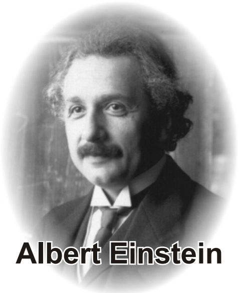
Detection of Black Holes

The Power of Robust Theory and Mathematics


Albert Einstein

Black holes stir the mind to the heights of imagination. What do these gravitational wells from which light cannot escape look like? Does speaking of them as being visible even make sense? And if we can't see them, how would we locate them? The greatest scientific minds have struggled to understand black holes over the past century. In the face of many towering challenges, they now better understand these strange phenomena. Black holes are bizarre, but they still appear to follow the laws of physics.

This story describes how scientists have studied and detected black holes throughout the last century. Because black holes embody the most extreme physics in the Universe, significant efforts were required to understand and accept what theory had predicted. Most scientists had to overcome a sort of instinctual defense that told them such a weird object could not possibly exist in our Universe. Yet black holes repeatedly appeared in the equations of General Relativity Theory. In fact, they appeared so often that astrophysicists needed to accept that either black holes were real, or face the fact that one of their most treasured physical theories predicted absurdities. As you read, consider the role of theories in making predictions, and how scientists interpret and respond to them.

Historically, "dark stars" had been predicted as early as 1783 by John Michell and again a decade later by the man called the "Newton of France," Pierre-Simon Laplace. Their dark stars, based on Newtonian gravitation, had a gravitational well so strong that it pulled light back to the surface, like a model rocket speeding up and falling back to Earth. Because light could not leave the surface, these stars would be undetectable through optical means, leaving only the influence of their gravity as evidence of their existence. These ideas didn't take hold at the time because at the beginning of the 19th century, the concept of light changed from a particle that could be affected by gravity to that of a wave unaffected by gravity. In the 20th century, when evidence arose for light acting as both a particle and a wave, the talk of "dark stars" began anew.

Modern conceptions of black holes stem from Albert Einstein's Theories of Relativity. Because black holes are extreme instances of the effects of relativity, we'll take time to explain the basic physics involved and see how physicists interpreted the equations. Beginning with the publication of the General Theory in 1915, scientists toying with the limits of Relativity Theory realized the very weird possibilities that arose. The prediction and acceptance of black holes hinged on interpreting the predictions of Einstein's Relativity Theory.

1. In many cases, theories are incomplete at their birth. When first conceived, all scientific knowledge has a speculative character. As this story illustrates, much time usually passes before ideas are rejected or accepted by the scientific community. The theories of relativity, like all good scientific theories, explain natural phenomena, bring coherence to a field of study, and suggest research questions worth pursuing, how to go about answering those questions, and how to interpret data derived from research. How is this different than the meaning of the word "theory" in everyday usage?

Born in 1879, Albert Einstein's education has been typically misconstrued by popular journalism; he was in no way slow or incompetent. He loved to play the violin and study math, physics, and philosophy, and received top grades in these classes. However, the German educational system placed a great emphasis on a broad education. Unfortunately, the young Einstein couldn't muster interest in French or Geography. This hurt him going into the university and he had to retake his entrance exams several times. Once accepted to the Federal Institute of Technology in Switzerland, he learned to detest math from his teacher Hermann Minkowski, who once called him a "lazy dog" for his lack of enthusiasm.

However, Einstein remained a competent mathematician by university standards. In physics, Einstein's professor taught only old systems and nothing of the cutting edge electrodynamics. So Einstein taught himself contemporary physics, and in doing so, learned to conceptualize it. One of three students from his department to pass final exams, he thought a physics tutoring position would be reserved for him. However, his distant demeanor and lackluster academic reputation haunted him and he wasn't considered. To pay the bills he took a job as a patent clerk. Toiling daily with mundane tasks, he found plenty of time to systematize ideas he gained from scientists like James Maxwell, George FitzGerald, and Hendrik Antoon Lorentz, and philosopher Ernst Mach.

Note that doing science well requires significant collaboration with others. Science is not the solitary undertaking that many laypeople think.

1905 stands out as Einstein's most triumphant year when he published four revolutionary papers, but to little immediate fanfare. Of utmost importance to our story was his Special Theory of Relativity which put forth the speed of light as a universal constant limit of about 300,000 km/s. This was a break from the past. In Newtonian mechanics, space and time were absolute, and the speed of light in a vacuum could vary. For example, imagine you are moving toward a target at 10 km/s and shoot a bullet at the target. If the bullet moves at 5 km/s, then a person next to the target would measure the speed of the bullet at 15 km/s. But now consider the same situation where instead of shooting a bullet, you shine a flashlight at the target. The person next to the target would measures the velocity of the photons to be about 300,000 km/s, even though you're moving towards her. You drive left, right, up, down, backwards, and she always detects the speed of light to be 300,000 km/s. That's the constant speed of light in Special Relativity. In Newtonian mechanics, the speed of light would vary with motion, reading between 299,990 and 300,010 km/s, but Einstein's Special Relativity asserted this is impossible.


Hermann Minkowski

2. People often wrongly see science as unimaginative. One of Einstein's often-cited quotations is that in science, imagination is more important than knowledge. How does his and other scientists' work illustrate that both imagination and knowledge are important?

Special relativity dictates that instead of space and time being absolute, the speed of light is absolute, and space and time can be relative to one's movement through them. Almost a century of research has supported the following to be in accord with the predictions of special relativity. As an object with mass approaches the speed of light, three things occur: (1) its length is shortened, (2) its mass increases, and (3) it experiences a slowing of time. The most famous part of Special Relativity came in Einstein's fourth paper of 1905, where he concluded the interchangeability of mass and energy in the famous equation $E=MC^2$. These effects had a great influence on the development of the concept of black holes. But one aspect, gravity, remained missing from Special Relativity. And that prevented the immediate speculation about black holes.

Einstein's Special Relativity received little attention until it built up a base of support. One early convert happened to be Einstein's old math professor Hermann Minkowski, the one who lamented the weak mathematics in Einstein's work. Putting pen to paper in 1908, Minkowski clarified Einstein's system and drew up spacetime in a new mathematical way with 4 dimensions – 3 of space and 1 of time. Now when speaking of the Universe, space and time were considered to be on equal footing. Using Minkowski's mathematical model, physicists and mathematicians could better utilize Special Relativity and understand its implications. Most importantly, he had included the mathematical basis for that one thing which Einstein left out of the Special Theory: gravity. Minkowski died shortly thereafter from complications with appendicitis before he got to see his work fully accepted. Inspired by Minkowski's mathematical spacetime, Einstein began working on his General Theory of Relativity, which discussed the curvature of spacetime in the presence of gravity.

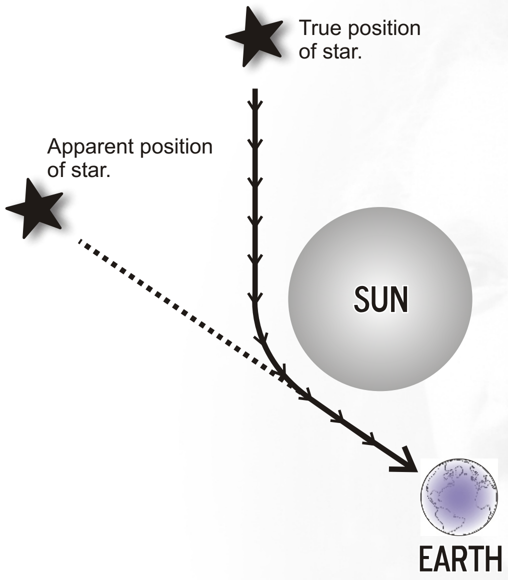
The General Theory of Relativity did not come easy to Einstein. He used an archaic mathematical system and stumbled across the equations on numerous occasions. The eminent German mathematician David Hilbert, who had given advice to Einstein, announced after publication that, “Every boy in the streets of Göttingen understands more about four-dimensional geometry than Einstein. Yet, in spite of that, Einstein, not the mathematicians, formulated the general relativistic laws of gravity.” Within a few years, General Relativity would be established as the best physical system to describe the large world, and it has held this position for almost a century.

3. Often, the elite scientists set the tone of response for a proposed idea. Imagine you are Einstein, already a scientist of great renown, and the top mathematician of your country questions your mathematical ability. How do you think this would affect how other scientists use and view your work? How does this illustrate that science is a social endeavor?

The most important feature of General Relativity as it relates to black holes is the warping of spacetime in a gravitational field. A common description (although not entirely accurate) is of a bowling ball on the center of a trampoline. Mass causes "indentations," or *warps*, in the fabric of spacetime. Greater mass causes greater warps. The theory predicts that a significant warpage could bend light. Arthur Eddington, British astronomer and relativity expert, confirmed this in 1919 after he observed the Sun bending light from background stars during a solar eclipse.

FIGURE 1

Effect of sun-sized mass bending the light from a star.



Eddington observed that the position of a star can appear to shift when a massive object bends its starlight. To a person on Earth the star will appear to be located to the side of the sun, when in fact it is behind the sun.

Given this very brief overview of Relativity, keep in mind the following things as they relate to black holes:

- the speed of light is constant and the fastest speed in the universe.
- gravity warps spacetime and can bend light. A strong enough gravitational well could bend light so much that it is forever trapped.
- time slows down at high speeds and near intense gravitational wells.
- objects inhabit their own 'frame of reference.'

Much of the intellectual hurdle in understanding black holes comes from conceptualizing the vast difference in the frames of reference between yourself and a black hole. For now, keep in mind that as much as the Universe seems recognizable in your own frame of reference, your surroundings would be almost as recognizable if you were to live in a black hole. Sound weird? That's the exact feeling scientists had to overcome to understand and accept black holes, which would be considered speculation for about 50 years.

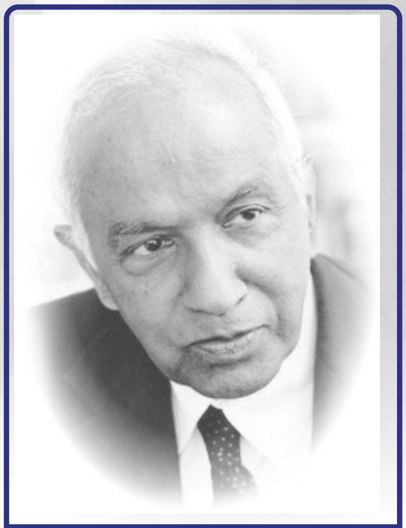
Don't despair if you find all this confusing. Understanding Relativity requires an intellectual jump. Within a span of ten years, every physicist, astronomer, and mathematician working in this area had to decide whether to make this jump to an entirely new way of understanding the universe. What would you have done? Historically, noted scientists were found in each camp.

In 1916 Karl Schwarzschild, the 42-year old Director of the Potsdam Observatory, was serving the German Army in Russia during World War I. He got his hands on a copy of Einstein's article introducing General Relativity, and wanted to mathematically describe the curvature of spacetime around a very massive object. Schwarzschild realized that each mass had a critical radius, now called the "Schwarzschild radius," the point at which a collapsing object can no longer resist the crunch of gravity and will collapse, or *implode*, and form a *singularity*. At this time, a singularity was a mathematical term, which meant the appearance of infinities in the equations – in this case a point of infinite density, infinite warpage of spacetime, infinite time dilation, and infinite length contraction. In a singularity, light could not even leave the surface and bend back like Michell and Laplace's dark stars; it would just never leave in the first place. Schwarzschild's singularity literally sapped the energy of light to the point that it no longer existed. Einstein read a few of Schwarzschild's papers to the Prussian Academy of Science in 1916, and in June, had the unfortunate task of announcing Schwarzschild's death on the Russian front. While scientists accepted Schwarzschild's geometry, they generally disagreed with the reality of his singularitiesat the time, an answer of infinity meant an error in the mathematics or an unfeasible solution.

Many people wrongly think experiments using a step-by-step method are the sole route to scientific knowledge. But in this field, bringing a singularity into the lab to study is impossible! When dealing with enormous distances and the role of time (the farther away we look, the older the object is since it takes the light longer to reach us), other methods are necessary. In this case, note the importance of mathematics and then seeking evidence for phenomena that would be consistent with the mathematically-based theory.

Singularities presented such an absurdity that the elite men of Relativity – Einstein and Eddington – made great efforts to disprove them. Einstein argued that during gravitational collapse, at 1.5x critical radius gravity would be pulling particles at the speed of light. To collapse any further, the particles must break the speed of light, which was impossible. Einstein's misstep was that he insisted there must be some pressure counteracting gravity at all times, which was later shown to be a wrong assumption. Eddington argued that nature must have some way to avoid a Schwarzschild singularity, and introduced a poorly-received system that saved stars from such a collapse. With Einstein and Eddington unable to convince colleagues of the impossibility of singularities, some continued to consider the implications of such objects. However, there was also no reason to believe the Universe actually harbored these bizarre physical entities – theory seemed inconclusive, and observation seemed impossible. Eventually, singularities received a boost of attention from the discussion of white dwarfs and neutron stars.

First spotted by telescopes in the early 1930s, white dwarfs are the corpses of middle-sized stars, like our Sun. Many researchers were introduced to them through Eddington's book *The Internal Constitution of Stars*. One of these researchers was a brilliant young Indian, Subrahmanyan Chandrasekhar. Accepted to do doctoral work at Cambridge, Chandraskehar brought Eddington's book on board his ship to England, and while en route calculated an upper limit on the mass of white dwarfs, now called the "Chandrasekhar Limit." It said that white dwarfs above 1.4 solar masses (the mass of our own sun) would undergo further gravitational collapse. The process hinged on *electron degeneracy pressure*. Imagine this: if an atomic nucleus is magnified to the size of a football field, the electrons 'orbit' at set distances with a diameter equal to the earth. Now, the electrons can occupy any position in their orbits as long as it doesn't simultaneously occupy a position held by another electron. When pressure is applied and many nuclei are forced into close quarters, as is the case in a collapsing star, the electrons find their positions limited. Unable to share space with other electrons, they forcefully "kick" all over the place. This creates an outward pressure, called "degeneracy pressure." A white dwarf balances the inward attraction of gravity with outward electron degeneracy pressure. Although he didn't flesh out what happened to the white dwarfs above the Chandrasekhar limit, his equations clearly showed these heavier stars would collapse to a singularity. When Chandrasekhar presented this information before assembled colleagues in 1935, Eddington, without forewarning Chandrasekhar, followed with a presentation railing against the collapse to the absurd singularity. Chandrasekhar, feeling betrayed by his idol, maintained a professional cordiality with Eddington although never fully trusted him again.



Subrahmanyan Chandrasekhar

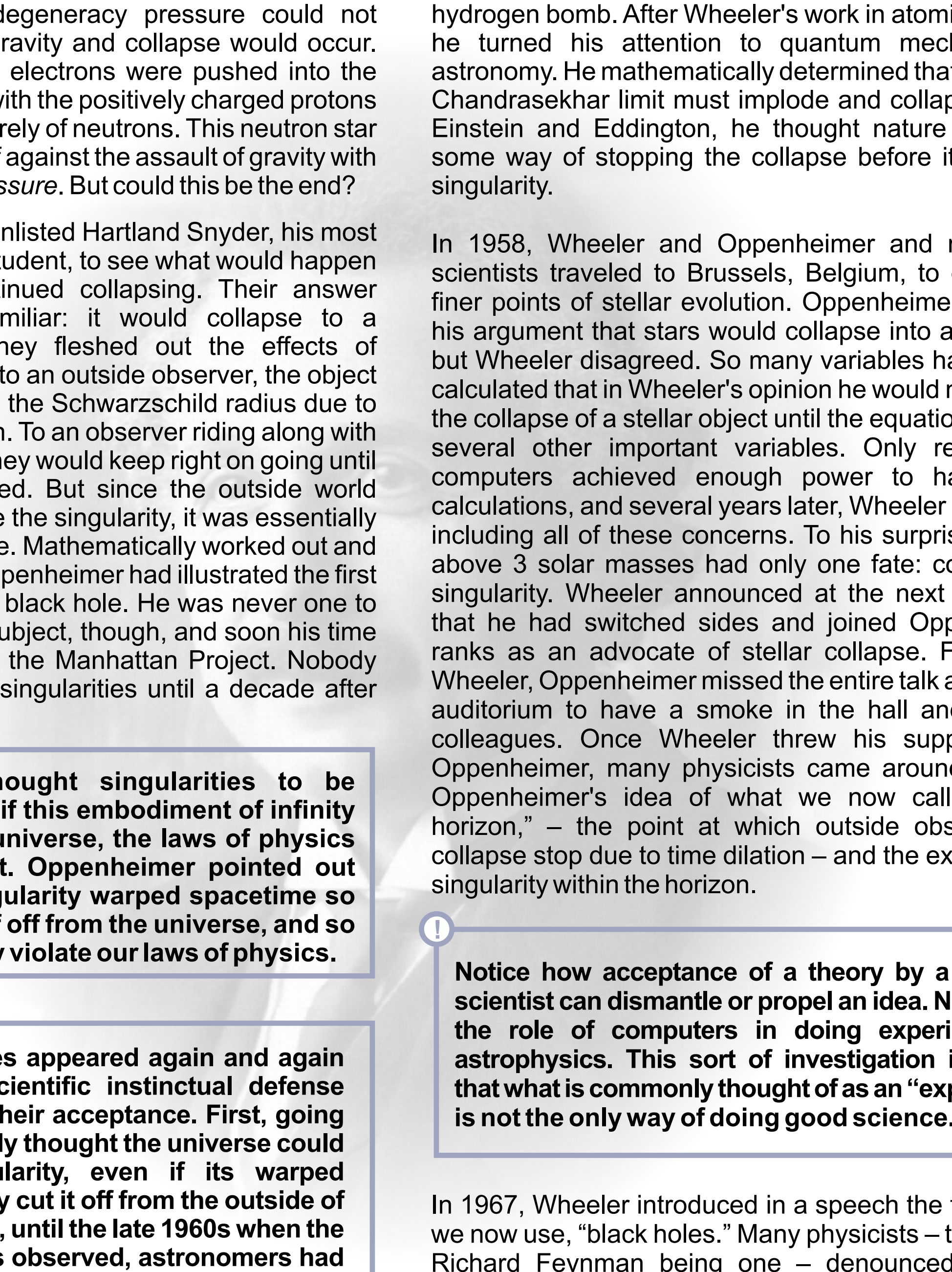
What happened when a white dwarf collapsed? We know now that it forms a neutron star, but in the 1930s, the concept of a star formed entirely of neutrons seemed too fantastic to accept. In America, Fritz Zwicky proposed neutron stars almost on a whim to explain what remained after a supernova, but never really followed through with the equations.

4. Note that Zwicky's work was certainly based on sound scientific thought. His is the concept that is widely accepted today. However, without the equations to support his view, his work was perceived as haphazard and was not taken seriously. What evidence do scientists require before they take a speculative idea seriously? How might this vary between different scientific disciplines?

In the Soviet Union, Lev Davidovich Landau proposed that all stars might house neutron cores. He rushed the paper off to print in order to appear useful to the tyrannical Stalinist regime. However, he was soon jailed on trumped up charges of giving information to the Nazis. Landau was Jewish, so the charges seemed ridiculous. But his paper did reach Western ears, and influenced one researcher who is probably very familiar to you already: Robert Oppenheimer.

Oppie, as his students called him, made his name in the 1930s as one of the most skilled mathematicians of his day. He took a split position at Caltech and the University of California, Berkeley, so he could keep in touch with many colleagues and enjoy a variety of scenery. Known for chain smoking, he would often stand at the blackboard in front of a class of students with a cigarette in one hand and a piece of chalk in the other, his students silently guessing when he would try smoking the chalk. During semester breaks he brought graduate students on vacation to form "think tanks" and exchange ideas. One of the greatest mentors and scientists of this century, Oppenheimer is forever associated with the building of the uranium bomb during World War II.

Unfamiliar with Landau or the predicament surrounding



his paper and certainly not knowing his plight in a Soviet prison, Oppenheimer critiqued Landau by arguing that only stars far smaller than the sun could have a neutron core. But how small? And could a neutron core existing entirely on its own be possible? With graduate students, Oppenheimer worked out that between 1.4 and 3 solar masses the electron degeneracy pressure could not withstand the force of gravity and collapse would occur. The negatively charged electrons were pushed into the nucleus and interacted with the positively charged protons to produce a system entirely of neutrons. This neutron star would then balance itself against the assault of gravity with *neutron degeneracy pressure*. But could this be the end?

In 1939, Oppenheimer enlisted Hartland Snyder, his most mathematically skilled student, to see what would happen if a neutron core continued collapsing. Their answer should sound very familiar: it would collapse to a singularity. However, they fleshed out the effects of relativity on the object – to an outside observer, the object would stop collapsing at the Schwarzschild radius due to gravitational time dilation. To an observer riding along with the collapse, however, they would keep right on going until the singularity is reached. But since the outside world would never actually see the singularity, it was essentially shut off from the universe. Mathematically worked out and physically described, Oppenheimer had illustrated the first modern incarnation of a black hole. He was never one to spend much time on a subject, though, and soon his time was entirely devoted to the Manhattan Project. Nobody would say much about singularities until a decade after World War II.

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Many scientists thought singularities to be impossible because if this embodiment of infinity interacted with our universe, the laws of physics seemed to fall apart. Oppenheimer pointed out that gravity in a singularity warped spacetime so much that it cut itself off from the universe, and so would not technically violate our laws of physics.

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Although singularities appeared again and again in equations, the scientific instinctual defense stood in the way of their acceptance. First, going into the 1960s, nobody thought the universe could truly have a singularity, even if its warped spacetime completely cut it off from the outside of the universe. Second, until the late 1960s when the first neutron star was observed, astronomers had no reason to believe stars would collapse to produce such small and powerful cosmic engines. Third, no astronomer believed a massive object could undergo the necessary implosion to create a singularity. They could envision an *explosion*, but not an *implosion*. Very slowly, these barriers came down in the 1950s and 1960s.

John Archibald Wheeler was in many ways the counterbalance to Robert Oppenheimer. Both were great teachers and fantastic scientists, and they both worked on atomic weapons. Whereas Oppenheimer would forever feel guilt over his involvement in creating the uranium bomb, Wheeler prided himself in helping develop the hydrogen bomb. After Wheeler's work in atomic weapons, he turned his attention to quantum mechanics and astronomy. He mathematically determined that stars at the Chandrasekhar limit must implode and collapse, but like Einstein and Eddington, he thought nature must have some way of stopping the collapse before it reached a singularity.

In 1958, Wheeler and Oppenheimer and many other scientists traveled to Brussels, Belgium, to discuss the finer points of stellar evolution. Oppenheimer presented his argument that stars would collapse into a singularity, but Wheeler disagreed. So many variables had not been calculated that in Wheeler's opinion he would not concede the collapse of a stellar object until the equations included several other important variables. Only recently had computers achieved enough power to handle such calculations, and several years later, Wheeler ran a model including all of these concerns. To his surprise, any star above 3 solar masses had only one fate: collapse to a singularity. Wheeler announced at the next conference that he had switched sides and joined Oppenheimer's ranks as an advocate of stellar collapse. Fed up with Wheeler, Oppenheimer missed the entire talk as he left the auditorium to have a smoke in the hall and chat with colleagues. Once Wheeler threw his support behind Oppenheimer, many physicists came around to accept Oppenheimer's idea of what we now call an “event horizon,” – the point at which outside observers see collapse stop due to time dilation – and the existence of a singularity within the horizon.

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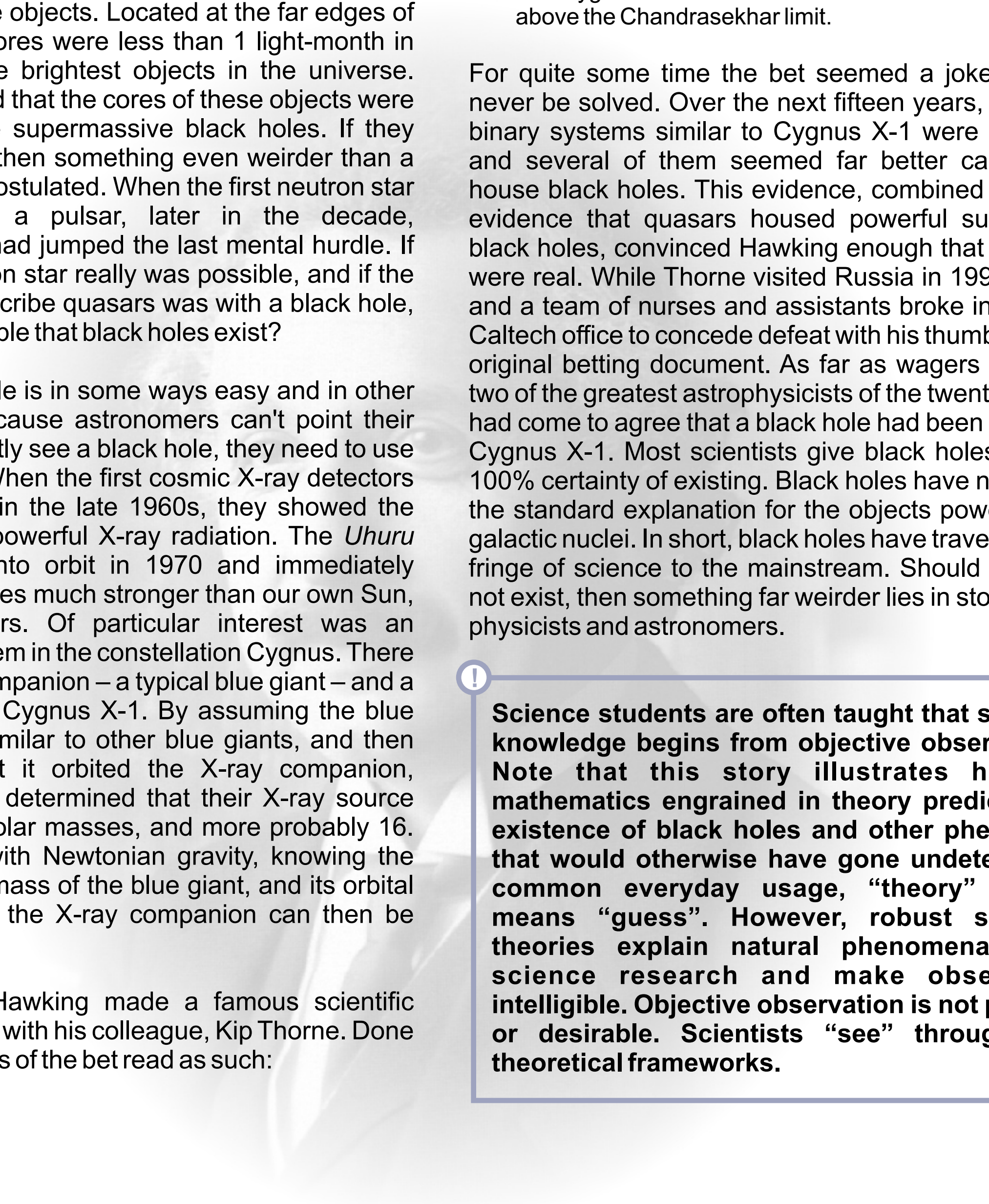
Notice how acceptance of a theory by a luminary scientist can dismantle or propel an idea. Notice also the role of computers in doing experiments in astrophysics. This sort of investigation illustrates that what is commonly thought of as an “experiment” is not the only way of doing good science.

In 1967, Wheeler introduced in a speech the terminology we now use, “black holes.” Many physicists – the luminary Richard Feynman being one – denounced Wheeler's choice of words, either because it was inaccurate or a bit racy. Wheeler admits in his autobiography that he chose the name because it was similar to the already familiar term “black body.” In any case, the term “black hole” owes its existence to him, despite the object's utter dissimilarity to a hole. Many scientists became more inclined to accept black holes as the inevitable outcome of General



Relativity. The challenge, however, remained in detecting an object so devoid of signals.

In the 1960s, observations of quasars and neutron stars thrust black holes back into the spotlight. The first quasar had actually been seen over thirty years earlier. Now with improved radio telescopes, astronomers realized the sheer power of these objects. Located at the far edges of the universe, their cores were less than 1 light-month in diameter but are the brightest objects in the universe. Astronomers realized that the cores of these objects were almost certain to be supermassive black holes. If they were anything else, then something even weirder than a black hole must be postulated. When the first neutron star was observed, as a pulsar, later in the decade, astronomers finally had jumped the last mental hurdle. If implosion to a neutron star really was possible, and if the only way we can describe quasars was with a black hole, then might it be possible that black holes exist?

Detecting a black hole is in some ways easy and in other ways very hard. Because astronomers can't point their telescopes and directly see a black hole, they need to use indirect resources. When the first cosmic X-ray detectors went into operation in the late 1960s, they showed the Universe awash in powerful X-ray radiation. The *Uhuru* satellite was sent into orbit in 1970 and immediately detected X-ray sources much stronger than our own Sun, stunning astronomers. Of particular interest was an apparent binary system in the constellation Cygnus. There was a visible light companion – a typical blue giant – and a bright X-ray source, Cygnus X-1. By assuming the blue giant had masses similar to other blue giants, and then measuring how fast it orbited the X-ray companion, astronomers initially determined that their X-ray source must be at least 4 solar masses, and more probably 16. This can be done with Newtonian gravity, knowing the force of gravity, the mass of the blue giant, and its orbital period, the mass of the X-ray companion can then be determined.

In 1974, Stephen Hawking made a famous scientific wager on this system with his colleague, Kip Thorne. Done partly in jest, the terms of the bet read as such:

> Whereas Stephen Hawking has such a large investment in General Relativity and black holes and desires an insurance policy, and whereas Kip Thorne likes to live dangerously without an insurance policy, Therefore be it resolved that Stephen Hawking bets 1 year's subscription to Penthouse as against Kip Thorne's wager of a 4-year subscription to Private Eye, that Cygnus X-1 does not contain a black hole of mass above the Chandrasekhar limit.

For quite some time the bet seemed a joke that might never be solved. Over the next fifteen years, many more binary systems similar to Cygnus X-1 were discovered, and several of them seemed far better candidates to house black holes. This evidence, combined with further evidence that quasars housed powerful supermassive black holes, convinced Hawking enough that black holes were real. While Thorne visited Russia in 1990, Hawking and a team of nurses and assistants broke into Thorne's Caltech office to concede defeat with his thumbprint on the original betting document. As far as wagers admit truth, two of the greatest astrophysicists of the twentieth century had come to agree that a black hole had been observed in Cygnus X-1. Most scientists give black holes an almost 100% certainty of existing. Black holes have now become the standard explanation for the objects powering active galactic nuclei. In short, black holes have traveled from the fringe of science to the mainstream. Should black holes not exist, then something far weirder lies in store for future physicists and astronomers.

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Science students are often taught that scientific knowledge begins from objective observations. Note that this story illustrates how the mathematics engrained in theory predicted the existence of black holes and other phenomena that would otherwise have gone undetected. In common everyday usage, "theory" usually means "guess". However, robust scientific theories explain natural phenomena, guide science research and make observation intelligible. Objective observation is not possible or desirable. Scientists "see" through their theoretical frameworks.

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