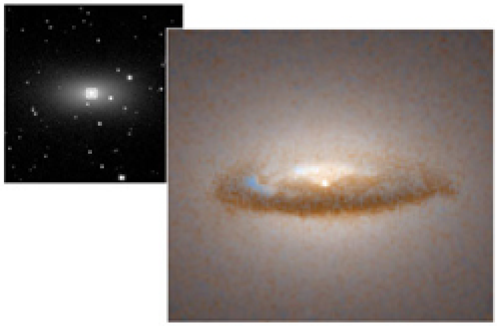
Finally, Observational Confirmation!

How can one detect a black hole if nothing can escape from it? When a black hole and a normal star revolve around each other, the normal star's envelope might get close enough to the black hole to be ripped off and swallowed. The ripped-off gas first becomes a fast rotating disk, so hot it emits X-rays. Very energetic X-rays are, therefore, telltale signs of a fast rotating accretion disk around a neutron star, or a black hole.

Binary stars are useful because we can obtain the limit for their masses by measuring the orbital speed of one of the two components (by Kepler's laws). We can deduce the mass of the companion in this way. If the mass of one of the stars turns out to be more than the critical mass of a few solar masses, then one can be sure that it is a black hole. That is how black holes are discovered. Perhaps the first object to be generally recognized as a black hole is the X-ray binary star Cygnus X-1. Its effect on its companion star suggested as early as 1971 that it must be a compact object with a mass too high for it to be a neutron star.

Beside black holes of stellar size, there are other black holes that have masses millions or even a billion times the mass of the Sun. Million-solar-mass black holes are thought to live in the center of every galaxy, including our galaxy, the Milky Way. The black hole shown above sits in the middle of the galaxy called NGC 7052, surrounded by gas and dust 3,700 light-years in diameter. The mass of this black hole is 300 million times the mass of our Sun. Billion-solar-mass black holes, also called supermassive black holes (you must love astronomical terms!) are nested in the core of quasars.

These black holes were first postulated in 1974 by Sir Martin Rees, Astronomer Royal to the Queen. This type of black hole is formed by the gravitational collapse of the center of a large cluster of stars.



In the center of the elliptical galaxy NGC 7052, a dust disk circles a black hole. Scientists speculate this dust is the remnant of an ancient galactic collision and it will be drawn into the black hole in several billion years. ©STScI, U.Washington, NASA

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Black Holes and the Two Incompatible Pillars of Physics

Einstein did not like the singularity in the center of black holes. Nobody does, because such objects are painful reminders that the two pillars of modern physics are incompatible. Behind a black hole’s event horizon hides a large amount of mass compressed down to a miniscule size. At this tiny scale length, Quantum Mechanics must be adopted. Quantum Mechanics has no prescription for gravity, yet the core of a black hole, despite having the physical scale of a particle, is so extremely massive that gravity, and hence the physics of general relativity, are a necessity. An object like a black hole is called a physical catastrophe because the mathematics we use to determine its properties breaks down at the black hole center, or singularity. In mathematics, this usually means that one of your equations leads to an infinite result.

In the mid-1990s, several physicists found that black holes are fully consistent with String Theory, a novel and still controversial way of reconciling general relativity and Quantum Mechanics. (We will talk more about String Theory in Week 6.) The mathematics for this theory is quite involved, and many physicists do not believe that anything good will ever come from it. However, there might come a day when string theorists will finally tame their horrendously complicated equations and come up with a fully consistent description of the universe—a theory that will replace general relativity and Quantum Mechanics in an elegant way. I, for one, have faith.

Related Links

Subramanyan Chandrasekhar: Autobiography

Read an autobiography of Chandrasekhar, a 1983 winner of the Nobel Prize in Physics, on the Nobel e-Museum site. Additional documents, including his Nobel lecture and press releases, are available.

Virtual Trips to black holes and Neutron stars

A number of short animations show what it's like to travel towards and around both black holes and neutron stars, based on Einstein's Theory of General Relativity. Look at the movies frame by frame, to learn more about how Einstein's theories help predict the warping of space-time.