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A study of formation and evolution of Black Hole

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Abstract
Objects whose gravitational fields are too strong for light to escape were first considered in the 18th century by John Michell and Pierre-Simon Laplace. The first modern solution of general relativity that would characterize a black hole was found by Karl Schwarzschild in 1916, although its interpretation as a region of space from which nothing can escape was first published by David Finkelstein in 1958. Black holes were long considered a mathematical curiosity; it was not until the 1960s that theoretical work showed they were a generic prediction of general relativity. The discovery of neutron stars by Jocelyn Bell Burnell in 1967 sparked interest in gravitationally collapsed compact objects as a possible astrophysical reality. A black hole can be formed by the death of a massive star. When such a star has exhausted the internal thermonuclear fuels in its core at the end of its life, the core becomes unstable and gravitationally collapses inward upon itself, and the star's outer layers are blown away.

Keywords: Black Hole, General Relativity, Chandrashekhar Limit, Schwarzschild radius

Introduction

A **black hole** is a region of space-time where gravity is so strong that nothing (no particles or even electromagnetic radiation such as light) can escape from it. Marcia Bartusiak traces the term "black hole" to physicist Robert H. Dicke who in the early 1960s reportedly compared the phenomenon to the Black Hole of Calcutta, notorious as a prison where people entered but never left alive.

The idea of a body so massive that even light could not escape was briefly proposed by astronomical pioneer and English clergyman John Michell in a letter published in November 1784. John Michell used the term "dark star" for "black hole". Michell's simplistic calculations assumed such a body might have the same density as the Sun, and concluded that such a body would form when a star's diameter exceeds the Sun's by a factor of 500 and the surface escape velocity exceeds the usual speed of light. Michell correctly noted that such supermassive but non-radiating bodies might be detectable through their gravitational effects on nearby visible bodies. Scholars of the time were initially excited by the proposal that giant but invisible stars might be hiding in plain view, but enthusiasm dampened when the wavelike nature of light became apparent in the early nineteenth century.

In 1915, Albert Einstein developed his theory of general relativity, having earlier shown that gravity does influence light's motion. Only a few months later, Karl Schwarzschild found a solution to the Einstein field equations, which describes the gravitational field of a point mass and a spherical mass. A few months after Schwarzschild, Johannes Droste independently gave the same solution for the point mass and wrote more extensively about its properties. This solution had a peculiar behaviour at what is now called the Schwarzschild radius. The nature of this surface was not quite understood at the time.

In 1924, Arthur Eddington showed that the singularity disappeared after a change of coordinates. It took until 1933 for Georges Lemaître to realize that this meant the singularity at the Schwarzschild radius was a non-physical coordinate singularity. Arthur Eddington did however comment on the possibility of a star with mass compressed to the Schwarzschild radius in a 1926 book, noting that Einstein's theory allows us to rule out overly large densities for visible stars like Betelgeuse.

In 1931, Subrahmanyan Chandrasekhar calculated, using special relativity, that a non-rotating body of electron-degenerate matter above a certain limiting mass (now called the Chandrasekhar limit at 1.4 $M_\odot$) has no stable solutions. His arguments were opposed by many of his contemporaries like Eddington and Lev Landau, who argued that some yet unknown mechanism would stop the collapse. They were partly correct as a white dwarf slightly more massive than the Chandrasekhar limit will collapse into a neutron star which is stable. But in 1939, Robert Oppenheimer and others predicted that neutron stars above another limit (the Tolman–Oppenheimer–Volkoff limit) would collapse further for the reasons presented by Chandrasekhar, and concluded that no law of physics was likely to intervene and stop at least some stars from collapsing to black holes. Their original calculations, based on the Pauli Exclusion Principle, gave it as 0.7 $M_\odot$; subsequent consideration of strong force-mediated neutron-neutron repulsion raised the estimate to approximately 1.5 $M_\odot$ to 3.0 $M_\odot$. Observations of the neutron star merger GW170817, which is thought to have generated a black hole shortly afterward, have refined the TOV limit estimate to ~2.17 $M_\odot$. Oppenheimer and his co-authors interpreted the singularity at the boundary of the Schwarzschild radius as indicating that this was the boundary of a bubble in which time stopped. This is a valid point of view for external observers, but not for infilling observers. Because of this property, the collapsed stars were called "frozen stars", because an outside observer would see the surface of the star frozen in time at the instant where its collapse takes it to the Schwarzschild radius.

In 1958, David Finkelstein identified the Schwarzschild surface as an event horizon, "a perfect unidirectional membrane: causal influences can cross it in only one direction". This did not strictly contradict Oppenheimer's results, but extended them to include the point of view of infalling observers. Finkelstein's solution extended the Schwarzschild solution for the future of observers falling into a black hole. A complete extension had already been found by Martin Kruskal, who was urged to publish it. These results came at the beginning of the golden age of general relativity, which was marked by general relativity and black holes becoming mainstream subjects of research. This process was helped by the discovery of pulsars by Jocelyn Bell Burnell in 1967, which, by 1969, were shown to be rapidly rotating neutron stars. Until that time, neutron stars, like black holes, were regarded as just theoretical curiosities; but the discovery of pulsars showed their physical relevance and spurred a further interest in all types of compact objects that might be formed by gravitational collapse. In this period more general black hole solutions were found.

In 1963, Roy Kerr found the exact solution for a rotating black hole. Two years later, Ezra Newman found the axisymmetric solution for a black hole that is both rotating and electrically charged. Through the work of Werner Israel, Brandon Carter, and David Robinson the no-hair theorem emerged, stating that a stationary black hole solution is completely described by the three parameters of the Kerr–Newman metric: mass, angular momentum, and electric charge. Work by James Bardeen, Jacob Bekenstein, Carter, and Hawking in the early 1970s led to the formulation of black hole thermodynamics. These laws describe the behavior of a black hole in close analogy to the laws of thermodynamics by relating mass to energy, area to entropy, and surface gravity to temperature. The analogy was completed when Hawking, in 1974, showed that quantum field theory implies that black holes should radiate like a black body with a temperature proportional to the surface gravity of the black hole, predicting the effect now known as Hawking radiation.

On 11 February 2016, the LIGO Scientific Collaboration and the Virgo collaboration announced the first direct detection of gravitational waves, which also represented the first observation of a black hole merger. On 10 April 2019, the first direct image of a black hole and its vicinity was published, following observations made by the Event Horizon Telescope in 2017 of the supermassive black hole in Messier 87's galactic centre.

At first, it was suspected that the strange features of the black hole solutions were pathological artifacts from the symmetry conditions imposed, and that the singularities would not appear in generic situations. This view was held in particular by Vladimir Belinsky, Isaak Khalatnikov, and Evgeny Lifshitz, who tried to prove that no singularities appear in generic solutions. However, in the late 1960s Roger Penrose and Stephen Hawking used global techniques to prove that singularities appear generically. For this work, Penrose received half of the 2020 Nobel Prize in Physics.

Formation of Black Hole

Given the bizarre character of black holes, it was long questioned whether such objects could actually exist in nature or whether they were merely pathological solutions to Einstein's equations. Einstein himself wrongly thought black holes would not form, because he held that the angular momentum of collapsing particles would stabilize their motion at some radius. This led the general relativity community to dismiss all results to the contrary for many years. However, a minority of relativists continued to contend that black holes were physical objects, and by the end of the 1960s, they had persuaded the majority of researchers in the field that there is no obstacle to the formation of an event horizon. Penrose demonstrated that once an event horizon forms, general relativity without quantum mechanics requires that a singularity will form within. Shortly afterwards, Hawking showed that many cosmological solutions that describe the Big Bang have singularities without scalar fields or other exotic matter. The Kerr solution, the no-hair theorem, and the laws of black hole thermodynamics showed that the physical properties of black holes were simple and comprehensible, making them respectable subjects for research. Conventional black holes are formed by gravitational collapse of heavy objects such as stars, but they can also in theory be formed by other processes.

Gravitational collapse

Gravitational collapse occurs when an object's internal pressure is insufficient to resist the object's own gravity. For stars this usually occurs either because a star has too little fuel left to maintain its temperature through stellar nucleosynthesis or because a star that would have been stable receives extra matter in a way that does not raise its core temperature. In either case the star's temperature is no longer high enough to prevent it from collapsing under its own weight. The collapse may be stopped by the degeneracy pressure of the star's constituents, allowing the condensation of matter into an exotic denser state. The result is one of the various types of compact star. Which type forms depends on the mass of the remnant of the original star left if the outer layers have been blown away (for example, in a Type II supernova). The mass of the remnant, the collapsed object that survives the explosion, can be substantially less than that of the original star. Remnants exceeding 5 $M_\odot$ are produced by stars that were over 20 $M_\odot$ before the collapse.

If the mass of the remnant exceeds about 3-4 $M_\odot$ (the Tolman–Oppenheimer–Volkoff limit) either because the original star was very heavy or because the remnant collected additional mass through accretion of matter, even the degeneracy pressure of neutrons is insufficient to stop the collapse. No known mechanism (except possibly quark degeneracy pressure, see quark star) is powerful enough to stop the implosion and the object will inevitably collapse to form a black hole.

The gravitational collapse of heavy stars is assumed to be responsible for the formation of stellar mass black holes. Star formation in the early universe may have resulted in very massive stars, which upon their collapse would have produced black holes of up to 10^3 $M_\odot$. These black holes could be the seeds of the supermassive black holes found in the centers of most galaxies. It has further been suggested that massive black holes with typical masses of ~10^5 $M_\odot$ could have formed from the direct collapse of gas clouds in the young universe. These massive objects have been proposed as the seeds that eventually formed the earliest quasars observed already at redshift. While most of the energy released during gravitational collapse is emitted very quickly, an outside observer does not actually see the end of this process. Even though the collapse takes a finite amount of time from the reference frame of infalling matter, a distant observer would see the infalling material slow and halt just above the event horizon, due to gravitational time dilation. Light from the collapsing material takes longer and longer to reach the observer, with the light emitted just before the event horizon forms delayed an infinite amount of time. Thus the external observer never sees the formation of the event horizon; instead, the collapsing material seems to become dimmer and increasingly red-shifted, eventually fading away.

Gravitational collapse requires great density. In the current epoch of the universe these high densities are found only in stars, but in the early universe shortly after the Big Bang densities were much greater, possibly allowing for the creation of black holes. High density alone is not enough to allow black hole formation since a uniform mass distribution will not allow the mass to bunch up. In order for primordial black holes to have formed in such a dense medium, there must have been initial density perturbations that could then grow under their own gravity. Different models for the early universe vary widely in their predictions of the scale of these fluctuations. Various models predict the creation of primordial black holes ranging in size from Planck mass to hundreds of thousands of solar masses.

Despite the early universe being extremely dense—far denser than is usually required to form a black hole-it did not re-collapse into a black hole during the Big Bang. Models for gravitational collapse of objects of relatively constant size, such as stars, do not necessarily apply in the same way to rapidly expanding space such as the Big Bang.

High-energy collisions

Gravitational collapse is not the only process that could create black holes. In principle, black holes could be formed in high-energy collisions that achieve sufficient density. As of 2002, no such events have been detected, either directly or indirectly as a deficiency of the mass balance in particle accelerator experiments. This suggests that there must be a lower limit for the mass of black holes. Theoretically, this boundary is expected to lie around the Planck mass ($m_P=\sqrt{\hbar c/G} \approx 1.2\times10^{19}$ GeV/$c^2 \approx 2.2\times10^{-8}$ kg), where quantum effects are expected to invalidate the predictions of general relativity. This would put the creation of black holes firmly out of reach of any high-energy process occurring on or near the Earth. However, certain developments in quantum gravity suggest that the minimum black hole mass could be much lower as low as 1 TeV/c^2. This would make it conceivable for micro black holes to be created in the high-energy collisions that occur when cosmic rays hit the Earth's atmosphere or possibly in the Large Hadron Collider at CERN. These theories are very speculative and the creation of black holes in these processes is deemed unlikely by many specialists. Even if micro black holes could be formed, it is expected that they would evaporate in about 10^{-25} seconds, posing no threat to the Earth.

Growth of Black Hole

Once a black hole has formed, it can continue to grow by absorbing additional matter. Any black hole will continually absorb gas and interstellar dust from its surroundings. This is the primary process through which supermassive black holes seem to have grown. A similar process has been suggested for the formation of intermediate-mass black holes found in globular clusters. Black holes can also merge with other objects such as stars or even other black holes. This is thought to have been important, especially in the early growth of supermassive black holes, which could have formed from the aggregation of many smaller objects. The process has also been proposed as the origin of some intermediate-mass black holes.

Evaporation and Shrinkage of Black Hole

In 1974, Hawking predicted that black holes are not entirely black but emit small amounts of thermal radiation at a temperature $\hbar c^3/(8\pi G M k_B)$; this effect has become known as Hawking radiation. By applying quantum field theory to a static black hole background, he determined that a black hole should emit particles that display a perfect black body spectrum. Since Hawking's publication, many others have verified the result through various approaches. If Hawking's theory of black hole radiation is correct, then black holes are expected to shrink and evaporate over time as they lose mass by the emission of photons and other particles. The temperature of this thermal spectrum (Hawking temperature) is proportional to the surface gravity of the black hole, which, for a Schwarzschild black hole, is inversely proportional to the mass. Hence, large black holes emit less radiation than small black holes.

A stellar black hole of 1 $M_\odot$ has a Hawking temperature of 62 nanokelvins. This is far less than the 2.7 K temperature of the cosmic microwave background radiation. Stellar-mass or larger black holes receive more mass from the cosmic microwave background than they emit through Hawking radiation and thus will grow instead of shrinking. To have a Hawking temperature larger than 2.7 K (and be able to evaporate), a black hole would need a mass less than the Moon. Such a black hole would have a diameter of less than a tenth of a millimeter.

If a black hole is very small, the radiation effects are expected to become very strong. A black hole with the mass of a car would have a diameter of about 10^{-24} m and take a nanosecond to evaporate, during which time it would briefly have a luminosity of more than 200 times that of the Sun. Lower-mass black holes are expected to evaporate even faster; for example, a black hole of mass 1 TeV/c^2 would take less than 10^{-88} seconds to evaporate completely. For such a small black hole, quantum gravitation effects are expected to play an important role and could hypothetically make such a small black hole stable, although current developments in quantum gravity do not indicate this is the case.

The Hawking radiation for an astrophysical black hole is predicted to be very weak and would thus be exceedingly difficult to detect from Earth. A possible exception, however, is the burst of gamma rays emitted in the last stage of the evaporation of primordial black holes. Searches for such flashes have proven unsuccessful and provide stringent limits on the possibility of existence of low mass primordial black holes. NASA's Fermi Gamma-ray Space Telescope launched in 2008 will continue the search for these flashes.

If black holes evaporate via Hawking radiation, a solar mass black hole will evaporate (beginning once the temperature of the cosmic microwave background drops below that of the black hole) over a period of 10^{64} years. A super massive black hole with a mass of 10^{11} (100 billion) M⊙ will evaporate in around 2×10^{100} years. Some monster black holes in the universe are predicted to continue to grow up to perhaps 10^{14} M⊙ during the collapse of super clusters of galaxies. Even these would evaporate over a timescale of up to 10^{106} years.

Conclusion

The theory of general relativity predicts that a sufficiently compact mass can deform spacetime to form a black hole. The boundary of the region from which no escape is possible is called the event horizon. Although the event horizon has an enormous effect on the fate and circumstances of an object crossing it, according to general relativity it has no locally detectable features. In many ways, a black hole acts like an ideal black body, as it reflects no light. Moreover, quantum field theory in curved space-time predicts that event horizons emit Hawking radiation, with the same spectrum as a black body of a temperature inversely proportional to its mass. This temperature is on the order of billionths of a kelvin for black holes of stellar mass, making it essentially impossible to observe.

Black holes of stellar mass are expected to form when very massive stars collapse at the end of their life cycle. After a black hole has formed, it can continue to grow by absorbing mass from its surroundings. By absorbing other stars and merging with other black holes, supermassive black holes of millions of solar masses (M⊙) may form. There is consensus that supermassive black holes exist in the centers of most galaxies.

The presence of a black hole can be inferred through its interaction with other matter and with electromagnetic radiation such as visible light. Matter that falls onto a black hole can form an external accretion disk heated by friction, forming quasars, some of the brightest objects in the universe. Stars passing too close to a supermassive black hole can be shred into streamers that shine very brightly before being "swallowed." If there are other stars orbiting a black hole, their orbits can be used to determine the black hole's mass and location. Such observations can be used to exclude possible alternatives such as neutron stars. In this way, astronomers have identified numerous stellar black hole candidates in binary systems, and established that the radio source known as Sagittarius A*, at the core of the Milky Way galaxy, contains a supermassive black hole of about 4.3 million solar masses.

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