Environmental Science Institute
THE UNIVERSITY OF TEXAS AT AUSTIN

1 University Station C9000
Austin, TX 78712
(512) 471-5847
www.esi.utexas.edu

Crushing Stars

Lesson plan for grades 6-8
Length of lesson: 1 Class Period (45-60 minutes)
Authored by: Jesús Aguilar-Landaverde, Environmental Science Institute, February 7, 2012

SOURCES AND RESOURCES:

- Hyperphysics General Definition Reference
  http://hyperphysics.phy-astr.gsu.edu/hbase/force.html
- White Dwarfs and Neutron Stars: An Introductory Lesson
  http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit3/extreme.html
- Black Holes: An Introductory Lesson
  http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit3/blackholes.html

POTENTIAL CONCEPTS TEKS ADDRESSED THROUGH THIS LESSON:

§112.18.b Astronomy, Grade 6: (8B, 11B)
§112.19.b. Physics, Grade 7: (7A)
§112.20.b. Physics, Grade 8: (6A, 6C)
§112.20.b. Astronomy, Grade 8: (8A, 8B)

PERFORMANCE OBJECTIVES:

Students will be able to:

- Describe the main forces involved in stellar structure equilibrium.
- Identify the everday quantity known as weight as a force.
- Relate the force of weight to the mass of the system in question.
- Describe qualitatively the known end states of stars.

MATERIALS (per group of four):

- 1 standard balloon, preferably not the long type

CONCEPTS:

Equilibrium in physics describes a state in which opposing influences on a system are balanced. Very commonly, these influences are forces.

A **force** is a physical influence that causes a system or body to change its velocity. That is, it causes the system to accelerate.

1 University Station C9000
Austin, TX 78712
(512) 471-5847
www.esi.utexas.edu

Gravitational force is one of the fundamental forces known. We experience this force daily as **weight**, and the force is a result of the inherent attractive property of matter (e.g. the Moon to the Earth *and* the Earth to the Moon) by virtue of its **mass**. That is to say, it follows from the measure of the *amount* of matter of a system (mass).

Hydrostatic Equilibrium: Simply, a star maintains its shape throughout its lifetime (between hundreds of millions of years to billions). In order for this to happen, as it does in the Sun currently, the pressure from the heat and radiation in the Sun must constantly *balance* the enormous *force* of gravity that it exerts due to the Sun's tremendous mass (approx. 2,000,000,000,000,000,000,000,000,000,000 kg!) [or, 2x 10^30 kg].

Stellar 'death': Given that stars have a limited amount of 'fuel' to fuse, at some point this available resource (for a common star, Hydrogen is fused into Helium) is extinguished. If nuclear reactions cease, then the pressure resisting gravity in the star diminishes and so gravity begins to dominate the star. That is, the star begins to collapse. The physical processes that take place next are quite complicated and are admittedly not completely understood by astrophysicists. However, modern theory of stellar evolution and empirical observations hold that a star will end in one of the three following "paths:"

- **White Dwarf:** This is the expected end state for about 97% of the stars that are observed by astronomers. The average size of a white dwarf star is about the size of Earth. However, these stars are considerably more massive than Earth (the average observed white dwarf mass is about three-fifths the mass of the sun). The Sun will one day become a white dwarf after in its final life stages.
- **Neutron Star:** These exotic objects are even *more* extreme. No larger across than just a few *miles,* any matter that falls onto these stars is destroyed as it is spun to tremendous speeds before colliding. The result is that all matter on the star appears uniform (mostly neutrons). These stars range between one and two solar masses.

$$g = \frac{GM}{r^2}$$

Figure 1: Equation of gravitational acceleration. G is the gravitational constant, M is the mass of the star, and r is the radius.

  This higher mass and smaller size results in tremendous gravity! The lightest butterfly on Earth would weigh over 1 million pounds on a Neutron star! This is higher than that of a white dwarf.
- **Black Hole:** Gravity's ultimate "win." Not even the special pressures that support white dwarfs and neutron stars can sustain a star if the **mass** is too high. A black hole is a region of space (space-time) from which not even light can escape! Stellar black holes can occur, according to theory, when the mass of a collapsing star exceeds approximately 10 solar masses.

BACKGROUND:

The amount of matter (mass) in stars is nearly unimaginable given our everyday experiences. The Sun alone is over 300,000 times more massive than the Earth. It follows, then, from our understanding of gravity on Earth

1 University Station C9000
Austin, TX 78712
(512) 471-5847
www.esi.utexas.edu

that the gravity (or, the acceleration due to gravity) on the Sun and other stars must be much higher. In this lesson, the student is exposed to the possible terminal evolutionary states for stars based on their masses. This lesson is focused on gravity, and how the force of gravity depends on mass, stellar structure, and the exotic stellar remnants that result from gravity in space. The lesson will also build on the students' experiences with ordinary balloons and the forces at work when a balloon is inflated. This will lead into the students' later introduction to the basics of stellar structure evolution.

PREPARATION:
Have the balloon for demonstration ready prior to the lesson. You may wish to have the recommended introductory websites above on stellar evolution (or other site of your choice, preferably with images) prepared on a projector for the Elaborate section.

ENGAGE:
The instructor will demonstrate an inflated balloon to the classroom and will elicit students' pre-existing knowledge of the equilibrium at work in an inflated balloon. (See questions)

Ask: These are example questions (and teacher hints *in italics*) to probe and guide the students

- What is this balloon filled with?
- What state of matter is air in?
- Why doesn't the balloon just sag when I fill it with air?
    - What makes it keep its shape?
        - Is it the air? If so, does the balloon air have air in it when it is not inflated?
        - Is it the fact that the balloon is tied at the end?
        - Couldn't I just tie the balloon when it is deflated?
        - Wouldn't it have both air and a closed end if I did that?

    The driving concept here is that there must be something pushing/stretching/pulling the balloon outward when it is inflated because it is not normally like this. This "something" is a force, and it is the force due to the pressure of the gas. If the students do not mention pressure, you may need to give them hints contained in the bullet point immediately above. This leads to the following critical question:

    - Where is this force/pressure coming from?

    Here the goal is to guide the students to think along the lines of the kinetic theory of ideal gases although they may not have learned of it yet. That is to say, you may need to introduce the students that a gas, in this case air, is composed of molecules bouncing around the classroom. Appealing to their pre-existing knowledge of the states of matter, if it indeed exists, then this can be reinforced by the fact that gases take the shape of their container (the classroom. Their atoms or molecules move more freely than those of solids or liquids to fill the volume of the classroom. If these air molecules of air run into each other or the walls, they just bounce of each other like billiard balls.

1 University Station C9000
Austin, TX 78712
(512) 471-5847
www.esi.utexas.edu

- Propose this idea to the students: "Imagine that we take an empty classroom full of air and begin shrinking it until it is the size of the doghouse. No air is allowed to escape. What can we say about our billiard ball molecules?"
- "Do they run into each other more often? Less often?"

- What if I cut a small hole in the balloon? [the instructor may do so]
    - Why doesn't the balloon just stay inflated?
    - What makes it shrink, as you say? *[The restoring force of the balloon plays a role here; students may better associate this with a rubber band, a slinky, or a spring]*
    - Is there a trade-off between this thing called pressure and this rubber band-like property of the balloon?

Note to teachers: The intended goal of this exercise is to hint at the idea that an inflated balloon is in an equilibrium state. The gas that fills the balloon is exerting a pressure against the walls of the balloon. At the same time, the natural properties of the rubber of the balloon want to pull the balloon back to its smaller, deflated state. For this equilibrium state, that is, in order to maintain a shape, there must be *air* in the balloon. The random motions of the air molecules themselves are exerting the pressure. If we remove these molecules under pressure, then the equilibrium is lost. *This is the key for leading into a discussion on stellar evolution.*

EXPLORE: The question for the students now is this: "You are given a school bus. Your principal tells you that you need to find a way to fit the school bus into a bag the size of a basketball to make room for a new car. The basketball can't change its size. How would you go about doing this, if you can?" The students should work in groups at the teacher's discretion

1. This example may appear unrealistic, however it is building on the concept that gases, even the already dense plasma gases in stars, can be made to change their shapes.
2. Students may respond with incredulity, but the instructor should nevertheless assure them that this is not an endeavor of fantasy. Such a thing **is** possible within the laws of physics.
3. It might help here to remind the students of the thought experiment of the classroom and the balloon shrinking. The **volume** of the classroom is changed, but the *amount* of gas (mass) is **conserved**.
4. The idea is to get students thinking even more in terms of forces, ultimately in light of gravitational force, which may not be one of the immediate guesses of the students.
    a. Some students might suggest crushing the school bus with an extremely object. This is a great opportunity to hint on gravity. Why is that object heavy? What is weight? Is it different from mass? What if we tried doing that on the moon?

EXPLAIN:

Using the appropriate signal(s), the instructor should regain the attention of the classroom. On an overhead, on a white/chalkboard, or on a computer, the teachers should record the solutions of the groups.

1 University Station C9000
Austin, TX 78712
(512) 471-5847
www.esi.utexas.edu

- For each mechanical solution the students provide, ask how they might find the fuel, energy, or resources to accomplish the task (after all, this *is* possible in the universe!)
- If the discussion reaches a dead-end, appeal again to the concept of **weight** Example: I take a regular soda can. I stand on it, and the can is crushed and now takes up less space. [Here, we're ignoring the minute energy my leg muscles had to use to climb up to the can]
    - Why was the can crushed?
    - Is it because I'm heavy? What does that mean, to be heavy?
        - ***Caveat: Many students confuse the meanings of weight and mass.***
    - Does the can experience a force when it's crushed? Is my weight a force?
    - Let's imagine the moon. If I, the *same person*, stand on the *same can* on the surface of the moon, will the can be more crushed or less crushed?
    - If not, then what changed?
        - Did the force of **gravity** change?
        - If yes, do you mean to say that gravity can change my weight?
- The instructor should probe the students by suggesting the same experiment with a flipped-over aluminum bucket or paint can. The average person does not weigh enough to crush these objects simply by standing on them. It requires heavier and heavier things to accomplish this (e.g. a horse, an elephant, a truck, etc). The idea is that **mass** is the other contributor to weight.

ELABORATE:

The instructor here would lead the students back to the bus problem with the following question:

- What sort of **weight**, or **mass,** or **gravity** would you need to crush a **bus** into a basketball size?

As the students' hypotheses are discussed, it should be noted that any weight that could accomplish this on the Earth would break right through the Earth's crust! (implying that this is not possible, at least not on Earth)

The teacher at this point should present the terminal evolutionary states for stars and especially their truly tremendous gravities:

- A white dwarf is roughly the equivalent of a school bus collapsing into a basketball size. [**Gravity** drives this force**,** and this is due to the star's tremendous **mass**.]
- A typical white dwarf star is roughly the size of the Earth. The sun is about 100 times the size of Earth and over 300,000 times as massive. The staggering density of a white dwarf star results in a surface gravity on order 100 million times that of Earth. A teaspoon of matter of a white dwarf would weigh several times on Earth!
- Even further, the analog for the gravity on a neutron star is like crushing a school bus into a point as wide as a human hair!

Environmental Science Institute
THE UNIVERSITY OF TEXAS AT AUSTIN

1 University Station C9000
Austin, TX 78712
(512) 471-5847
www.esi.utexas.edu

EVALUATE:

Thought questions: Either of these could serve as a free-response answer for either an in-class assignment or homework:

- What about planets like Jupiter and Saturn? Can they become white dwarfs or neutron stars? Why/why not?

The purpose of these questions is to again relate the final stages described of stars to the mass and gravity of the collapsing stars. The masses of the planets can hardly compare to that of the sun and so thus cannot undergo this type of collapse.

- Space shuttles must travel at very high speeds to enter orbit from Earth. From what you know about stellar evolution, how would these speeds change were we to launch an imaginary rocket from the surface of a white dwarf? What about from a black hole?
    - Here, the rockets must work against the Earth's gravity. A rocket must accelerate to a speed called the **escape velocity** in order to break free from the Earth's gravitational field.
        - For reference, the Earth's escape velocity is about 25,000 mph
        - For an average white dwarf, this number is about 11 **million** mph
        - In the limit, the escape velocity for a black hole is greater than the speed of light (~671 **million** mph)!!! This means that not even *light* can break free (hence the name, black hole)!