Black Holes: Eccentric Enigmas of Space

Matthew Murray

17 July 2017

Math 190s | Dr. Hubert Bray

Duke University

Introduction

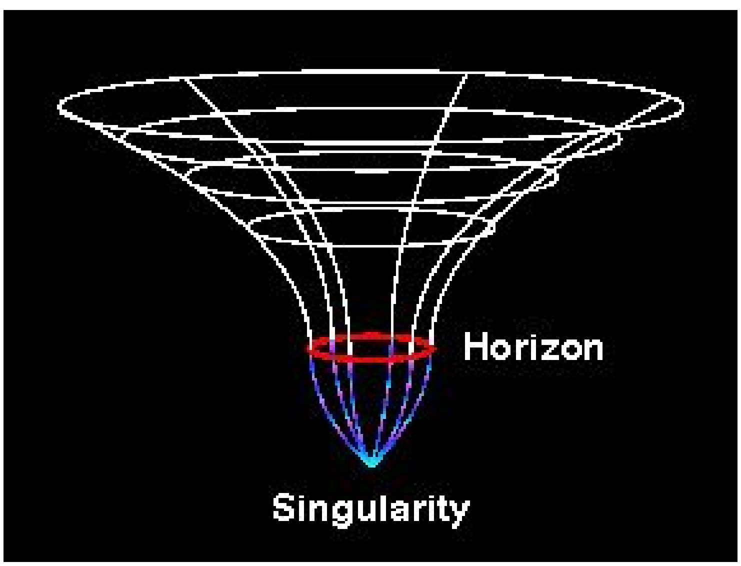
Black holes are certainly some of the most puzzling astronomical objects that exist. For the most part, the laws of physics abide to the vast blanket that is spacetime, but black holes represent exceptions to some of these laws. While they were initially predicted by Einstein's general theory of relativity, for a while, Einstein, as were many other scientists, was very skeptical as to whether or not black holes actually existed. General relativity, as well as the Schwarzschild metric, tells us that anything can be compressed into a black hole if it is crushed into a small enough space known as its Schwarzschild radius. The Schwarzschild radius of any mass (M) can be given using the following equation:

$$R_s = 2GM/c^2$$

In this equations, "R_s" represents the Schwarzschild radius, "G" represents a gravitational constant, M represents the mass of the object in kilograms, and "c" represents the speed of light, which is about 2.998×10^8 km/s. With the mass of the Earth being about 5.972×10^{24} kg, and the gravitational constant equaling $6.67408 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$, one can calculate that the Schwarzschild radius of the Earth equals about 0.00887 meters (0.887 centimeters), the size of a small marble. Once any object reaches this miniscule radius, it will become so dense that nothing, not even light, will be able to escape the black hole. As further noted by general relativity, any object that enters through the event horizon of a black hole must travel to a single point: the singularity. While theoretically anything, even humans, can be compressed into black holes, in reality, only certain sized stars–the rule of thumb is that it must be a star of at least 10 solar masses–can really be compressed into black holes due to the presence of Hawking Radiation. Put simply, in 1974 Stephen Hawking proposed a theory that black holes emit subatomic particles called Hawking Radiation until they rid themselves of their energy and evaporate completely. The theory also states that very small black holes lose more mass, meaning that most miniature black holes evaporate very rapidly. The other factor to take into consideration is that smaller stars (such as the sun) simply do not have enough enough mass to exert the gravitational force upon themselves that is needed to become a black hole.

Parts of a black hole

In order to properly search for a black hole, researchers must first understand the basic structure and main components of one. The part of a black hole researchers most directly look for is the event horizon. The event horizon is often referred to as the entrance of the black hole–as it contains the Schwarzschild radius–and is a point of no return, meaning that once an object passes the event horizon, that object is physically incapable of escaping the black hole. Outside observers also cannot see beyond the event horizon due to its incredibly miniscule radius.

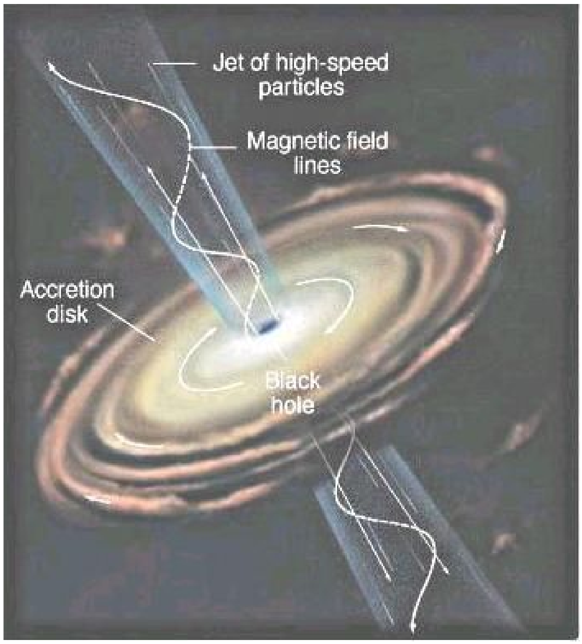


At the center of a black hole lies the point of greatest density, the singularity. Once something reaches the singularity some of the most basic laws of physics break down, as nothing, not even light, can escape the black hole's infinite amount of density and gravity. Renowned American physicist Kip Thorne further describes the singularity as "the point where all laws of physics break down."[1] Once an object reaches the singularity it is instantly "spaghettified" due to the various gravitational forces that are being exerted on it from nearly every direction and as a result loses its dimensionality completely. Unfortunately, due to Roger Penrose's Principle of Cosmic Censorship, singularities are always hidden behind event horizons, and since no light can escape from an event horizon, singularities cannot be seen or directly observed. There is however one exception to this hypothesis: the singularity that caused the Big Bang.[2]

The other main portion of a black hole is the accretion disk, a disk of stellar material that spirals toward the black hole. Because the matter in this accretion disk may have to give up a lot of energy in order for it to fall into a black hole, accretion disks can sometimes be extremely bright, even more bright than the light of billions of stars combined.[3]

---

[1] http://www.physicsoftheuniverse.com/topics_blackholes_singularities.html
[2] https://en.wikipedia.org/wiki/Cosmic_censorship_hypothesis
[3] http://minerva.union.edu/vianil/web_stuff2/Structure_of_Black_Holes.htm



How do we detect black holes?

One of the greatest challenges in searching for black holes is that they are inherently invisible, meaning that scientists cannot observe black holes with the same telescopes that they use to view stars, planets, galaxies, etc. Nonetheless, scientists are able to detect black holes by observing the effect they have on their surrounding matter. For example, when a black hole passes through an area of interstellar matter, gas, dust, and other debris that have not already fallen into the black hole may form an accretion disk around it. As noted previously, accretion disks contain particles at the edge of black holes that move at incredibly high speeds and have been heated to millions of degrees. These particles, which continuously circle the black hole in lieu of falling into it, rapidly rub and bump against each other before arriving at the event horizon. The physical contact between the particles then emits extremely high radiation that scientists are able to detect. Nonetheless, scientists must be cautious of the fact that the particles can be surrounding a space object this is not a black hole, so one must mathematically verify the presence of the black hole by examining the quality of the radiation from the accretion disk, which allows scientists to detect the speed of the moving particles. The speed of the particles can then be used to calculate the size of the dense object, and if that object is below its Schwarzschild radius, they know that they have found a black hole.[4]

X-rays have proved to be another source of detecting black holes. X-rays are emitted when a star passes a black hole. As the star passes, the black hole may accelerate the star toward itself and cause matter from the star to accelerate to speeds close to the light, thereby emitting x-rays.[5] NASA has recently developed a telescope called NuSTAR that specializes in identifying the sources of x-rays. Similar to how medical x-rays can travel through layers of skin to capture images of a patient's bones, NuSTAR can see past all the gas and dust that surrounds a black hole to see the area near the event horizon. The NuSTAR instrument consists of two grazing telescopes. Once launched into orbit, the two telescopes are able to communicate with each other and detect high levels of energy by extending their respective focals. NuSTAR is currently exploring the depths of space and has been doing so since its launch on June 13, 2012.[6] Two other powerful x-ray telescopes that are currently orbiting the Earth include the Chandra X-ray Observatory and the XMM Newton telescope, both of which have been able to identify hundreds of x-ray sources.

Moreover, scientists can also detect black holes through extreme gamma ray bursts that form when black holes collide with neutron stars to produce other black holes. These gamma ray bursts (GRB's) are often brighter than supernovae and more than one trillion times brighter than

---

[4] https://science.nasa.gov/astrophysics/focus-areas/black-holes
[5] http://hubblesite.org/explore_astronomy/black_holes/encyc_mod1_observatories.html
[6] https://www.nasa.gov/feature/jpl/chorus-of-black-holes-sings-in-x-rays

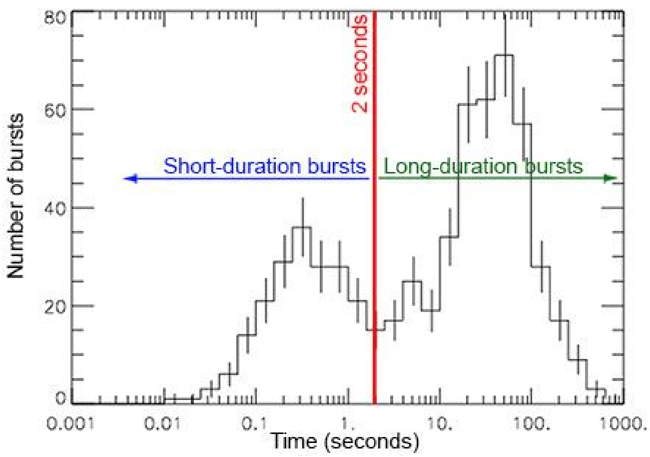
the sun. GRB's were accidentally discovered in the 1960's when US military satellites were looking to see if the Soviets were honoring the nuclear treaty established between the two superpowers. Because nuclear reactors release gamma rays, the satellites contained gamma ray detectors.[7] While the Soviets did honor the treaty–no nuclear reactions were set off–they did detect gamma rays far off in space that were later determined to come from black hole collisions.

There are two main types of GRB's: long bursts and short bursts, both of which can be associated with the formation of black holes. Long bursts, which last anywhere from two seconds to a few hundred seconds, averaging a duration of about 30 seconds, occur when extremely massive stars die in supernovae. Occasionally, these collapsing stars form black holes near their cores. Short bursts–as implied by their name–are briefer, lasting last anywhere from a few milliseconds to 2 seconds long with an average duration of 0.3 seconds. In addition to the fact that they are shorter, shorts bursts are about ten times dimmer than their counterparts but do emit more energetic gamma rays. Unlike long bursts, short bursts are not well understood by the scientific community and remain a mystery to most astrophysicists, as they were not discovered until 2005 when telescopes captured images of short burst afterglows but did not see evidence of a supernova. As stated by George Ricker, head of NASA's HETE satellite, the first short burst observed on July 9, 2005 initially came across as "the dog that didn't bark."[8] Nonetheless, several hypotheses regarding their causes do exist. The leading theory is that they occur when two neutron stars collide to form a black hole or when a neutron star collides with another black hole to form a larger black hole. The collision–whether it is between two neutron stars or a black hole and a neutron star–would be incredibly powerful and send gravitational waves rippling

---

[7] https://imagine.gsfc.nasa.gov/science/objects/bursts1.html
[8] https://science.nasa.gov/science-news/science-at-nasa/2008/20oct_briefmystery

through space time. Scientists are currently trying to develop more advanced gravitational wave detectors, with the most notable one Laser Interferometer Gravitational-wave Observatory (LIGO) located at various locations across the US.



This graph shows the number of bursts observed by the BATSE instrument on the Compton Gamma-ray Telescope.

Another strategy used to pick out black holes involves examining the orbits of astronomical objects that circle the center of galaxies. Scientists can analyze characteristics of what the stars are actually orbiting to see if it is a black hole. By examining the speed of the speed of the star's orbit, researchers can then calculate the mass and density of the object that is being orbited and thereby determine if it is below its Schwarzschild radius. This method has been used several times to detect supermassive black holes that are commonly found at the center of galaxies. An interesting note regarding orbiting is that orbiting a black hole is no different than orbiting any other celestial body. So, if the Sun were to collapse into a black hole, even though it would be less than 6 kilometers across, the Earth, as well as the rest of the planets in the solar system would continue to orbit the black hole, as the gravitational force exerted by this black hole would be the same because it would have the same mass.

One the most notable recent international collaborations that sought to directly view the immediate environment of a black hole was the Event Horizon Telescope (EHT). Put simply, the EHT team sought to capture images of the black hole's internal environment at the same resolution in which scientists can currently do with the event horizon, and achieve this all from the surface of the Earth. Initially, the EHT team sought to improve a technology called very long baseline interferometry (VLBI). VLBI involves linking various radio dishes together to create a virtual planet-sized telescope.[9] Since the recordings at each satellite station have to be stable enough so that there are not "jitters" in between signals, the team decided to use atomic clocks called Hydrogen Masers that time-stamp the recorded data. Hydrogen Masers have proved to be so precise that they lose only 1 second every 100 million years! Furthermore, in order to ensure simultaneous recordings the telescopes are synced every one millionth of a second using GPS clocks.

To reiterate, the EHT functions mainly by collecting light from black holes using various telescopes distributed throughout the Earth. Once the light has given the scientists a sense of the fundamental structure of the black hole, the team then uses imaging algorithms to fill in the gaps, or in other words, give themselves a sense of what the rest of the black hole looks like. The algorithms and captured light are then used to generate an image. An analogy the EHT team often uses to give the public a better understanding of their processes is to think of the measurements they record as notes in a song. Searching for a black hole, as well as developing an image of it, with these often scattered measurements is like trying to name a song while hearing only broken, unconnected notes.[10]

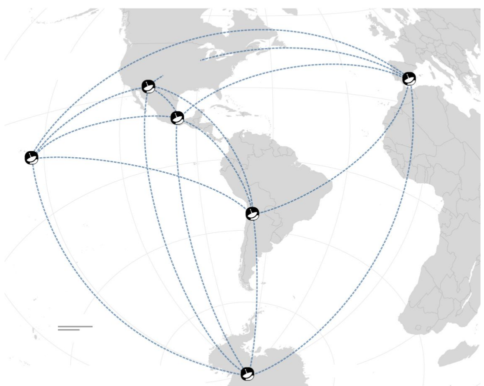
The EHT team started its most recent search on April 4, focusing on two black holes: Sagittarius A*, the black hole at the center of the Milky Way Galaxy, and a much more massive black hole, M87, at the center of nearby galaxy Virgo A. The team set off in search of these

---

9 https://en.wikipedia.org/wiki/Very-long-baseline_interferometry

10 http://eventhorizontelescope.org/

black holes with six different synchronized radio telescopes spread throughout the globe in the following locations: Arizona Radio Observatory Submillimeter Telescope (US), James Clerk Maxwell Telescope (US), Large Millimeter Telescope (Mexico), IRAM 30-Meter Telescope (Spain), Atacama Pathfinder Experiment (Chile), South Pole Telescope (Antarctica).



This image is an unlabeled diagram of the various telescope locations of the EHT.

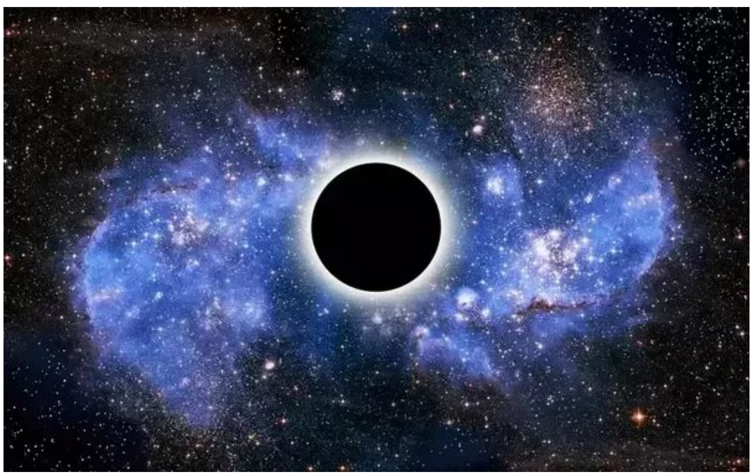
One should note that this attempt was the first time the EHT team used the Atacama Pathfinder Experiment (ALMA) and the South Pole Telescope, both of which were key contributors in the trial's success. ALMA proved to be crucial because its ability to spot incredibly small objects from far distances–even a golf ball on the moon–which helped when trying to locate the small event horizons of both black holes. While the actual image capturing process proved to be an immense success, a full portrait will not come about until a few months, as the data from the telescopes must be flown from the South Pole to Germany (it cannot be transferred electronically) in about 5 months to see if a picture can be produced.[11]

Problems that come with looking for black holes

In addition to the important fact that black holes cannot be directly seen, there are several other problems that one must deal with when searching for black holes. To start, black holes are fairly rare, as most stars–like red dwarves–are not massive enough to become black holes. Red dwarf is a term used to describe cool objects, whether they be K- and M-dwarfs or brown dwarfs

11 http://news.nationalgeographic.com/2017/04/black-hole-event-horizon-telescope-pictures-genius-science/

(which are not true stars due to the lack of hydrogen fusion in their cores). Their characteristics include burning at a lower temperatures (reaching a maximum temperature of just 6,380ºF), making them much dimmer than the sun. Once they burn through their supply of hydrogen red dwarfs will become white dwarfs–dead stars that do not undergo fusion–and once they burn through their heat they become black dwarfs. The fact that most stars do not become black holes–as roughly 1 in every 1,000 will become a black hole–means that black holes are somewhat rare.[12]



Albeit being a fairly inaccurate representation of a black hole, this picture demonstrates the difficulty of observing a black hole because they seem to blend in with the rest of space if one were to zoom in. While the Milky Way (and most galaxies) has about 100 million black holes, most of these are invisible and only about a dozen have been identified.

Notable Black Hole Discoveries

In addition to the recent discoveries made by the EHT, another remarkable discovery has been recently made as a group of researchers from the University of New Mexico (UNM) found a pair of supermassive black holes with a combined mass that is 15 times that of the sun. The two

12 https://www.space.com/23772-red-dwarf-stars.html

were found orbiting each other in galaxy called 0402+379, which is an outstanding 750 million light years away from Earth. The team used the Very Long Baseline interferometry (VLBI) and was eventually able to measure the radio frequencies emitted by the black holes to try and draw out their orbit which measured out to be a staggering 24,000 years.[13]

Moreover, a solid amount of progress has also been made with regards to black holes within the Milky Way. In 1964, Cygnus X-1 was the first black hole to be discovered, and was finally identified as a black hole in 1971, as researchers were able to detect it through its strong x-ray emissions. Cygnus X-1 is a stellar black hole with a mass of about 14.8 solar masses and is about 5 million years old.[14] The closest black hole to Earth is A0602-00. Detected through x-rays in 1974, A0602 is only 2800 light years away and weighs about 9-13 solar masses.[15]

The black hole that is currently of most interest to astrophysicists is Sagittarius A*. Sagittarius A* is by far the largest black hole in the Milky Way and was discovered in 1974 as an astronomical radio source. Like most supermassive black holes in elliptical galaxies, Sagittarius A* migrated to the galactic center of the Milky Way in a process known as mass segregation, which is likely what enabled it to accumulate such a large size.

Conclusion

Like most objects in space, there is almost an innumerable amount of black holes, and what researchers have actually seen so far is only a tiny fraction of the black holes that actually exist. While us, mere mortals will never be able to fully wrap our heads around the enigmas that are black holes, researchers have and will continue to make progress at understanding these anomalous figures of the universe.

---

13 https://www.sciencealert.com/orbiting-supermassive-black-holes-have-been-observed-for-the-first-time

14 https://en.wikipedia.org/wiki/Cygnus_X-1

15 https://en.wikipedia.org/wiki/A0620-00

Works Cited

"A0620-00." *Wikipedia*. Wikimedia Foundation, 26 June 2017. Web. 16 July 2017.

"Black Holes." *NASA*. NASA, n.d. Web. 16 July 2017.

Cassella, Carly. "Orbiting Supermassive Black Holes Have Been Observed For The First Time." *ScienceAlert*. N.p., 28 June 2017. Web. 16 July 2017.

"Cosmic Censorship Hypothesis." *Wikipedia*. Wikimedia Foundation, 12 July 2017. Web. 16 July 2017.

Cowen, Ron. "Astronomers May Finally Have the First Picture of a Black Hole." *National Geographic*. National Geographic Society, 13 July 2017. Web. 16 July 2017.

"Cygnus X-1." *Wikipedia*. Wikimedia Foundation, 15 July 2017. Web. 16 July 2017.

"Event Horizon Telescope." *Event Horizon Telescope*. N.p., n.d. Web. 16 July 2017. <http://eventhorizontelescope.org/science>.

"Gamma-ray Bursts." *NASA*. NASA, n.d. Web. 16 July 2017.

Greicius, Tony. "Chorus of Black Holes Sings in X-Rays." *NASA*. NASA, 27 July 2016. Web. 16 July 2017.

Mastin, Luke. "Main Topic: Black Holes and Wormholes." *The Physics of the Universe*. Physics of the Universe, n.d. Web. 16 July 2017.

Phillips, Tony. "Brief Mystery: What Are Short Gamma-ray Bursts?" *NASA*. NASA, 20 Oct. 2008. Web. 24 July 2017.

Redd, Nola Taylor. "Black Holes: Fact, Theory, & Definition." *Space.com*. N.p., 9 Apr. 2015. Web. 16 July 2017.

Redd, Nola Taylor. "Red Dwarfs: The Most Common and Longest-Lived Stars." *Space.com*. N.p., 21 Dec. 2016. Web. 16 July 2017.

Schodel, R., A. Eckart, C. Iserlohe, R. Genzel, and T. Ott. "A Black Hole in the Galactic Center Complex IRS 13E?" (n.d.): n. pag. 21 Apr. 2005. Web. 16 July 2017. <https://arxiv.org/pdf/astro-ph/0504474v1.pdf>.

"Very-long-baseline Interferometry." *Wikipedia*. Wikimedia Foundation, 10 July 2017. Web. 16 July 2017.

Viani, Lucas. "The Structure of Black Holes." *Structure of Black Holes*. N.p., n.d. Web. 16 July 2017.

“What Instruments Do Astronomers Use to Find Black Holes?" *Hubblesite*. N.p., n.d. Web. 16 July 2017.