Part I: How and Where are Elements Created?

From: X-ray Spectroscopy and the Chemistry of Supernova Remnants

A Series of Lesson Plans by
Allie Hajian and Maggie Masetti (NASA/GSFC, Greenbelt, MD)
Rick Fowler (Crossland High School, Temple Hills, Maryland)
Angela Page (Hyattsville Elementary School, Hyattsville, Maryland)

Objectives

Students will read and write about the chemistry and spectroscopy of stars and supernova remnants, as well as understand their relevance and impact on human life. Students will also learn about cutting edge technology that will help us to build better instruments with which to study the Universe.

Each section has several pages of background material relevant to the associated activities and the lesson plan as a whole. The background sections include short exercises or thought questions developed to help the student reach a better understanding of the material presented. Each section also has activities developed by real teachers - designed to bring important concepts in astronomy right into the classroom. Each activity is correlated to national science and math standards for grades 9 - 12. These activities show how interrelated chemistry, physics, and astronomy really are.

Outline of Unit

Part I: How and Where are Elements Created?

- **Background:** *The Life Cycles of Stars: How Supernovae Are Formed* – Describes the life of a high-mass star - as well as its death in a giant supernova explosion.
- **Background**: *The Dispersion of Elements* – Describes how supernova explosions not only disperse the elements created inside a star, they create new elements.
- **Activity**: *Fusion Reactions* – In this activity, each student is given a card with an element produced inside stars on it - the students then form fusion reactions that occur within stars.

Part II: What is Electromagnetic (EM) Radiation? How is it created in atoms? What units are used to characterize EM radiation?

- **Background**: *How Do the Properties of Light Help Us to Study Supernovae and Their Remnants?* – Students learn about the electromagnetic spectrum.
- **Activity**: *Calculation Investigation* – Students learn about unit analysis by converting energies to wavelengths to frequencies.
- **Background**: *Atoms and Light Energy* – Describes how atoms emit light, and how we can use this to learn about astronomical objects.
- **Activity**: *Calculate the Energy!* – Students will calculate the energy differences in different energy states of the Bohr atom of Hydrogen.

Part III: What tools are used to identify elements? What importance do X-rays have to astronomy?

- **Background**: *Introduction to Spectroscopy* – Everything you ever wanted to know about spectroscopy but were afraid to ask!
- **Activity**: *Graphing Spectra* – Practice drawing graphs of spectra, and understanding the different ways spectra can be represented, as well as what each representation can tell us.
- **Activity**: *Flame Test* – A chemistry experiment that shows how heated elements emit different colors of light.
- **Activity**: *Design an Element Poster Advertisement* – Students will discuss what they have learned about atoms and elements in their own words, designing a poster advertisement for their chosen element. Students will use more than just their right brain to think about science!

Part IV: How does the newest technology help us to understand the Universe?

- **Background**: *All About The Microcalorimeter* – All about microcalorimeter technology, the next generation X-ray spectrometer.

- **Activity**: *Identifying Light Energy by Temperature Changes* – Learn first hand how a microcalorimeter really works
- **Activity**: *Identifying Elements in Supernova Remnants using Spectra* – Now the students get to take all they have learned and really apply it. Students will identify the elements present in a supernova remnant by analyzing its spectrum.
- **Background**: *A Plethora of X-ray Telescopes* – Learn about existing and future X-ray telescopes and what they hope to accomplish.
- **Activity**: *Satellite Venn Diagram* – Students will organize the information about X-ray observatories into a Venn diagram.
- **Activity**: *Writing Assignment* – As a closing activity, students will demonstrate the ability to use text information and data to persuade a reading audience of the benefits of using calorimeter detectors to do X-ray astronomy.

Part I: How and Where are Elements Created?

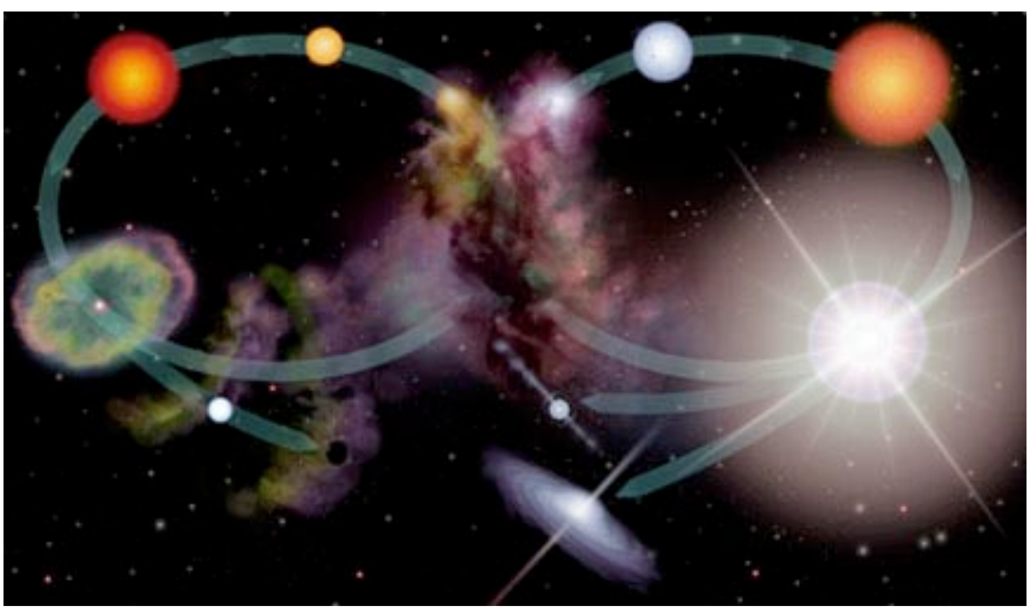
The Life Cycles of Stars: How Supernovae Are Formed

It is very poetic to say that we are made from the dust of the stars. Amazingly, it's also true! Much of our bodies, and our planet, are made of elements that were created in the explosions of massive stars. Let's examine exactly how this can be.

Life Cycles of Stars

A star's life cycle is determined by its mass. The larger its mass, the shorter its life cycle. A star's mass is determined by the amount of matter that is available in its nebula, the giant cloud of gas and dust from which it was born. Over time, the hydrogen gas in the nebula is pulled together by gravity and it begins to spin. As the gas spins faster, it heats up and becomes as a protostar. Eventually the temperature reaches 15,000,000 degrees and nuclear fusion occurs in the cloud's core. The cloud begins to glow brightly, contracts a little, and becomes stable. It is now a main sequence star and will remain in this stage, shining for millions to billions of years to come. This is the stage our Sun is at right now.

As the main sequence star glows, hydrogen in its core is converted into helium by nuclear fusion. When the hydrogen supply in the core begins to run out, and the star is no longer generating heat by nuclear fusion, the core becomes unstable and contracts. The outer shell of the star, which is still mostly hydrogen, starts to expand. As it expands, it cools and glows red. The star has now reached the red giant phase. It is red because it is cooler than it was in the main sequence star stage and it is a giant because the outer shell has expanded outward. In the core of the red giant, helium fuses into carbon. All stars evolve



The life cycle of a low mass star (left oval) and a high mass star (right oval).

the same way up to the red giant phase. The amount of mass a star has determines which of the following life cycle paths it will take from there.

The illustration above compares the different evolutionary paths low-mass stars (like our Sun) and high-mass stars take after the red giant phase. For low-mass stars (left hand side), after the helium has fused into carbon, the core collapses again. As the core collapses, the outer layers of the star are expelled. The outer layers form a planetary nebula. The core remains as a white dwarf and eventually cools to become a black dwarf.

On the right of the illustration is the life cycle of a massive star (10 times or more the size of our Sun). Like low-mass stars, high-mass stars are born in nebulae and evolve and live in the Main Sequence. However, their life cycles start to differ after the red giant phase. A massive star will undergo a supernova explosion. If the remnant of the explosion is 1.4 to about 3 times as massive as our Sun, it will become a neutron star. The core of a massive star that has more than roughly 3 times the mass of our Sun after the explosion will do something quite different. The force of gravity overcomes the nuclear forces that keep protons and neutrons from combining. The core is thus swallowed by its own gravity. It has now become a black hole that readily attracts any matter and energy that comes near it. What happens between the red giant phase and the supernova explosion is described below.

From Red Giant to Supernova: The Evolutionary Path of High Mass Stars

Once stars that are 5 times or more massive than our Sun reach the red giant phase, their core temperature increases as carbon atoms are formed from the fusion of helium atoms. Gravity continues to pull carbon atoms together as the temperature increases and additional fusion processes proceed, forming oxygen, nitrogen, and eventually iron.

The two supernovae, one reddish yellow and one blue, form a close pair just below the image center (to the right of the galaxy nucleus)

Image Credit: C. Hergenrother, Whipple Observatory, P. Garnavich, P.Berlind, R.Kirshner (CFA).

When the core contains essentially just iron, fusion in the core ceases. This is because iron is the most compact and stable of all the elements. It takes more energy to break up the iron nucleus than that of any other element. Creating heavier elements through fusing of iron thus requires an input of energy rather than the release of energy. Since energy is no longer being radiated from the core, in less than a second, the star begins the final phase of gravitational collapse. The core temperature rises to over 100 billion degrees as the iron atoms are crushed together. The repulsive force between the nuclei overcomes the force of gravity, and the core recoils out from the heart of the star in a shock wave, which we see as a supernova explosion.

As the shock encounters material in the star's outer layers, the material is heated, fusing to form new elements and radioactive isotopes. While many of the more common elements are made through nuclear fusion in the cores of stars, it takes the unstable conditions of the supernova explosion to form many of the heavier elements. The shock wave propels this material out into space. The material that is exploded away from the star is now known as a supernova remnant.

The hot material, the radioactive isotopes, as well as the leftover core of the exploded star, produce X-rays and gamma rays.

For the Student
Using the above background information, (and additional sources of information from the library or the web), make your own diagram of the life cycle of a high-mass star.

For the Student
Using the text, and any external printed references, define the following terms: protostar, life cycle, main sequence star, red giant, white dwarf, black dwarf, supernova, neutron star, pulsar, black hole, fusion, element, isotope, X-ray, gamma-ray.

Reference URLs:

Supernovae
http://imagine.gsfc.nasa.gov/docs/science/know_l1/supernovae.html
http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernovae.html

Life Cycles of Stars
http://imagine.gsfc.nasa.gov/docs/teachers/lifecycles/stars.html

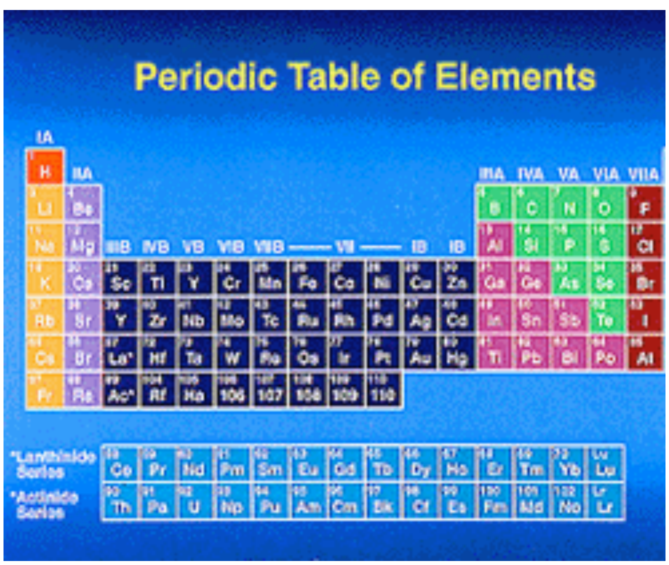
The Dispersion of Elements

In addition to making elements, supernovae scatter them. The elements that are made both inside the star as well as the ones created in the intense heat of the supernova explosion are spread out in to the interstellar medium. These are the elements that make up stars, planets and everything on Earth – including us. Except for hydrogen and some helium created in the Big Bang, all of the stuff we, and the Earth around us, are made of, was generated in stars, through sustained fusion or in supernova explosions.

Enrichment of the Space Between the Stars

The most common elements, like carbon and nitrogen, are created in the cores of most stars, fused from lighter elements like hydrogen and helium. The heaviest elements, like iron, however, are only formed in the massive stars that end their lives in supernova explosions. Still other elements are born in the extreme conditions of the explosion itself. Without supernovae, life would not be possible. Our blood has iron in the hemoglobin, which is vital to our ability to breath. We need oxygen in our atmosphere to breathe. Nitrogen enriches our planet's soil. Earth itself would be a very different place without the elements created in stars and supernova explosions.

How do the elements that are released in the wake of a supernova explosion end up in the make-up of a planet like Earth? Though we normally think of space of being empty, it actually isn't. It might seem empty since the average particle density of interstellar space is around 1 atom per cubic centimeter, but there are some 1037 tons of this thin matter in our Galaxy alone! We call the matter that fills the space between the stars the "interstellar medium" or ISM.



The Periodic Table of the Elements

Supernovae change the chemical composition of the ISM, by adding elements that were not present before, or were only present in trace amounts. Though these explosions only occur a few times a century in our Galaxy, they are responsible for the synthesis of all the elements heavier than iron, including many we come across in daily life, like copper, mercury, gold, iodine and lead. Most of the elements that are produced in supernovae have small cosmic abundances and very few have been directly detected in the interstellar medium. The ISM is also enriched in other ways, by stars losing mass due to the solar wind for example, but supernovae are the main means in which it becomes enriched with heavier elements.

The gradual enrichment of the interstellar medium with heavier elements has made subtle changes to how stars burn: the fusion process in our own Sun is moderated by the presence of carbon. The first stars in the Universe had much less carbon and their lives were somewhat different from modern stars. Stars that will be formed in the future will have even more of these heavier elements and will have somewhat different life cycles. Supernovae play a very important part in this chemical evolution of the Universe.

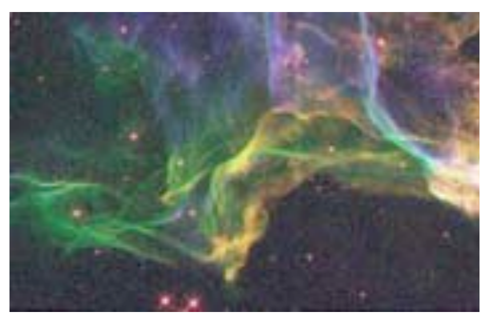
Chaos and Structure

The Crab Nebula

The chaos caused by supernovae, like the one that created the Crab Nebula (shown at left), is also responsible for the complex structure of the ISM. A supernova creates shock waves through the interstellar medium, compressing the material there, heating it up to millions of degrees. Astronomers believe that these shock waves are vital to the process of star formation, causing large clouds of gas to collapse and form new stars. No supernovae, no new stars.

What is the time scale? In tens of thousands of years after the initial explosion, a supernova remnant may grow to 100 light years in diameter. A few hundreds of thousands of years after the explosion, the ejecta will eventually mix in with the general interstellar medium. The supernova has thus enriched the interstellar medium with heavy elements across a sphere a thousand light years across or so. This means that millions or even billions of years may elapse between the supernova explosion that creates an atom of gold, for example, and the formation of the solar system where the atom eventually ends up. That's a long time! In this amount of time, a star can circle the Galaxy several times - and two stars that started off being next to each other may have ended up on the opposite side of the Galaxy!

It is impossible to speculate which specific supernovae created the heavy elements that ended up in a specific solar system; the heavy elements that are in your body and in objects around you, are the products of many different supernovae over many millions of years all over the Galaxy. Over many millions of years, the interstellar medium is continuously enriched by thousands of supernovae. That makes it all the more amazing when one tiny corner of the interstellar medium becomes dense enough, and a solar system is formed.



The Cygnus Loop
Credit: J. Hester (ASU), NASA

For the Student
Using the text, and any external printed references, define the following terms: supernova remnant, interstellar medium, light year.

Reference URLs:

Supernovae
http://imagine.gsfc.nasa.gov/docs/science/know_l1/supernovae.html
http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernovae.html

Life Cycles of Stars
http://imagine.gsfc.nasa.gov/docs/teachers/lifecycles/stars.htm

Element Production in the Universe
http://zebu.uoregon.edu/disted/ph123/l10.html
http://aether.lbl.gov/www/tour/elements/stellar/stellar_a.html

Activity – Fusion Reactions

Days Needed: 1-2
Grade Level : 11 - 12

Objective

Students will learn about the elements created in the cores of high-mass stars in this activity.

Science and Math Standards

NSES

- Content Standard B:
  - Structure of Atoms
  - Interactions of energy and matter
- Content Standard G:
  - Nature of Scientific Knowledge

Pre-requisites

- Students should be familiar with basic chemistry.
- Students should also have read the background sections on the Life Cycles of the Stars and the Dispersion of Elements.

Introduction

Elements are produced in the cores of high-mass stars by fusion reactions. All stars start by burning hydrogen and end up creating many heavier elements inside their cores. It is this kind of star that will eventually spread the elements it created in its core when it dies in a supernova explosion.

Engagement

Using colored clay, either home-made or store-bought, make a model of the core of a star. If time allows, the class can do this themselves, otherwise, the teacher can demonstrate it for the class.

Materials:

- 8 colors of clay, either home-made or store-bought (see recipe for home-made clay here: http://amazingmoms.com/htm/artclayrecipes.htm)
- ball-bearing or other small metallic ball (large silver beads would work)
- plastic knife

Procedure:

Cover the ball-bearing or bead with one color of clay - make the layer of clay at least half an inch thick. Use another color of clay to make a layer over the first. Do this until you have 8 layers of clay, each a different color, each at least half an inch thick. Now, cut the ball in half to make a cross section (you'll have to cut around the ball-bearing). The inside shows the different layers present in the core of a high-mass star. Each of those layers of clay belongs to a different element. The ball-bearing is the iron core of the star. At the end of the day's activity, the class will come back to the model and learn what the different layers are.

Exploration

Materials:

Index cards with elements written on them. You'll need

- 4 hydrogen-1 (^{1}H)
- 13 helium-4 (^{4}He)
- 4 carbon-12 (^{12}C)
- 1 magnesium-24 (^{24}Mg)
- 4 oxygen-16 (^{16}O)
- 1 sulphur-32 (^{32}S)
- 1 neon-20 (^{20}Ne)
- 1 silicon-28 (^{28}Si)
- 2 nickel-56 (^{56}Ni)
- 2 cobalt-56 (^{56}Co)
- 2 iron-56 (^{56}Fe)
- 2 iron-57 (^{57}Fe)
- 2 iron-58 (^{58}Fe)
- 1 iron-59 (^{59}Fe)
- 3 neutrons (n)
- 4 positrons (e+)
- 2 neutrinos
- at least 7 energy

Procedure:

Give each student an index card with an element written on it. Have the students move about the classroom and construct fusion reactions. Their goal is to form the reactions that create helium, carbon, magnesium, oxygen, sulphur, neon, nickel, cobalt, and 4 different isotopes of iron. The teacher should assist or give hints as necessary.

The students should end up with the following fusion relationships:

$4\,(^{1}H) \rightarrow {}^{4}He + 2\,e^{+} + 2$ neutrinos + energy
$3\,(^{4}He) \rightarrow {}^{12}C$ + energy
$^{12}C + {}^{12}C \rightarrow {}^{24}Mg$ + energy
$^{12}C + {}^{4}He \rightarrow {}^{16}O$ + energy
$^{16}O + {}^{16}O \rightarrow {}^{32}S$ + energy
$^{16}O + {}^{4}He \rightarrow {}^{20}Ne$ +energy
$^{28}Si + 7(^{4}He) \rightarrow {}^{56}Ni$ + energy

$^{56}Ni \rightarrow {}^{56}Co + e^+$ (positive Beta Decay)
$^{56}Co \rightarrow {}^{56}Fe + e^+$ (positive Beta Decay)
$^{56}Fe + n \rightarrow {}^{57}Fe$
$^{57}Fe + n \rightarrow {}^{58}Fe$
$^{58}Fe + n \rightarrow {}^{59}Fe$

When the students create a correct reaction, write it on the board – keep the reactions in the order they are in the table above. The order is important.

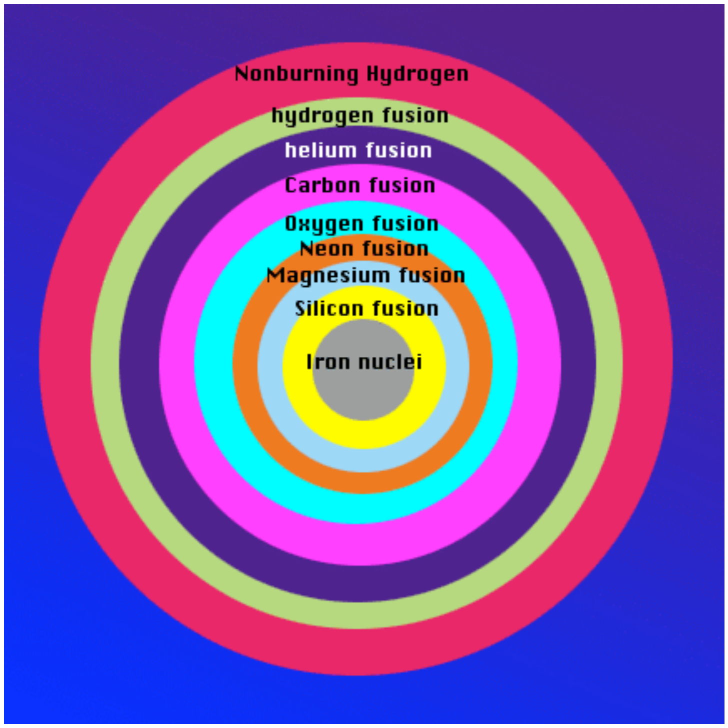
Adapting for class size: The number of cards handed out will vary depending on class size. If your class size is small, only do 2 or 3 reactions at a time, handing out only the cards with elements that are in those reactions. Just be sure every student has a card. If your class size is large, do about half the reactions at a time, giving the students only the cards used in those reactions. If there are not enough cards to go around, give out extra energy cards. It is all right to have more than one student representing energy in a reaction. When the students are done, collect those cards and hand out the cards used in the rest of the fusion reactions and have the class form them.

When the class is done forming reactions, have them examine the reactions and their order. They should see, that like high-mass stars, they have created heavy elements, even though they started with just hydrogen. A high-mass star converts its hydrogen to helium, helium to carbon, carbon to magnesium, carbon and helium to oxygen, oxygen to sulfur, oxygen and helium to neon, and silicon and helium to nickel. The unstable isotope of nickel created undergoes positive beta decay and forms an isotope of cobalt that in turn decays into iron. Positive beta decay is when a proton becomes a neutron, and a positron is emitted. A high-mass star creates many unstable isotopes of iron and actually goes through a series of reactions that cause the star to make heavier and heavier nuclei of elements, all the way up to bismuth-209 - the heaviest known nonradioactive nucleus.

This process is the origin of the copper and silver in the coins in our pockets, the lead in our car batteries, and the gold in the rings on our fingers!

Now that the class is aware of the order in which the elements are created in a star, bring them back to the model of the core of the star from the beginning of class. The ball bearing is the iron core of the star. The layers outside it are where various nuclei fuse. Have the students associate a layer of clay with an element that is being produced by the high-mass star. This will illustrate that as the temperature of the star increases with depth, the ash of each burning stage becomes the fuel for the next stage. Surrounding the core of iron nuclei is a layer of silicon fusion, then magnesium, then neon, then oxygen, then carbon, then helium, and lastly, in the relatively cool periphery of the core, hydrogen fuses into helium. A layer of non-burning hydrogen envelops the core.

Have the class draw their version of the onion-like nature of the core of a star based on the model and explain the process that occurs at each layer for homework. Here is an example:



An example of a drawing depicting the layers of elements in the core of a high-mass star

Evaluation

Have each group of students explain the reaction they have made and why they think it is correct. Their individual diagrams and explanations of the core of a high-mass star may also be evaluated.

Reference URLs

Element Production

http://zebu.uoregon.edu/disted/ph123/l10.html
http://aether.lbl.gov/www/tour/elements/stellar/stellar_a.html
http://library.thinkquest.org/17940/texts/ppcno_cycles/ppcno_cycles.html
http://csep10.phys.utk.edu/guidry/violence/supernovae.html
http://zebu.uoregon.edu/~soper/Sun/fusion.html
http://zebu.uoregon.edu/~soper/Sun/fusionsteps.html

Reference Book:

Astronomy Today, by Eric Chaisson and Steve McMillan.