

Black Holes

I. Welcome to an Amazing Universe

Black holes exert a strong pull on both the scientific and the popular imaginations. They often prove beyond the limits of our abilities to comprehend. Indeed, they sound like a lot of nonsense from a bad movie. But black holes have gone from being a “purely theoretical fancy” to being the objects of cutting-edge scientific study. Strong evidence now exists that black holes not only exist, but also may exist in the centers of every galaxy. We have a good theory, general relativity that describes what happens around a black hole. It is a theory, which completely overturned our commonplace notion of space and time, and nowhere do we see its amazing predictions made so strikingly as around black holes. Through a study of black holes, we will begin to piece together our picture of the fundamental physics of spacetime. And no doubt, the Universe holds many surprises for us in our quest!

II. Introduction to Black Holes

Black holes have been around since the beginning of time, but we didn't know much about them until the last few decades when astronomers started looking at the Universe in radio, infrared, ultraviolet, X-ray, and gamma-ray light. However, the concept of a black hole has been around for over 200 years. English clergyman John Michell suggested in 1784 that some stars might be so big that light could never escape from them. A few years later, French mathematician Pierre Simon de Laplace reached the same conclusion. Michell and Laplace both based their work on the ideas about gravity put forth by Isaac Newton in 1687. Newton had said that objects on Earth fall to the ground as a result of an attraction called gravity. The more massive (heavier) an object is, the greater its pull of gravity. Thus, an apple would fall to Earth, as opposed to the other way around. His theory of gravity ruled unchallenged until 1915 when Einstein's general theory of relativity appeared. Instead of regarding gravity as a force, Einstein looked at it as a distortion of space itself. Where the two theories of gravity predict differences, general relativity has always proven to be more accurate.

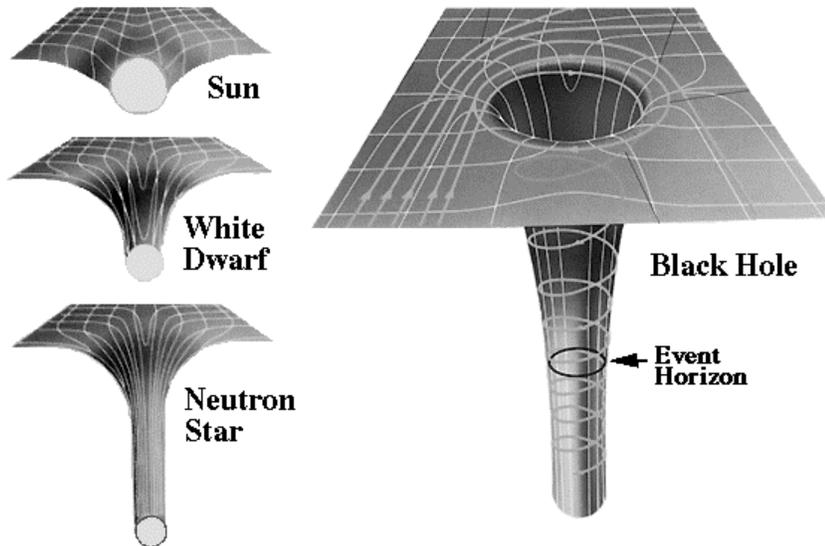
Shortly after the announcement of Einstein's theory, German physicist Karl Schwarzschild discovered that the relativity equations led to the predicted existence of an object into which other objects could fall, but out of which no objects could ever come. Today, thanks to American physicist John Wheeler, we call such an object a "black hole". Schwarzschild predicted a "magic sphere" around a very dense object where gravity is so powerful that nothing can move outward. This distance has been named the Schwarzschild radius. It is also often referred to as the event horizon, because no information about events occurring inside this distance can ever reach us on the outside. The event horizon can be said to mark the surface of the black hole, although in truth the black hole is the singularity in the center of the event horizon sphere. Every black hole has a singularity at its center.

Black holes are the evolutionary endpoints of stars at least 40 or 50 times as massive as the Sun. If a star that massive or larger undergoes a supernova explosion, it may leave behind a massive (several solar mass) burned-out stellar remnant. With no outward forces to oppose gravitational forces, the remnant will collapse in on itself. The star eventually collapses to the point of zero volume and infinite density, creating what is known as a "singularity". As the density increases, the path of light rays emitted from the star are bent and eventually wrapped irrevocably around the star. Any emitted light is trapped into an orbit by the intense gravitational field; it will never leave. Because no light escapes after the star reaches this infinite density, it is called a black hole.

III. Hands-on Black Holes?

Model a Black Hole

This demonstration allows for a visual depiction of the effect of a large mass on the fabric of spacetime. In particular, what effect a black hole does or does not have on the other stars around it and how that effect depends on the mass of the black hole. Remember that Newton saw objects with increasing mass as having an increasing escape velocity; Einstein saw them as making deeper "dents" in the fabric of spacetime!



A black hole makes such a deep "dent" that it forms a bottomless well. The sides of the well are so steep that even light cannot escape once it has fallen deeper into the well than the event horizon depth.

Materials:

- * Large latex balloon cut open and pulled flat, or sheet of latex
- * Round bowl, 4”- 5” in diameter
- * Tape
- * Package of small round beads
- * 1” solid ball bearing (the eraser end of a pencil can be used as a replacement)

Procedure:

1. Tape the sheet of latex (this represents space-time) tightly across the top of some round object, such as a bowl or even a coffee cup. The sheet should not be so tight that it will tear if stretched further, but should be taut enough that there are not any wrinkles!
2. Scatter a few beads on the sheet of latex (this represents matter that is near the black hole). Make sure they are spread out to all parts of the sheet.
3. Gently place the ball bearing onto the sheet of latex (this represents the black hole). Try not to let it bounce! If you don't have a ball bearing, gently push down on the center of the sheet with the eraser end of a pencil.
4. Explain what happened to the matter when the black hole was put into place. Why did this occur?
5. What would happen if the ball bearing was heavier (or if you push harder on the pencil)? What physical analogy to the black hole may be made?

Tin Foil, Balloons, and Black Holes

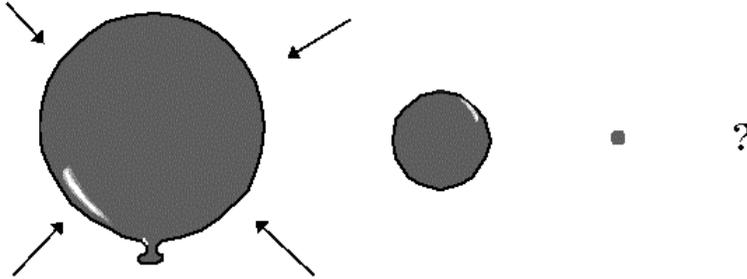
Materials:

- * Two round, black balloons
- * Several feet of tin foil
- * Balance or scales
- * Vernier caliper or ruler
- * Tape

Let us first conceptualize the formation of a black hole:

Blow up the balloon and tie the end so it remains inflated. Cover the outside of the balloon with tin foil so that it stays on the balloon. We will now consider this to be our star, with the balloon representing the “core” and the tin foil representing the “surface material”. Weigh the star by taping it to the scale and record this (and all future) measurement in a data table. Now squeeze your star such that the balloon bursts inside the tin foil. (Think of this as the simulation of the enormous mass of the star collapsing inward toward the core.) Weigh the star again. Now crumple the tin foil into a loosely

compacted ball. Weigh it again. Measure its diameter. Now crush it into a smaller ball. Weigh it and measure its diameter. Crush it into as small a ball as you can with your hands. Weigh it and measure its diameter.



What do you notice from your measurements about the weight of the crumpled ball as the size of the ball changes? What about changes in the density of the ball, where density equals mass divided by volume (for a sphere, the volume is equal to $\frac{4}{3} \pi r^3$)? How small would you have to make the ball of tin foil for it to achieve the average density of the Sun (1.4 g/cm^3)? What about the density of a neutron star (10^{37} g/cm^3)? How small would you have to make the ball for it to become a black hole? Hint: Use the equation $R = \frac{2GM}{c^2}$, where R is the radius of the event horizon, M is the mass of the black hole, G is the universal gravitational constant, and c is the speed of light. $G = 6.67 \times 10^{-11} \text{ m}^3/\text{kg}\cdot\text{sec}^2$ and $c = 3 \times 10^8 \text{ m/sec}$.

Now let us think about the black hole itself:

The black hole is actually a point, a singularity. Around it is an event horizon, which separates our Universe from the unknowable space immediately around the black hole singularity. The radius of the event horizon sphere is determined solely by the amount of mass in the black hole.

Blow up the second black balloon...thinking as you do that with each breath making the balloon larger in size, you are modeling the effect of the black hole growing larger in mass. Tie off the end of your inflated balloon and consider yourself now to be a spaceship approaching the event horizon of your black hole balloon. What can you tell me about the black hole inside the black latex sheeting of your balloon? How does this relate to the concept of an event horizon around a singularity?

Based on an idea from Jeffrey F. Lockwood, Sahuaro High School, Tucson, AZ.
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IV. Additional Resources

Websites

Imagine the Universe!
<http://imagine.gsfc.nasa.gov/>

Besides the information you will find about black holes in the *Imagine the Universe!* Website, try these other sites:

- http://starchild.gsfc.nasa.gov/docs/StarChild/universe_level1/black_holes.html
This page explains for the grade K-4 student what black holes are and how we know they exist.
- http://starchild.gsfc.nasa.gov/docs/StarChild/universe_level2/black_holes.html
This page contains information about black holes and how we know they exist for a grade 5-8 student, links to glossary terms and a movie about a "Journey into a Black Hole."
- <http://jean-luc.ncsa.uiuc.edu/Movies/>
This Web site has virtual reality and informational movies on black holes. This site is associated with NCSA, and is for students in middle school and above.
- <http://w3.gti.net/cmmiller/blkhle.html>
This Web site features a discussion on black holes and neutron stars for a non-technical audience.

Books

- Gaustad, John & Zeilik, Michael, *Astronomy: The Cosmic Perspective*- second edition, John Wiley & Sons, Inc., 1990. This text was designed for an introductory astronomy course for upper high school or undergraduate students who want a comprehensive view and understanding of modern astronomy, including black holes (see Chapters 20 & 21).
- Mitton, Jacqueline & Simon, The Young Oxford Book of Astronomy, Oxford University Press, Inc., 1995. This book explains many concepts in astronomy from the Solar System, galaxies, and the Universe, including black holes. Intended for the middle or high school student.
- Seward, Frederick D. and Charles, Philip A., *Exploring the X-ray Universe*, Cambridge University Press, 1995. Explains X-ray astronomy and astrophysics along with its most recent developments. Intended for the undergraduate science major, or above.
- *Voyage Through the Universe: Stars, Time-Life Books*. This volume is one of a series that examines the Universe in all its aspects. General information for the upper high school student (and above), related to black holes, will be found in the 'Neutron Stars and Black Holes' chapter.
- Couper, Heather and Henbest, Nigel, *Black Holes*, Dorling Kindersley Publ., 1996. A colorful introduction to the many strange behaviors and appearances of black holes. Intended for middle school to high school levels.

- Hawking, Stephen, *The Illustrated A Brief History of Time*, Bantam Books, 1996.
- Novikov, Igor, *Black Holes and the Universe*, Canto Edition, Cambridge University Press, 1995.

Magazine Articles

- Charles, Philip A. & Wagner, R. Mark, "Black Holes in Binary Stars: Weighing the Evidence", *Sky and Telescope*, May 1996, vol. 91, no. 5. From this article, one can understand that by making X-ray observations, astronomers are sometimes able to detect black holes (especially when coupled to a normal star in a binary system). Intended for the high school student interested in science, or above.
- Schulkin, Bonnie, "Does a Monster Lurk Closeby?", *Astronomy*, September 1997, vol. 25, no. 9. Describes the possibility of a massive black hole existing at the heart of our Milky Way Galaxy. Intended for the high school student interested in science, or above.
- Bernstein, Jeremy, "The Reluctant Father of Black Holes", *Scientific American*, June 1996, vol. 274, no. 6. Discusses the details of how Einstein's equations of gravity are the foundation of the modern view of black holes. Intended for the high school student who is interested in science, and above.