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THE CHEMICAL COMPOSITION OF STARS AND THE UNIVERSE

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ABSTRACT

A prediction of standard inflationary cosmology is that the elemental composition of the medium out of which the earliest stars and galaxies condensed consisted primarily of hydrogen and helium[4] He, with small admixtures of deuterium, lithium[7] Li, and[3] He. The most redshifted quasars, galaxies, and Lyα absorbers currently observed, however, all exhibit at least some admixture of heavier elements, as do the most ancient stars in the Galaxy. Here we examine ways in which the abundance of these same elements, if present before the epoch of Population III formation, might be observationally established or ruled out.

KEYWORDS: Inflationary cosmology, redshifted quasars, galaxies.

Of what is the Universe made?
What are the ingredients for the Cosmic Recipe?

If we can answer these questions, we may gain some clue to the history of our universe.

People have long known that the stars are far, far away; in the nineteenth century, astronomers finally measured the distances to a few nearby stars with reasonable accuracy. The results were so large -- thousand of trillions of miles -- that most people figured we'd never be able to visit them or learn much about them. After all, we can't go to a star, grab a sample, and bring it back to earth; all we can do is look at light from the star. In fact, at least one prominent philosopher and scientist went on the record as saying that we'd never be able to figure out their compositions.

Of all objects, the planets are those which appear to us under the least varied aspect. We see how we may determine their forms, their distances, their bulk, and their motions, but we can never know anything of their chemical or mineralogical structure; and, much less, that of organized beings living on their surface.

But just a few decades after this pessimistic statement, astronomers were starting to identify elements in the solar atmosphere. We now have a good idea about the chemical makeup not only of the stars, but of the entire visible universe.

What about the Earth?

It's easy to figure out the chemical composition of the Earth: just dig up some dirt, and analyze it. Well, maybe it's a bit more complicated than that.

We live on the surface of the Earth, which may contain a different mix of elements than the inner regions. Up here, at the surface, we can divide the environment into several pieces:

- The atmosphere
  - 78% nitrogen
  - 21% oxygen
  - 1% other stuff (carbon dioxide, water vapor, argon, etc.)
- The oceans
  - Water: 2 hydrogen, 1 oxygen
- The solid crust
  - 62% oxygen (by number of atoms)
  - 22% silicon
  - 6.5% aluminum
  - Bits of iron, calcium, potassium, sodium, etc.

If we count the total number of atoms in each component, the atmosphere is by far the least important, and the solid crust by far the most important. One could pretty much ignore the air and the water.

But, of course, even the solid crust is just the outer layer of a very much larger interior. We can't dig down more than a few miles into the Earth, so we can't determine the composition of the interior directly; but we can find clues in the material ejected from volcanoes, and also in the behaviour of seismic waves as they move through the Earth. Since we know the radius and the mass of the Earth, we can calculate its overall average density, which turns out to be about 5500 kilograms per cubic meter, or about 5.5 grams per cubic centimetre: 5.5 times denser than water. The upshot of all this indirect evidence is that we believe the interior of the Earth is made up of

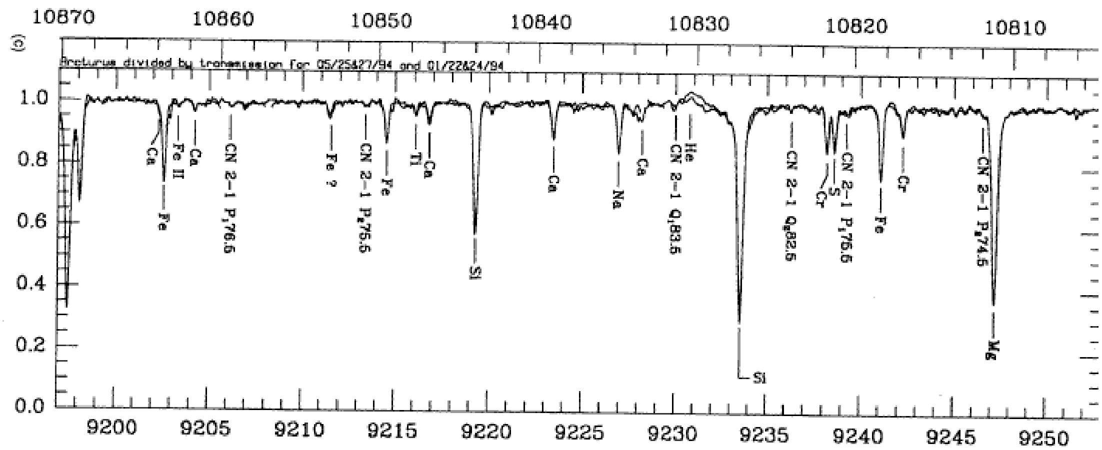
- A central core
  - Mainly iron
  - Smaller amounts of nickel and cobalt
- An intermediate mantle
  - Mostly oxygen and silicon
  - Some iron, magnesium, etc.

Overall, since the core and the mantle comprise most of the atoms of the Earth, the chemical composition of our planet is dominated by iron, oxygen, and silicon.

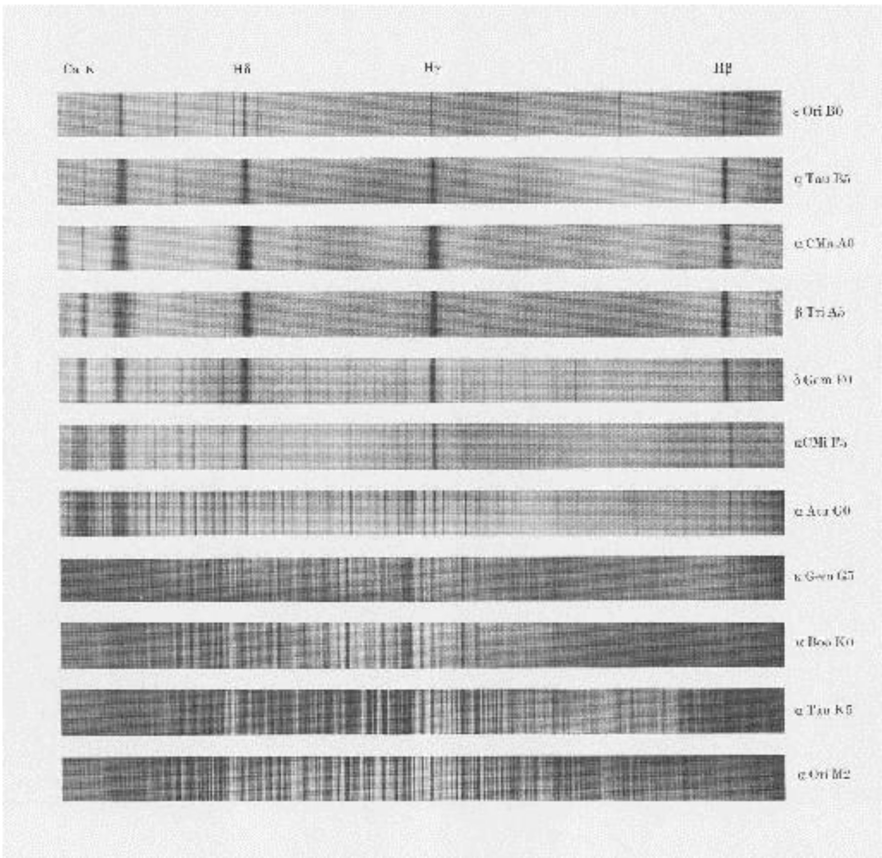
The chemical composition of the stars

In the early days of astrophysics, scientists thought that the stars were probably similar to the Earth in chemical composition. When they passed starlight through a prism and examined the resulting spectrum, they found absorption (and occasionally emission) lines of many elements common here on Earth.

For example, here's a portion of the spectrum of Arcturus (taken from a paper by Hinkle, Wallace and Livingstone, PASP 107, 1042, 1995):



Now, different stars have spectra which look very different (click on image to see larger version):



Does this mean that the chemical composition of stars varies wildly? Initially, scientists thought the answer was "yes."

In the nineteen-twenties, Cecilia Payne studied the spectra of stars, and devised a way to figure out the temperature and true chemical composition of stars. She concluded that the atmospheres of stars werez

- NOT made up of the same mix of elements as the Earth
- NOT wildly variable in composition but in fact,
- **Almost entirely hydrogen**, in almost all stars

This was so surprising that scientists ignored or rejected the idea for several years. Eventually, after further study confirmed Payne's work, the astronomical community had to concede that the stars were, in fact, very different from the Earth. They appeared to be made up of:

- 90% hydrogen (by number of atoms)
- 10% helium
- Tiny traces of **heavy elements** (everything else).

The chemical composition of interstellar clouds

Our galaxy contains not only stars, but also clouds of gas and dust. Some glow brightly, lit up by nearby stars:

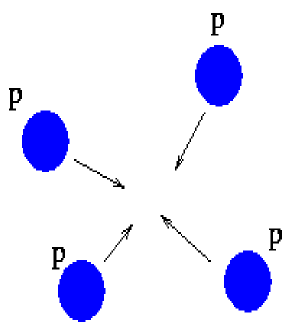
Other clouds appear dark, because they absorb and scatter the light which tries to pass through them:

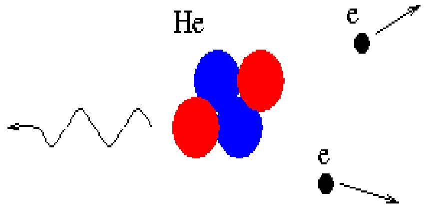
It is often easier to determine the composition of nebulae than of stars, since we can see into the center of the nebula. The spectra of these objects show that they, too, are almost completely made of hydrogen and helium, with tiny amount of other elements.

When we look at different galaxies, we find some variation in the amount of heavy elements. The Milky Way, for example, has more iron (relative to hydrogen) than the Large Magellanic Cloud; and the Large Magellanic Cloud has more iron (relative to hydrogen) than the Small Magellanic Cloud.

We believe that heavy elements can be created by the fusion of light elements at the centers of stars.

- Hydrogen fuses into helium (in all stars)
- Helium fuses into heavy elements (in high-mass stars)





Galaxies with lots of heavy elements must have had several generations of stars, some of which have ejected material from their interiors into the interstellar medium and enriched it with helium and heavy elements.

Astronomers use the letters **X, Y** and **Z** to denote the fraction of material (by mass) which made up by hydrogen, helium, and everything else:

X = 1.0	Y = 0.0	Z = 0.0	pure hydrogen
X = 0.5	Y = 0.5	Z = 0.0	hydrogen/helium mix
X = 0.0	Y = 0.5	Z = 0.5	helium/heavy mix

When we analyze the composition of nebulae in different galaxies, we find a slight correlation between the fraction of helium and the fraction of heavy elements:

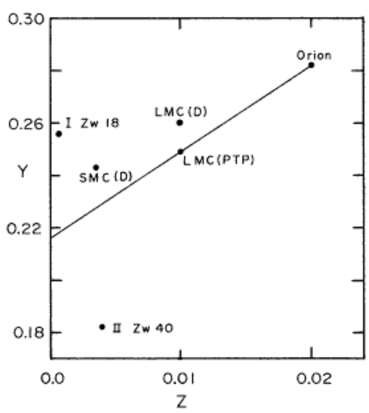


Figure 5 The observed chemical composition (by mass). The straight line corresponds to $\Delta y/\Delta z = 3.3$.

Why should there be such a connection? We think the answer is

- All galaxies started out with only hydrogen and helium (so **Z = 0**)
- A first generation of stars created helium and heavy elements in their cores, and ejected some into the interstellar clouds
- In some galaxies, a second generation of stars has created even more helium and heavy elements
- In some galaxies, third or fourth generations of stars have spewed even more helium and heavy elements into interstellar space

If we can find galaxies which have had little star formation since they were formed, we can use them to measure the **primordial abundance** of helium, relative to hydrogen.

The primordial abundances

Recent observations place the primordial abundance of hydrogen and helium at the following ratio:

$$\frac{\text{Number of hydrogen atoms}}{\text{Number of helium atoms}} = 12.5$$

In our own corner of the Milky Way, this ratio is currently about 10. There has evidently been quite a bit of nuclear processing of hydrogen into helium by previous generations of stars in our galaxy.

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