Black Holes

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This was written for a friend.

Contents

1 Introduction

When you hear the term "black hole," what comes to mind? Is it something sinister? Well, a black hole is a region of spacetime where gravity is so strong that nothing can escape, not particles or even electromagnetic radiation like light. According to general relativity theory, a sufficiently compact mass can deform spacetime to form a black hole. The event horizon is the point beyond which there is no way out.

Although it has a huge impact on the fate and circumstances of an object passing through it, general relativity says it has no locally detectable features. In many ways, a black hole acts like an ideal black body, as it reflects no light.

A black hole has been shown to completely depend on three parameters - mass, angular momentum and electric charge. This is actually pretty nice-each and every thing about this kind of body needs only 3 parameters to describe it!

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 (EHT) in 2017 of the supermassive black hole in Messier 87's galactic centre.

In March 2021, the EHT Collaboration presented, for the first time, a polarized-based image of the black hole which may help better reveal the forces giving rise to quasars.

1.1 History

In 1783, a Cambridge professor named John Michell published a paper in the Philosophical Transactions of the Royal Society of London stating that a star that was sufficiently massive and compact would have such a strong gravitational field that light could not escape: any light emitted from the star's surface would be dragged back by the star's gravitational attraction before it could get very far away. Michell speculated that there could be a lot of stars like this. We would feel their gravitational tug even if we couldn't see them since the light from them wouldn't reach us. Such objects are now known as black holes, because that is exactly what they are: black voids in space.

1.2 Etymology

John Michell used the term "dark star", and in the early 20th century, physicists used the term "gravitationally collapsed object". Marcia Bartusiak, a science writer, attributes the term "black hole" to physicist Robert H. Dicke, who reportedly compared the phenomenon to the Black Hole of Calcutta, a notorious prison where people entered but never left alive, in the early 1960s.

Life and Science News magazines used the term "black hole" in print in 1963, as did science journalist Ann Ewing in her article "'Black Holes' in Space," published on January 18, 1964, as a report on a meeting of the American Association for the Advancement of Science in Cleveland, Ohio.

A student reportedly suggested the phrase "black hole" at a John Wheeler lecture in December 1967; Wheeler adopted the term for its brevity and "advertising value," and it quickly caught on, leading some to credit Wheeler with coining the phrase, as Stephen Hawking did in his book "A Brief History of Time."

2 Formation and Evolution

- Binary Hole Systems: The LIGO experiment, which announced the first-ever detection of gravitational waves on February 11, 2016, observed gravitational waves emitted by a binary black hole system comprised of two black holes of approximately 30 solar masses each. Two black holes orbit each other in a binary black hole system.

  In this case, the two black holes inspiraled towards each other until they collided, resulting in the formation of a single black hole. The merger of the two black holes produced gravitational waves, which are waves of expanding and contracting spacetime that spread out from the new black hole.

  As they passed through the earth, they caused the earth to expand and contract by about the width of an atomic nucleus, sufficiently large to be detected in an interferometry experiment.

- Stellar Death: Star death is one mechanism of black hole formation. When a star runs out of fuel, it explodes into fragments, burning the remaining fuel and resulting in a supernova, a sudden outburst of energy by a dying star. A supernova occurs when there is a sudden disruption in the ongoing nuclear reactions in the core, resulting in an explosion that accelerates the star's particles away from it in a cosmic shockwave.

  A supernova's energy output is roughly equivalent to the energy output of a medium-sized star over its entire lifetime. A supernova lasts about a month before the remaining mass collapses under its own gravity, forming a neutron star. The densest stars known to exist are neutron stars (though not the theoretically densest possible stars). This star's fate is determined by its mass.

  If the mass of the star exceeds about three times that of the sun, it will eventually collapse into a black hole. The Tolman-Oppenheimer-Volkoff limit is the upper limit on the size of a neutron star.

- Black Hole Accretion A compact star in a binary system, particularly an accreting binary system, can form a black hole. When a lower mass star expands into a more compact star, it is said to accrete more particles, often forming an astronomical structure known as an accretion disk. Accretion disks can form around black holes and resemble accretion onto a neutron star or white dwarf.

- Bipolar Mass Ejection Looking for rapidly ejected mass from a local region of spacetime is one way to detect a black hole. Some of the material accreting on a black hole may gain a significant amount of angular momentum, propelling it above the escape velocity. It may then be ejected at high velocity in the direction defined by the rotation of the black hole. This is referred to as bipolar flow. However, ejected mass could also come from accreting neutron stars. The magnitude of the object's mass is the key difference between a neutron star and a black hole, and estimating the mass of the unseen object that is ejecting particles is a key means of proving that bipolar mass is associated with a black hole.

3 Schwarzschild Radius

The Schwarzschild radius (sometimes historically referred to as the gravitational radius) is a physical parameter in the Schwarzschild solution to Einstein's field equations that corresponds to the radius defining the event horizon of a Schwarzschild black hole. It is a characteristic radius associated with any quantity of mass.

The Schwarzschild radius was named after the German astronomer Karl Schwarzschild, who calculated this exact solution for the theory of general relativity in 1916. The name "Schwarzschild" also happens to literally translate to "black shield," ironically.

The Schwarzschild radius is given as

$$r_s = \frac{2GM}{c^2}$$

, where G is the gravitational constant, M is the object mass, and c is the speed of light. In natural units, the gravitational constant and the speed of light are both taken to be unity, so the Schwarzschild radius is $r_s = 2M$.

4 Hawking Radiation

In 1974, Stephen Hawking predicted that black holes are not entirely black but emit small amounts of thermal radiation at a temperature

$$\frac{\hbar \cdot c^3}{8 \cdot \pi \cdot G \cdot M \cdot k_B}$$

, where $\hbar$ is the reduced Planck constant, c is the speed of light, k_B is the Boltzmann constant, G is the gravitational constant, and M is the mass of the black hole.

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. Hawking radiation is central to the black hole information paradox, which has received a lot of attention recently.

If an object with finite entropy (and thus some finite amount of information in the statistical sense) falls into a black hole, but the black hole evaporates due to Hawking radiation, it appears that the information has been forever destroyed, in violation of the second law of thermodynamics.

Thus, it appears that information must be destroyed when entering a black hole, which contradicts the idea that in general relativity, nothing special happens to an observer falling into a black hole at the instant he or she crosses the event horizon. Recent resolutions of the paradox suggest among other things that the Hawking radiation does in fact contain the information (i.e., correlations in entropy) of whatever fell into the black hole.

5 Further Reading

- Hawking, Stephen (1988). A Brief History of Time. Bantam Books, Inc. ISBN 978-0-553-38016-3
- Black Hole from Brilliant.org
- Wikipedia's Entry on Blackhole