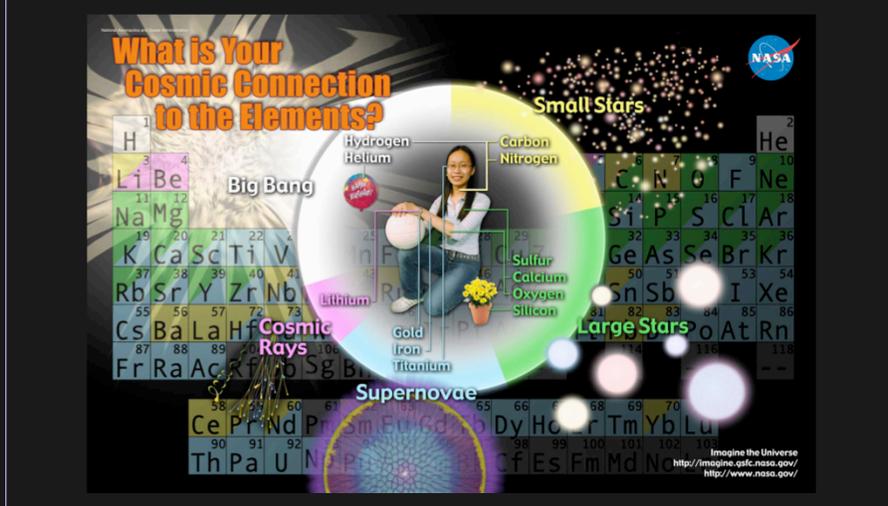


# Your Cosmic Connection to the Elements

James Lochner (USRA) & Suzanne Pleau Kinnison (AESP), NASA/GSFC



July 2006 - a revision to update this with the new version of the poster and periodic table. Slide #6 now contains links to relevant portions of the talk. Also, Meredith fixed the inclusion of the sound files for the Nickelodion demo (slides 26-28)

First public version. Notes are from presentation by Sara Mitchell in Aug 2003. The notes provide a script that may be used with the slides.

Tell participants that we will be pondering the question asked on the poster, "What is your cosmic connection to the elements?"

# Elementary Connections

The image shows a standard periodic table of elements. The elements are arranged in rows and columns based on their atomic number and chemical properties. The table includes elements from Hydrogen (H) to Oganesson (Og), with atomic numbers ranging from 1 to 118. The lanthanide and actinide series are shown as separate rows below the main table.

What is this? [Periodic Table]

What does it show? How is it arranged?

Can you tell me some of the elements you encounter every day, in the objects all around you? Tell me an object and the element(s) in it.

[Have audience make the connection between everyday objects and the elements in the periodic table. For example:

Gold in jewelry

Aluminum in soda cans

Titanium in eye glass frames

Hydrogen and oxygen in water

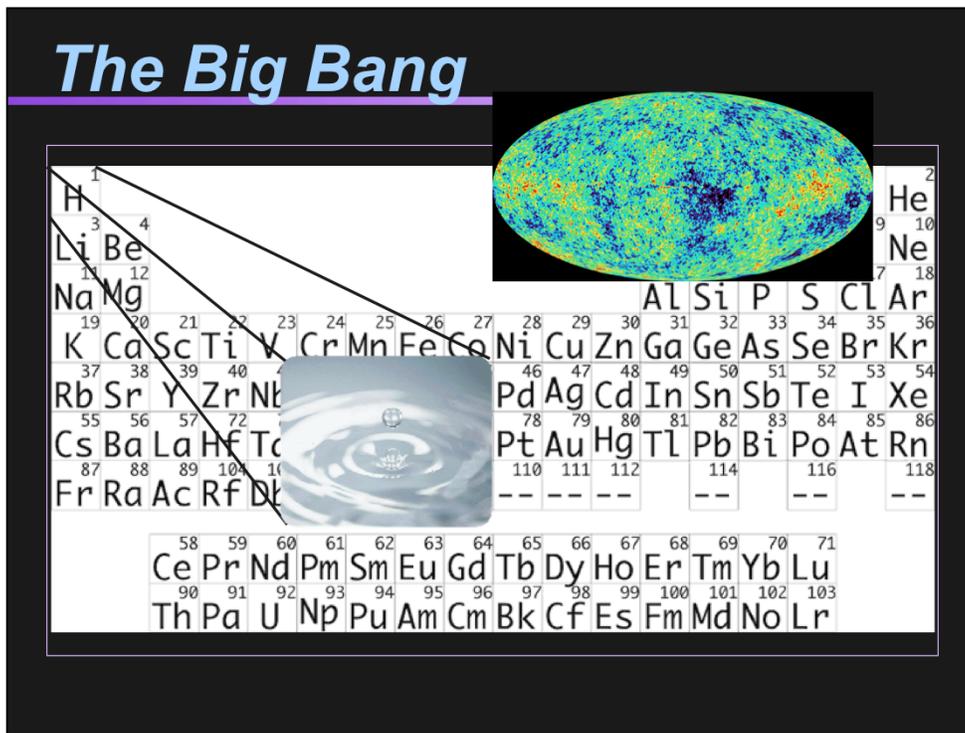
Calcium in milk and bones

Nitrogen in the air]

**Make sure they identify some elements heavier than Iron.**

End with question: **Where do these elements come from?** (Some may say, the earth. Let this lead to solar system (and its formation), and ultimately the stars.)

# The Big Bang



Now let's start at the beginning, with the Big Bang. The Big Bang created Hydrogen, Helium, and a tiny amount of Lithium. [Click for WMAP.]

The image is from the Wilkinson Microwave Anisotropy Probe, which is a long and fancy name that we usually shorten to "WMAP." This is a baby picture of the universe, from when it was a mere 379,000 years old.

The image shows differences in the temperature of the microwave background. The average background temperature is 2.73 degrees above absolute zero. The red areas are "warmer" than this, and the blue areas are "cooler."

WMAP is sensitive to measuring differences in temperature as small as millionths of a degree, so when we say "warmer" or "cooler," we may be referring to fluctuations of thousandths or millionths of degrees.

The WMAP results confirmed several ideas we had about the universe -- the age of the universe is 13.7 billion years, and stars started forming 200 million years after the Big Bang. It did this using the fluctuations measured this image.

The Cosmic Microwave Background was one of the strongest pieces of evidence for the Big Bang theory.

## *The Big Bang Cosmology*

- The expansion of the universe began at a finite time in the past, in a state of enormous density, pressure and temperature.
- “Big Bang” is a highly successful family of theories with no obvious competitor.
  - Explains what we see, and has made several successful predictions.

The first important question is:

### **What is the Big Bang?**

Most astronomers theorize that the Universe started with a massive explosion. This happened at a finite time, and everything was very hot, very dense, and under a lot of pressure.

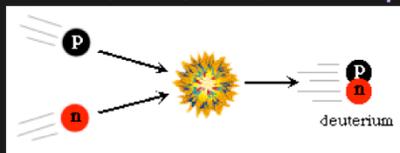
The Big Bang is a very successful family of theories that explains what we see and has made several predictions that have been confirmed. The Big Bang is consistent with observations we've made.

[This explanation of what the Big Bang is and why it is used may be helpful to some teachers in areas where formation of the universe is a sensitive topic.]

## Big Bang Nucleosynthesis

Within first three minutes, Hydrogen & Helium formed.

- At  $t = 1$  s,  $T = 10,000,000,000$  K: soup of particles: photons, electrons, positrons, protons, neutrons. Particles created & destroyed.
- At  $t = 3$  min,  $T = 1,000,000,000$  K:  $p + n \Rightarrow D$



- $D + D \Rightarrow He$

Right after the explosion, things are very, very hot, over  $10^{32}$  degrees! Matter and energy are expanding outward.

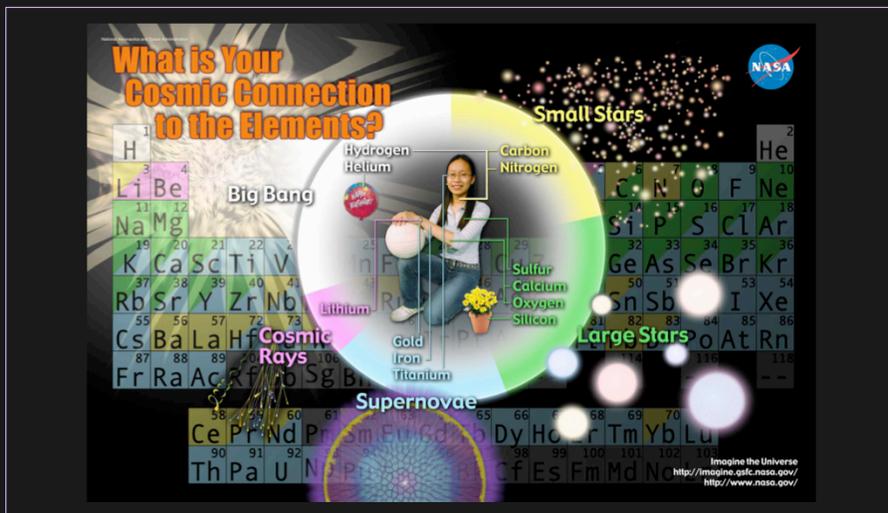
At one second after the Big Bang, the temperature is ten billion degrees and we have a “particle soup.” It’s really too hot and energetic for any nuclei heavier than Hydrogen to form, so we mostly have lots of particles being created and destroyed -- protons, electrons, neutrons, positrons, and plenty of other “-ons.” But things are cooling down pretty quickly. After three minutes have passed, the temperature has dropped to one billion degrees, and we see the first particles coming together. A proton and a neutron join to form Deuteron, the nucleus of Deuterium (or “heavy water”).

From the Deuterium, we can get Helium -- two Deuterons join to form one Helium. Very occasionally, enough Deuterium collide to form Lithium, but this was rare.

As the Universe expands, the temperature falls and soon it is too cool for more nuclei to form. This is what the Big Bang forms in the first few minutes -- 95% Hydrogen and 5% Helium (and a trace amount of Lithium).

Atoms form at  $T = 3,000$  K when the electrons “recombine” with the nuclei to form atoms. At this “recombination”, the universe becomes transparent. This 3,000 K black body radiation has been redshifting ever since, and is now 2.7 K.

## Your Cosmic Connection to the Elements?



On this page, certain elements are linked to other sections of the presentation:

“carbon” -> small stars

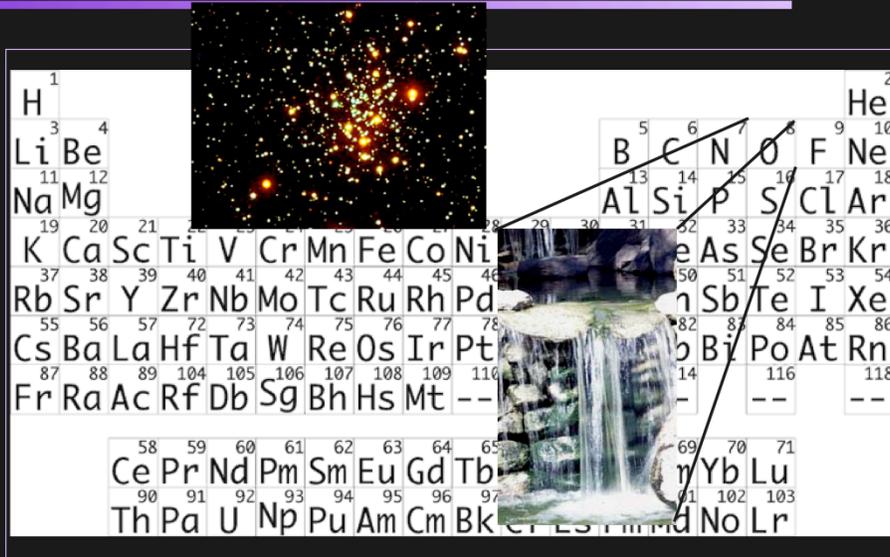
“calcium” -> large stars

“iron” -> supernovae

“lithium” -> cosmic rays

At the end of each of those sections (except cosmic rays), there is a thumbnail poster in the lower right corner. Clicking on it will return you to this page. Hence this page may be used as an anchor and reference throughout the talk.

# Small Stars



So where do we get the rest of these elements?

Let's move along, to small stars. What do we mean by "small"?

Well, only in astronomy can you call something  $2 \times 10^{30}$  kg "small"! Our Sun is a small star, and so are stars smaller than about five times the mass of our Sun. These stars run on similar processes, and share a similar fate.

[click to show waterfall]

These small stars form Helium, Carbon, Nitrogen, and Oxygen in their cores through FUSION

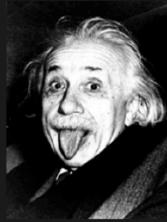
## Small Stars: Fusion of light elements

Fusion: (at 15 million degrees !)

$4\text{ }(^1\text{H}) \Rightarrow\text{ }^4\text{He} + 2\text{ e}^+ + 2\text{ neutrinos} + \text{energy}$

Where does the energy come from ?

Mass of four  $^1\text{H} >$  Mass of one  $^4\text{He}$



$$E = mc^2$$

[Click to reveal “Fusion.”]

Elements in small stars are formed through FUSION. At what temperature does fusion start? Does anyone remember?

[let people “bid” on the temperature until ~15 million degrees]

[Click to reveal answer]

Why does it have to be that hot?

[To overcome the electrostatic repulsion of the positive protons.]

[Click for equation.]

These small stars fuse Hydrogen into Helium in their cores.

The energy comes from the slight excess of mass of the 4 input H as compared to the resulting He. The mass gets converted into energy via  $E=mc^2$

## *Small Stars to Red Giants*

---

After Hydrogen is exhausted in core,

Energy released from nuclear fusion no longer counter-acts inward force of gravity.

- Core collapses,
  - Kinetic energy of collapse converted into heat.
  - This heat expands the outer layers.
- Meanwhile, as core collapses,
  - Increasing Temperature and Pressure ...

Eventually, the Hydrogen runs out. Remember, there is a balance between the energy created by fusion and the star's gravity that keeps it from collapsing. Without fusion, the gravity isn't balanced, and the star's core collapses. This collapse causes an increase in temperature and pressure, and the star puffs up and becomes a red giant!

## *Beginning of Heavier Elements*

At 100 million degrees Celsius, Helium fuses:  
 $3\ ^4\text{He} \Rightarrow\ ^{12}\text{C} + \text{energy}$

After Helium exhausted, small star not large enough to attain temperatures necessary to fuse Carbon.



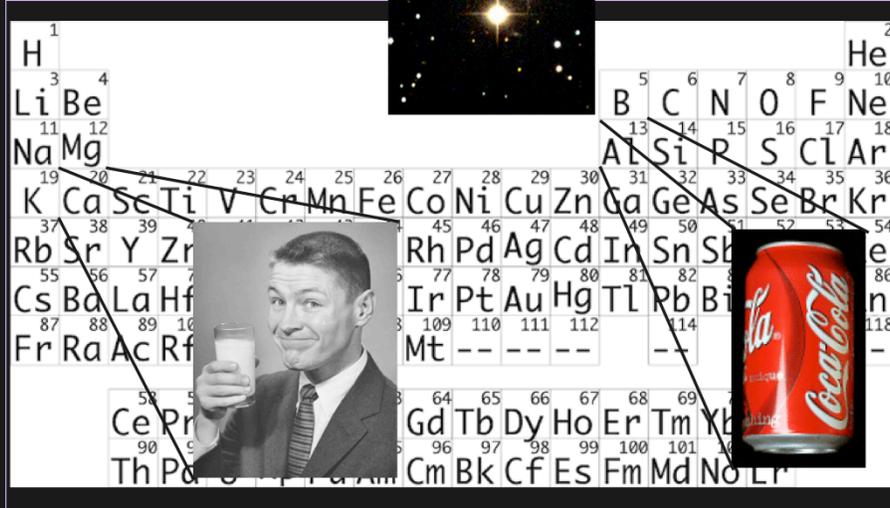
The core continues to increase in temperature and pressure, reaching 100 million degrees. At this temperature, it is hot enough to fuse Helium into Carbon. The energy from this fusion keeps the star from collapsing. Nitrogen and Oxygen fuse in a similar way.

But eventually, the core runs out of materials again, and we don't make any heavier elements. In fact, this cycle ends with another core collapse, expelling the extended atmosphere as a planetary nebula.

So where do we get the heavier elements? At this point, we only have Hydrogen, Helium, Carbon, Nitrogen, and Oxygen.

Click on the poster icon in the lower right to return to slide #6.

# Large Stars



Large stars continue where small stars leave off.

These are stars larger than 5 times the mass of our Sun.

[Click twice to reveal Calcium and Aluminum examples.]

Large stars create many of the heavier elements beyond what the small stars produce, like the Calcium in milk and the Aluminum in cans.

## *Heavy Elements from Large Stars*

Large stars also fuse Hydrogen into Helium, and Helium into Carbon.

But their larger masses lead to higher temperatures, which allow fusion of Carbon into Magnesium, etc.

Just like small stars, large stars fuse Hydrogen into Helium, and Helium into Carbon.

But the larger mass leads to higher temperatures, and a series of core collapses create heavier elements through fusion.

## Element Formation through Fusion

Light Elements → Heavy Elements

H																	He	
Li	Be											B	C	N	O	F	Ne	
Na	Mg											Al	Si	P	S	Cl	Ar	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub							
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

$^{28}\text{Si} + 7(^4\text{He}) \rightarrow ^{56}\text{Fe}$

This periodic table demonstrates the fusion reactions in large stars. [click]  
 Notice that we're always moving from lighter to heavier, from left to right.

We've seen (click #1)  $^1\text{H} \rightarrow ^4\text{He}$  and (2)  $^4\text{He} \rightarrow ^{12}\text{C}$ .

These are further representative reactions that occur in massive stars:

(3) Carbon to Magnesium ( $^{12}\text{C} \rightarrow ^{24}\text{Mg}$ )

(4) Helium and Carbon to Oxygen ( $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{O}$ )

(5) Oxygen to Silicon ( $^{16}\text{O} \rightarrow ^{32}\text{Si}$ ) or Oxygen to Sulfur and He

(6) Helium and Oxygen to Neon ( $^4\text{He} + ^{16}\text{O} \rightarrow ^{20}\text{Ne}$ )

(7) Helium and Silicon to Nickel (which decays to Cobalt and then to Iron via successive positive beta decays) ( $^{28}\text{Si} + 7(^4\text{He}) \rightarrow ^{56}\text{Ni} \rightarrow ^{56}\text{Co} + e^+ \rightarrow ^{56}\text{Fe} + e^+$ )

**NEARLY ALL ELEMENTS THROUGH IRON ARE CREATED THROUGH FUSION IN LARGE STARS.**

Energy is no longer released in the reactions to form elements heavier than Iron. These heavier elements require the INPUT of energy for creation.

Again, we lose the balance between internal pressure and the force of gravity, and the star collapses again.

Click on the poster icon in the lower right to return to slide #6.

# Supernova



1																	2				
H																	He				
3	4											7	8	9	10						
Li	Be											B	C	N	O	F	Ne				
11	12											13	14	15	16	17	18				
Na	Mg											Al	Si	P	S	Cl	Ar				
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36				
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr				
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54				
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe				
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86				
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn				
87	88	89	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118				
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	--	--	--	--	--	--	--	--	--				
		58	59											64	65	66	67	68	69	70	71
		Ce	Pr											Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
		90	91											96	97	98	99	100	101	102	103
		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr						

The collapse of a large star causes an explosive shock wave, blowing most of the star's mass into space in a SUPERNOVA.

A supernova is very hot and energetic, and able to create heavier elements than fusion created in the star's core.

[Click to reveal Gold and Titanium.]

The input of energy needed to create elements beyond Iron is available in the supernova. From this we get the remaining naturally occurring elements, like the Gold in jewelry and Titanium in glasses frames.

## *Supernova*

---

Fusion of Iron takes energy, rather than releases energy.

So fusion stops at Iron.

Energy released from nuclear fusion no longer counter-acts inward force of gravity.

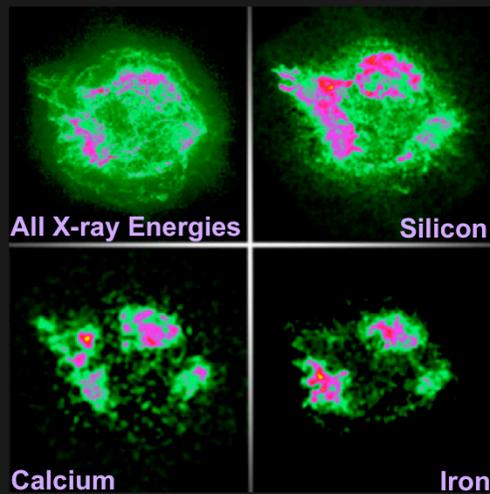
But now there is nothing to stop gravity.

Massive star ends its life in supernova explosion.

# Supernova

Explosive power of a supernova:

- Disperses elements created in large stars.
- Creates new elements, especially those heavier than Iron.



Supernovae are able to do two very important things:

- (1) Create new, heavier elements.
- (2) Disperse the elements that were created in the star that exploded.

These images are from Chandra, showing the Cassiopeia A supernova remnant in different x-ray energies. These images show the distribution of elements ejected in the explosion. They are part of a gas that's about 50 million degrees.

In these images, yellow regions show the most intense concentration, followed by red, purple, and green.

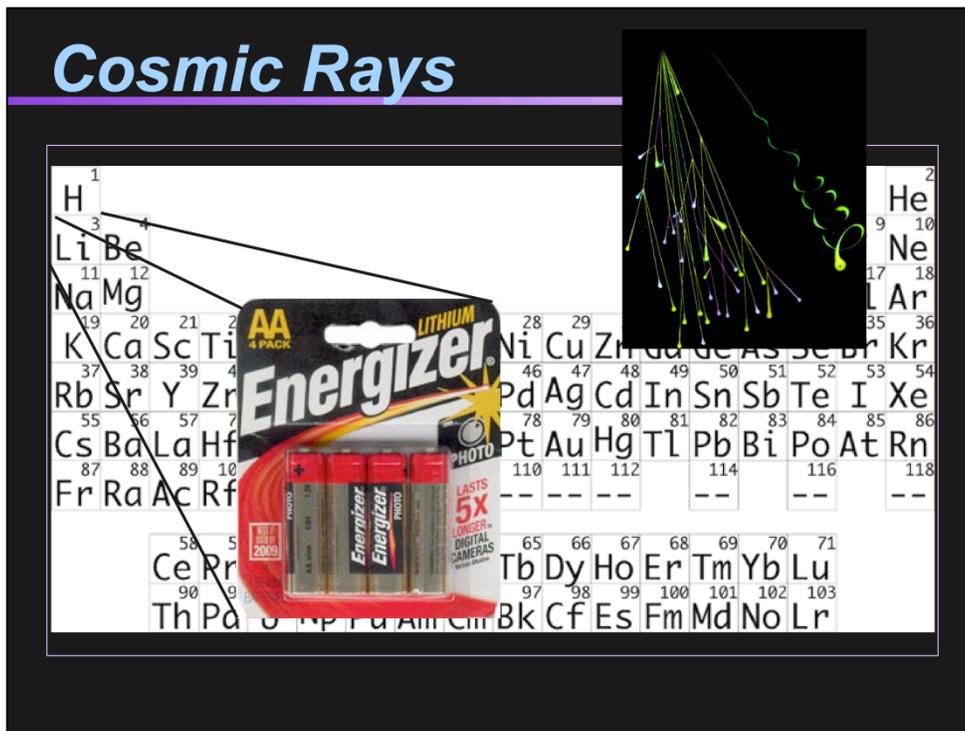
The upper left image is from all X-ray energies, and the others are centered on the lines of particular elements (Silicon, Calcium, and Iron).

Note the asymmetry, especially in silicon, possibly due to an asymmetry in the explosion. The iron image suggests that the layers of the star were overturned either before or during the explosion.

Click on the poster icon in lower right to return to slide #6

[All images are 8.5 arc minutes on a side (28.2 light years for a distance to Cas A of 11,000 light years).]

# Cosmic Rays



Did anyone notice that we missed a few elements?

We get H and He from the Big Bang, and C through Iron in stars, and heavier elements from supernovae... what did we miss?

**LITHIUM, BERYLLIUM, AND BORON!**

[Click to reveal Lithium batteries.]

These elements are mostly formed through cosmic ray interactions.

What are cosmic rays?

Cosmic rays are high-energy particles moving through space at velocities close to the speed of light. They're little bits of matter, often the nuclei of the elements, most likely sent zinging through space by supernova explosions (or perhaps stellar winds).

## Cosmic Rays

Lithium, Beryllium, and Boron are difficult to produce in stars.

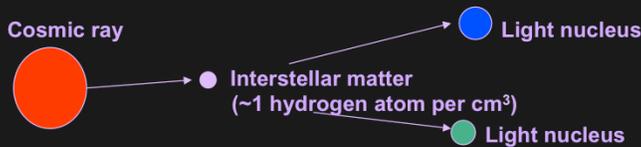
(L, Be, and B are formed in the fusion chains, but they are unstable at high temperatures, and tend to break up into residues of He, which are very stable).

So what is the origin of these rare elements?  
=> Collisions of Cosmic Rays with Hydrogen & Helium in interstellar space.

Lithium, Beryllium, and Boron are formed in stars, but they're very unstable at the high temperatures in the core of stars. Therefore, they break down quickly into Helium.

These elements are predominantly created through the collision of cosmic rays with the atoms of Hydrogen and Helium found in interstellar space. When cosmic rays hit atoms, they produce new elements.

## Cosmic Rays Collisions with ISM



Lithium, beryllium, and boron and sub-iron enhancements attributed to nuclear fragmentation of carbon, nitrogen, oxygen, and iron with interstellar matter (primarily hydrogen and helium).



The cosmic rays are travelling so fast through space, it hits the Hydrogen or Helium with a lot of force, and parts of its nucleus can be “chipped off.”

Here’s a diagram of such a collision!

When the cosmic ray hits the Hydrogen or Helium, it fragments into two smaller, lighter nuclei.

In the equation at the bottom of this slide, Carbon, Nitrogen, Oxygen, or Iron nuclei collide with Hydrogen or Helium in the interstellar medium to create lighter elements -- Lithium, Beryllium, Boron, or other elements lighter than Iron.

So these interactions create elements that weren’t stable enough to be created at the high temperatures required for fusion in a star.

## Cosmic Elements

1																	2																																																								
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White - Big Bang									Pink - Cosmic Rays																																																																
Yellow - Small Stars						Green - Large Stars						Blue - Supernovae																																																													

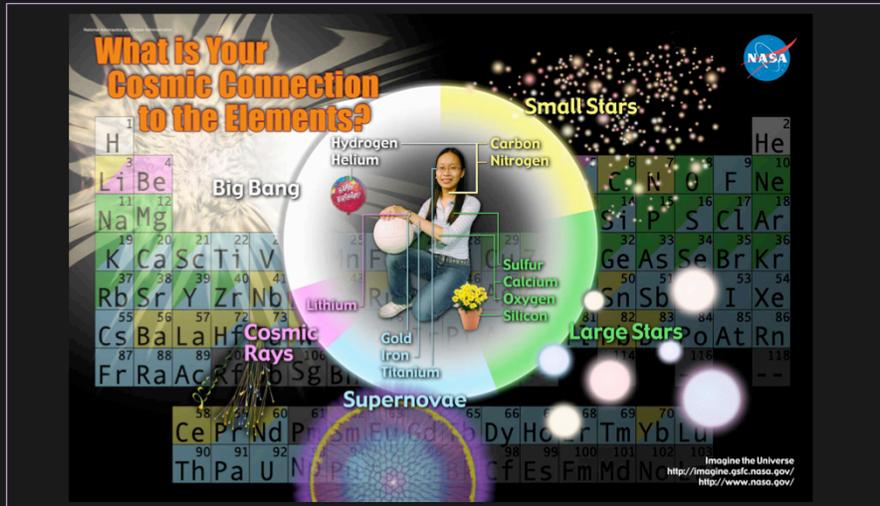
This is a summary of the major production mechanisms for each of the elements. Note that it is the background for the poster.

Many elements are generated from more than one process, and where there are two nearly equal contributors (each contributing at least 30% of the abundance), we gave the element two colors.

This table presents a slightly more complicated story than the narrative for the talk. Small stars contribute to some of the heavier elements through the process of neutron capture in Asymptotic Branch Giants, a stage in the life cycle of “small” stars with masses 2-8 times that of the sun. In the core of this Giant, free neutrons may be captured by heavy elements (e.g. Iron) existing in the core. After enough neutron captures, the core becomes unstable, with the neutron decaying into a proton and electron, producing a heavier element (e.g. Fe  $\rightarrow$  Co). Conditions in these Giants are right to produce elements from niobium to bismuth.

$^7\text{Li}$  is also made in AB Giants. ( $^6\text{Li}$  is made via Cosmic Ray interactions)

## Your Cosmic Connection to the Elements?



The poster draws together all of the ideas in this presentation.

We're in the center, surrounded by all sorts of everyday objects (glasses, balloon, plants, etc.).

These objects demonstrate our connection to the elements of which they are composed.

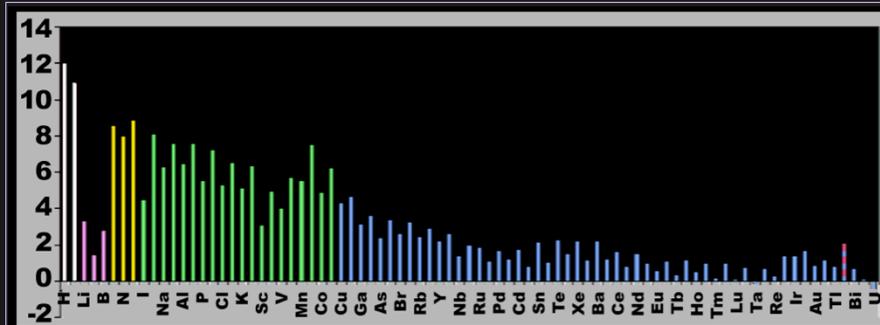
The background is the periodic table, which represents all of the elements.

And the sphere around the center connects the elements (and the objects) to the cosmic processes which created them!

So we are all made of stars (or at least of space)!

Note that the back of the poster has some of the basic information from this presentation for a quick guide to the poster.

# Composition of the Universe



Actually, this is just the solar system.

Composition varies from place to place in universe, and between different objects.

This is a graph of elemental composition.

The vertical scale is logarithmic, with H arbitrarily set to  $10^{12}$  so that the elements with the lowest abundance still have a value of  $10^0$ , or 1.

So this scale reflects powers of ten -- Hydrogen is at  $10^{12}$ , Helium is around  $10^{11}$ , and so on.

This is color-coded in a simple manner, and does not reflect the complexities of the 2005 revision.

You can see the big peaks for Hydrogen and Helium, both produced in the Big Bang. There's a dip for Lithium, Beryllium, and Boron because they're not really produced through fusion, but by cosmic ray interactions. From there, there's a relatively steady decrease in abundance, moving through the elements made in small stars to the ones only made in large stars, then supernovae...

[Lead is striped to show creation by radioactive decay.]

[Click for the text!]

This is really just the solar system! It's hard to get a picture like this for the whole universe -- composition varies in different areas of the universe. Our solar system makes a nice model.

## **“What’s Out There?”**

(Developed by Stacie Kreitman, Falls Church, VA)

A classroom activity that demonstrates the different elemental compositions of different objects in the universe.

- Demonstrates how we estimate the abundances.

Allow 10-15 minutes for the activity.

Participants are given bottles which model the elemental composition of the Sun, the interstellar medium, carbonaceous Chondrites (meteorite), the earth’s atmosphere, and the elements formed in a supernova explosion. Participants are also given a key as to what element each substance represents, and the abundances in each substance.

Give 1 bottle to each group of 2-3. After they’ve all had time to determine what they have, have each group say what they have and how they determined that.

The activity includes a “mystery” bottle with a substance not listed on the key. Those groups should first share what they think the composition is. Then the entire audience can attempt to determine what the substance is.

See <http://imagine.gsfc.nasa.gov/docs/teachers/elements/> for the activity.

## Top 10 Elements in the Human Body

	Element	by # atoms
10.	Magnesium (Mg)	0.03%
9.	Chlorine (Cl)	0.04%
8.	Sodium (Na)	0.06%
7.	Sulfur (S)	0.06%
6.	Phosphorous (P)	0.20%
5.	Calcium (Ca)	0.24%
4.	Nitrogen (N)	1.48%
3.	Carbon (C)	9.99%
2.	Oxygen (O)	26.33%
1.	Hydrogen (H)	61.56%

Source: <http://www.sciencenet.org.uk/database/Biology/9608/b00600d.html>

Element	Symbol	%	Notes
Oxygen	O	65.0	Water; organic compounds
Carbon	C	18.5	Organic compounds
Hydrogen	H	9.5	Water; organic compounds
Nitrogen	N	3.2	Part of all protein molecules
Calcium	Ca	1.5	Bones/teeth; clotting; hormones
Phosphorous	P	1.0	Nucleic acids/ATP; bones/ teeth
Sulfur	S	0.3	Component of many proteins
Chlorine	Cl	0.2	Water movement between cells
Sodium	Na	0.2	Water balance; extracellular fluid
Magnesium	Mg	0.1	Muscle contraction and nerves
Iodine	I	<0.1	Production of thyroid hormone
Iron	Fe	<0.1	Basic component of hemoglobin

Elements that make up less than 0.1% of the body are “trace elements”, like:

Some trace elements are:

cobalt          copper          fluorine

## *Spectral Analysis*

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We can't always get a sample of a piece of the Universe.

So we depend on light !

## Spectral Analysis

Each element has a unique spectral signature:

- Determined by arrangement of electrons.
- Lines of emission or absorption arise from re-arrangement of electrons into different energy levels.



Composition is usually determined through spectroscopy. Each element gives off a unique “signature” of specific wavelengths of light, which we see as bright lines in its spectrum.

By measuring the relative intensities of the lines from different elements, we can determine their abundance in an object being observed.

The optical spectrum of H shows the Balmer lines - transitions to/from the  $n=2$  electron shell. From red to blue, this spectrum shows H-alpha (transition from  $n=3$  to  $n=2$ ), H-beta (transition from  $n=4$ ), H-gamma (transition from  $n=5$ ), and H-delta (faintly).

We're used to seeing these spectra. What if you could hear them ?

## ***Nickel-odeon Classroom Activity***

(Developed by Shirley Burris, Nova Scotia)

Spread a rainbow of color across a piano keyboard



Then, “play” an element



**Hydrogen**

Print a colored spectrum, cut it into strips, and lay the strips on the keys of a musical keyboard.

Then put down the emission spectrum of an element, and line up the lines with the keys.

Then play the element.

## More Musical Elements



Now play another element

Helium



And Another

Carbon



Play helium. Go back and play H again, and ask them to listen for the difference. The difference arises from the yellow-green line.

After you play carbon, note that you can play the elements either as chords (as we did) or as individual notes up the scale. Also note that you can place the spectrum any where you want, but around middle C is usually best.

The chords won't sound familiar, which is good, because you want participants (and students) to listen for the differences (rather than for something they recognize).

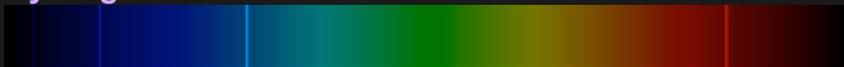
## Getting a Handle on Water



Oxygen



Hydrogen



All together now ... Water

You can now combine elements, either to create molecules or to create the substances we analyzed in the bottles.

## Your Cosmic Connection to the Elements?

What is Your Cosmic Connection to the Elements?

Big Bang

Small Stars

Large Stars

Supernovae

Imagine the Universe  
<http://imagine.gsfc.nasa.gov/>  
<http://www.nasa.gov/>

<http://imagine.gsfc.nasa.gov/docs/teachers/elements/>

Check out the website at the bottom of this slide for this presentation and more activities and materials. The web site contains an on-line version of the booklet which accompanies these materials, and a link to an order form for requesting a hard copy of the poster and booklet.

So we have pondered this question, and hopefully we have some better ideas about the answer. And if you need further inspiration ... (next slide)

## *Cosmic Connections*

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To make an apple pie from scratch,  
you must first invent the universe.

Carl Sagan