Supernova Explosions

Summary

Students are reminded that the Universe is made up of elements and that the heavier elements are created inside of a star as they learned in the "Elements and You" activity. They are introduced to the life cycle of a star and to the way in which a star's mass affects its process of fusion and eventual death. Students discuss the physical concept of equilibrium as a balancing of forces and observe an experiment to demonstrate what happens to a soda can when the interior and exterior forces are not in equilibrium. An analogy is made between this experiment and core collapse in stars, to show the importance of maintaining equilibrium in stars. Finally, students participate in an activity which demonstrates how mass is ejected from a collapsed star in a supernova explosion, thereby dispersing heavier elements throughout the Universe.

Objectives

- ★ To introduce the life cycle of a star
- ★ To discuss the forces at work inside a star
- ★ To understand the role of mass in determining the extent of fusion and the fate of a star
- ★ To learn about core collapse of a star
- ★ To simulate mass ejection and understand how to populate the Universe with the heavy elements from the interior of stars during a supernova explosion

Materials

- ★ Colored balloons (1 of each of the following colors: red, orange, yellow, green, blue, and violet)
- ★ Empty aluminum soda cans (needs to be clean and not at all crushed; we recommend having several)
- ★ Hot plate (or Bunsen burner and screen/ring setup)
- ★ Large, deep bowl of ice water
- ★ Tongs or oven mitts
- ★ Hoberman sphere *
- ★ Basketballs (or kickballs, soccer balls, etc.; ideally at least a few – the more you can get, the more students can participate at once) **
- ★ Tennis balls (approximately the same number as the larger balls – a few extra in case they get lost is a good idea) ***
- ★ (Optional) Model clay star from Elements and You session

** Information about where to purchase this can be found in Appendix B.*

*** This activity can also be done using smaller balls. Larger balls will bounce very high, which is more spectacular, but can cause damage if you are doing this activity indoors. With smaller balls it is possible to have an entire classroom set so that all girls can do the activity at once. It is a personal choice. If you choose to go with smaller balls, you will need tennis balls and ping-pong balls instead of basketballs and tennis balls.*

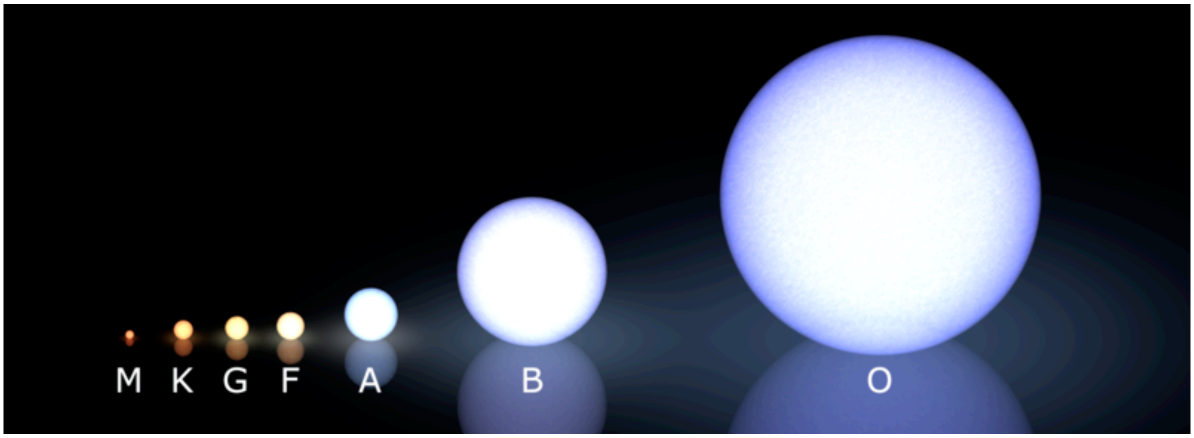
**** If you are planning to run this program more than once, consider buying non-pressurized tennis balls. Pressurized ones will lose pressure with time, and will no longer bounce. Non-pressurized ones do not have this problem, and you will save money in the long run.*

The supplies for this session are laid out on a table.

Background

Stars are big balls of hot gas, mostly hydrogen. Our Sun is a star, the closest one to Earth, and this is why it looks so much bigger and brighter than the other stars in the sky. Even though the Sun may look small in the sky (compared to Earth), it is actually enormous! The Sun is about 330,000 times more massive than the Earth. Its radius is about a 100 times that of the Earth, which means that a million Earths can fit inside the Sun! Our Sun is large relative to the planets, but it is an average size compared to other stars. In the extreme, stars can be up to 100 times more massive than the Sun.

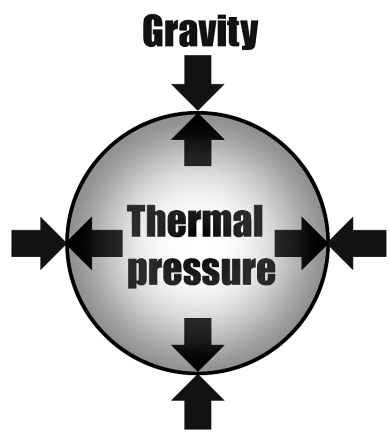
Astronomers classify stars by their spectra – the colors of light they emit. Most stars actually emit many kinds of light, but a star can look one color because that is the brightest part of its spectrum. When people first started looking at the spectra of stars, they looked especially at the amount of light coming from hydrogen. They called the stars with the most hydrogen emission type A stars, then type B, C, and so on. Later, people realized that thinking of classes of stars by their color made more sense and gave more information because blue stars are the hottest, brightest, and most massive stars, while red stars are the coolest and least massive stars. So, the classes (A, B, C…) were reordered, some of them dropped out, and we ended up with the order OBAFGKM (from blue to red, hot to cool, high mass to low mass).



This graphic illustrates the respective sizes of the different spectral classes of stars. Image Credit: Lucas V. Barbosa

Some kinds of stars and other astronomical objects are brightest in colors that we cannot see with our eyes, but that does not mean that they do not put out some light in the optical. Students probably talked about different kinds of light in the Rainbow Analysis activity. Astronomers have special cameras and telescopes that can look at different kinds of light to study different astronomical objects. Sometimes people also use these cameras on Earth, such as using night-vision goggles to let people see infrared light.

Stars generate energy by converting lighter elements into heavier elements through nuclear fusion in their cores. These elements are the "fuel" that generates a star's energy that then flows outward and counterbalances the inward pull of gravity. Stars spend the majority of their lives with these two forces in balance, as shown in the image to the right.



The balance of forces within a star.

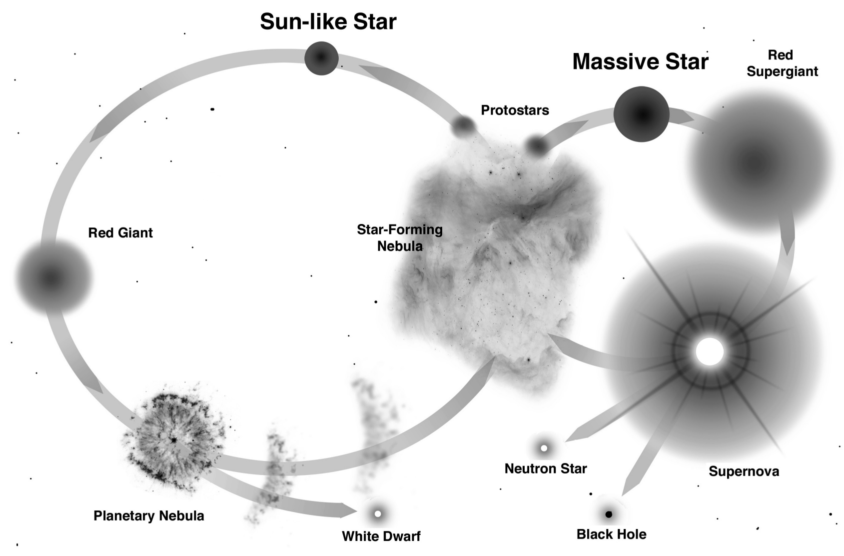
Stars go through a cycle of "birth" and "death," but the timescales involved are much longer than what we associate with living things (millions or billions of years). Young stars are born in a cloud of gas and dust called a nebula. Particles inside these nebulae collide and clump together to form stars. When enough material has accumulated, the pressure and temperature in the core exceeds a critical threshold and fusion begins. A star is born!

The lifetime of a star depends on how massive it is. Small stars can live many billions of years, but the most massive stars will only live a few million years. Our Sun is a medium star that is 4.5 billion years old and about halfway through its life cycle.

The number of elements created through the fusion process in a star is dependent on its size. All stars start out fusing hydrogen into helium, but the small, cool stars will stop after that and will not go on to fuse any other elements.

Stars of intermediate mass like our Sun spend the majority of their lives (many billions of years) in a stage of their lives known as the "main sequence," during which they fuse hydrogen into helium in their cores. Once this fusion ends, they expand into the "red giant" phase. When our Sun enters this stage of its life in 5 billion years scientists think the Sun could puff up so big that it will swallow the Earth. Our Sun will then have a brief phase in which helium is fused into carbon. Depending on their mass, some intermediate sized stars can go on to fuse nitrogen or even oxygen. After they run out of fuel that they can fuse, red giants blow off their outermost layers that then form a disk of material around the star called a "planetary nebula." These objects were originally named this because they look like a planet when seen through older telescopes, but in reality they have nothing to do with planets.

The hot core that is left behind is approximately the size of the Earth and is called a "white dwarf." White dwarfs are very dense — a teaspoonful of white dwarf material would weigh 15 tons on Earth! — and shine for many more billions of years as they slowly cool.



The lifecycles of both a small to medium star and a massive star.

The very hottest and most massive stars can continue the process of fusion (in shells, as described in the Elements and You activity) until they are left with iron cores. Iron requires much more energy to fuse than the other elements did because it is the most stable element. In fact, more energy is needed to start the fusion of iron than it would actually produce. So instead of providing energy for the star like fusing other elements did, iron demands energy that the star can't afford, and therefore the iron core doesn't fuse into another element, and the star stops producing energy.

The most massive stars reach the end of this cycle in only a few million years. When these stars run out of elements that can be fused, the force of gravity finally overwhelms the outward push from the energy generated by the fusion. As a result, the core of the star collapses catastrophically and releases enough energy to blow apart the rest of the star. These "supernova explosions" are so bright that they briefly outshine entire galaxies! Supernovae (the plural of supernova) also have so much energy that iron can be fused into heavier elements during these explosions. In addition, all the elements that were formed inside the stars are spewed out when they explode, and elements are dispersed throughout the Universe.

We know the Sun is a later-generation star because even though it is still only fusing hydrogen, it contains those heavier elements that can only be formed inside massive stars and distributed by supernovae (we know that from spectroscopy, among other ways). Since the Big Bang only produced hydrogen and helium, most of the elements in our bodies - like carbon, hydrogen, nitrogen, oxygen, and trace amounts of many others – must have come from the explosion of earlier stars! We are all literally made of star stuff!

After the supernova, only the core of the massive star is left behind, which will then turn into either a neutron star or a black hole. A neutron star is an extremely dense star whose gravity is so strong that protons and electrons combine to form neutrons. The density in the interior of a neutron star is much higher than in the interior of a white dwarf — a sugar-cube sized lump of neutron star material would weigh 100 million tons on Earth!

If the star is particularly massive, the stellar core that's left after the explosion is still too massive to support itself against gravity. Therefore, it continues to collapse until it forms a black hole, which is a point in space with tremendous gravity – so great that not even light can escape from it, hence the term "black" hole. We will explore black holes more in the session called "Black Holes in Orbit."

Preparation

1. Make sure you have ice made up ahead of time. Although this activity can work without ice as long as you have very cold water, it is easier with ice water.

2. It is a good idea to practice the imploding can trick (ideally with the same tools you will have during the session) before you are called upon to perform in front of students. Make sure that you can see plenty of steam from the can and can hear it bubbling before inverting it onto the water. This can be a temperamental demonstration, and practice helps a lot.

3. Also, it may take a while for the water in the can to boil, so it's a good idea to start it heating before starting the activity, or have a helper set it up ~15 minutes before you get to that part of the activity. (Actual heating times will vary depending on your hotplate.)

Activity

Review: Elements

As the activity begins, ask the students what they have learned about elements in the Universe (if they have already participated in the Elements and You activity) or what they know about elements (if they have not participated in the Elements and You activity). Remind them that the elements of which they are made (carbon and oxygen, for instance) are very rare in the Universe and are made in stars. They should know that the stuff created inside stars needs to get out somehow (in a big explosion). Try to ask them questions and unearth any possible misconceptions before the rest of the activity begins. What is an element? What are different kinds of elements? What is an atom? What is an atom made of?

In this activity, we are going to figure out how to make a star explode in order to distribute different elements into the Universe! Not all stars will become supernovae, so first we need to understand the life cycle of stars.

Talking Point: Forces in a Star

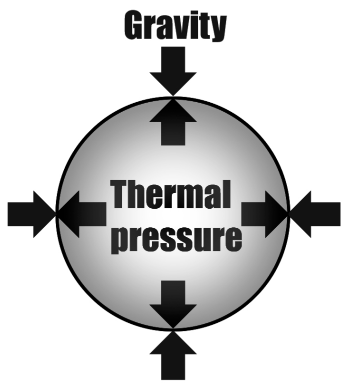
How do different sized stars behave and how do they age?

Ask the students about what they know about forces. What is a force? What kinds of forces do they know about?

A key concept to reinforce is that there are different types of forces at work in a star – two of these are gravity, which holds objects and materials together, and pressure from hot material and fusion, which fights the gravity and pushes outward.

All stars fight gravity by releasing large amounts of energy through fusion. Remember that fusion is the process stars use to create different types of elements. Lighter atoms join together to create heavier atoms and release energy. This is a complicated process, but we can think of it simply. Remind them of the demonstration with clay balls from the morning's Elements and You activity.

The more mass that a star has, the hotter it can get in its core, and the more it can use energy from fusion to support itself from collapse, because the pressure from the fusion energy pushes outward against the gravitational pressure pushing inward. The key here is that these forces are in balance through most of the star's life.

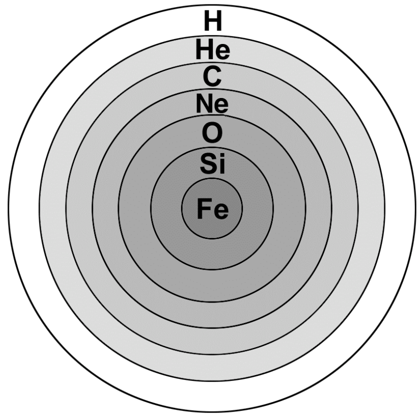


Gravity and thermal pressure remain in balance for most of a star's life.

Demonstrate this balance by having two volunteers come up and face each other. If they press their hands against each other with the same force, nothing happens.

Two girls demonstrate the balance of forces within a star.

Bigger stars can fuse heavier and heavier elements. This process stops with iron (Fe), if you remember from the Elements and You activity. This process creates layers of different elements like an onion.



The layers of different elements within a star form an onion-like structure.

(It is helpful to have the model star to refresh their memories.) We'll talk about iron more in a few minutes.

1. **What happens at the end of fusion?**
   Ultimately, all stars will lose the ability to fuse elements, because they run out of elements that they can fuse. At this point, the core may be dense enough to support itself – the gravity pushing down is not strong enough to crush the core. (The following description demonstrates at what stage a star loses this ability to fuse elements and whether the star is light enough to support itself by other means.)

2. **So, what are the different kinds of stars, and what happens to them?**
   Now, we'll look at how a star changes over time (or evolves) depending on its mass. Ask the students whether they think the most massive stars will be the hottest or the coolest. (Answer: hottest.) Ask them what colors of light come from the hottest and the coolest things. (Answer: hottest stars are bluer and cooler ones are redder – they may or may not come up with this response.)

<u>**Activity: Stellar Life Cycle** (approximately 10 minutes)</u>

Main Sequence Star Masses, Balloon Diameters, and Balloon Colors

Have six students blow up balloons according to the following table.

Spectral Class	**Relative Mass**	**Balloon Color**	**Relative Radius**	**Balloon Diameter**	**Comments:**
O	23	Violet	7.4	19 in	Fuse → Fe – run out of fuel
B	8	Blue	4.3	10.5 in	Supernova → Black Hole
A, F	1.6	Green	1.4	4 in	Supernova → Neutron Star

G (Sun)	1	Yellow	1	2.5 in	Fuse → O – stable “white dwarf”
K	0.8	Orange	0.8	2 in	
M	0.4	Red	0.6	1.5 in	Fuse → H, He – stable, cool

Please note, this is a table of Main Sequence (ordinary stars that shine because of fusion) – NOT an evolutionary progression.

Girls line up with their balloon colors.

A common way to remember the spectral types (OBAFGKM) in order is with the pneumonic, “oh be a fine girl/guy, kiss me.” Some students may recognize this pneumonic.

Red/Orange Stars: These stars have very cool temperatures (as far as stars go). They can fuse hydrogen into helium, but not much else. The helium in the core won't get hot enough to fuse together. The star will cool off and become inactive. The same kind of pressure that keeps us from sinking into the ground due to gravity will hold up the star against gravity until the end of time.

Yellow/Green Stars: These stars are similar to our Sun. They can fuse hydrogen into helium. It can also get hot enough to fuse the helium into carbon and oxygen, (and a few other elements in very small quantities). The star doesn't get hot enough to fuse carbon or oxygen into heavier elements, but the star is light enough that the dense carbon/oxygen core can support the star. This endpoint is called a white dwarf. These stars do not have enough mass to result in a supernova.

Blue/Violet Stars: Now we are getting somewhere! This is a really hot and really massive star, and it can do all the things the other stars can do and more! Fusion of elements will continue until the core is mostly iron. But here, we run into two problems: (Ask students what these might be.)

(1) Iron can't fuse into anything else (they should have learned this in the Elements and You activity).
(2) The star is too massive to be supported by the iron core in the same way the other stars are.

So we've reached a breaking point. The iron core is going to get hotter and hotter and hotter until, through a complicated process, the iron atoms come apart into the smaller components. This leads into the next activity.

Demonstration: Implosion (approximately 10 minutes)

The core of the blue/violet star now has no way supporting itself against gravity. Tell the students that we will now explore what happens inside the star when the fusion stops.

Warning: Make sure students don't get too close to this one! The hot plate remains hot for most of this session!

Place a small amount of water in an empty aluminum soda can (about 1-2 tablespoons). Too much water will cause this demonstration to not work. Set the cans on the hot plate. Heat the can until the water starts to boil. When plenty of steam starts to come out of the opening in the top of the can, pick up the can with an oven mitt or tongs and quickly flip it over (open side down) into a bowl of cold water. The can will instantly implode with a crunching sound.

Soda cans that have been crushed as part of a demonstration.

Why does this happen, and how does it relate to our massive star?

When you buy the aluminum can from the store and it still has liquid in it, the can holds its shape due to the equilibrium between the pressure from the soda inside directed outward and the pressure of the air outside of the can directed inward.

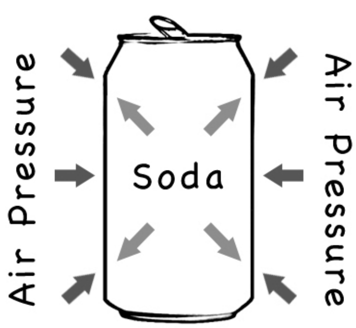


Diagram showing the balance of forces in a can full of soda.

After the can has been emptied of liquid, the shape is held in equilibrium by the pressure of the air inside the can directed outward and the pressure of the air outside of the can directed inward.

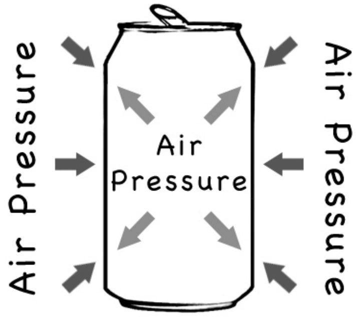
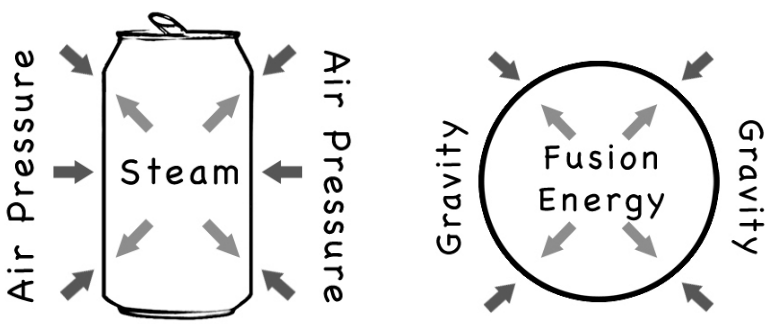


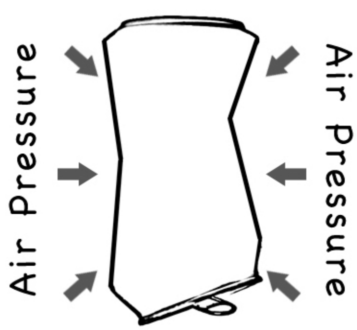
Diagram showing the balance of forces in a can after the soda has been emptied.

Heating the water in the can causes it to turn into steam, which drives the air out of the can because the steam has higher pressure. 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 outside air directed inwards (analogous to the gravity of the star directed inwards).



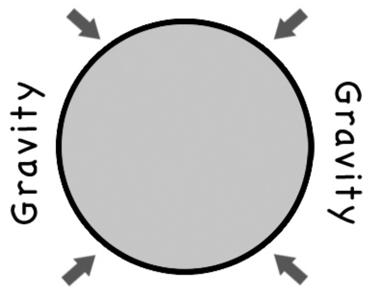
During our demonstration we heat water in our soda can, which means the can fills with steam, which balances the air pressure from outside. We compare this to the balance of forces in a star during the majority of its life.

When the can is inverted over the cold water, the steam instantly condenses into water. The water occupies a much smaller volume than the steam did, resulting in much less pressure inside the can. With nothing on the inside to balance the outside pressure the can will implode (like the core of a star collapsing).



This diagram shows the can collapsing because there is no longer a balance of forces.

This is sort of like what happens in a supernova, the end of the line for large stars. The star collapses when the two forces that were balancing each other – pressure outwards from the energy generated at the center countering the force of gravity inwards – are no longer in equilibrium.



The lack of fusion energy inside the star to balance the gravity causes the final collapse of the star.

The central core of the star collapses (similar to the implosion of the can) and the material in the rest of the star starts to fall onto this core. It rebounds and sends the material in the star flying out. This is what is called a supernova explosion and the power of this rebound effect can be seen in the next demonstration. Supernovae do a very important job in the Universe – the explosion sends all those elements out into space and makes new elements with its energy.

Demonstration: Getting from an Implosion to an Explosion (approximately 5 minutes)

Discuss the difference between an *implosion* (falling inward) and *explosion* (going outward). We saw that the can imploded because the pressure inside the can disappeared. But when we think of a supernova, we think of an explosion. So how do we get from an implosion to an explosion?

Show the students the Hoberman sphere. We can use this sphere to answer our question. You can invite a student up to do this demonstration if you would like.

Open the sphere all the way, and then let it collapse under its own gravity. Try to do this so that it is still falling when it collapses all the way (in other words, while it is still in the air rather than on the ground).

A woman lets a Hoberman sphere collapse upon itself while in the air.

What happened when the sphere reaches the end of its collapse? You should be able to observe a "bounce" at the end when all of the parts falling towards each other rebound off of each other. This can be difficult to see, so you probably want to show them the collapse and bounce a few times. This is how we turn an implosion into an explosion.

Activity: Atmosphere Ejection (approximately 10 minutes)

Now let's take a look at the supernova explosion itself.

Give students a pair of differently sized balls. Have as many students as possible participate, within the limits of your supplies. Have these students stand in a group.

Ask the students to predict how high each ball will bounce when dropped (not thrown at the ground, just gently dropped). Once the students have made their predictions, let them try it.

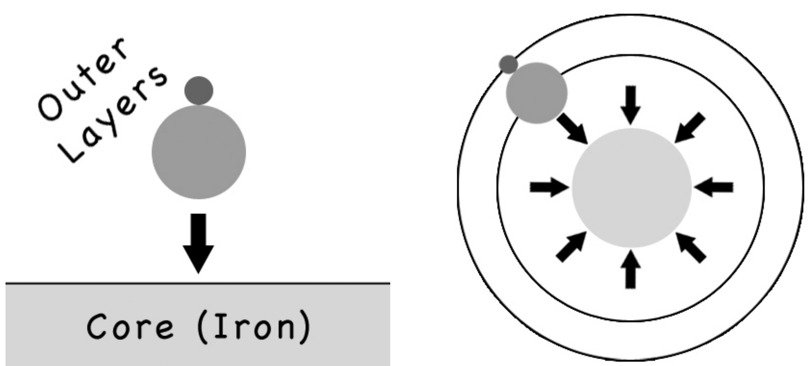
Now ask the students to predict how high the balls will bounce if they are dropped with the smaller ball stacked on top of the larger one, as pictured below.

A girl holds her two balls as part of this activity.

Have everyone yell "3-2-1-SUPERNOVA!" and drop their stacked balls at once. What happened? Assuming the two balls fell together, the smaller ball should suddenly rebound with a lot of energy. It will bounce higher than it did when it was dropped by itself – potentially much higher – while the larger ball doesn't bounce much at all. Do this activity several times so that everybody has a chance to do this activity at least once.

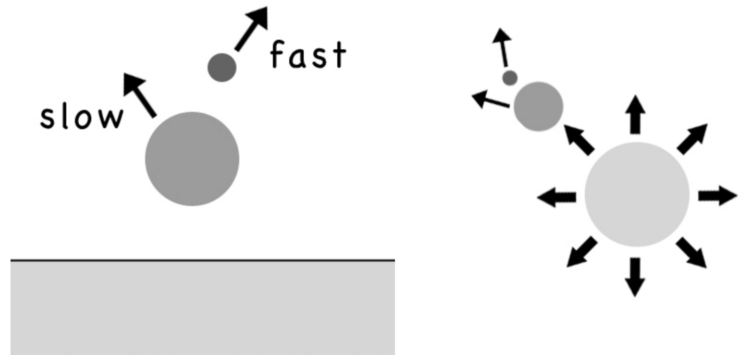
So why does this happen? In this situation, the smaller ball absorbs the energy of the larger ball. Since it is so much smaller, that energy is capable of doing a lot more, and the ball bounces much higher than it did before.

So how does this relate to our supernova explosion? In this experiment, the ground (Earth) represents the dense inner core of a star. The larger ball represents the outer part of the core that is falling inward as the star collapses. The smaller ball represents the outer layers – or atmosphere – of the star. This comparison is illustrated in the following images.



Illustrations of the balls in this activity as the layers of a star falling towards the iron core as it goes supernova.

We saw earlier what happens to turn our star's collapse into an explosion. The bounce we witnessed with the Hoberman sphere is what we are looking at now in more detail. Our two balls hit the floor, and the smaller one rebounds with a lot of energy, just like the outer layers of our star. This idea is again illustrated in the following images.



Illustrations of the tennis and ping pong balls as the outer layers of a star shooting off into space after it has rebounded off of the iron core during a supernova explosion.

Now have the students imagine what it would be like if everyone on Earth did this experiment at the same time. With the idea of 7 billion balls shooting off in all directions from the Earth at the exact same time, we start to get a more accurate mental image of a supernova.

Talking Points: Wrap-up (approximately 5 minutes)

Discuss with the students the following key concepts that we learned in this activity to check for comprehension.

★ Every star is fighting against gravity. They start doing this using the energy released by fusing hydrogen into helium. Some stars will only get this far and will only have the structure of the matter itself to help in the fight against gravity.

★ Other stars can get hot enough to fuse helium, carbon, etc. The hottest/most massive stars will get to the point where they have an iron core, but this is a problem because iron doesn't fuse without an input of energy, and stars are too massive to be supported any other way.

★ Not all stars will end their lives in a spectacular supernova. Generally only the ones that are massive enough to reach iron in their core will do so.

★ With the loss of material to fuse (because iron cannot be fused without an input of energy), we lose our initial balance, and the star implodes (collapses inward). Stuff in the core and bottom of the atmosphere will "bounce" when it meets the wave of energy from the core rebound. This bounce will cause the outer layers of the atmosphere to violently explode (fly outward). In the remaining core, the neutrons might be able to hold up what's left. This is what's called a neutron star. If the remainder of the core is too massive even for neutrons, it will become a black hole.