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The Origin of The Elements

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Introduction

2019 is the 150th anniversary of the first formulation of the periodic table, originally conceived by Dimitri Mendeleev. This was an important milestone in understanding the properties of elements and ultimately the structure of atoms.

Atoms

Atoms are composites of neutrons and protons, which together reside in the nucleus, and electrons. More than 99.9% of an atom's mass is in the nucleus. Any two atoms with identical numbers of protons belong to the same chemical element. However, atoms with the same number of protons but different number of neutrons are called isotopes. For example, hydrogen has 3 known isotopes: hydrogen-1, deuterium and tritium (see Fig. 1). Of these only hydrogen-1, deuterium are stable. Isotopes have similar chemical and molecular properties but crucially different masses and stabilities.

Figure 1: This isotopes of hydrogen and helium.

There are several different processes responsible for the re-arrangement of atoms. The most important of these is nuclear fusion. This is where two nuclei combine to form a new, more massive, nuclei, often with left-over sub-atomic particles such as neutrons, positrons, and neutrinos. Fusing atomic nuclei requires very high temperatures making it difficult to harness except in extreme conditions. Instead of fusing, nuclei can simply capture neutrons. For example, silver-109 can capture a neutron to become silver-110, which is unstable. As it turns out this is a crucial ingredient to explain the formation of the heavy elements. Atoms can also break apart of decay. There are several different types but one of the most important is beta decay. In beta decay a neutron effectively decays to form a proton, electron, and anti-neutrino. For example, the unstable silver-110 can decay to form cadmium-110.

Abundances

In the Solar System around 75% of the mass is hydrogen, while 23% is helium, and only 2% is heavier elements. The abundances of elements in the solar system can be seen Fig. 2. This reveals that lighter elements like hydrogen, helium, carbon, nitrogen, and oxygen are all much more abundant that elements like gold and silver. There are some exceptions to this general trend, for example beryllium which is both light and very rare. We also see there are gaps in the table - these elements which have no stable isotopes.

Figure 2: The abundances of elements in the Solar System. Elements are colour coded by their abundance on a logarithmic colour scale.

Instead of the Solar System we can look at abundances of the elements in the Earth's crust, shown in Fig. 3. This reveals a very different picture with elements like oxygen (O), silicon (Si), and iron (Fe) now being much more abundant. Silver is now more abundant than helium, despite helium being the second most abundant element in the wider Solar System.

Figure 3: The abundances of elements in the Earth's crust. Elements are colour coded by their abundance on a logarithmic colour scale.

We can do the same thing but for humans, shown in Fig. 4. Humans have large amounts of oxygen, nitrogen, carbon, hydrogen, and calcium.

Figure 4: The abundances of elements in humans. Elements are colour coded by their abundance on a logarithmic colour scale.

Origins

The current consensus in cosmology is that our Universe emerged from a hot, dense state almost 14 billion years ago. For the first 10 seconds of the Universe's history it was too hot for atomic nuclei to exist. However, as the Universe expanded it cooled and eventually nuclei could form. Over the next 20 minutes a variety of fusion reactions (see below) led to almost all neutrons being "locked" up into helium, this is **Big Bang Nucleosynthesis**. Not all the protons because helium-4 as there were many of more of them to begin with. While it is possible to fuse beyond helium this didn't happen at this time as the initial product is unstable. This means that to get beyond helium you need to rapidly fuse with another helium nucleus, something that occurs very rarely in the early Universe.

Fig. 5 shows the periodic table with elements now coloured by both their abundance (colour) and how much of the element we have accounted for so far (opacity) using the scale shown in Fig. 6. This reveals that we have (so far) accounted for almost all the Solar System's hydrogen and helium, a small fraction of the lithium, but little of everything else.

Figure 5: The fraction of elements accounted for by Big Bang Nucleosynthesis also colour coded (see Fig. 6) by their abundance in the Solar System (see Fig. 2).

A few hundred million years after the Big Bang clouds of gas can collapse to form stars. In the cores of stars energy is produced by nuclear fusion which halts further collapse, at least until the star runs out of suitable fuel. For most of star's lifetime it converts hydrogen to helium. Eventually however, the star will run out of core hydrogen. As noted previously fusing helium is hard because it requires very high temperatures and the initial fusion product, in this case beryllium, is unstable. However, some stars are able to overcome these challenges and are able to rapidly fuse three helium nuclei before the beryllium decays. This is the Triple-alpha process and it is important for powering the giant stars. Low-mass stars like the Sun, are never able to fuse beyond nitrogen and carbon. And the end of their lifetimes an inert core of nitrogen and carbon called a white dwarf slowly cools and contracts. The outer layers of the star are able to disperse leaving a planetary nebula. The contribution of **low-mass stars** to the periodic table is shown in Fig. 7. Low-mass stars are able to contribute the remaining helium along with most of the oxygen and nitrogen. As it turns out low-mass stars also make a contribution to heavy elements. However, this is only possible when there already are some heavy elements. This is discussed later.

In stars a few times more massive than the Sun fusion can progress beyond carbon/nitrogen. This is achieved by fusing each subsequent fusion product with helium to form larger and larger elements. This is called the alpha-ladder. Up to nickel this process produces energy, which is important for keeping a star stable against collapse. However, after nickel fusion reactions require more energy in than you get out. This immediately saps the core of energy resulting in a collapse and producing an explosion called a core collapse supernova. The periodic table including BBN, low-mass stars, and high-mass stars is shown in Fig. 8. This reveals that many of the light elements have now been fully explained.

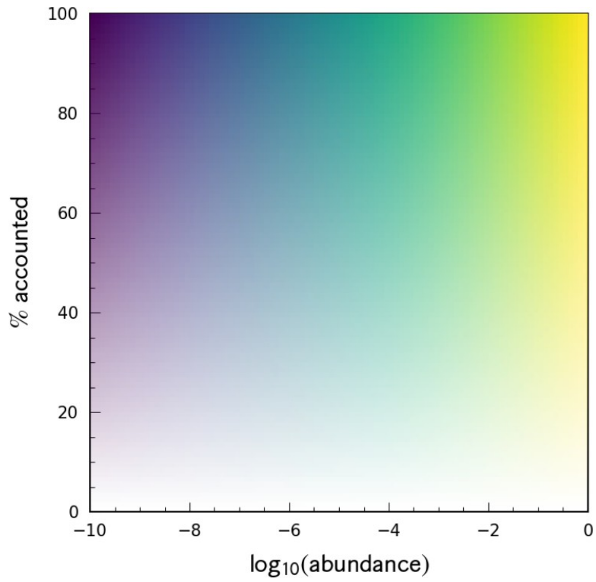

Figure 6: The scale adopted to show the abundance and fraction accounted.

Figure 7: The fraction of elements accounted for by BBN and low-mass stars also colour coded (see Fig. 6) by their abundance in the Solar System (see Fig. 2).

Figure 8: The fraction of elements accounted for by BBN, low-mass stars, and high-mass stars, also colour coded (see Fig. 6) by their abundance in the Solar System (see Fig. 2).

Individual stars (and BBN) are alone able to explain many of the light elements. However, we are still missing many of the iron group (Cr, Mn, Fe, Co, Ni) and the heavier elements. The key to explaining these lies in the fact that most stars live in multiple systems where, in some cases, stars can be so close they can interact with each other.

In one example of a binary interaction a white dwarf, the left-over remnant of a star like the Sun, can accrete material from a neighbour. Eventually the white dwarf can steal so much material that it can no longer support itself. When this happens, the entire star explodes in a thermonuclear explosion called a **Type Ia Supernova**. These events produce huge amount of iron group elements, as shown in Fig. 9. Together with BBN, and individual stars, we can explain almost the entire first four periods of the periodic table.

Figure 9: The fraction of elements accounted for by BBN, low and high mass stars, and Type Ia supernovae, also colour coded (see Fig. 6) by their abundance in the Solar System (see Fig. 2).

Many of the nuclear reactions that occur in stars and during stellar explosions produce huge numbers of neutrons. These can be absorbed by nuclei to create successively more heavier elements. For example, silver-109 can absorb a neutron becoming silver-110. However, silver-110 is unstable and decays to form cadmium-110. Through this process of neutron capture and subsequent beta decay it is possible to build up the heavy elements. An example of this process stretching from silver-109 to antimony-121 is shown in Fig. 10.

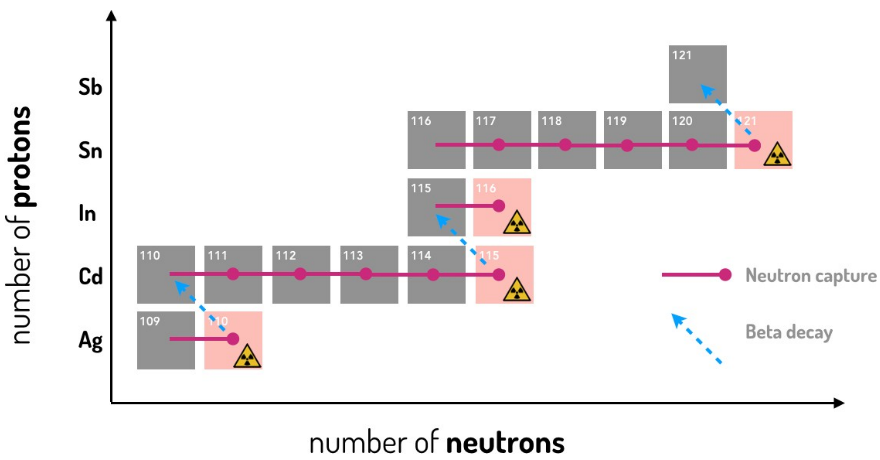

Figure 10: The conversion of silver-109 to antimony-121 via neutron capture and beta decay.

This process occurs in all the stars we've considered so far as is responsible for creating a signification fraction of the heavy elements, as shown in Fig. 11.

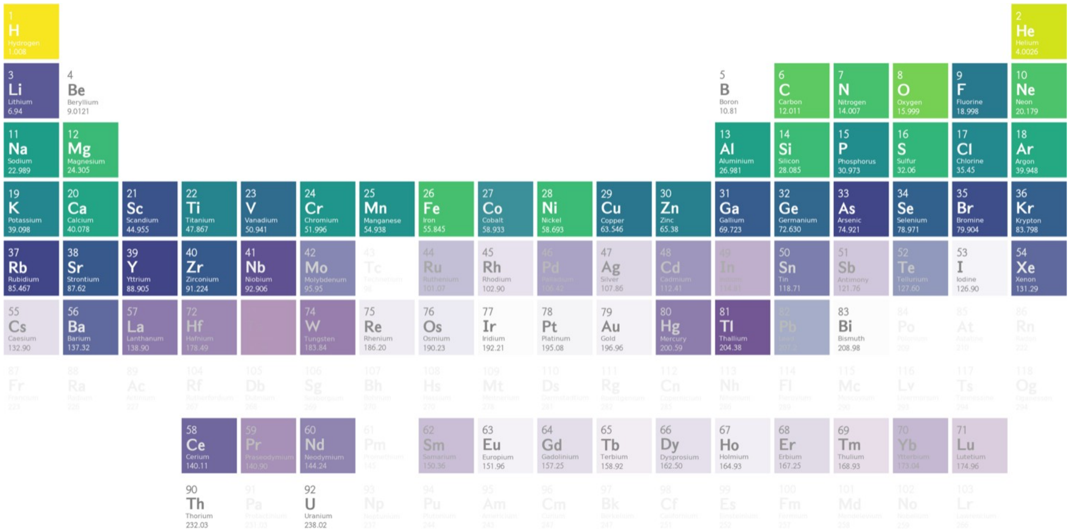

Figure 11: The fraction of elements accounted for by BBN, low and high mass stars, and Type Ia supernovae, including the buildup of heavy elements via neutron capture and β-decay. Elements are also colour coded (see Fig. 6) by their abundance in the Solar System (see Fig. 2).

Notably missing from Fig. 11 are the light elements beryllium (Be) and boron (B). These elements are actually created when cosmic rays, highly energetic individual particles, impact carbon-12 effectively knocking off a proton. This process, **cosmic ray spallation**, explains the origin of beryllium and boron.

As can be seen in Fig. 11 many of the heavy elements are still not full accounted for. The origin of these elements actually lies in the interaction of an even more extreme type of object - neutron stars. Neutron stars form when massive stars die. As the name suggests they're mostly made of free neutrons though they do have normal atoms in them as well. Occasionally it's possible that two neutron stars are able to collide into each other. When this happens huge numbers of neutrons are produced allowing heavy elements to be assembled through neutron capture. While this has been hypothesised for a while it was only recently, in 2017, confirmed. This confirmation was made possible by the LIGO experiment, which instead of detecting light, detects gravitational waves. In 2017 the collision of two neutron stars was detected by LIGO providing an approximate location on the sky. Subsequent efforts by normal telescopes revealed the visible light signature of this collision crucially including the signature of the formation of heavy elements. This process, together with the other process, now appears to allow us to fully account for all the elements, as shown in Fig. 12.

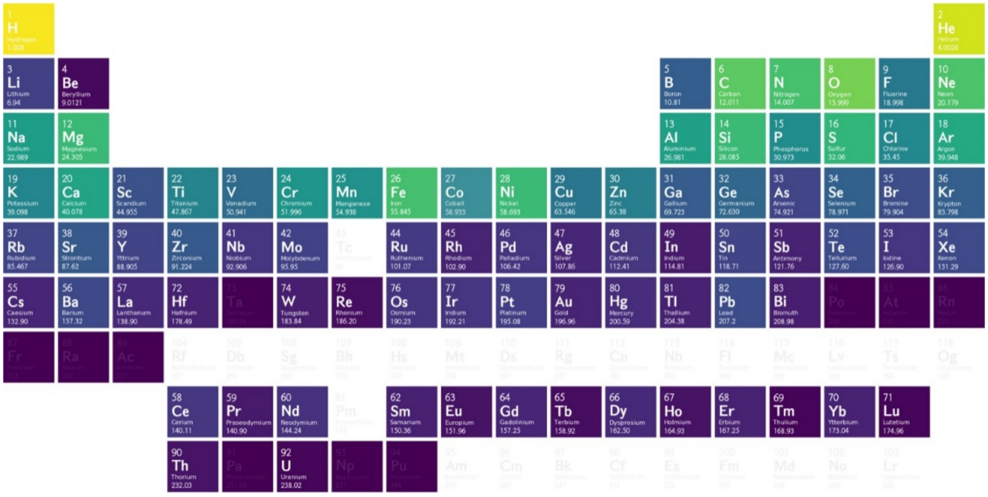

Figure 12: The fraction of elements accounted for by BBN, low and high mass stars, Type Ia super- novae, and neutron star mergers. Elements are also colour coded (see Fig. 6) by their abundance in the Solar System (see Fig. 2).

We now appear to have a broadly complete picture of the formation of the elements. However, while it appears we have the picture broadly correct, there remain many details which are still not fully understood.

Further Reading

- **Nuclear Fusion**: https://en.wikipedia.org/wiki/Nuclear_fusion
- **Abundances of the Elements**: https://en.wikipedia.org/wiki/Abundance_of_the_chemical_ elements(general introduction with references).
- **Nucleosynthesis**: https://en.wikipedia.org/wiki/Nucleosynthesis (general introduction to nucleosynthesis with references).
- **Big Bang Nucleosynthesis**: https://en.wikipedia.org/wiki/Big_Bang_nucleosynthesis (general introduction); Burles, Scott; Nollett, Kenneth M.; Turner, Michael S. (1999-03-19). "Big-Bang Nucleosynthesis: Linking Inner Space and Outer Space". https://arxiv.org/ abs/astroph/9903300.
- **Stellar Nucleosynthesis**: https://en.wikipedia.org/wiki/Stellar_nucleosynthesis(general introduction); Ray, A. (2004). "Stars as thermonuclear reactors: Their fuels and ashes". https://arxiv.org/abs/astro-ph/0405568.
- **Core Collapse Supernovae**: https://en.wikipedia.org/wiki/Supernova#Core_collapse (general introduction).
- **Type Ia Supernovae**: https://en.wikipedia.org/wiki/Type_Ia_supernova (general intro- duction).
- **Neutron Star Mergers**: https://en.wikipedia.org/wiki/Neutron_star_merger (general introduction with references); Abbott, B. P.; et al. (LIGO, Virgo and other collaborations) (October 2017). "Multi-messenger Observations of a Binary Neutron Star Merger". The Astro- physical Journal. 848 (2): L12. https://arxiv.org/abs/1710.05833.