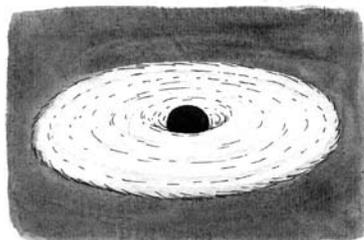


Monster of the Milky Way

PROGRAM OVERVIEW

NOVA explores the nature of black holes and follows scientists as they seek to understand the supermassive black hole at the center of our galaxy.



The program:

- explains how a black hole forms and provides simulations revealing what might be the nature of space surrounding and inside a black hole.
- details the nature of the event horizon that surrounds the black hole—nothing within the horizon, including light, can escape its gravity.
- chronicles how astronomers first found evidence supporting the existence of black holes and details the methods they used to infer the presence of these unobservable objects.
- follows astronomers who race to confirm the existence of a supermassive black hole in the center of our Milky Way galaxy.
- notes that astronomers have already found evidence that suggest there may be supermassive black holes at the centers of nearly all large galaxies throughout the universe.
- suggests how these black holes may have formed.
- reviews how black holes may affect the matter surrounding them and explores theories about how they evolve.
- recounts how, since 2002, astronomers worldwide have been able to observe the galactic center's black hole flaring up.
- considers what may happen to the galactic center's black hole when it eventually encounters a larger black hole found in the nearby Andromeda galaxy.

Taping Rights: Can be used up to one year after program is recorded off the air.

BEFORE WATCHING

- 1 List on the board what students know about black holes. Where did students learn their information (e.g., science fiction books or movies, articles, news reports)? Have students rate each fact with how confident they feel about its accuracy. Add any questions students have about black holes.
- 2 Organize the class into three groups and have each group take notes on one of the following topics: how astronomers search for black holes and the challenges of learning about them, what is known about black holes in general, and what is known about the supermassive black hole in the center of our galaxy.

AFTER WATCHING

- 1 Have each group that took notes on the same topic present their notes to the class. Review how scientists determined what is in the center of our galaxy. What evidence led them to know it was a supermassive black hole? What do scientists still want to know about black holes?
- 2 Based on the information from the program, have students revisit the list on the board and compare their previous understanding to what they know now. Have students provide data to support or disprove the facts and answer the questions listed. Assign teams to research and report back any remaining facts or questions not answered by the program.

CLASSROOM ACTIVITY

Activity Summary

In Part I, students use a balloon and aluminum foil ball model to explore changes in density vs. volume as a massive star evolves into a black hole. In Part II, students turn to calculations to discover the implications of increasing density with decreasing size.

Materials for Teacher

- glass of water
- piece of wood
- aluminum pellet
- iron rod
- piece of gold jewelry
- overhead transparency
- set of different-colored transparency pens

Materials for Each Team

- copy of the “Dense, Denser, Densest?” student handout
- copy of the “Getting Really Dense” student handout
- 50-cm-long piece of aluminum foil (by standard 30.4 cm wide)
- one 22.86 cm (9-in) balloon
- 44-cm-long piece of string
- pan balance
- tape measure
- graph paper
- calculator

Background

A star spends most of its life fusing hydrogen into helium. During this time, a balance exists between the energy being released and the gravity of the star. Once a star uses up all the hydrogen in its core, gravity takes on a bigger role. Gravity’s influence on the core causes it to contract further, setting off a cascade of fusion of lighter elements into heavier ones. In very massive stars this cascade continues until only non-fusible iron remains. During this process, the core releases a far greater amount of energy, which radiates outward and expands the gas in the outer layers of the star. As a result, the star swells. Even though the total amount of energy emitted goes up, because of its large size, the star actually cools off. It becomes red and bloated, so astronomers call this kind of star a “red giant.”

Eventually, gravity once again comes to dominate. If the star is massive enough (a mass more than about 20 times greater than that of our sun), then it can fuse iron nuclei. Because iron takes more energy to fuse than it releases, the core is robbed of the heat it needs to balance gravity. (This process also absorbs electrons, which help support the core against its own crushing gravity.) When iron begins to fuse, it’s like the legs are kicked out from under the core. It collapses inward within only a fraction of a second, releasing a vast amount of energy which flashes outwards, tearing off the outer layers of the star. The star explodes in an event called a supernova.

LEARNING OBJECTIVES

Students will be able to:

- name the major characteristics of a black hole.
- understand that the density of an object is the ratio of its mass to its volume.
- calculate density.

KEY TERMS

black hole: A collapsed star that has a region surrounding it from which nothing can escape, not even light.

density: A characteristic of matter defined by the amount of mass of material per unit volume.

event horizon: The boundary of a black hole that marks the region surrounding the black hole from which nothing can escape. The radius of this region is known as the Schwarzschild radius.

fusion: The process in which the nuclei of atoms combine to form larger ones at high pressure and temperature.

gravitational force: The force of attraction between objects that contain either mass or energy.

mass: The amount of matter a sample of material contains, measured in grams or kilograms.

neutron star: An extremely small, super-dense star formed as a result of a supernova explosion.

Schwarzschild radius: The radius of the event horizon of a black hole.

volume: The amount of space matter occupies.

CLASSROOM ACTIVITY (CONT.)

What happens to the core when it collapses depends on its mass. If it is between 1.4 and three to four times as massive as our sun, it will become a dense neutron star (a neutron star is about 11 kilometers in diameter; a teaspoonful of it weighs about a billion tons—as much as all the cars on Earth would weigh). Up to a certain size, a neutron star can resist the inward pull of gravity. But if it is more than two and a half solar masses, gravity wins and the neutron star collapses into a black hole. When this happens, the core digs itself deep into the fabric of spacetime, crushing the matter itself right out of existence. All that remains is a region of extremely curved spacetime, the ghost of the collapsed stellar core, the center of which is called a singularity.

Because black holes are so compact, their gravitational pull is such that once something ventures too close, it cannot escape. Not even light can break out. The point of no return is the event horizon surrounding the black hole. Matter within the horizon falls inexorably down to the very center, where it gets crushed in the black hole's singularity, an unfathomable place of collapsed space and time, where the known laws of physics break down.

The radius of this sphere-shaped event horizon, known as the Schwarzschild radius, varies according to the black hole's mass. The expression that determines the radius of the event horizon is:

$R = 2GM/c^2$, where R is the radius of the event horizon, M is the mass of the black hole in kg, 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 $c = 3 \times 10^8 \text{ m/sec}$)

Material falling into the black hole forms an accretion disk of gas and dust outside of the event horizon, which spirals inward toward the black hole. In addition, the black hole may have jets of hot gas and energy streaming outward perpendicular to the accretion disk.

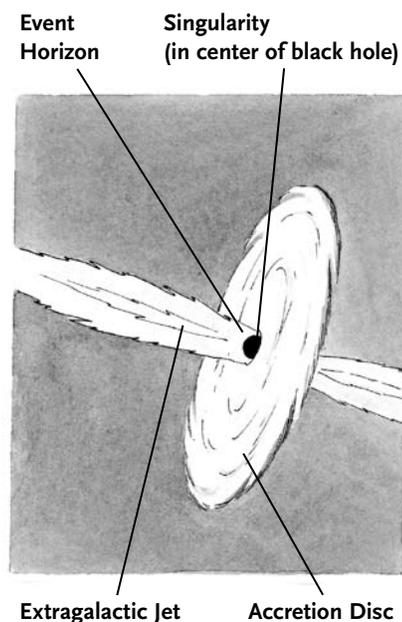
Some scientists claim that black holes open onto other universes. No one really knows. While black holes have been studied mathematically, no one has directly observed one. Astronomers infer the existence of black holes from the effect they have on the material around them (i.e., observing X-ray emissions resulting from gas being heated near a black hole due to its strong gravitational pull). Our Milky Way galaxy has a supermassive black hole in its center with a mass four million times that of the sun. Moreover, every decent-sized galaxy likely has one of these supermassive black holes in its core.

In the first part of this activity, students use aluminum balls to model the formation of a black hole. Students associate the physical act of crushing aluminum foil (using mechanical forces) into smaller and smaller spheres with the gravitational effects on a collapsing star. In the second part of the activity, students calculate the aluminum ball's density as it becomes smaller and smaller. They also consider how small it would need to be to become a black hole.

HOW BLACK HOLES FORM

www.pbs.org/nova/blackholes/form.html

Find a description and images related to black hole formation in this NOVA slide show.



CLASSROOM ACTIVITY (CONT.)

Procedure

Part I

- 1 Prior to the activity, set up the balances at student lab stations. Create enough 50-centimeter sheets of aluminum foil for each team.
- 2 To introduce the activity, ask students what they know about black holes. Ask them how they think black holes form. Use the background information to review how black holes are formed, what their components are, and where they are believed to exist.
- 3 Explain to students that they will be modeling how a star's interior, called the core, evolves into a black hole. The balloon students blow up represents a star 20 times the mass of our sun shining steadily as it converts its interior reserves of hydrogen to helium, a process known as nuclear fusion. The tension in the balloon material represents gravity trying to collapse the star's core, and the pressure from the air inside the balloon represents the heat in the star's core trying to make it expand. The aluminum foil represents the star's core. Guide students through what each stage represents prior to or during the activity:
 - The first aluminum ball that students form symbolizes the star's core during most of its lifetime. Ask students to imagine that this core is inside the balloon and is surrounded by layers of the star as it burns its hydrogen fuel. The star itself is vastly larger than the aluminum ball.
 - The first compaction represents what happens after the star burns through its hydrogen fuel, becomes a red giant, and then cools and begins to fuse lighter elements into heavier ones, all the while becoming increasingly more dense. The star alternately heats and cools during this time and gravity takes on a bigger role each time the star cools. Have students continue to visualize the core inside the balloon.
 - The second compaction symbolizes the iron core that is left after the star has burned through all its lighter elements. When iron fuses, it takes away energy from the core that is needed to support the star. Once this happens, gravity takes the upper hand and the star's core collapses under its own weight. The star goes supernova.
 - Crushing the aluminum ball down further with the hammer symbolizes the hot, dense core left behind after the star goes supernova. (Students will pop the balloon prior to making this compaction to symbolize the supernova explosion.) At this point, a quantum mechanical effect called neutron degeneracy pressure prevents further collapse. However, if the neutron star is more than two and a half solar masses, gravity is so strong that even the nuclear forces from the neutron star can't stop it—the core will collapse and become a black hole.

STANDARDS CONNECTION

The “Dense, Denser, Densest?” activity aligns with the following National Science Education Standards (see books.nap.edu/html/nses/).

GRADES 5–8

Science Standard B

Physical Science

- Properties and changes of properties of matter
- Motions and forces

GRADES 9–12

Science Standard B

Physical Science

- Conservation of energy and increase in disorder
- Structure of atoms
- Motions and forces

Science Standard D

Earth and Space Science

- The origin and evolution of the universe

Video is not required for this activity.

Classroom Activity Author

Jeff Lockwood taught high school astronomy, physics, and Earth science for 28 years. He has authored numerous curriculum projects and has provided instruction on curriculum development and science teaching methods for more than a decade.

CLASSROOM ACTIVITY (CONT.)

- 4 Discuss the limitations of this model with students. *(This model is intended to approximate the stages a star goes through on its way to becoming a black hole; it does not accurately represent the sizes of the core or the layers surrounding a star at various times in its life cycle or of the actual compaction of matter in a star.)*
- 5 Prior to beginning the activity, discuss density with students. Show students the glass of water, piece of wood, aluminum pellet, iron rod, and piece of gold jewelry. Ask students which items they think are most dense. Why? Discuss density, providing the density of the objects you have shown:
 - wood (0.5 g/cm³)
 - water (1 g/cm³)
 - aluminum (2.7 g/cm³)
 - iron (8 g/cm³)
 - gold (19.3 g/cm³)Point out that the average density of the sun is 1.4 g/cm³ (note that the sun is about 1/20th the mass of a star that would become a black hole). Inform students that as forces are applied to most (non-liquid) substances and they are squeezed into a smaller space or volume, their density changes.
- 6 Draw a one-centimeter cube on the blackboard. Ask students which of the following elements would weigh the most (be the most massive) within the box: water, aluminum, or gold. *(Gold, the densest naturally occurring element on Earth. The box will hold 1 gram of water, 2.7 grams of aluminum, or 19.3 grams of gold.)*
- 7 Organize students into teams and distribute the student handouts and materials to each team. Review activity directions with students.
- 8 Have students inflate their balloons until the string goes just around the widest part of the balloon (about twice the size of a grapefruit) and then tie the balloons off. Then have students use string or measuring tape to measure, in centimeters, the balloon's diameter in two directions, at 90-degree angles to each other, to find the average diameter and radius. Help teams through this process if needed.
- 9 Have students follow the directions listed on their "Dense, Denser, Densest?" student handout. After students have compressed and remeasured their aluminum ball twice they will bring it to you to hammer down further. Note that it is fairly difficult to compress the foil to a sphere with a diameter of less than two centimeters. (See Activity Answer on page 7 for a typical value.)
- 10 Have each team report its data points for you to plot on the overhead (plot volume on the y-axis and density on the x-axis). Use a different color for each team's results. This will allow you to discuss reasons for any data differences and delete any outliers before you draw a final best-fit curve. The graph will appear to be headed to zero. Ask students whether the aluminum ball really goes away. *(In the case of the creation of a black hole, for all practical purposes the matter collapses to infinite density, but mathematically it does not disappear entirely. You may want*

CLASSROOM ACTIVITY (CONT.)

to note to students that if you were to continue to magnify the graph, it would come very close to zero—about 10^{-50} —but would not reach it.)

- 11 To conclude, hold up the aluminum pellet again. Tell students that the aluminum pellet demonstrates the maximum density of aluminum obtainable on Earth (2.7 g/cm^3). (Forces between the electrons of each atom repel each other more strongly than any force on Earth that could make the pellet smaller.) Explain that only in the collapse of massive stars during supernova events can forces be exerted strongly enough to overcome the repulsion of the electrons in the atoms. In fact, when very large stars go supernova, even the forces of repulsion in the nuclei of atoms are overcome, enabling the mass in the core of the star to be compressed until it virtually disappears and a black hole is formed.
- 12 If you would like, continue to the next part of the activity to have students work out on paper how much the density of the aluminum would need to be increased for it to become a black hole.
- 13 As an extension, have students create a time line of the theory of black holes and observational evidence that supports their existence.

Part II

- 1 In this part of the activity, students will calculate the increasing density of their aluminum stars as they get smaller and smaller. Have students perform the calculations up until their aluminum stars are calculated to be the size of neutrons (the average radius of a neutron is equal to 10^{-15} m).
- 2 Once they have completed the neutron calculations, inform students that as dense as their aluminum star would be if it were the size of a neutron, that is nothing compared to what happens when a neutron star becomes a black hole—when the star becomes unimaginably dense in virtually zero volume! Tell students that this is a very hard model to conceptualize as there is nothing that exists in our normal experience that it can be compared to.
- 3 Have students perform the final calculation of how small the aluminum star would have to be to become a black hole, and then how large the black hole's event horizon would be. Discuss with students whether it would be possible to create a black hole out of a piece of aluminum foil. *(It is theoretically possible, but would take more energy than is currently available.)*
- 4 As an extension, have students calculate the Schwarzschild radius of the black hole in the center of our Milky Way galaxy, which is thought to have a mass of about 4 million suns (mass of our sun = 2×10^{30} kilograms)

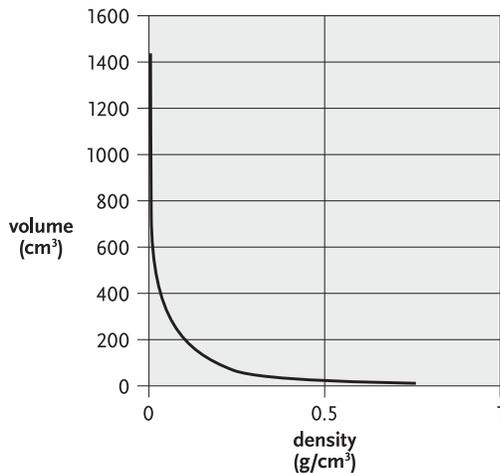
$$R = 2GM/c^2 = 2 \times 6.67 \times 10^{-11} \text{ m}^3/\text{kg}\cdot\text{sec}^2 \times (4 \times 10^6 \text{ suns} \times 2 \times 10^{30} \text{ kg/sun}) / (3 \times 10^8 \text{ m/sec})^2 = 1.2 \times 10^{10} \text{ m or } 1.2 \times 10^7 \text{ km or } 7.4 \text{ million miles in radius}$$

ACTIVITY ANSWER

Sample Data Table and Graph*

Part I

Trial #	Mass (g)	R ₁ (cm)	R ₂ (cm)	R _{avg} (cm)	V (cm ³)	D (g/cm ³)
1	14.1	7.6	6.4	7.0	1,432	0.0098
2	14.1	4.5	4.7	4.6	406	0.035
3	14.1	2.5	2.3	2.4	58	0.24
4	14.1	1.7	1.5	1.6	17	0.83



* Measurements based on two sheets of foil about 50 centimeters in length and a balloon about 14 centimeters in diameter. The total mass of aluminum is 14.1 grams in the example.

Part II

Going down to ... one centimeter

$$V = 4/3\pi R^3 = 1.33 \times 3.14 \times (1 \text{ cm})^3 = 4.19 \text{ cm}^3$$

$$D = M/V = 14.1 \text{ g}/4.19 \text{ cm}^3 = 3.437 \text{ g/cm}^3$$

And farther down to ... one millimeter

$$V = 4/3\pi R^3 = 1.33 \times 3.14 \times (.1 \text{ cm})^3 = .0019 \text{ cm}^3$$

$$D = M/V = 14.1 \text{ g}/.0042 \text{ cm}^3 = 3370 \text{ g/cm}^3$$

And farther down to ... a neutron

$$V = 4/3\pi R^3 = 1.33 \times 3.14 \times (1 \times 10^{-13} \text{ cm})^3 = 4.0 \times 10^{-39} \text{ cm}^3$$

$$D = M/V = 14.1 \text{ g}/4.2 \times 10^{-39} \text{ cm}^3 = 3.4 \times 10^{39} \text{ g/cm}^3$$

And finally down to a ... black hole

$$V = 4/3\pi R^3 = 1.33 \times 3.14 \times (\text{approaches } 0)^3 = 0 \text{ cm}^3$$

$$D = M/V = 14.1 \text{ g}/0 \text{ cm}^3 = \infty$$

Your black hole's event horizon

$$R = 2GM/c^2 = 2 \times 6.67 \times 10^{-11} \text{ m}^3/\text{kg}\cdot\text{sec}^2 \times .0141 \text{ kg}/(3 \times 10^8 \text{ m/sec})^2 \\ = 2.09 \times 10^{-29} \text{ m}$$

The size of the event horizon if our sun were to become a black hole

$$R = 2GM/c^2 = 2 \times 6.67 \times 10^{-11} \text{ m}^3/\text{kg}\cdot\text{sec}^2 \times 2 \times 10^{30} \text{ kg}/(3 \times 10^8 \text{ m/sec})^2 \\ = 3,000 \text{ m (about 3 km)}$$

ACTIVITY ANSWER

What would life be like on Earth if the sun was replaced by a black hole with the mass of the sun?

There would be no light or warmth because no light could escape the black hole. Anything falling into the black hole would make X-rays and possibly gamma rays, sending out lethal amounts of radiation. Nothing could survive. However, assuming that the black hole was the same mass as the sun, the Earth would continue to orbit as it does now.

Would Earth be sucked into the black hole?

Earth would not be sucked into the black hole, assuming the black hole had the same mass as the sun. Since the mass at the center of the solar system remains the same, Earth's orbital velocity and path would not change.

Major funding for NOVA is provided by Google. Additional funding is provided by the Howard Hughes Medical Institute, the Corporation for Public Broadcasting, and public television viewers.

Google™ HHMI 

Major funding for Monster of the Milky Way is provided by the National Science Foundation and by NASA's Gamma Ray Large Area Space Telescope (GLAST).



This material is based upon work supported by the National Science Foundation under Grant No. ESI-0337286. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

LINKS AND BOOKS

Links & Books

Links

NOVA—Monster of the Milky Way
www.pbs.org/nova/blackhole
Watch the program online, learn about how black holes form, discover what little black holes are, look at some of the other marvels of the universe, and more.

Black Hole Encyclopedia

hubblesite.org/explore_astronomy/black_holes/encyclopedia.html
Explains the nature, formation, and existence of black holes.

Black Holes

glast.sonoma.edu/teachers/blackholes/index.html
Provides information about black holes; an educator's guide of activities; and links to additional lessons, games, and resources about black holes.

No Escape: The Truth about Black Holes

amazing-space.stsci.edu/resources/explorations/blackholes/teacher/sciencebackground.html
Contains background information about black holes, including facts about how they form, how light can be trapped in them, the kinds of black holes that exist, and more.

Books

A Nature Company Guide: Skywatching

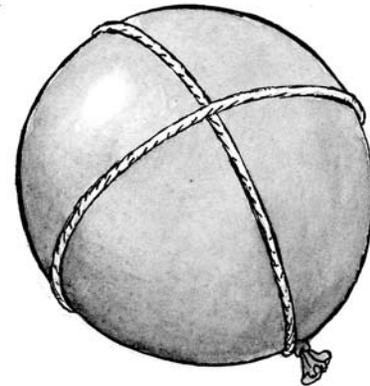
by David H. Levy.
Time-Life Books, 1995.
Provides a general overview and discussion of astronomical objects, including black holes.

The Young Oxford Book of Astronomy

by Jacqueline & Simon Mitton.
Oxford University Press, 1995.
Explains many concepts in astronomy from the solar system, galaxies, and the universe, including black holes.

Dense, Denser, Densest?

Black holes are some of the most intriguing objects in the universe. They have tremendous mass and density, so nothing can escape once it has fallen in, not even light. But how do black holes form? In this activity, you will use a model to investigate this question. You will use your hands to apply force to aluminum foil, making it into progressively smaller spheres. In nature, gravitational force does this job inside massive stars. Just how dense can you make your model star?



Procedure

- 1 To make your star model, obtain a balloon from your teacher and blow it up until your piece of string fits around the widest part. Once you've done that, tie it off. Measure the diameter of the balloon in centimeters in two different directions and average your two measurements. Then calculate the average radius from that.
- 2 Compute the volume of the balloon ($V = 4/3\pi R^3$). Record your answer in the table below.
- 3 Form your piece of aluminum foil into a loose ball that represents the core of your balloon star. Use the balance to find the mass of the aluminum in grams.
- 4 Compute the density of the stellar core (Density = Mass/Volume).
- 5 Crush the aluminum foil (gently) into a smaller ball. This represents the core as your star burns through fuel it has.
- 6 Find the volume, mass, and density of the new stellar core.
- 7 Now use your hands and compress the aluminum into the smallest ball you can. This represents the star's iron core that cannot be compressed any smaller.
- 8 Find the volume, mass, and density of your compressed stellar core.
- 9 Next, pop your balloon (your star has just gone supernova!). Bring your foil ball to your teacher, who will use a hammer to crush it down as far as possible to represent the neutron star you have just created.
- 10 Find the volume, mass, and density of the new neutron star model prepared by your teacher.
- 11 Report your data points to the teacher, who will be graphing each team's data on an overhead.

Data Table

Trial #	DATA				CALCULATED VALUES	
	Mass (g)	Radius ₁ (cm)	Radius ₂ (cm)	Radius _{avg} (cm)	Volume (cm ³)	Density (g/cm ³)
1						
2						
3						
4						

Getting Really Dense

In the first part of this activity, you crushed an aluminum ball more and more and measured its increasing density. Now you will do some calculations to determine how much more dense that ball would become if you could continue to compress it. Then you will determine the size of your aluminum ball black hole's event horizon—the point past which nothing returns.

Going down to ... one centimeter

Imagine that you could overcome electric forces and compress your aluminum into a sphere one centimeter in diameter. What would its density be? Using the graph you created, calculate its value using $D = M/V$.

And farther down to ... one millimeter

What is the density of your ball of aluminum if it is squeezed into a sphere 1 millimeter in diameter? Calculate its value using $D = M/V$.

And farther down to ... a neutron

What would the density of your model be if you could compress your aluminum into a sphere the size of a neutron (the average radius of a neutron is equal to 10^{-15} m)? Calculate its value using $D = M/V$.

And finally down to a ... black hole

The mass of a black hole is squeezed into a sphere with a radius very close to zero that results in a volume that is very close to 0 cm^3 . What is the density of a black hole using this volume? Calculate its value using $D = M/V$.

Your black hole's event horizon

Any mass can become a black hole if there is enough force to make it small enough. Imagine that your aluminum foil star model became a black hole. Determine the radius of its event horizon, called the Schwarzschild radius. The expression that determines the radius of the event horizon is:

$R = 2GM/c^2$, where R is the radius of the event horizon, M is the mass of the black hole in kg, 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 $c = 3 \times 10^8 \text{m/sec}$)

The event horizon if our sun were to become a black hole

Our sun is not massive enough to ever go supernova and produce a black hole. It will evolve into a red giant star and later will become a white dwarf star, slowly cooling over billions of years to a black ball of carbon atoms. But if our sun could become a black hole:

- What would the size of its event horizon be ($M_{\text{sun}} = 2 \times 10^{30} \text{kg}$)? Use the equation above to calculate its value.
- What would life be like on Earth if the sun was replaced by a black hole with the mass of the sun?
- Would Earth be sucked into the black hole?

