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INSIDE EINSTEIN'S UNIVERSE

<u>"Journey to a Black Hole" Demonstration Manual</u>

What is a black hole? How are they made? Where can you find them? How do they influence the space and time around them? Using hands-on activities and visual resources from NASA's exploration of the universe, these activities take audiences on a mind-bending adventure through our universe.

Many of these activities were inspired by or adapted from existing activities. Each such write-up contains a link to these original sources. In addition to supply lists, procedure and discussion, each activity lists a supplemental visualization and/or presentation that illustrates a key idea from the activity. Although many of these supplemental resources are available from the "Inside Einstein's Universe" web site, specific links are given, along with a brief annotated description of each resource.

http://www.universeforum.org/einstein/

Note: the science of black holes may not be immediately accessible to the younger members of your audience, but each activity includes hands-on participatory aspects to engage these visitors (pre-teen and below).

Introduction to Black Holes

Made of nothing but space and time, black holes are among the strangest of nature's creations. Anything falling into a black hole, including light, is forever gone from our universe. Black holes were long predicted to exist, but only recently have they been discovered throughout our own galaxy and other galaxies in the universe.

In principle, any object - even a rock - can be made into a black hole, by squeezing it into a tiny enough volume. Under these conditions, the object continues to collapse under its own weight, crushing itself down to zero size. However, according to Einstein's theory, the object's mass and gravity remain behind, in the form of an extreme distortion of the space and time around it. This distortion of space and time is the black hole.

The resulting black hole is the darkest black in the universe: No matter how powerful a light you shine on it, no light ever bounces back, because the light is swallowed by the hole. A black hole is a true "hole" in space: Anything that crosses the edge of the hole - called the "horizon" of the hole - is swallowed forever. For this reason, black holes are considered an edge of space, a one-way exit door from our universe; nothing inside a black hole can ever communicate with our universe again, even in principle.

However black holes are even stranger than that. According to Einstein's theory, as you get closer to a massive body, the flow of time slows down, compared to flow of time far from the object. Near a black hole, the slowing of time is extreme. From the viewpoint of an observer outside the black hole, time stops. For example, an object falling into the hole would appear frozen in time at the edge of the hole.

Inside the horizon of a black hole is where the real mystery lies. According to Einstein's theory, the flow of time itself draws falling objects into the center of the black hole. No force in the universe can stop this fall, any more than we can stop the flow of time.

At the very center of the black hole is where our understanding breaks down. Einstein's theory of gravity seems to predict that time itself is destroyed at the center of the hole: time comes to an abrupt end there. For this reason, a black hole is sometimes described as the "reverse of creation." But no one knows how or why time could come to an abrupt end, any more than we know how time was created in the first place. Einstein's theory of gravity no longer applies at these tiniest scales of distance, and new laws of nature must be found that describe what happens at the center of a black hole.

Does the inside of a black hole lead to another universe, as some scientists have speculated? The truth is, no one really knows. We cannot do a direct experiment to find out, even in principle, because no information or evidence can ever get back out of a black hole. That's what makes it so important to find and study black holes from the outside, while at the same time developing theories that can more confidently predict what might happen on the inside.

1. How to Make a Black Hole

What is a black hole and where do they come from?

Adapted from Goddard Space Flight Center's "Aluminum Foil, Balloons, and Black Holes" activity

http://imagine.gsfc.nasa.gov/docs/teachers/blackholes/imagine/page12.html

Supplies:
- 3 30-35 cm sheets of aluminum foil per balloon
- 1 or more balloon(s)
- Object for popping balloon (scissors, pen, sharpened pencil, pin, etc.)
- Volunteer(s)
- Ear protection for your volunteers

Procedure:

1. Blow up several balloons (one for each volunteer) or invite your volunteers to blow the balloons up themselves. Tie off the ends when you/they are done.

2. Cover the inflated balloons with several sheets of aluminum foil. These layers of foil represent the outer layers of your "Model Star". Be generous with the foil and cover the balloon thoroughly. It works best if you use several 30-35 cm long sheets and wrap around at least twice.

3. Explain that the balloons represent the cores of their stars. Inside the cores of stars, thermonuclear fusion is happening—lighter elements are fusing together to create heavier elements (hydrogen to helium, then helium to carbon, and so on up to iron). In this model, the air pushing outward on the inside of the balloon represents the heat and pressure generated by this "thermonuclear" fusion.

4. Explain that stars spend most of their lives in a constant battle between fusion and gravity. Invite your volunteers to use their "Crushing Hands of Gravity" to *gently* push on the surface of their foil-covered balloons. They will notice that they cannot make their stars collapse because the outward force generated by fusion within the star balances the gravity inward.

5. As you hand out earplugs or headphones to your volunteers explain that when a star runs out of fuel in its core, it has entered the final stages of its life. In order to simulate this, we must get rid of the air in the center of the balloon.

6. You or your volunteer(s) should now pop the balloon(s). Make sure that the foil retains its original shape around the balloon(s). This action represents the moment in a stars life when it runs out of fuel in its core, and fusion no longer

generates enough heat and pressure to resist the collapse of gravity.

7. Your volunteer(s) should now use their “Crushing Hands of Gravity” to simulate the enormous mass of the star collapsing inward toward the core. With fusion unable to support the star from within, gravity wins and a star collapses.

8. Point out to students that the mass of the star has not changed very much, but the size has. (If you like, you can have on hand an “un-collapsed” foil-covered balloon to compare to the new collapsed star.)

9. Introduce to your audience the concept of density—mass per unit volume. A black hole is very massive, but the mass is concentrated in a very small volume (in the case of black holes, zero volume—see “Discussion” for Activity 2). Because of this concentration of mass, the curvature of space (i.e. the strength of the gravity) **nearby** the black hole is much more extreme than if the mass were spread out through a larger (lower density) volume. This is illustrated nicely in steps 23-25 of Activity 6: Modeling a Black Hole.

10. The next two activities in this manual offer further insight into the density of black holes and their gravitational effect on nearby objects.

Discussion:

All stars are in a constant battle between pressure and gravity during most of their life. In all cases, gravity will eventually win, but the final end state of a star’s collapse is dictated by the original mass of the star. Incredible amounts of mass are needed to collapse an object into a point, so only the most massive stars will become black holes. The next activity explores the different end states for different mass stars.

Note that this exercise, like all models, does a good job of demonstrating some aspects of the real thing and other aspects not as well.

1. This activity better models the formation of a neutron star than a black hole. This is because you have a tight ball of crumpled aluminum left, that you cannot (no matter how hard you squeeze) shrink it down to zero size. A black hole is a true “hole” in space. Unlike a neutron star or a crumpled ball of foil, a black hole has no surface. You cannot stand on a black hole’s “horizon”; in fact, you wouldn’t even notice that you’d crossed the horizon until you tried to turn back and leave! (The horizon is a point of no return—a spherical one-way street.)

2. The aluminum in this model represents the outer layers of the star, which in a supernova explosion is blown out into space. What collapses to form a neutron star or a black hole is the core of the star. On the scale of

the balloon, this core would be microscopic in size (or you can say the size of a tiny grain of salt), Interestingly, a red giant star in the last stages of its life has an average density less than your balloon full of air!

This exploration is adapted from a classroom activity, which includes a more mathematical approach to the formation of black holes. The full write-up is available on Imagine the Universe! web site listed above.

Accompanying Visual Resource:

Death of a Star
http://www.nasa.gov/centers/goddard/news/topstory/2003/0319hete.html
This animation depicts the death of a massive blue star that has depleted its nuclear fuel. This crisis within the star's core triggers a massive pair of explosions: a supernova and a gamma-ray burst. Inside the star where we cannot see, the core has collapsed and formed a black hole. Within a few seconds of its formation, the black hole launches jets of matter. The jets (white plumes) break through the outer shell of the star less than ten seconds after the black hole is created. These jets, along with internal 'winds,' tear the star apart in a supernova event (swirling bands of color and expanding blue ring). With the outer part of the star gone, we can now see the black hole, surrounded by a disc of material (red) swirling around it. Interactions within the disc and around the black hole continue to generate amazingly powerful jets of energy.

2. The Little Black Hole That Couldn't

What is the difference between white dwarfs, neutron stars, pulsars and black holes?

Supplies:

- Volunteers
- A teaspoon
- (Optional) 2 balloons: one yellow, one blue
- (Optional) A rotating desk chair
- (Optional) A flashlight

Procedure:

PREPARATION

1. (Optional) Blow up the two balloons so that the blue balloon is larger than the yellow balloon.

ACTIVITY

2. Review the general process of stellar evolution—fusion in a star's core provides enough outward force to prevent the star from gravitational collapse; when a star "dies" it runs out of fuel in its core, causing the star to collapse in on itself; the outer layers of the star are ejected out into space, leaving nothing but a collapsed core behind. The mass of the star dictates what type of collapsed core will be left behind. This activity explores the different types of objects that a star can become at the end of its life. (If you're feeling morbid, these objects could be described as "stellar corpses." It can be noted in Step 9, however, that a black hole, because it has no surface, is more like a ghost than a corpse.)

3. (Optional) Hold up your two balloons to illustrate two different types of stars. Smaller, less massive stars, like our Sun, are relatively cool—red or yellow. Larger, more massive stars burn hotter—white or blue. (Side note: higher temperatures are generated by a higher rate of fusion in the core, which is necessary to balance the stronger gravitational collapse of the higher mass object. Your audience is probably familiar with the idea that "white hot" is hotter than "red hot.")

4. Gather your volunteers in a line, arms outstretched so that their fingertips are touching.

5. Make a white dwarf: the line "collapses" so that your volunteers have their hands on their hips, sticking out their elbows so they can touch the elbows on either side of them. These (very stubborn-looking) pieces of star refuse to collapse any further, creating a "white dwarf." This is what will happen to stars around the

mass of our Sun. (Tell your audience to mark their calendars for approximately 5 billion years.)

6. Explain that white dwarf stars are prevented from collapsing by the electrons that are packed together as tightly as nature permits. Remember that electrons orbit outside the nucleus of an atom. Stars with similar masses to our Sun do not have enough gravity to overcome this resistance from the electrons, and so the width of atoms are the limit of how far these “low to medium mass” stars can collapse

7. Point out how much closer the volunteers are to each other. The material in a white dwarf is so densely packed that one teaspoon of white dwarf would weigh more that 25 elephants! (Your audience may wish to model the noise made by 25 elephants at this point.)

8. Now we are going to take a star with even more mass, so that gravity is even stronger. Gravity is so strong that we can collapse this star so that our volunteer atoms overcome the resistance from electrons, and collapse down to their very neutrons. Instruct your volunteers to move together again until their hands are by their sides. How close are they now?

9. This star, under the influence of even more gravitational attraction of even more mass than the star that became a white dwarf, is now held up by the resistance of neutrons being squeezed together as tightly as nature permits. This so-called “neutron star” is even denser than a white dwarf—one teaspoon of neutron star weighs more than 20 MILLION elephants!

10. (Optional) Scientists have evidence that most, if not all, neutron stars are actually spinning in space. The magnetic field around a spinning neutron star creates jets that shoot out from the star’s magnetic poles. If we have just the right view of this star, we can see these jets as pulses of light in space. This pulsing neutron star is known as a “pulsar.” You can model this effect using a flashlight and a swivel chair:

    a. Invite a volunteer to sit on the swivel chair and hand him or her a flashlight. Your volunteer is the pulsar and the flashlight is one of its jets.

    b. Turn off the lights and have the volunteer turn on the flashlight, holding it perpendicular to the floor. (The light will be pointing out at the audience—you may need to warn people not to look directly into the light!)

    c. Spin your volunteer on the chair. As s/he spins, the light from the “jet” will flash in and out of the audience’s view. This is called a “lighthouse effect” because it looks like the beam of light from a lighthouse.

d. An example of a pulsar is at the heart of the Crab Nebula. In 1054 A.D. astronomers observed a supernova. We now see the scattered remains of this once-mighty star as a nebula in space. Recent observations in x-ray light have revealed the pulsar at the center of this nebula: astronomers observe both a tiny source of light at the center as well a disc and jets of material around it. The Crab pulsar rotates about 30 times every second.

11. Stars with low to medium masses become white dwarfs. High-mass stars end their lives as neutron stars (or pulsars). The most massive stars, however, end their lives as black holes. If your volunteers were to become black holes, they would need to collapse so far—and squish together so much—that they would overcome every force holding them together and collapse in on themselves, disappearing from view forever. Your boss at your institution probably doesn't like it when you turn visitors into black holes, and your volunteers' families probably wouldn't like it very much either, so the time has come to thank your volunteers and move on to another demonstration.

12. Give everyone a big round of applause.

Discussion:

This activity is a kinesthetic model of how black holes are created. It can be used to talk about stellar evolution and how a star's mass affects its fate, or to talk about density. In principle, any object—even a rock—can be made into a black hole, by squeezing it into a tiny enough volume. Under these conditions, the object continues to collapse under its own weight, crushing itself down to zero size. Should you be able to squeeze a mountain to the size of an atomic nucleus, or the Earth into a marble or the Sun into a ball 3 km across, each would disappear as a black hole. Such compressions are (as far as we know) impossible. Only very massive objects—more than eight times the mass of the Sun—have the gravity to be compressed this tightly.

Consider the above compressions, in comparison with more day-to-day objects:

Density of lead atom: 11 g/cm^3
Density of iron atom: 8 g/cm^3
Average density of the Sun: 1.4 g/cm^3
Density of water: 1 g/cm^3
Density of a proton or neutron: ~1.5 x 10^{15} g/cm^3

The specific numbers are not as important as getting a sense of how much more dense these strange objects (white dwarfs, neutron stars, black holes) are than the objects we usually think of as "dense." The heaviest thing your audience is likely to have encountered would be lead or gold. These objects are, of course, made up of atoms. However, atoms are mostly empty space, with essentially all of the mass in the nucleus. In fact, the radius of an atom is 10,000 times larger than the radius of its atomic nucleus. In a neutron star, material is packed together to the density of an atomic nucleus, making it roughly* $(10{,}000)^3$ or one trillion times as dense as "normal" atomic matter.

A black hole is even more bizarre—although its diameter is comparable to that of a neutron star, the material inside the event horizon is, in theory, compressed together in zero volume and therefore infinite density.

Obviously, our conception of density does not compare to what's going on as a neutron star or black hole is formed. Our conclusion is this: we may not understand what matter is like inside a black hole, but we know that it is not matter as we know it.

*The exact physics of creating a neutron star is slightly more complicated, so the numbers are rough approximations.

Accompanying Visual Resource:

Crab Nebula Movie
http://chandra.harvard.edu/photo/2002/0052/movies.html
IMAGES: http://chandra.harvard.edu/photo/2002/0052/index.html
This movie shows dynamic rings, wisps and jets of matter and antimatter around the pulsar in the Crab Nebula as observed in X-ray light by Chandra (left, blue) and optical light by Hubble (right, red). The movie was made from 7 still images of Chandra and Hubble observations taken between November 2000 and April 2001. To produce a movie of reasonable length the sequence was looped several times, as in looped weather satellite images. The inner ring is about one light year across. [Runtime: 0:19] Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

3. It's a Bird! It's a Plane! It's a Supernova!

What really happens when a star explodes?

These demonstrations were originally written by Donna Young, Wright Center Research Associate, Wright Center for Science Education and distributed by the Chandra X-ray Observatory education program. Additional input was provided by astronomers at NASA's Goddard Space Flight Center, John Hopkins University, and the Space Telescope Science Institute.

> http://chandra.harvard.edu/edu/formal/demos/snr.html
> http://www.pha.jhu.edu/~annh/PATCH/supernova_demos.pdf

Supplies:

- Empty aluminum can
- Hot plate or Bunsen burner
- Bowl of cold water
- Tongs/oven mitts
- (Optional) Hoberman sphere
- Basketball (or soccer ball)
- Tennis ball
- (Optional) Two angel food cakes
- (Optional) Serrated knife
- (Optional) A few sheets of colored cellophane
- (Optional) Electronic balance

Procedure:

MASSES OF STARS

1. Review the general process of stellar evolution—fusion in a star's core provides enough outward force to prevent the star from gravitational collapse; when a star "dies" it runs out of fuel in its core, causing the star to collapse in on itself; the outer layers of the star are ejected out into space, leaving nothing but a collapsed core behind.

CONTRACTION

2. Place approximately two tablespoons of water in an empty aluminum soda can.

3. Set the can on a hot plate or a screen/ring setup over a Bunsen burner.

4. Heat the can until the water starts to boil. [As the water boils, the steam generates pressure pushing outward, inside the can.]

5. When the steam starts to come out of the opening in the top of the can, quickly pick up the can with an oven mitt or tongs and invert into a bowl of cold water.

6. The can will instantly implode with a crunching sound. [The sudden condensation of the steam inside the can immediately ceases to generate pressure pushing outward.]

7. (Optional) You can use a Hoberman sphere to transition between the core contraction and mass ejection stages of this activity:

    a. We saw that the can imploded because the pressure inside the can disappeared, but why do we get an explosion?

    b. Show your audience the Hoberman sphere and explain that we can use a cool toy—a plastic sphere—to simulate the imploding core of a star.

    c. Open the sphere all the way, and then let it go, so it collapses under its own gravity.

    d. Ask your audience what happened when the sphere collapsed. They will tell you that it “bounced” at the end.

    e. Explain that it started to collapse, but then the collapse stopped because stuff falling in from one side collided with the stuff falling in from the opposite side

MASS EJECTION

8. Drop each ball individually on the floor so that the audience can see how far above the floor the basketball and the tennis ball rebound.

9. Place the tennis ball on top of the basketball and hold them out in front of you.

10. Let go of both balls at the same time so that they fall towards the floor together.

11. When the two balls hit the floor the tennis ball will suddenly rebound with enough energy to hit the ceiling. [The basketball, which reached the ground first, rebounded and transferred its energy to the tennis ball.]

(OPTIONAL) CORE DENSITY

12. Cut one of the cakes into pieces and use them to stuff the hollow center of the second angel cake.

13. Use the knife to cut pieces of the stuffed angel cake into a roughly round shape.

14. Loosely wrap the round angel cake with a few sheets of the colored cellophane.

15. Take the cellophane layers off and throw them into the air. [The star's outer layers are blown into space, producing what we observe as supernova remnants. See "Accompanying Visual Resources" for examples of such images.]

16. Squeeze the angel cake into as small a sphere as possible. [The core of the star collapses catastrophically.]

Discussion:

The three major phenomena associated with supernovas explosions can be demonstrated with easily available and inexpensive materials. The imploding can and basketball/tennis ball demos are commonly used in physics classes; however they are not usually associated with core contraction and the detonation of stellar atmospheric layers. The most difficult concept for students to understand is density. The angel cake and cellophane is a good approximation of the amount of material that remains in the core and its size, and the amount of material that gets blown away. Because all supernovas remnant images show all the beautifully colored materials that have been blown away from the star and the core cannot be seen, students have a common misconception that the star has literally blown itself apart, which is not the case.

CONTRACTION
The empty aluminum can is held in equilibrium by the pressure of the air inside the can directed outwards and the pressure of the air outside of the can directed inwards. Heating the water in the can causes the water to turn into steam. The steam drives all of the air out of the can. Now the can is held in equilibrium by the pressure of the steam pushing outwards (analogous to the radiation pressure in the core of the star) and the pressure of the air outside of the can directed inwards (analogous to the gravity of the star directed inwards.) When the can is inverted over the cold water, the steam instantly condenses. (This is similar to the sudden "condensation" of electron degenerate matter to neutron degenerate matter.) Now there is no pressure inside the can. The outside air pressure then causes the can to implode (analogous to the core of a star collapsing without radiation pressure as a counterbalance to gravity.)

MASS EJECTION
When the core of the star implodes it contracts catastrophically, just like the imploding can. At the end of the contraction the material in the core comes together with such a large amount of force that it rebounds. As the core

(represented by the basketball) contracts, all the outer atmospheric layers (represented by the tennis ball) are also contracting and following the core. They are less dense and take a little longer to contract than the core. When the core (basketball) rebounds, the atmospheric layers (tennis ball) are still in-falling towards the core. The rebounding core meets the incoming atmospheric layers with enough energy to literally blow the atmospheric layers away from the star due to the transfer of momentum from the basketball to the tennis ball. This is the supernova explosion.

CORE DENSITY
The supernova remnant consists of the outer atmospheric layers (analogous to the cellophane) and a highly dense core (analogous to the squeezed angel cake.) The expelled atmospheric layers contain approximately 5% of the mass of the star, and the remaining 95% of the mass is in the core. The density of an object increases if the volume of the object decreases. The volume of the angel cake can be decreased until there is no more air between the pieces of cake. The mass of the cake does not change – it is the same before squeezing as it is after squeezing. The mass of the core of the star does not change – it simply occupies a smaller volume. (With an electronic balance this can be demonstrated mathematically by taking the mass of the angel cake before and after. The change in density can also be calculated by measuring the diameter of the angel cake before and after squeezing.)

Accompanying Visual Resources:

Supernova Explosion (with Dissolve to Cassiopeia A)
http://chandra.harvard.edu/resources/animations/pulsar.html
When a massive star explodes, it creates a shell of hot gas that glows brightly in x-rays. These x-rays reveal the dynamics of the explosion. This animation of a supernova explosion dissolves into the first photograph taken with the Chandra X-ray Telescope—supernova remnant Cassiopeia A.

Images of Supernovae and Supernova Remnants
NASA's Great Observatories have photographed a number of supernovae and supernova remnants. Choose your favorites from the links below. Note that the beautifully colored material in the supernova remnant images is analogous to the cellophane in the "Core Density" activity.

http://chandra.harvard.edu/photo/category/snr.html
http://hubblesite.org/newscenter/newsdesk/archive/releases/category/star/supernova
http://hubblesite.org/newscenter/newsdesk/archive/releases/category/nebula/supernova%20remnant/

4. Where Are the Black Holes?

What are the sizes, scales, and locations of black holes in our universe?

Adapted from Astronomical Society of the Pacific/Night Sky Network's "Our Galaxy, Our Universe" and "Black Hole Survival Guide" activity kits

http://www.astrosociety.org/education/nsn/nsnpress.html
http://nightsky.jpl.nasa.gov/

A full write-up for building an edible scale model of the Milky Way galaxy is included as part of the "Journey to the Beginning of Time" demonstration manual on the "Inside Einstein's Universe" web site. This activity incorporates the locations of black holes into that model.

Supplies:

- 2 Cookies, quarters, or other round objects between 1 and 2 inches in diameter
- Poppy seeds
- A raisin
- (Optional) Cake decorating sprinkles or birdseed

Procedure:

1. Have a short discussion with your audience about what a black hole is. (You may wish to use one of the previous activities to talk about these ideas.)

2. Ask your visitors where they think black holes are in our universe. Are they in our solar system? In the Milky Way?

3. Tell your audience that you are going to build a scale model of our solar system, within the Milky Way galaxy of stars, to get a feel of where black holes are.

4. Position yourself on one side of the stage and explain that the cookie you are holding represents our entire solar system—with the Sun a tiny speck of sugar at the center and Pluto orbiting around the edge. (Our Earth would be located less than a millimeter from the center.)

5. Invite a volunteer to come up and hold the second cookie at approximately the distance of the next closest star. (Note again that the star itself is a speck of sugar at the center of the cookie and the rest of the cookie represents any planets that are orbiting around that star, if they exist!) The audience may wish to offer their own advice about your volunteer's position.

6. When your volunteer (and the majority of the audience) is satisfied with the distance between the two stars, ask if they want to know the true distance on

this scale. Then, reveal that your volunteer would need to travel two soccer (or football) fields away in order to create an accurate scale model of the distances between stars!

7. Thank your volunteer. (S/he may now eat the solar system if s/he likes.)

8. Tell your audience that there are approximately 200 billion stars in the entire Milky Way Galaxy*. Ask how big they think our galaxy would be on this scale.

9. Reveal that the entire Milky Way galaxy is the size of North American. Imagine North American 25 miles thick, filled with 200 billion tiny floating sugar specks, each approximately 2 soccer (football) fields apart!

10. Now that you have a model of our galaxy, you are ready to populate it with black holes. Scientists estimate that typical galaxies have, on average, one million black holes. (This is about one half of one percent the number of stars in a typical spiral galaxy.) Each black hole is the ghost of a dead star—a very massive star that has ended its life in a dramatic explosion called a supernova. Because black holes are dead stars, we find black holes in the same locations as stars.

11. Take your poppy seeds and scatter them throughout North America. On this scale, one million poppy seeds would fit into a cube 4 inches on a side! You can use Appendix A to identify and locate several black holes whose locations in our galaxy are known.

12. Many people have heard of the "supermassive" black hole at the center of our galaxy. Evidence suggests that most, if not all, galaxies like the Milky Way have giant black holes at their core. But how big is this black hole in our North America-sized galaxy with our Sun a speck of sugar and our solar system the size of cookie?

13. Take out a raisin and show it to the audience. In the scale model that we have built, the giant black hole in the center of the Milky Way, with the mass of 3 million Suns, is the size of a raisin! Horizon.

14. Because our entire galaxy is the size of North America, we are going to put this raisin in Kansas to complete our model. (No wonder Dorothy wanted to go over the rainbow!)

15. Your model is now complete. You may wish to show your audience the map of the Milky Way, with the locations of known black holes. (This image can be downloaded from the "Inside Einstein's Universe" web site. A black and white version of this image appears at the end of this manual.) You can also use the

coordinates in Appendix A to map the black holes on a planetarium sky or constellation map.

* If you like, you can spend more time talking about the 200 billion stars using your cake decorating sprinkles or a handful of birdseed. 200 billion sprinkles would fill 14 school buses without any room for the drivers or students! 200 billion pieces of birdseed would cover a football field to the depth of four feet!

Discussion:

Scaling the dimensions of the galaxy to North America is a dramatic introduction to the scale of space, and the distance between objects. You can use this model to address some common misconceptions about black holes, such as the hazards they pose. Are there black holes in/near the Solar System? No. Would a black hole at the distance of the closest star pose a threat to us here on Earth? **Not a bit!**

This scale model also illustrates the problems with finding black holes at vast interstellar distances, as well as the currently impossible technical challenge of imaging a black hole (even stars are point sources and they have a million times the diameter of a stellar mass black hole). All but one of the 12 black holes listed are part of a binary system with a normal star. Currently, the only other way to discover a black hole is through gravitational lensing.

Accompanying Visual Resource:

Real Images of [The Material Around] Actual Black Holes
http://www.universeforum.org/einstein/resource_journeyblackhole.htm
The Universe Education Forum has created a Power Point slide show with real images of (the material around) actual black holes. Although black holes themselves are invisible, they reveal themselves by their influence on the matter around them. NASA's Chandra Observatory, which is designed to detect X-ray light, has recorded stunning images of hot gas being pulled into orbit around actual black holes throughout our universe.

This web site also contains the map mentioned in Step 11 of this activity. Note that the image of Milky Way as seen from outside it is an artist's impression and represents of a view of the Milky Way that we can never actually have.

5. Black Holes for Breakfast

What does a black hole look like?

Adapted from Sonoma State University's "Tasty Active Galaxy" activity

http://glast.sonoma.edu/teachers/popup.html
http://glast.sonoma.edu/teachers/popup/tastyag/tastyagnea04.pdf

Supplies:

- 2 ice cream cones
- 1/2 egg bagel (top)
- 1 donut hole
- Chocolate frosting
- Butter knife

Procedure:

1. Gather all the ingredients in front of you on a table.

2. Place the donut hole in the middle of the bagel half. (If the bagel's hole is not large enough, trim the inner edges with the knife.) The bagel represents the "disk" of material accreting around the black hole, while the donut represents the black hole itself. (Remember, however, that a black hole has no surface—it is a true "hole" in space and time!)

3. Gently push the ice cream cones into the middle of the donut hole to represent the "jets" coming out from space around the black hole.

4. Spread the chocolate frosting on the outside edge of the bagel to create the "torus" of material at the outer edge of the accretion disk.

5. See if you can eat your black hole before it swallows you!

Discussion:

What does a black hole eat? The answer is anything that gets too close! In the universe that means interstellar gas (and sometimes unfortunate stars that have wandered too close). As the gas falls towards the black hole it is spun into a rapidly rotating disc called an accretion disc that, because of friction between the atoms, heats to millions of degrees (at this temperature, atoms have been stripped of most of their electrons and are left positively charged. Such a gas is called a plasma). The black hole and its spinning accretion disc act like a giant dynamo to create powerful magnetic fields. Most of the gas will spiral into the black hole but some is caught up in the magnetic vortex and shot back into space in two jets from the poles of the black hole. These jets of charged particles travel at almost the speed of light, and can span the entire host galaxy. Remember that the jets don't come from inside the black hole (nothing can emerge from a black hole) but originate just above its surface.

Although this activity models a supermassive black hole at the center of an active galaxy (often referred to as an Active Galactic Nucleus, or AGN), the basic anatomy of all black holes is generally the same. Learn more about active galaxies at http://glast.sonoma.edu/.

Accompanying Visual Resources:

Zoom in to a Black Hole
http://astroe2lc.gsfc.nasa.gov/docs/astroe_lc/education/education.html
We can observe black holes by looking at the effects on the matter in their immediate vicinity. This animation zooms in to the center of an ordinary galaxy, revealing the telltale signs of the black hole at its heart: hot discs of gas, spinning at nearly the speed of light, and a pair of jets, at right angles to the disc, shooting back into space.

Black Hole Animation
http://chandra.harvard.edu/resources/animations/blackholes2.html
Astronomers now believe that supermassive black holes reside at the center of most, if not all, galaxies. If the galaxy in this animation were the size of a city, the black hole would be a mere dust speck at its center. In reality, these black holes are millions of miles across and the accretion disc surrounding them are the size of a solar system.

6. Modeling a Black Hole

What happens to space and time around a black hole? What would happen if the Sun became a black hole?

Adapted from the Astronomical Society of the Pacific/Night Sky Network's "Black Hole Survival Guide" activity kit.

http://www.astrosociety.org/education/nsn/nsnpress.html
http://nightsky.jpl.nasa.gov/

Another version of this is Goddard Space Flight Center's "Model a Black Hole" activity, from the Imagine the Universe! program:

http://imagine.gsfc.nasa.gov/docs/teachers/blackholes/imagine/page11.html

Supplies:

- Bucket (12" diameter or larger recommended)
- A handful of marbles
- 2 smaller marbles ("peewees" < 1/2 inch) or large round craft beads
- Bungee cord or large rubber band
- Stretch fabric squares (latex or spandex)
- Drinking straws
- Large, heavy lead fishing weight (~ 2.5-3 lb) (coat before use)
- Small, lighter lead fishing weight (~ 4-8 oz) (coat before use)
- Liquid plastic (e.g. Plastidip™) for coating the lead weights
- (Optional) Sport ball, equal in weight to one of your lead weights (a softball or baseball should work well for this)

If you do not have access to weights, you can use the eraser end of a pencil to simulate the distortion of space. (Use more force to simulate more mass.)

Procedure:

PREPARATION

1. Coat the lead weights, as directed by the instructions on the liquid plastic. (Be sure you give them enough time to dry before using them with visitors.)

2. Stretch the fabric over the mouth of the bucket, fastening it with the rubber band or bungee cord. This will be your model of spacetime, described below.

ACTIVITY

3. Let your audience know that you will be talking about some very weird ideas—Einstein's predictions about the nature of space and time, or even more strangely, spacetime. Here are some ways to get people thinking about these new ideas:

    a. Ask your audience what comes to mind when they think about empty space? (Chances are, they will say "nothing.") One of Einstein's most revolutionary ideas was that empty space is not actually nothing—it has energy and can be influenced by the objects within it. (You may wish to hold up a spare piece of stretchy fabric to demonstrate how space can be stretched or twisted.)

    b. Ask your audience what comes to mind when they think about time? What is a second? Is a second always a second? Once again, Einstein's theories introduced the idea that time is not absolute. Gravity can affect the flow of time—stretching or squeezing it to make it faster or slower.

    c. Ask your audience how far away a nearby city or the front door of your building is. Solicit answers until you have both a time and a distance description of the geographic relationship (for example, New York is about 200 miles, or five hours, away from Boston). Although this analogy is not attempting to model the mathematical concept of spacetime, it shows your audience that you can think about space and time in related ways.

4. If you have not already done so, stretch the fabric over the mouth of the bucket, fastening it with the rubber band or bungee cord, to create your spacetime model. (If you wish to make these ideas more accessible to the younger crowd, you may wish to refer to "space" rather than spacetime in the steps below.)

5. Explain to your audience that the fabric represents the "fabric" of spacetime. There is spacetime all around us everywhere, in all directions. This just represents one small portion of spacetime and in *only two dimensions*.

Massive objects affect the fabric of spacetime:

6. Invite a volunteer to compare the two weights—which one has more mass?

7. Introduce your audience to Einstein's revolutionary idea that mass distorts the very fabric of spacetime by placing the less massive weight in the center of the fabric. What happens to the spacetime when mass is introduced? (It curves.)

8. Replace the small weight with the larger (heavier) weight. Ask the audience what happens to the fabric. How much does spacetime curve around this? (More.)

9. Explain that objects with more mass distort spacetime more than objects with less mass. For example, spacetime around Sun has greater curvature than the spacetime around Earth, because the Sun is more massive than the Earth. Ask your audience how much curvature the spacetime around the Moon would have.

Einstein defined gravity by the curvature of spacetime:

10. Now we are going to fly some space probes through our curved spacetime. Use the marbles to represent small space probes. Invite a volunteer to place one probe at the edge of the fabric with large mass at the center and let it go. What happens? (The "spaceship" should "fall" toward the mass.)

11. Repeat Step 9 with the smaller mass at the center, and ask your volunteer to observe the differences between the two curvatures. Which "falls" faster? (This is Einstein's model of gravity: The more the mass, the more the curvature, and the stronger the gravity.)

12. Remove the weights from the fabric. Get a volunteer to roll a marble across the fabric of spacetime (no bouncing!). The marbles move across (through) spacetime in straight lines.

13. Now place the small weight on the fabric and get another volunteer to roll a marble. (It should follow the curve of the fabric, making an arced trajectory or a complete loop—an orbit.)

14. Point out that even though the volunteer pushed the marble in a straight line, it moved on a curved path. This model demonstrates Einstein's explanation for planetary orbits: The Earth orbits the Sun because the Sun curves spacetime around it. Now you can ask your audience: Why does the Moon orbit Earth? (Answer: because the Moon follows the path created by the Earth's curving of spacetime.) Note that this is a different model than Newton's explanation for planetary orbits, which involves a force between the two bodies. In Newton's model of gravity, space itself plays no role.

15. Ask your audience how they would leave a planet. In a rocket? What does a rocket need to do? Fight gravity! The more gravity, the more powerful the rocket you need. Now we're going to pretend to be rockets.

16. Hold up the two weights and ask your audience which object they think it will be easier to launch the rocket from—the more massive one or the less massive one? Which one is going to be harder to escape from? Which one is curving space more?

17. Place the small weight on the fabric to represent the Moon. Your spaceship, a small marble, lies on its surface. Your volunteer is the rocket engines. Blowing

through the straw represents the rocket fuel and acceleration needed to propel the spaceship off the surface. You want your spaceship to either go into orbit or to leave the Moon to travel to another planet.

18. Give a volunteer a straw and tell them to blow their spaceship marble into orbit around the weight (no spitting please!).

19. Now replace the small weight with the larger weight. Challenge your volunteers to launch their spaceships now! Give a volunteer a straw and tell them to blow their spaceship marble into orbit around the weight (no spitting please!). Were the audience's predictions correct?

20. The more mass, the steeper the gravitational hill you need to climb – the greater the escape velocity needed. More massive objects have even stronger gravity. Trying to launch a rocket from a neutron star would be like blowing your marble spaceship up the wall of a well. What about a black hole? The curvature around a black hole would be like a bottomless pit!

Presentation Tip: When your visitors blow through the straw, if they continue too long they can get light-headed. Warn them to stop if they feel light-headed, or limit each person to three tries at a time.

What would happen to the Earth and the planets if the Sun became a black hole?

21. Reassure the audience that the Sun will not die for billions of years and when it does, it will become a white dwarf, a small compact star about the size of Earth, but let's imagine!

22. Hand a volunteer the sport ball and the weight of similar mass. Can your volunteer confirm that the two objects have about the same amount of mass?

23. Now ask your audience what is different. The ball represents the Sun and the weight represents the Sun collapsed under the influence of gravity–representing a black hole. Which of these is going to curve spacetime more?

24. Test the audience's predictions using your fabric and bucket set-up.

Discussion

Even though the sizes are different, the masses of the sport ball and the weight are the same. At large distances (i.e. near the edge of the fabric) the curvature in the fabric due to either mass is roughly the same. Same mass…same curvature…same gravitational pull.

However, things are different when you're up close to the lead weight. For the amount of mass involved, you can get much closer in to the lead weight as its mass is concentrated in a smaller volume. Because of your proximity, the curvature of the fabric is more extreme. Same mass…more curvature…stronger gravitational pull.

Let's do an imaginary experiment with our Sun. With a mass of one solar mass (by definition!), it has a radius of roughly 750,000 km. At its surface we feel the gravitational pull of 1 solar mass, 750,000 km from the center of the Sun. Now turn the Sun into a 1 solar mass black hole (remember, this is imaginary). It would have a radius of 3 km. At its surface (or in the case of a black hole, its horizon), we feel the gravitational pull of 1 solar mass a mere 3 km from its center. At such close proximity the curvature of spacetime, which we experience as gravity, is extreme.

(Of course, for a black hole, you needn't stop at the horizon. You can continue to the center of the black hole–the singularity–putting yourself at effectively zero distance from the 1 solar mass, and experiencing infinite curvature. At least, that's the theory…)

Notes on this Activity:

Gravity as the curvature of spacetime (or even just space!) is a very strange concept, and the elastic sheet model is one of the most popular ways to introduce the idea. It is of course a two-dimensional model and the presenter may want to spend a little time emphasizing this. Spacetime around an actual planet or black hole is stretched radially inwards in all directions.

Another tricky idea is that of "escape velocity." What, exactly, is meant by escape velocity? This term sometimes causes people to think you can truly escape from Earth's gravitational field (or, for example, from the Sun's gravitation field)–that if you get away from the surface of Earth there will no longer be any gravitational pull. You can escape from orbiting the Sun, Earth, or Moon, but you will never be totally free of any object's gravitational field. Gravity extends forever, getting weaker with distance. If you're going fast enough, you can overcome an object's gravitational pull–you can keep going and not get pulled back.

When talking about black holes, it is important to be aware of possibly misconceptions held by members of the audience.

1. Many children and adults hold the misconception that a black hole will suck in everything. Emphasize that as long as an object, such as a star, is orbiting fast enough, it will not be pulled into the black hole. The Sun orbits the center of our Galaxy where there is a giant black hole – but we are

very far away and orbiting fast enough to stay out (26,000 light years away and orbiting at 220 km/sec or 137 mi/sec). This is illustrated in activity 7.

2. Many people think it must be easy to travel to a black hole. NASA doesn't actually send probes to black holes and no one has ever visited one – they are too far away. The nearest black hole is many light years away – many trillions of miles. Scientists study them from here with giant telescopes in space. NASA wants to search for black holes in our galaxy and other galaxies to learn what happens near black holes and what role they may have played in the formation of early galaxies in the universe.

More About Spacetime:

NASA's Gravity Probe-B satellite is testing two of Einstein's predictions about the distortion of spacetime around massive objects, by measuring the distortion around the Earth. You can learn more about this exciting mission and its incredible science at http://einstein.stanford.edu/

Variations on this Activity

This model can also be created on a larger scale, by using a large sheet of stretchy fabric and a bowling ball, or using a jogging trampoline and a shot put. With these set-ups, you can use balls such as ping-pong balls or tennis balls, as the "test particles." A good comparison for a 6-pound bowling ball is a 6-pound exercise ball; it weighs the same, but is noticeably smaller, and therefore denser.

Accompanying Visual Resources:

Space Time Lab
http://www.universeforum.org/bh_popup_spacetimelab.htm
This online laboratory lets you explore how a planet and a black hole affect the space and time around them. You might think that an inch is an inch and a second is a second no matter where you are in the universe. But Einstein discovered that black holes have enough mass to distort the scale of space and time around it.

7. How to Spot a Black Hole

How can we see black holes?

Adapted from Adler Planetarium and Astronomy Museum's "Black Hole Detection" curriculum guide.

http://www.adlerplanetarium.org/education/resources/gravity/5-8_gq5-3.shtml

Supplies:

- 1 glow in the dark necklace
- (Optional) 1 black "costume," such as a robe, tunic, or cape
- Black back drops for any windows
- A big, dark, empty space where students can move freely without harm
- (Optional) Rope, approximately 3 feet (1 meter) long.
- (Optional) Rag doll or stuffed animal

Note: If a dark room is not available, you can do this activity using a white or brightly colored lab coat instead of a glow-in-the-dark necklace.

Procedure:

PREPARATION

1. Make sure the room can be dark, covering any windows as necessary

ACTIVITY

2. Explain that the many stars in the universe are in "binary systems," a pair of stars that orbit each other.

3. Invite two volunteers to come up and demonstrate this—they should stand facing each other, cross their wrists and hold hands. Once they are joined, they can start to rotate in a circle.

4. Explain that astronomers can use Newton's laws of motion to observe the dynamics of the system and figure out things like separation between stars and mass of stars.

5. (Optional) The following experiments can help your audience explore how the separation and relative mass of stars in a binary system affect their motion:

   a. Separation of stars: What happens if the two volunteers are connected by a rope, rather than their hands? Have your volunteers hold onto opposite ends of the rope as they spin. How long does it take them to complete one orbit? Now have them hold hands and spin. How fast do they spin when separated by a shorter distance? (Answer: much faster—the closer two stars are to each other, the faster they orbit and the shorter the period.)

b. Relative mass of stars: Replace one of your volunteers with a rag doll or stuffed animal. How does this smaller mass affect the system? (Answer: The relative masses of the objects orbiting each other affect how each object moves. If the two are well-balanced, both move equally; if they are not balanced, the less massive object whips around, while the more massive object hardly moves at all.)

6. Thank your volunteers.

7. Explain to your audience that some stars live shorter lives than others. When you have a system with different types of stars (for example, Albierio in the constellation Cygnus: a hot, massive blue star and a cooler, less massive orange star), one of the stars (the more massive one) will live its life and become a black hole, disappearing from view. The other star will continue to orbit the black hole, however. Its orbit is the clue to figuring out where black holes exist.

8. Invite two more volunteers to come up to the stage and give one of them a glow-in-the-dark necklace to wear as a headband. (If you have a black costume, the other volunteer should wear it.)

9. Have them join hands like your first set of volunteers and turn off the lights.

10. Set them spinning around each other. The glow-in-the-dark necklace will appear to move around an invisible object (the "black hole," not giving off any light).

11. Explain that astronomers look for stars that appear to be orbiting around "nothing." The dynamics of these systems show that there is some amount of mass around which these stars are orbiting, but it cannot be seen. This is one line of evidence for black holes—objects incredibly massive, in a very small amount of space.

12. Thank your volunteers and take back the glow-in-the-dark necklace (and costume).

13. One of the interesting things about these black hole binary systems is that some of the material on the surface of the orbiting star is drawn closer to the black hole by the black hole's strong gravitational attraction. As it succumbs to the tug of the black hole's gravity, it is drawn into a disc of material very close to the black hole, called an accretion disc. The material in the accretion disc is moving at incredible speeds around the black hole.

14. Instruct your audience to rub their hands together very quickly. What happens to the temperature of the molecules being rubbed together? (They should feel warmer than they did when they were not moving so quickly.)

15. Explain that as molecules heat up, their color changes. As your audience probably knows, a flame that is "white hot" is much hotter than an orange flame. A blue flame is even hotter. As temperature increases, the color moves through the blue, into the violet, and eventually, into the ultra-violet, which is too high-energy for our eyes to detect. Temperatures even hotter than ultraviolet glow x-ray hot, and we need x-ray telescopes to see them. The material in black hole accretion discs is so hot that it glows in x-rays.

16. The Chandra X-ray Telescope is looking for glowing masses of x-rays in space—the telltale accretion discs of these otherwise hidden black holes.

Discussion:

You may wish to use a demonstration here that shows evidence of "invisible" light. For example, some digital cameras have sensitivity in the very near infrared—you can use these infrared detectors to observe sources of infrared light, or heat. Shining black light on a glass of water filled with Borox™ will cause it to glow, due to the ultraviolet-fluorescing particles in the substance. Some craft or science supply stores sell ultraviolet-sensitive beads that glow when exposed to sunlight. Seeing that there are other types of light beyond that which our eyes can detect is a concrete connection to x-ray astronomy that your audience can make. The Chandra X-ray Observatory web site has a number of multi-wavelength astronomy images.

Accompanying Visual Resources:

Stars in the Galactic Center
http://www.mpe.mpg.de/ir/GC/
This animation shows the orbits of stars very close to the center of our galaxy over a period of 14 years: from 1992 through 2004 and projected to 2006 (watch the counter in the upper left corner). The red cross in the center marks the location of the invisible giant black hole in the center of our galaxy. See how fast the stars are moving as they pass by the central black hole. Scientists can figure out the mass and location of black holes by applying Newtonian physics to the motion of stars in the black hole's vicinity. Credit: Max-Planck-Institut für extraterrestrische Physik

Black Hole Extreme Exploration
http://www.nasa.gov/audience/forstudents/9-12/features/F_Black_Hole_Extreme_Exploration.html

The first animation on this page takes us on an imaginary journey to a black hole, an x-ray binary system known as Cygnus X-1. In this pair, an otherwise normal, hot blue star is in orbit around a black hole. As the star orbits, the tug of the black hole's gravity strips away the outer layers of the star, drawing them into a pancake-flat disc of x-ray hot radiation around the black hole.

The second animation on the page provides a close-up simulation of the hot gas around a black hole. The spiraling disc of gas gets hotter and hotter as it nears the black hole. On the point of falling into the black hole, the gas glows X-ray hot.

Real Images of Actual Black Holes
http://www.universeforum.org/einstein/resource_journeyblackhole.htm
This Power Point slide show contains real data from the Chandra X-ray Telescope—actual images of accretion disks around actual black holes.

8. Black Hole Hide and Seek

How can you stay safe in a universe filled with black holes?

Adapted from Astronomical Society of the Pacific/Night Sky Network's "Black Hole Survival Guide" activity kit

http://www.astrosociety.org/education/nsn/nsnpress.html
http://nightsky.jpl.nasa.gov/

Supplies:
- 2 sheets of foam board, roughly 11" x 17" (alternative: use black signboard, e.g. Coroplast®)
- 1 strong, small cylindrical magnet (e.g. AmazingMagnets.com, Item # T250B)
- A magnetic marble (e.g. School-Tech.com, Item #12610W2)
- (Optional) Towel or tray

Procedure:

PREPARATION

1. Bore or cut several holes in one of your sheets of foam board, with the same diameter as the cylindrical magnet. The magnet should fit snuggly into the hole but can be held in place with tape if necessary.

2. Place the magnet in one of the holes. The other holes allow you a variety of locations for the black hole.

3. Cover the foam board (and the magnet) with the second piece of foam board, so that the surface of space appears uniform.

4. Use the towel or a tray underneath the demo to keep the marbles from rolling away!

ACTIVITY

5. Ask your audience if they are worried that a black hole might "eat" them. Assure them that this is a common concern for many people, but nothing to worry about.

6. Remind them that a black hole's gravity is just like that of anything else in the universe—dependent on mass and distance from the object. Black holes are very massive, so their gravitational fields are very strong, but you still need to get very close (hundreds or thousands of miles) to suffer any severe effects. See the discussion in Activity 6: Modeling a Black Hole.

7. Bring out your cardboard apparatus and explain that there is a black hole hidden somewhere in this piece of space. Because black holes are “invisible,” we cannot see it with our eyes. Instead, we are going to look for it using “gravity.”

8. Invite a volunteer to come up and hand her one of the magnetic marbles.

9. Explain to your audience that this marble represents a piece of matter in space. This piece of matter will begin to orbit the black hole if it gets close enough to the black hole. Your volunteer’s job is to send the matter on a journey through space to find the black hole.

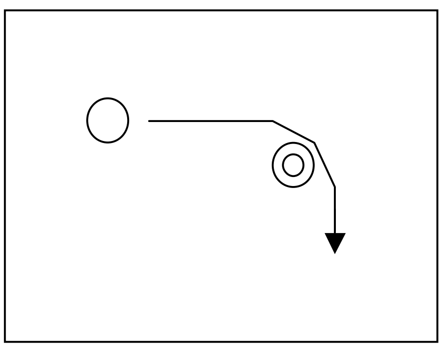
10. Have the volunteer roll the marble slowly across the cardboard.

11. If the marble rolls over the hidden magnet, its path will change; if its path does not change, it has not been affected by the black hole’s “gravity.”

12. Repeat this activity until the volunteer “discovers” the black hole.

13. If you like, repeat the entire activity with the marble in a different hole.

Illustration of effect:



Discussion:

In this activity, the magnetic force is being used to simulate the force of gravity, and it is very important to emphasize that **magnetism is *not* gravity**. One major difference is that gravity is always attractive, whereas magnetism can attract and repel. Gravity is also a much weaker force, and only becomes noticeable when dealing with massive (planet-sized or bigger) objects. We are therefore using magnetism as a model for gravity when the marbles attract each other. (Interestingly, the force acting between the Sun and the planets was initially attributed to magnetism by the great astronomer and mathematician Johannes Kepler in the early 17th century.)

Depending on how close (and how fast) the marbles encounter the hidden magnet, visitors will notice different outcomes:

Outcome A – If the marble passes by the magnet at a great distance, we notice no deflection. Both the magnetic and gravitational fields decrease with distance. When far away from the magnet, our marble is still under the influence of the magnetic force, but it is too weak for us to notice. Similarly with black holes, we need to get very close to notice their presence.

Outcome B – Some marbles will roll by the black hole but their path will be deflected. The passing object is traveling at greater than the escape velocity of the black hole at that distance, but we still detect the black hole through the deflection. If the magnetic marble is representing a photon of light, rather than a planet or star, this result models gravitational lensing.

Outcome C – Some marbles will be captured by the black hole's gravity and end up in orbit. This models how stars and gas can be captured by the black hole's gravity. We see this scenario in the accompanying visualization (see below). Notice how close an encounter you needed for such an outcome.

Accompanying Visual Resources:

Animation of a Star Ripped Apart by a Giant Black Hole
http://chandra.harvard.edu/resources/animations/blackholes.html
This animation shows what happens to a star that drifts too close to a giant black hole. At this very close distance, the star is subjected to the tidal forces caused by the black hole's gravity. The star is ripped apart by these forces and part of it is drawn into orbit around the black hole. The part that does not get drawn into orbit continues its journey through space.

Stars in the Galactic Center
http://www.mpe.mpg.de/ir/GC/
This animation shows the orbits of stars very close to the center of our galaxy over a period of 14 years: from 1992 through 2004 and projected to 2006 (watch the counter in the upper left corner). The red cross in the center marks the location of the invisible giant black hole in the center of our galaxy. See how fast the stars are moving as they pass by the central black hole. Scientists can figure out the mass and location of black holes by applying Newtonian physics to the motion of stars in the black hole's vicinity. Credit: Max-Planck-Institut für extraterrestrische Physik

9. Black Hole Lensing

What happens when a black hole crosses your field of view?

Supplies:

- A large image with a distinctive shape (perhaps Albert Einstein) or even an actual person such as yourself or a volunteer
- Wine glass (glass is better than plastic) (See Appendix B, Image 1)
- Protective gloves & goggles (See Appendix B, Image 1)
- A fine file tool for cutting base off wine glass (See Appendix B, Images 1, 2)
- Volunteer(s)
- Optional: Video camera (camcorder or surveillance-type camera)

Procedure:

PREPARATION

1. Purchase a wine glass made of clear transparent glass, without any color tint or patterns on the glass. A thicker stem is preferred. See Image 1 in Appendix B. You will be able to create two lenses from each wine glass, using both the base and globe to produce the desired gravitational lens optical effects.

2. Put on protective gloves & goggles. You must **always** use protective gloves & safety glasses while handling, etching and breaking glass. **Always!**

The following steps will most likely produce some glass dust and shards. Take care to choose a safe work area and thoroughly clean up any glass shards.

3. Use the fine file tool to score the stem of the wine glass, just as it begins to widen into the stem. (More information about these tools can be found in Appendix B, Image 2.) The location of this first score line should be just above the base as the glass begins to narrow into the slim stem. This is about 1 centimeter above the base, but use your best judgment, as the location of the score line is not too critical. See Images 1 and 3 in Appendix B. Follow this technique to etch a score line on the glass stem:

    a. Hold the wine glass by the globe firmly in one hand and the fine tool file in the other. See Appendix B, Image 4.

    b. Score a single complete circle around the stem, making sure the beginning and ending of the etched line connect. Make only *one etched line* for each place you wish to break the glass, as several scores will produce multiple fractures and a poor break, if not a shattered glass!

c. Do not score the glass at the second etching location yet. It is also important the single etched line's *start and finish meet cleanly* to produce a clean break in the glass.

d. You may want to brace the wine glass globe against a table or other durable surface as you score the glass stem. Remember, you **ARE** wearing protective gloves and glasses!

4. To detach the base from the stem of the wine glass, sharply tap the base against a hard surface, in one smooth yet firm motion, *abruptly halting the motion as the wine glass base hits the surface*. The base should strike the surface at an angle while the globe is protected in your gloved hand and the stem does not hit the surface. See Appendix B, Image 4. The glass should break cleanly at the scored line. If not, repeat the motion again with slightly more force. If it still does not break cleanly, carefully etch a slightly deeper groove into the *same score line*, making sure NOT to etch any additional lines. Repeat the firm tapping motion with less force before proceeding to a more forceful tap. If the base breaks away from the stem but produces an attached shard to the base, firmly hold the base and tap the shard against a hard surface at an angle, which will likely break away at the scored line mark.

   Suggested appropriate hard surfaces to strike the glass against are a wooden table or bench top, a low pile carpet over concrete floor, a linoleum floor, etc. You want a hard surface that has a slight "give" in its firm surface.

5. File down any sharp glass edges at the break of the detached base. We want to eliminate any possibility of injury. This will yield a disk-shaped lens. See Appendix B, Image 5 for examples of finished disc gravitational lens.

6. To produce another gravitational lens from the leftover wine glass globe and remaining stem, repeat steps 3 through 5 with the following notes:

   a. Be very careful handling the end of the stem, as this is very sharp and can easily injury you.

   b. The approximate location of second score line is noted in Appendix B, Image 1. The best position for the score line is very dependent on the type of wine glass you possess. How thick the glass is where the stem meets the globe and if you want to demonstrate more or less of lensing effect determines your choice. Most clear wine glass bases are quite similar, where as the globes vary greatly. We suggest you choose a score line that will result in more glass material in the globe lens than the base lens you just made, so show a stronger gravitational lens effect. See Appendix B, Image 5 for examples of different type globes.

c. Sharply strike the remaining stem and globe against a hard surface (AFTER you make the second scored line about the top of the stem, of course), you will very likely produce glass shards from the stem. Be aware of this. Thoroughly file down any sharp edges.

7. You have now made two gravitational lenses from one wine glass. Try creating another set from a different style or shaped wine glass. If not successful, try again with another wine glass. Always dispose of any glass material deemed a potential hazard.

SET UP

8. In the room where you plan to do the demonstration, post your background image on one of the far walls.

9. (Optional) If using a video camera, position the camera on a tripod and aim it at the background image or the position a person would stand to be imaged by the device.

10. (Optional) You may affix the base of the wine glass in front of the camera, with the cut end away from the camera.

ACTIVITY

11. Explain to your audience that a black hole distorts the view of space and time around it. (This is a very weird idea!)

12. If cut edge is not perfectly smooth, *FILE DOWN* these sharp edges *BEFORE* presenting to an audience. Otherwise, closely supervise the apparatus with protective gloves. Caution your volunteer(s) not to drop the breakable and fragile “black hole lens.”

13. Invite your volunteer(s) to view the world through their “black hole lens” by looking at the background image through the base of the wine glass. Alternatively, view the background image with the video camera as you pass the “black hole lens” in front of camera’s lens OR have someone walk through the location where the camera and “black hole lens” is focused on. What’s the view?

14. Can you create an “Einstein ring”—a very thin ring around the center of the lens—by looking at the image through the lens and just the right angle?

Discussion:

Einstein predicted that the actual shape of space and time around a massive object is distorted by the object's gravity. Light from a distant object would travel in a straight path to the observer, but if that light happens to pass close to a massive object, the light would follow the curved, warped space around the massive giant. This gravitational lens effect allows these massive objects to act like lenses that focus and amplify the light from distant objects.

Arthur Eddington was first to observed a shift in a distant star's position as its light passed close to a massive object to the way to an observer. During a solar eclipse in 1919, Eddington measured how a star's position shifted when observed near the Sun as compared to when it was not. This measured deflection matched Einstein's predictions of how the Sun's gravity would distort space (and time).

What must the geometry of the observer, the gravitational lens and the distant object of interest be for this effect to be seen? How easy is it to move the observer? Or the gravitational lens to point at the object you want to observe?

These ideas are explored in more depth in the scientist presentation "Einstein's Lens," available at http://www.universeforum.org/einstein/resource_lensing.htm. This presentation includes an image of the 1919 *New York Times* headline!

Accompanying Visual Resources:

Gravitational Lensing Simulation
http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/01/video/a
Short animation shows the gravity of a massive foreground object warping space. The light of background galaxies is bent as it passes the gravitational lens making the galaxies appear distorted and brighter. Credit: STScI, NASA

Baltimore's Inner Harbor Seen Through a Gravitational Lens
http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/01/video/b
Simulation of a gravitational lens moving across the Baltimore city skyline. The lens is produced by a compact and massive object, which bends space around it. This distorts light coming from any object behind the lens. The simulation shows how the lens distorts the background buildings. Credit: Frank Summers (STScI, NASA)

Image of Smithsonian Castle Seen Through a Gravitational Lens
http://cfa-www.harvard.edu/~bmcleod/castle.html
Image of how the Smithsonian Castle might look if a black hole with the mass of Saturn appeared in the middle of the National Mall. The effect is caused when a massive gravitational force bends light. Credit: Brian McLeod, SAO

Image of Abell 2218, A Galaxy Cluster Lens
http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/07/image/b
The massive galaxy cluster Abell 2218 is so compact that its gravity bends and focuses light from galaxies behind it. Acting as a telescope, Abell 2218 distorts these background galaxies into long faint arcs, allowed astronomers to detect the most distant galaxy yet measured. This young, still-maturing galaxy is faintly visible to the lower right of the cluster core. Credit: Andrew Fruchter (STScI) et al., HST, NASA.

Image of Abell 1689, A Galaxy Cluster Lens
http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/01/
The galaxy cluster Abell 1689 is one of the most massive objects in our universe. As predicted by Einstein's theory of gravity, the collective mass of this cluster is warping space, causing light from galaxies behind to bend, producing the faint bluish arcs visible in this image. This effect is a product of the combined mass of the galaxies and the dark matter in this cluster. Credit: NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA

Create your own Gravitational Lens with your image processor!
http://leo.astronomy.cz/grlens/grl0.html
Image processing software can be expanded by use of plug-in filters to create your own gravitational lens effects on any image. Provided by Leos Ondra, with assistance from the Filter Factory plug-in by Joseph Ternasky and Dave Corboy.

10. Spaghettification

What happens if you fall into a black hole?

http://www.adlerplanetarium.org/education/resources/gravity/5-8_gq5-2.shtml

Supplies
- A pair of scissors (If you need help with scissors, ask a parent or guardian)
- A stapler and staples
- Spaghettification Flip Book picture page, found at the end of this manual
- Colored Pencils
- Ruler
- (Optional) "Funhouse" mirror

Procedure

1. Print out the page below with the pictures of the astronaut on it.
2. Color the astronaut pictures.
3. Carefully cut out the 8 images of the astronaut.
4. Put the images in a stack, with #1 on top, then #2, then #3, and so on...
5. Staple the pictures together using the small lines in picture #1 as a guide.
6. Flip sheets from back to front. The spaceman should appear to stretch like the animation on the http://www.adlerplanetarium.org/education/activities/make-and-do/spaghettification.shtml
7. (Optional) For younger visitors who may not have the motor skills to create a flipbook, you can introduce this idea with a fun-house mirror that appears to stretch the visitors' legs.

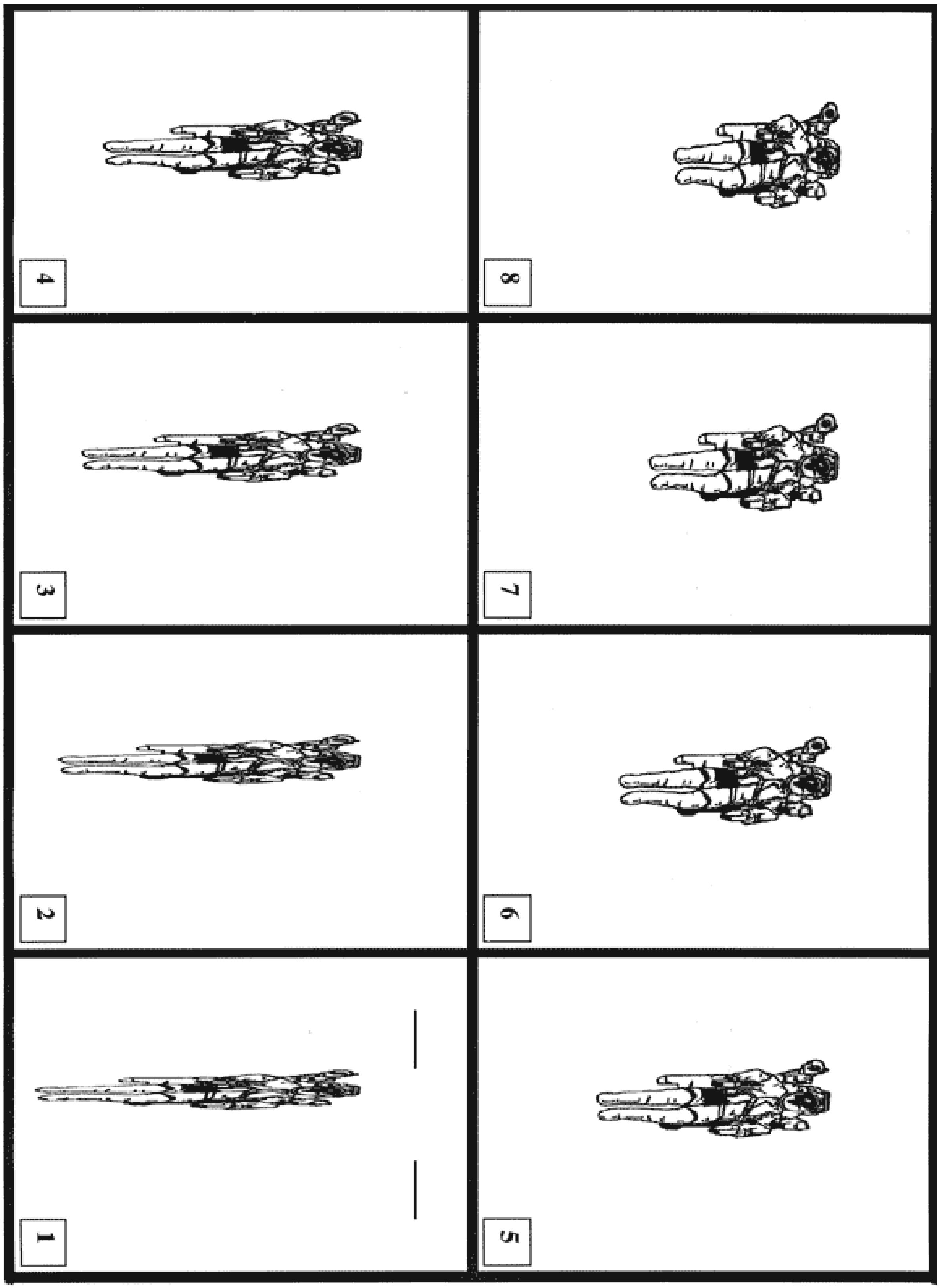
Discussion

No person has ever been close enough to a black hole to actually fall into one, but if a person ever got close enough, their body would stretch out as they were pulled into the black hole. This activity has visitors create a spaghettification flip book that will demonstrate how the strong gravitational pull of a black hole would stretch any astronaut unlucky enough to encounter one in space. It is called spaghettification because small objects will grow long and stringy like spaghetti as they are pulled into the black hole.

Gravity is what causes spaghettification. The force of gravity between two objects depends on three things: the mass of each object and the distance between them. The closer the two objects are the stronger the force of gravity between them. So if this imaginary astronaut is falling feet first towards a black hole, his feet are closer to the center of the black hole than his head. The force of gravity is therefore stronger on his feet than on his head. The difference in pull creates what is called a tidal force. This makes the astronaut (or anything else that gets too close) stretch out long and thin. The tides on Earth are caused by the tidal forces created by the Moon.

Accompanying Visual Resources:

Animation of a Star Ripped Apart by a Giant Black Hole
http://chandra.harvard.edu/resources/animations/blackholes.html
This animation shows what happens to a star that drifts too close to a giant black hole. At this very close distance, the star is subjected to the tidal forces caused by the black hole's gravity. The star is ripped apart by these forces and part of it is drawn into orbit around the black hole. The part that does not get drawn into orbit continues its journey through space.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Appendix A: Locations of Known Black Holes

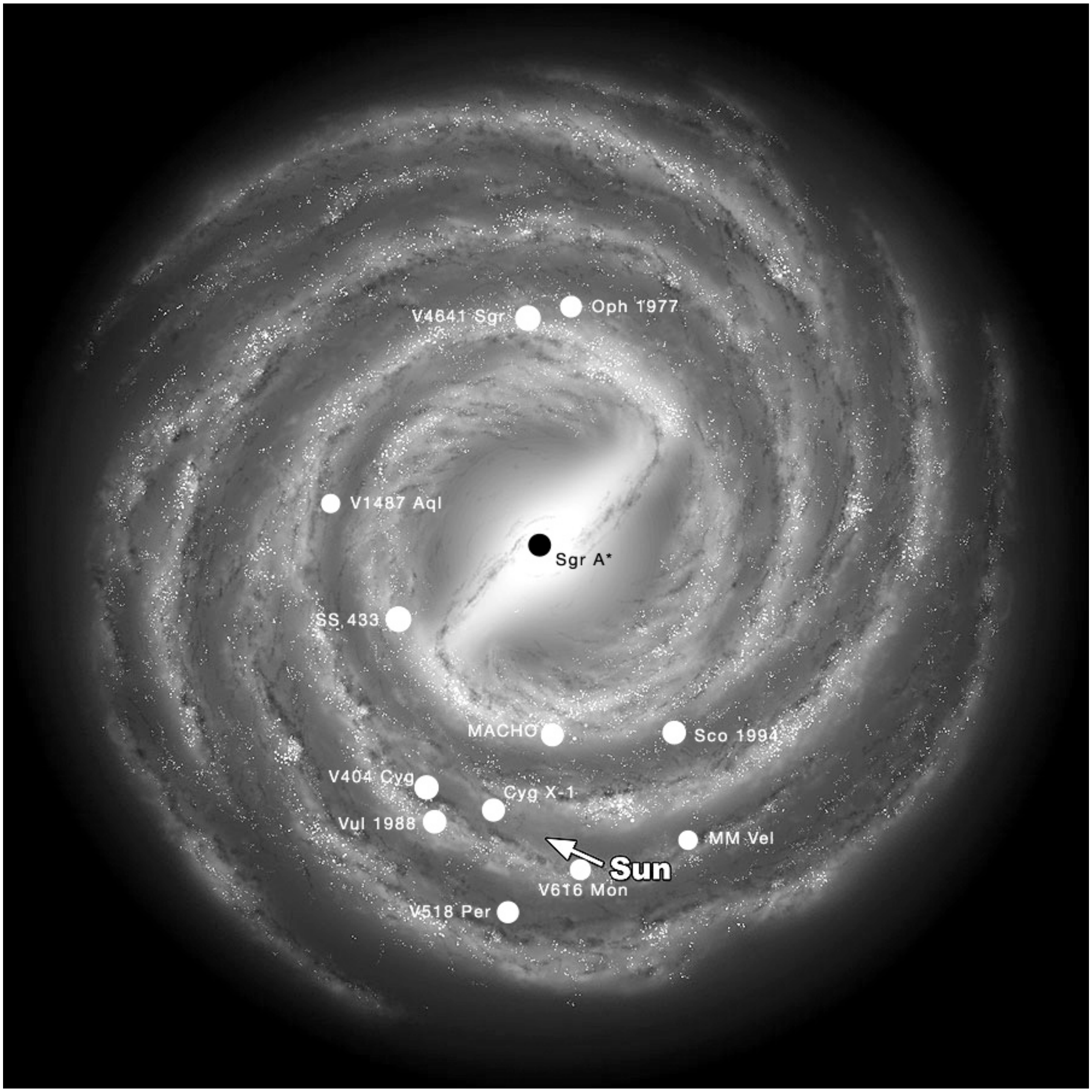
Stellar-mass Black Holes in our Milky Way galaxy

Name	Mass	distance light years	distance Miles*	Type**
V518 Per	4 solar	6500	163	Low Mass X-ray Binary
V616 Mon	11 solar	2700	68	LMXRB
MM Vel	4.5 solar	10,000	250	LMXRB
Nova Sco 1994	6 solar	10,000	250	LMXRB
Nova Oph 1977	7 solar	33,000	825	LMXRB
MACHO-98-BLG-6	6 solar	6,500	163	gravitational lensing event
V4641 Sgr	7 solar	32,000	800	microquasar
SS433	10 solar	16,000	400	BH with jet (microquasar)
V1487 Aql	14 solar	39,000	975	LMXRB
Cygnus X-1	10 solar	7,000	175	High mass X-ray binary
Nova Vul 1988	7 solar	6,500	163	LMXRB
V404 Cyg	12 solar	8,000	200	LMXRB

* Miles equivalent in the scale Milky Way model (Activity 1). 1 Mile = 40 light years
** High or Low mass refers to the mass of the companion star, not to the mass of the black hole itself.

Name	Coordinates		Magnitude	Companion	Orbital
	RA	Dec	M(V)	Spectrum	Period
V518 Per	04 21 43	+32 47	13.2	M4	5h
V616 Mon	06 22 44	-00 20	18.2	K4V	7.75h
MM Vel	10 13 36	-45 04	14.9	K6V	6.9h
Nova Sco 1994	16 54 00	-39 50	14.4	F5IV	15hr
Nova Oph 1977	17 08 14	-25 01	21	K5V	12.5hr
MACHO-98-BLG-6	17 57 33	-28 42	16	isolated	N/A
V4641 Sgr	18 19 22	-25 24	4	B9III	68hr
SS433	19 11 50	+04 59	14.2	A7I	13d
V1487 Aql	19 15 11	+10 56		K/M	820 hr
Cygnus X-1	19 58 22	+35 12	8.95	O9I	5d
Nova Vul 1988	20 02 50	+25 14	21	K5V	8.2hr
V404 Cyg	20 24 04	+33 52	11.5 (B)	K0IV	6d

Black Hole Locations in the Milky Way



Milky Way illustration courtesy NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

A color version of this map is available at
http://www.universeforum.org/einstein/resource_journeyblackhole.htm

You can overlay this map with a map of North America and assign physical locations to these objects, using the distances given under “Miles” in the table above.

Intermediate Mass Black Holes

Name	R.A.	Declination	Distance (1 Mly = 10^6 ly)	Mass (solar masses)
M110	00 40 25	+41 41 16	2.3 Mly	90,000
M31 G1	00 42 44	+41 16 08	2.3 Mly	90,000
M82	09 55 54	+69 40 57	12 Mly	>460
M15	21 29 58	+12 10 01	33,000 lyr.	2,500

Supermassive Black Holes

M31	00 42 44	+41 16 08	2.5 Mly	30 million
M33	01 33 51	+30 39 36	2.6 Mly	900,000
NGC 821	02 08 21	+10 59 42	79 Mly	37 million
M77	02 42 41	-00 00 47	49 Mly	15 million
NGC 3115	10 05 14	-07 43 07	32 Mly	1 billion
M105	10 47 49	+12 34 54	35 Mly	100 million
Mkn 421	11 04 27	+38 12 32	370 Mly	190 million
NGC 4151	12 10 33	+39 24 20	50 Mly	10 million
NGC 4459	12 29 00	+13 58 43	52 Mly	70 million
3C 273	12 29 06	+02 03 08	2146 Mly	billion
NGC 4473	12 29 48	+13 25 45	51 Mly	80 million
M87	12 30 49	+12 23 28	52 Mly	3 billion
NGC 4579	12 35 12	+12 05 36	55 Mly	2 million
M104	12 39 59	-11 37 23	30 Mly	500 million
NGC 5033	13 11 08	+36 51 48	61 Mly	500 million
NGC 5845	15 06 01	+01 31 01	84 Mly	240 million
NGC 6251	16 32 32	+82 32 17	300 Mly	600 million
Mkn 501	16 53 53	+39 45 36	420 Mly	1.6 billion
Sgr A*	17 45 40	-29 00 29	26000 ly	2 million
3C 371	18 06 06	+69 49 28	620 Mly	320 million
NGC 7052	21 18 33	+26 26 49	190 Mly	330 million
BL Lac	22 02 43	+42 16 40	937 Mly	billion
NGC 7457	23 01 00	+30 08 43	43 Mly	3.5 million

Appendix B: Pictures of Black Hole Lensing Equipment

Image 1: Materials for creating a gravitational lens out of a wine glass

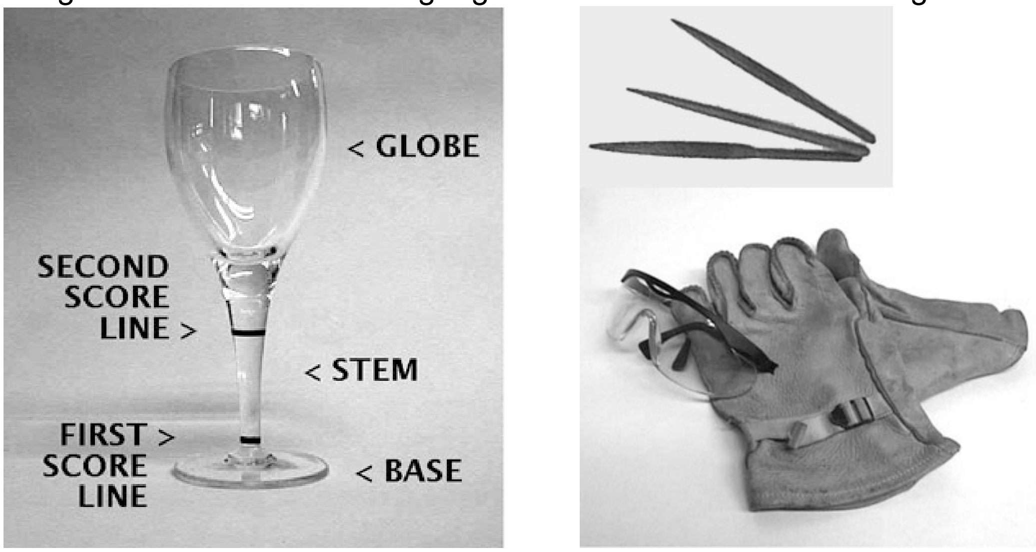
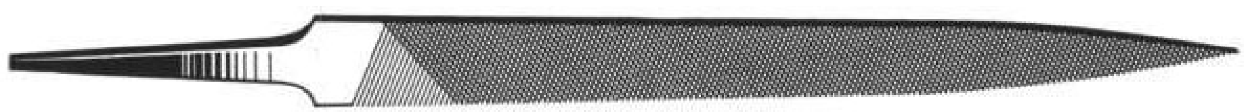


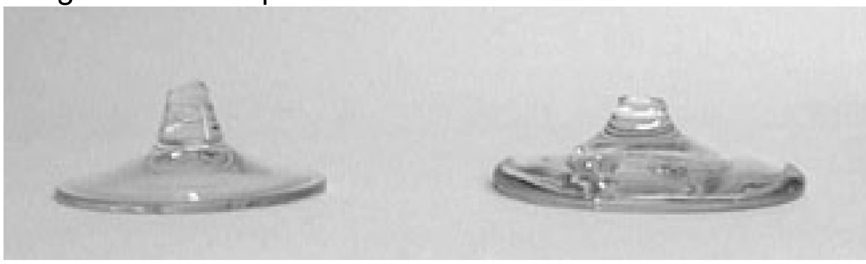
Image 2: Fine file tool for etching the base of glass:



The fine tool file for etching the glass can be a simple mill flat, square, taper, three-square or even a half-round file, as long as the file has an edge and cuts a fine line pattern. These fine finishing files made of carbon steel are also called Swiss-pattern files. Fine tool files produce very precise etched marks that score glass well. A coarse and random etched pattern is not desired and will produce a poor break in the glass. If you possess a non-round diamond file, use that tool instead, especially if you will be making numerous gravitational lenses. Diamond files are quite expense and are not necessary for making a few etches in glass, as fine carbon steel files work well.

Image 3: Removing the stem from the wine glass

Image 4: The completed lenses



The globe on the right will show stronger lensing effects than the left globe.

Image 6: A view through the lens

Note the distortion of red EXIT sign around the curve of the glass.

More NASA Resources on Black Holes

Universe Education Forum
http://www.universeforum.org/blackholelanding.htm

Imagine the Universe!
http://imagine.gsfc.nasa.gov/docs/science/know_l2/black_holes.html

Chandra X-ray Observatory
http://chandra.harvard.edu/xray_sources/blackholes.html

The "Inside Einstein's Universe" program and our affiliates offers a number of additional resources related to black holes:

"Black Hole Explorer" board game
http://www.universeforum.org/einstein/resource_BHExplorer.htm

Featured Black Hole Visualizations
http://www.universeforum.org/einstein/resources_visual.htm

MicroObservatory Black Hole Search
http://www.MicroObservatory.org

"Hunting for Black Holes" scientist presentation
http://www.universeforum.org/einstein/resource_hunting.htm

"Einstein's Lens" scientist presentation
http://www.universeforum.org/einstein/resource_lensing.htm

Space Time Laboratory
http://www.universeforum.org/bh_popup_spacetimelab.htm

Gamma-ray Burst Real-time Sky Map
http://grb.sonoma.edu

Chandra Resource Request Form
http://chandra.harvard.edu/edu/epo/request/index.html

We are always interested in how people are using these resources. You can contact the Universe Forum at einstein2005@cfa.harvard.edu or let us know about any special black hole events you have here: http://www.universeforum.org/eventreport.html

Thank you for your interest in the "Inside Einstein's Universe" program!