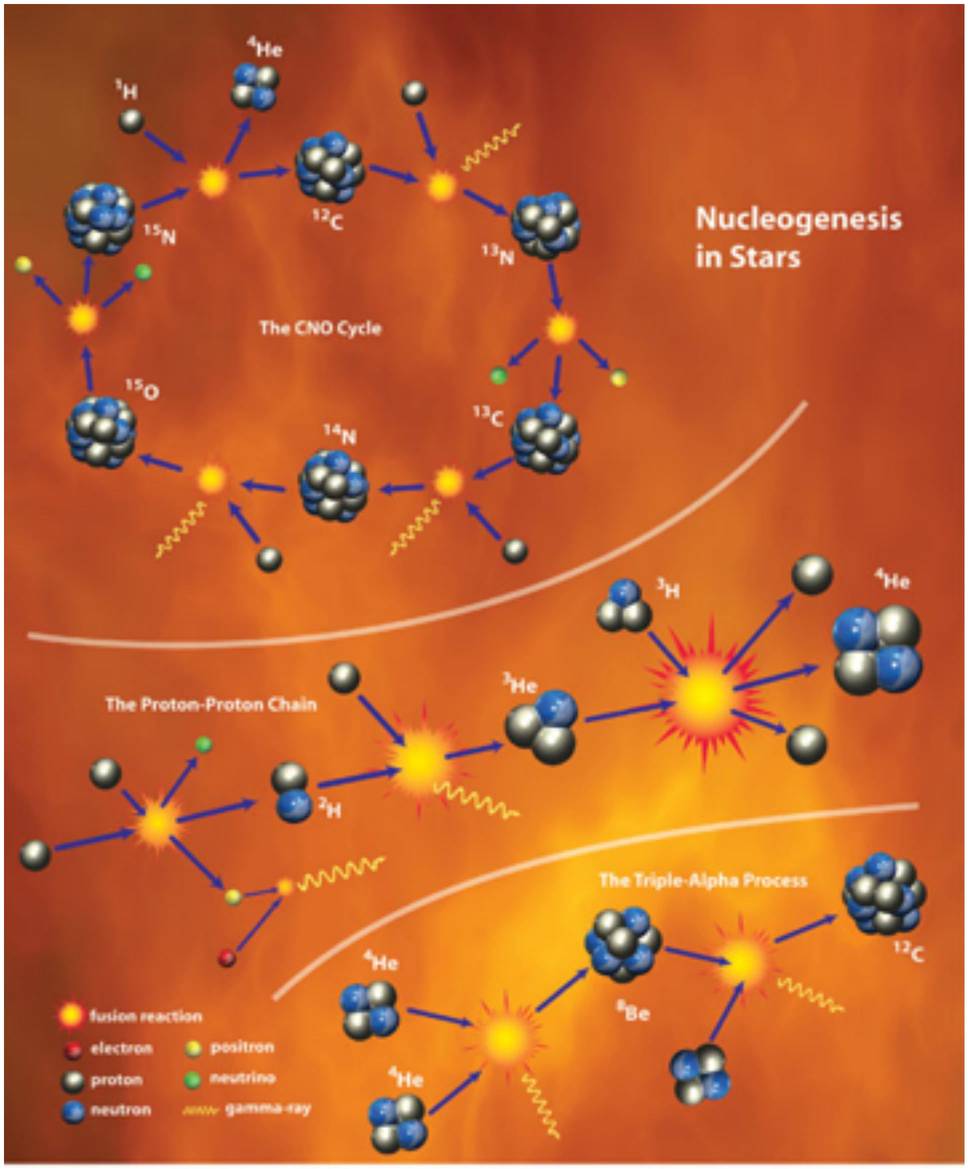
Lesson #2: Formation of Stars
Nuclear Processes: "What Makes a Star Shine?"



Nucleogenesis in stars. Image courtesy of Mark Tiele Westra

Lesson Summary

- **Grade level:** 6^{th} -12^{th}
- **Prep time:** ~30 min. to familiarize teachers with material and websites and to print out in-class worksheets.
- **Lesson time:** ~30 min. for presentation; ~ 1 hour high school activity; 30-45 minutes middle school activity; Two ~4 minute videos.

- **Learning outcomes**: The goal is to provide an introduction to the stellar lifecycle, and in particular, the nuclear processes that fuel a star throughout its life and how it is relevant to life in the universe.

What students do

Teachers may choose to paraphrase this section to introduce this first lesson to students.

This lesson is the first of the seven lessons regarding the terms of the Drake Equation. Any time we want to talk about looking for life in the universe, we have to start with our main player: stars. Stars are a necessary starting point to consider when discussing the existence of life in the universe. This is due to their overwhelming prevalence throughout the universe and their role as the primary energy source for planets on which life may arise.

Stars harbor planets, and planets harbor conditions for life to evolve on them. But how do stars "work"? This lesson will handle one important stellar process: fusion. It's what makes stars shine. You need to have a shining star to keep a planet nice and warm so it can "cook up" the ingredients for life on that planet.

Students will learn about the nuclear processes in stars that allow them to radiate huge amounts of energy. There will be an in-class activity that will allow them to solve basic problems in nuclear physics. This will allow them to practice learning the new material in addition to applying some quantitative reasoning skills. The lesson starts and ends with a short, relevant video to tie together concepts, and relate them to their daily lives.

At the end of this lesson, students will be able to:

- ✓ **Recognize** the concept of binding energies
- ✓ **Implement** knowledge to solve for nuclear binding energies
- ✓ **Infer** the eventual fate of stars based on the notion of binding energy
- ✓ **Recognize** a fusion reaction occurring
- ✓ **Infer** where heavier elements originated after learning the concept of fusion

The following Next Generation Science Standards will be addressed in this lesson:

Grades 6-8:

MS-PS1-1. Develop models to describe the atomic composition of simple molecules and extended structures.

MS-PS1-3. Gather and make sense of information to describe that synthetic materials come from natural resources and impact society.

Grades 9-12:

HS-PS1-2. Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.

HS-PS1-8. Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.

Resources needed:

- **Computer with internet access to the following websites:**
  - http://zebu.uoregon.edu/~soper/Light/fusion.html
  - http://www-spof.gsfc.nasa.gov/stargaze/SnucEnerA-2.htm.
  - http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/fuscon.html
  - http://www.wimp.com/astoundingfact/
    - Optional video on YouTube: http://www.youtube.com/watch?v=pusKlK1L5To

Science of the Topic

In this lesson, the students will learn about the internal nuclear processes that power a star. Stars are an important foundation in studying the possibilities of life arising throughout the universe for many reasons.

Read this to students:

In each galaxy there is on the order of or 100 billion stars and an estimated 100,000,000,000,000,000,000,000, or 100 sextillion stars – that's 23 zero's in there! - in the entire universe! Imagine picking up a gran of sand at the beach. Now imagine picking up a handful. There are an estimated more stars in the universe than grains of sand on every beach on Earth put together!

With each of these stars, there is a possibility of planetary systems orbiting many of them, if not most of them. Statistically, based on pure numbers, it is inconceivable to consider planet Earth to be the only place for life to exist, with that many stars out there! Furthermore, all of the elements heavier than hydrogen like carbon, oxygen, nitrogen, iron, etc. were formed in the nuclear furnaces at the center of stars and dispersed throughout the universe when the star goes supernova. These elements make up the carbon-based biological organisms we know today. Plus, stars are necessary to provide energy in the form of heat to orbiting planets and maintain a proper temperature that allow for water in a liquid state that, as far as we know, is fundamental for life to exist. We'll explore these ideas further in each of the next few Drake Equation term lessons.

This lesson will primarily focus on the energy created in tremendous quantities in the interior of stars from a process known as thermonuclear fusion. Don't worry, though. The concept name sounds complicated but the idea isn't. Stars contain enormous amounts of matter that is held together under its own gravity. This force of gravity attempts to squeeze all of this matter very tightly, creating enormous pressures and temperatures at the center of the star. In fact, the temperatures reach up to millions of degrees in temperature in the core. At these temperatures, the thermal energy of the atomic nuclei (which is made up of primarily the element hydrogen) is so great that it can overcome another force acting on all atoms, the electromagnetic repulsion of the protons which usually keeps them apart in an atom.

Teacher's Tip: Here, teachers can point to a periodic table and tie this to a chemistry lesson on the elements. Teachers may wish to show students Hydrogen on a site such as http://www.webelements.com/ and project the periodic table on this website so the class can go over where Hydrogen is. Teachers may want to review basic periodic table properties, such as its mass, number of protons/ electrons, etc., ahead of time or with students as an accompanying lesson.

As a result, they come into extreme proximity such that a much stronger, but much shorter range, attractive force, creatively called the strong force, fuses them together. The final result is a helium atom whose mass is lower than the sum of the mass of its parts. This loss of mass is a result of the binding energy released, governed by Einstein's famous equation, and is carried off in the form of high-energy photons. This process continues until the star runs out of hydrogen to fuel this reaction. If the star is massive enough, it can begin to fuse the helium into heavier elements such as lithium, beryllium, and further up the chain to carbon, oxygen, and beyond up to Iron.

Basically, nuclear fusion can result in the merging of two nuclei to form a larger one, along with the release of significantly more energy per atom than any chemical process. It occurs only under conditions of extremely high temperature and pressure. Nuclear fusion taking place in the cores of stars provides the energy released (as light) from those stars and produced all of the more massive atoms from primordial hydrogen. Thus the elements found on Earth and throughout the universe (other than hydrogen and most of helium, which are primordial) were formed in the stars or supernovas by fusion processes.

How long does this fuel last until the star dies? Depending on the mass of the star, the ultimate fate of the star can be a violent explosion, spewing these elements throughout the universe. Or if extremely massive, it surrenders to its own gravity and collapses to either a neutron star or black hole. A neutron star results from the gravitational collapse of a massive star. Such stars are composed almost entirely of neutrons, neutral subatomic particles in the center of atoms without electrical charge. A black hole forms when a very massive star collapses at the end of its life cycle and can be as much as a million masses of our sun. Black holes are black because they are so massive that nothing escapes their gravitational pull, not even light.

And if the star dies as a supernova, these exploded "remains" then get pulled together again by gravity, or by another baby star forming, millions of years later, and get reincorporated into the next star that forms. This is the stellar life cycle – a cycle of throwing around the elements in stellar explosions that make up planets, environments for life, and life like us and the reincorporating of these elements between different stellar systems and solar systems. The stellar life cycle, complete with simulations and activities for students, will be explored further in future iterations of this R-star Drake Term lesson.

Vocabulary List

Students can be given the following terms to define as a take-home or class discussion assignment at any part of this lesson which the teacher feels is appropriate, or just to have while doing the lesson for reference. If assigning these words for students to define, a print out sheet follows, with a fill-in date that students can write in themselves.

1. Atom – The fundamental unit of matter consisting of a really small, dense nucleus at the center surrounded by a cloud of electrons

2. Binding Energy – The amount of energy required to separate an object into its separate parts (e.g. a nucleus into its protons and neutrons)

3. Electromagnetic Force – One of the 4 fundamental forces of nature. It acts on charged particles such as electrons or protons in the presence of an electromagnetic field, like charges repel, opposite charges attract. It is the 2^{nd} strongest of the four forces

4. Fusion – The process in which multiple atomic nuclei join together, i.e. fuse, to form a single heavier nucleus

5. Gravity – One of the 4 fundamental forces of nature. It acts as an attraction between any physical bodies containing mass. It causes apples to fall, holds the moon in orbit around the Earth, and it holds stars together, but it is still the weakest of the four forces

6. Neutron – One of the constituent particles in the nucleus of an atom, it has no electric charge

7. Nucleon – A general term that refers to any of the particles in the nucleus of an atom, i.e. no distinction between protons and neutrons.

8. Nucleus – The small, extremely dense core of the atom consisting of nucleons (neutrons and protons). It is much smaller than the actual size of the atom, about

23,000 times smaller for a Uranium atom to about 145,000 times smaller for a Hydrogen atom.

9. Photon – A single quantum (i.e. single particle) of light or any other form of electromagnetic radiation.

10. Plasma – A state of matter—like solid, liquid, or gas—that is similar to a gas, but the particles are *ionized*. This means the atoms' nuclei are separated from their electrons.

11. Proton - One of the constituent particles in the nucleus of an atom, it has a positive electric charge of the same magnitude as an electron, i.e. $Q = +1$ e

12. Star – Massive light-emitting spheres of plasma held together by gravity. The nearest star to Earth is the Sun. They emit enormous amounts of energy produced through fusion.

13. Strong Force – One of the 4 fundamental forces of nature. It acts between extremely short distances, but is the strongest of the four forces and it binds the particles in the nucleus together in spite of the charge on the protons

14. Weak Interaction – One of the 4 fundamental forces of nature. It is responsible for the decay of particles and atoms and is the 2nd weakest of the four forces after gravity. Its presence is signified with the appearance of a neutrino in an interaction. It can turn protons into neutrons (and vice versa) in order to balance the number of them in the nucleus, a process that occurs frequently in stars.

Vocabulary list

Name: ______________________________
Due: ______________________________

1. Atom
2. Binding Energy
3. Electromagnetic Force
4. Fusion
5. Gravity
6. Neutron
7. Nucleon
8. Nucleus
9. Photon
10. Plasma
11. Proton

12. Star

13. Strong Force

14. Weak Interaction

Optional Activity: Short Movie on Fusion and Solar Energy

Time: 3:44 minutes

Level: 6th -12th grade

Standard with which it aligns: PS1.C. Nuclear Processes

About this activity:
Teachers can show this optional YouTube video if they have that capability. This is a video that puts into perspective how solar energy is used in everyday life, and then explains how fusion is responsible for that energy.

"Solar Energy - Nuclear Fusion in the Sun - Simplified Version" at http://www.youtube.com/watch?v=pusKlK1L5To.

Teacher's Tip: If teachers do not have access to YouTube, it is possible to use a downloader and save this video as a document file and play it offline without needing YouTube. This link shows you many ways that you can do this: http://answers.yahoo.com/question/index?qid=20100327173144AARZ4ce.

Activity 1: What Makes a Star Shine? (Middle School Version)

Time: 30-45 minutes

Level: 6th -8th grade

Standard with which it aligns: PS1.C. Nuclear Processes

About this activity: Students will be introduced to fusion through a worksheet of concepts related to fusion individually or as a group assignment or as a group race.

Learning Outcomes:

The following taxonomy for learning is adapted from Anderson and Krathwohl's (2001) taxonomy, which has two domains: Knowledge and Cognitive Process. According to these outcomes, after this activity, students will:

1. Remember ideas about nuclear fusion by

1.1 Identifying and defining the concept of nuclear fusion and what conditions must be available for fusion to occur by

1.1: **Recognizing** a fusion reaction occurring

2. **Understand** and apply this knowledge of fusion and be able to infer the origins of heavier elements found throughout the universe by

2.5: Inferring where heavier elements originated after learning the concept of fusion

Directions:

Teacher's Tip: Ahead of time, teachers are encouraged to go over the links and science concepts they wish to cover in this lesson.

Teachers should provide context and motivation for the problem: Why does a star shine? What is a star made of? Where did all the elements we see today, which were not present at the beginning of the universe, come from? Turn this into a class discussion based on the "Science of the Term" section.

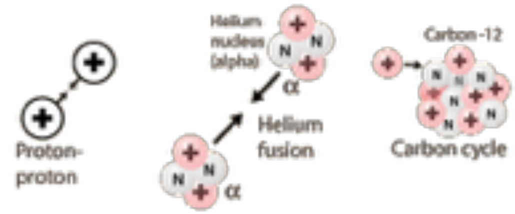
Next, go to http://zebu.uoregon.edu/~soper/Light/fusion.html. Use this site as a guide to introduce the concept of fusion. Be sure to mention the primary composition of stars, Hydrogen and Helium, the two lightest elements. Emphasize the enormous, several orders of magnitude (5.5 eV compared to eV), difference in energy output between the chemical process and nuclear process examples shown. And be sure to point out the mass number (number of nucleons, i.e. number of protons *and* neutrons) stays the same before and after, but not necessarily the number of protons *or* neutrons individually, however.

Teachers should hand out the worksheet that follows this page (adapted from Hyperphysics: http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/fuscon.html). Assign this as a class activity.

Teachers are encouraged to discuss results and implications, especially regarding the 2nd question, with the class, after this activity. It is important that students understand these concepts. Teachers can ask students if they were surprised to learn this, and if so, to explain why to the class.

Teacher's Tip: Alternatively, assign this as a group class assignment where each member of the group receives a single grade based on the same rubric found on the page that follows the worksheet. To make things fun and challenging, this can be a class race to see whose group turns in the worksheet and gets all questions correct. That group can receive a prize at the discretion of the teacher (i.e., extra credit, first in lunch line, etc.)

What Makes a Star Shine? (Grades 6-8)



Name (if group activity, list all group members):

____

Due: __________________

The enormous luminous energy of the stars comes from nuclear fusion processes in their centers. Nuclear reaction equations must balance just as chemical reaction equations do. The atomic number and atomic mass are shown for each particle (we don't care about the electrons in nuclear reactions). The atomic number, which indicates what the element is, is printed at the bottom left of the symbol for the element while the mass number is printed at the top right (although sometimes people use the top left) of the symbol. Both atomic number (number of positive particles) and mass number must be equal on both sides of the equation. Neutrinos are emitted from nuclear fusion reactions when beta (or positron) decay happens. The detection of these neutrinos gives scientists information about the fusion processes going on in stars.

For the following activity, the following notation will be used where X is the element symbol, A is the mass number (the total number of protons and neutrons) and Z is the atomic number (total number of protons).
Symbols for other particles:

stands for neutrino and has Z = 0 and A = 0.
stands for positron (a positively charged electron) and has Z = 1 and A = 0.
stands for gamma ray and has Z = 0 and A = 0.

The first step in Proton-Proton fusion to create Helium is:

1. Are the elements formed from all these fusion processes getting heavier or lighter? Why? ____
____
____

2. When the universe began at the Big Bang and it began to expand, the only element around was Hydrogen. But today, on Earth, there are many different elements, such as Carbon, Nitrogen, Oxygen, etc. that make up everything we know, including humans and animals! Where did all the other elements you know of come from?

Assessment

The following key should be used for the previous activity.

Answer Key: What Makes a Star Shine (Grades 6-8)

1. Are the elements formed from all these fusion processes getting heavier or lighter?
Response for full credit: They are getting heavier.

2. When the universe began at the Big Bang and it began to expand, the only element around was Hydrogen. But today, on Earth, there are many different elements, such as Carbon, Nitrogen, Oxygen, etc. that make up everything we know, including humans and animals! Where did all the other elements you know of come from?

Response for full credit: They came from the core of stars! In other words, the stars fused the hydrogen into heavier elements and, at the end of its life, exploded, scattering these heavier elements throughout the universe to form what we see today. That includes every element we have now on Earth and in the universe.

The following rubric should be used for the learning outcomes listed below when grading.

6^{th} – 8^{th} Grade Rubric	**Learning Objectives:**	
	To identify and define nuclear binding energies and how they apply to nuclear fusion	**To understand and apply the concept of binding energy to the binding energy curve**
Expert	Student correctly identified and defined: • 1. Concept of nuclear fusion • 2. What conditions must be available for fusion to occur	• Student correctly understood and applied knowledge of fusion • Student correctly inferred the origins of heavier elements found throughout the universe • Student correctly inferred where heavier elements originated after learning the concept of fusion
Proficient	Student mostly identified and defined: • 1. Concept of nuclear fusion • 2. What conditions must be available for fusion to occur	• Student mostly understood and applied knowledge of fusion • Student mostly inferred the origins of heavier elements found throughout the universe • Student mostly inferred where heavier elements originated after learning the concept of fusion
Intermediate	Student somewhat identified and defined: • 1. Concept of nuclear fusion • 2. What conditions must be available for fusion to occur	• Student somewhat understood and applied knowledge of fusion • Student somewhat inferred the origins of heavier elements found throughout the universe • Student mostly inferred where heavier elements originated after learning the concept of fusion

Novice	Student did not identify and define: • 1. Concept of nuclear fusion • 2. What conditions must be available for fusion to occur	• Student did not understand and apply knowledge of fusion • Student did not infer the origins of heavier elements found throughout the universe • Student did not infer where heavier elements originated after learning the concept of fusion

Activity 1: What Makes a Star Shine? (High School Version)

Time: 1 hour

Level: 9th -12th grade

Standard with which it aligns: PS1.C. Nuclear Processes

About this activity: Students will be introduced to fusion through a worksheet of concepts related to fusion.

Learning outcomes

The following taxonomy for learning is adapted from Anderson and Krathwohl's (2001) taxonomy, which has two domains: Knowledge and Cognitive Process. According to these outcomes, after this activity, students will:

1.1 Identify and define nuclear binding energies and how they apply to nuclear fusion by

1.1: **Recognizing** the concept of binding energies

3.2: **Implement** knowledge to solve for nuclear binding energies

2. Understand and apply this concept of binding energy to the binding energy curve and what happens to stars that have converted its core material into heavier elements where fusion is no longer energetically favorable by

2.5: **Inferring** the eventual fate of stars based on the notion of binding energy

Preparation:

Teachers should read and familiarize themselves with the treatment provided here to discuss the binding energy with students:

1. http://www-spof.gsfc.nasa.gov/stargaze/SnucEnerA-2.htm
2. http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/fuscon.html

Directions:

Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve changes in nuclear binding energies.

Normal stars stop producing light after having converted all of the material in their cores to carbon or, for more massive stars, to iron. Elements more massive than iron are formed by fusion processes but only in the extreme conditions of supernova explosions (description adapted from "A Framework for K-12 Science Education," 2012).

A more quantitative description of fusion is featured here. These concepts have been covered in "Science of the Topic" and a short class discussion may be appropriate to see what students remembered, especially with regard to the following take-home concepts:

Suggested class discussion questions to consider before diving in are:

- What is the mechanism that binds the nucleus together?
- Why is energy released when fusion occurs?
- Can stars just indefinitely fuse two lighter nuclei all the way up through the periodic table and beyond?

Then, teachers should hand out the 2-page worksheet on the next page as classwork or homework.

Teacher's Tip: Alternatively, assign this as a group class assignment where each member of the group receives the same grade, based on the same rubric found on the page that follows the worksheet. To make things fun and challenging, this can be a class race to see whose group turns in the worksheet and gets all questions correct. That group can receive a prize at the discretion of the teacher (i.e., extra credit, first in lunch line, etc.)

What Makes a Star Shine? (Grades 9-12)

Name (if group activity, list all group members:

____

____

Due: ________________________________

Instructions: Answer the following questions. Be as clear as possible.

1. State the main energy conversion process in suns and stars and describe the conditions that favor this kind of reaction.

2. What is binding energy?

3. Why is the binding energy of the nucleus given a negative sign?

4. Why can't we find elements in our environment whose atoms weigh 300 times as much as the proton?

The following questions will pertain to the binding energy curve given in Figure 1.

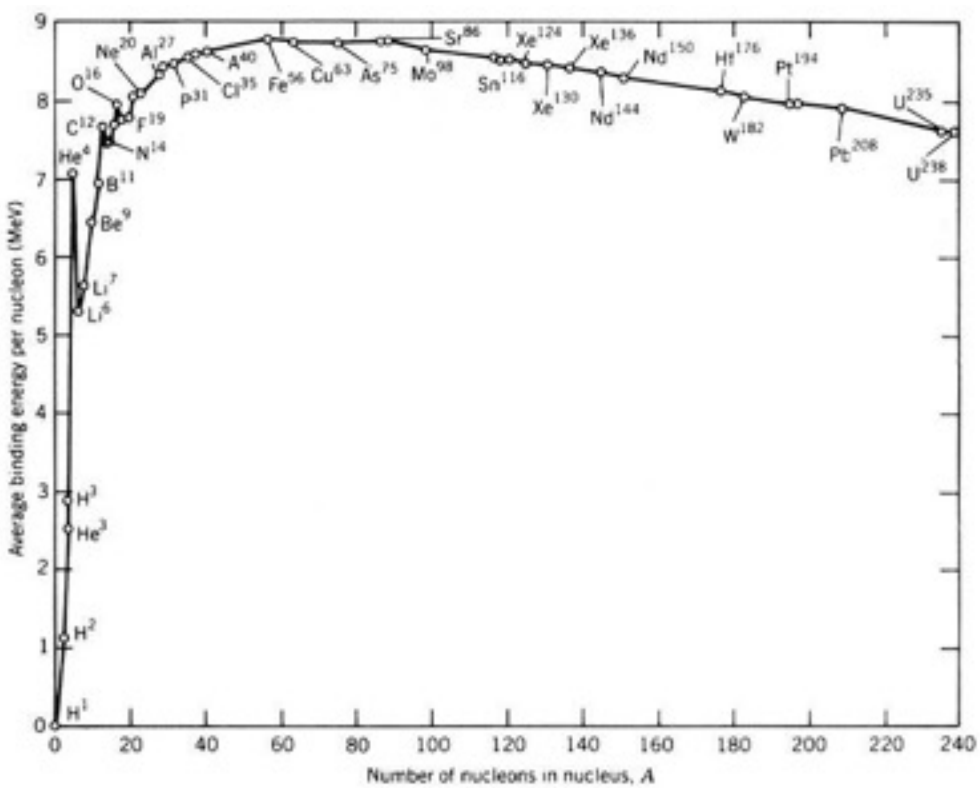


Figure 1: Nuclear Binding Energy Curve

5. According to the binding energy curve in Fig. 1 (which element is the most tightly bound, i.e. which has the highest binding energy per nucleon)?

6. From your answer in number 5, what does this tell you about the elements to the left of this element on the curve and the elements to the right of this element on the curve?

Assessment

The following key should be used for the previous activity.

Answer Key: What Makes a Star Shine (Grades 9-12)

1. State the main energy conversion process in suns and stars and describe the conditions that favor this kind of reaction.
The sun and the stars use the process of nuclear fusion to convert the enormous thermal kinetic energy into electromagnetic energy through fusion of hydrogen in the Sun's core, producing helium. Conditions for this to occur are typically extreme temperatures and pressures, which are present in the core of stars due to the overwhelming gravitational pull of all the mass.

2. What is binding energy?
Binding energy is the energy required to disassemble any larger whole into its constituent parts. In the case of nucleus, the nuclear binding energy corresponds to the energy to break up a nucleus into the same number of free nucleons (neutrons and protons) so that they are far enough from each other for any further interactions.

3. Why is the binding energy of the nucleus given a negative sign?
The energy of a nucleus is the extra energy available to use where the zero energy means all particles are independently spread out. A bound nucleus needs energy input to reach this "zero energy" state, so its energy is negative.

4. Why can't one find in our environment elements whose atoms weigh 300 times as much as the proton, or more?
Such nuclei contain too many protons repelling each other, and in spite of the strong nuclear attraction between their particles, are unstable.

5. According to the binding energy curve, which element is the most tightly bound, i.e. which has the highest binding energy per nucleon?
Iron

6. From your answer in number 5, what does this tell you about the elements to the left of this element on the curve and the elements to the right of this element on the curve?

To the left of iron, it is still energetically favorable for fusion to occur, but to the right, if two nuclei heavier than iron were to fuse, the resulting nucleus would have a binding energy lesser than the two original nuclei which is not energetically favorable. Hence the only way elements as heavy as Uranium occur is from supernovae which have enormous energies that essentially brute force the nuclei to fuse. This explains the rarity of elements such as Uranium and why Iron is so common.

The following rubric should be used for the learning outcomes listed below when grading.

9^{th} – 12^{th} Grade Rubric	**Learning Objectives:**	
	To identify and define nuclear binding energies and how they apply to nuclear fusion	**To understand and apply concept of binding energy to the binding energy curve and what happens to stars that have converted its core material into heavier elements where fusion is no longer energetically favorable**
Expert	• Student correctly recognized and defined the concept of binding energy Student correctly implemented knowledge to understand nuclear binding energies	Student correctly inferred the eventual fate of stars based on the notion of binding energy
Proficient	• Student mostly recognized and defined the concept of binding energy • Student mostly implemented knowledge to understand nuclear binding energies	Student mostly inferred the eventual fate of stars based on the notion of binding energy
Intermediate	• Student somewhat recognized and defined the concept of binding energy • Student somewhat implemented knowledge to understand nuclear binding energies	Student somewhat inferred the eventual fate of stars based on the notion of binding energy

Novice	• Student did not recognize and defined the concept of binding energy • Student did not implement knowledge to understand nuclear binding energies	Student did not infer the eventual fate of stars based on the notion of binding energy

Activity: Watch Clip: Pop Culture Astrophysicist Neil DeGrasse Tyson's Most Astounding Fact

Time: 3:33 minutes

Level: 9th -12th grade

About this activity:
At the end of the lesson, show the following video to tie up the concepts together and put them into perspective for the students: http://www.wimp.com/astoundingfact/.
Students may recognize Dr. Tyson. He is a popular TV science personality and directs New York City's Hayden planetarium. He also hosts a podcast called Star Talk Radio and PBS series NOVA Science Now (and you can watch full length episodes for free online at http://www.hulu.com/nova-sciencenow which is highly encouraged in the classroom.)

Congratulations!

You've completed the R* lesson. Here we have highlighted only one of the processes that make stars shine. If we want to search for life, how would we pick and choose among the countless stars to search? Which stars should we "wish upon"? Future iterations of this lesson will go through several other crucial stellar properties, and life cycles of stars. Here, students should have understood that the stellar life and death cycle depends upon a lot of energetic reactions that fuel a star. But when that fuel is gone, that star will explode and distribute the elements it created throughout its stellar "neighborhood." The consequences of this will be discussed in future iterations. Stay tuned!

For now, let's move on to planets. Planets form around stars. Now that we have some ideas as to how stars work, let's examine how we know which planets may harbor environments for life, or habitable environments. Which kinds of planets do scientists hunt for and how do they find them? Let's examine this in the F_p lesson.