Name: _____ Date: _____

Dark Stars and Doubters

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On 27 November 1783, a paper by John Michell, an English clergyman and astronomer, was read to the Royal Society in London. Michell accepted Newton's view that light is a stream of tiny particles, and he reasoned that a star's gravity should slow those particles as they climbed away. Push the idea far enough and you reach a startling conclusion. A star as dense as the Sun but 500 times wider would pull so hard that its light could never escape. Such a star would be invisible. Then Michell added the sentence that makes him worth remembering: a dark body like this might still be detected by the way its gravity tugs on visible objects nearby. More than two centuries later, astronomers would find black holes in exactly that way.

The logic rests on escape velocity, the speed something needs to break free of a body's gravity without any further push. From Earth's surface, it is about 11.2 kilometers per second. Inside the edge of a black hole, it is greater than 299,792 kilometers per second. That is the speed of light, and nothing can travel faster. Michell, and the French mathematician Pierre-Simon Laplace independently in 1796, pictured their dark stars as enormous. The modern picture is the opposite: not a huge star but an extraordinarily compact one. The intuition was right, but the physics behind it was Newton's, and Newton's theory of gravity would eventually be replaced. The replacement would make dark stars both stranger and harder to believe in.

In 1915 Albert Einstein published general relativity, which describes gravity not as a force but as a bending of space and time by mass. Within months, the astronomer Karl Schwarzschild found an exact solution to Einstein's equations for a single, non-spinning ball of mass. At a particular distance from the center, some terms in the solution became infinite. No one understood what that distance meant. Today it is called the Schwarzschild radius, and it marks the event horizon. Its size is simple to estimate: about 2.95 kilometers for every Sun's worth of mass. A black hole of ten Suns has a horizon about thirty kilometers from its center. Earth's mass, crushed to its Schwarzschild radius, would be roughly the size of a marble.

That simple rule hides a surprise. Because the radius grows in step with the mass, while volume grows with the cube of the radius, a heavier black hole is less dense on average, not more. Double the mass and the average density inside the horizon drops to a quarter. Carry the arithmetic far enough and the numbers become absurd. A black hole of a hundred million Suns has an average density inside its horizon about the same as that of water. The word dense, so often used to describe black holes, turns out to be true for small ones and misleading for giant ones. What defines a black hole is not how tightly matter is packed but whether it has an edge from inside which the escape velocity exceeds the speed of light.

For decades, many leading physicists treated the Schwarzschild radius as a mathematical accident. In a 1926 book, the astronomer Arthur Eddington argued that a star squeezed to that size pointed to a flaw in the theory, not to something real. In 1939 Einstein himself used general relativity to argue that black holes were impossible; he believed pressure or rotation would always stop a collapsing star in time. That same year, J. Robert Oppenheimer and his student Hartland Snyder calculated what happens when a star collapses with nothing to stop it. Seen from far away, the collapse slows and slows, and the star appears to freeze at its Schwarzschild radius. Time near the horizon, as measured by a distant observer, runs ever more slowly.

The idea gradually hardened into physics. In 1958 David Finkelstein described the Schwarzschild surface as a perfect one-way membrane: causes can cross it inward, but never outward. In January 1965, Roger Penrose proved mathematically that black holes really can form, and that at their centers lies a singularity where the known laws of physics stop working. The name followed. In December 1967, someone in the audience at a lecture by the physicist John Wheeler reportedly suggested the phrase black hole, and Wheeler adopted it. He is often credited with inventing the term, but it had already appeared in print in 1963. Penrose was awarded half of the 2020 Nobel Prize in Physics for his proof, more than half a century after he made it.

Proofs on paper are not observations. The first strong candidate came from the sky in 1971, when Riccardo Giacconi's team found that an X-ray source called Cygnus X-1, about 7,000 light-years away, flickered quickly and irregularly, the signature of something small. A massive blue star orbits it, and gas pulled from that star heats up as it spirals inward. By 1974 most astronomers considered Cygnus X-1 a black hole, though complete certainty may never be possible. In 1975 Stephen Hawking made a friendly bet with Kip Thorne that it was not a black hole. He said later that he was hoping to lose: if black holes did not exist, his years of work on them would be wasted. He conceded in 1990.

The second kind of evidence was Michell's own method. From the early 1990s, two teams, led by Reinhard Genzel and Andrea Ghez, tracked the stars at the center of our galaxy. They had to peer through dust and correct for the blurring of Earth's air. One star, S2, completes an orbit every sixteen years. In May 2018 it swept past the center at about 7,650 kilometers per second, nearly three percent of the speed of light, and its motion matched general relativity. The orbits require about four million solar masses packed into a region no larger than our solar system. A supermassive black hole is the only explanation anyone has found that fits. Genzel and Ghez shared the other half of the 2020 Nobel Prize for the discovery, made by the very method Michell had proposed.

The third kind of evidence is not light at all. On 14 September 2015, the two LIGO detectors in Louisiana and Washington registered gravitational waves, ripples in space-time itself. They came from two black holes of about 29 and 36 solar masses. The two merged 1.3 billion years

ago. In the final fraction of a second, about three Suns' worth of mass was converted into gravitational waves. Each detector can sense a change in the length of its four-kilometer arms smaller than one ten-thousandth of the width of a proton. Black holes had been inferred from light and from orbits; now their collision could be measured directly. Then came pictures. In April 2019, a worldwide network of radio dishes called the Event Horizon Telescope published the first direct image of a black hole and its surroundings, in the galaxy Messier 87. In 2022 it released one of Sagittarius A*. The images show the black hole's shadow, not the horizon itself.

Better evidence has also made black holes harder to explain. In 2024 the Gaia mission reported a dormant black hole about 33 times the mass of the Sun, found, as Michell suggested, from the wobble of a star orbiting it. It was the heaviest black hole born from a star ever found in our galaxy. Current theories of how big stars die struggle to make one that large. Still, its partner star is poor in heavy elements, a hint that it was born from an early giant star that was poor in them too. At the other extreme, some supermassive black holes already existed within the first billion years after the universe began, and nobody knows how they grew so big so fast. Many scientists also suspect there may be primordial black holes formed in the first second of the universe, but no one has yet found definite proof that they exist.

The deepest puzzle came from Hawking himself. In 1974 he showed that, once quantum physics is included, black holes should give off a faint glow, now called Hawking radiation. They are not perfectly black. For a black hole of one solar mass, the glow corresponds to a temperature of about 62 billionths of a degree above absolute zero, far colder than the 2.7-kelvin afterglow that fills the universe, so black holes that size or larger absorb more than they emit and keep growing. But in principle a black hole could evaporate, and Hawking's calculation suggested that the details of whatever fell in would then be lost forever, which quantum theory forbids. Most physicists now believe the information survives somehow. How it survives remains one of the great unsolved problems in physics.

Questions

1. What did John Michell predict in 1783 about how a dark star might be found?

A. By the pull of its gravity on visible objects near it

B. By the sound it makes

C. By the bright light it gives off

2. Why does the book say calling all black holes "dense" is misleading?

A. Black holes contain no mass at all

B. Because heavier black holes have a lower average density inside the horizon, a giant one can be about as dense as water

C. Because black holes are made of gas

3. What did Einstein try to show in 1939?

A. That gravitational waves exist

B. That light has weight

C. That black holes were impossible

4. In this book, what does "dormant" mean when it describes a black hole?

A. It is not feeding on any gas, so it gives off no light

B. It is about to explode

C. It is very young

5. Why did Hawking say he hoped to lose his bet about Cygnus X-1?

A. He did not like Kip Thorne

B. If black holes did not exist, his work on them would be wasted

C. He had already seen the answer

6. What makes the information paradox a problem?

A. Black holes are too far away to study

B. LIGO could not find any black holes

C. Hawking's calculation suggested information could be destroyed, which quantum theory forbids

Words to know

velocity: speed

singularity: where physics breaks

ripples: small waves

dormant: not feeding, dark

primordial: from the beginning

Answer key: Dark Stars and Doubters

1. A. By the pull of its gravity on visible objects near it
2. B. Because heavier black holes have a lower average density inside the horizon, a giant one can be about as dense as water
3. C. That black holes were impossible
4. A. It is not feeding on any gas, so it gives off no light
5. B. If black holes did not exist, his work on them would be wasted
6. C. Hawking's calculation suggested information could be destroyed, which quantum theory forbids