CHEMICAL ENRICHMENT OF THE UNIVERSE BY STARS

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Keywords: stellar evolution, nuclear reactions, nucleosynthesis, chemical evolution, stellar composition, stellar interior, stellar models, stars, fusion, neutron capture, nuclear burning, hydrogen burning, AGB stars, supernovae

Contents

Summary

We discuss how stars enrich the Galaxy with all of the elements we see around us. We begin by discussing the various nuclear reaction chains and cycles and their properties. We then show how these occur in stars, and how they combine with the structure and evolution of a star to expel those elements into the Galaxy. Finally we briefly discuss how this information is used to create a model for the chemical enrichment of the Galaxy.

1. Introduction

Our topic for discussion covers the smallest and the largest length scales – we will see how the physics of sub-atomic particles leads to changes in the bulk composition of the Universe as a whole. In the middle, providing the link between the two extremes, sit the stars, nature's nuclear fusion reactors. It is the stars that do the nuclear cooking and then provide a mechanism for getting the results of that cooking to the surface of the star and then later into the Galaxy. Through a combination of mixing events, mass ejection and huge explosions, the stars enrich their immediate surroundings with the products of their earlier evolution. What was once a gas composed only of hydrogen and helium from the Big Bang now contains carbon, nitrogen, oxygen, silicon, iron etc. Indeed, it now contains all of the elements needed to make planets and life itself. The next generation of stars forms from this new mixture. These stars behave differently as a result of their different composition. Yet they also "cook" new elements and somehow return them to the Galaxy. Slowly the composition of the Galaxy changes due to these effects, in a process known as "galactic chemical evolution". As the Galaxies change composition, so too does the Universe.

We will not be able to cover all aspects of this topic here; the reader is referred to other topics in this series as useful background and introductory material. But we will attempt to give an introduction to the topic of how stars enrich the Universe.

2. Nuclear Reactions in Stars

The first step in our journey is to understand the main nuclear burning phases in stars. (We refer the reader to the article on Big Bang nucleosynthesis to see how that event produced the hydrogen and helium from which the first stars will form.) It is this nuclear burning that provides the star with the energy source to hold itself up against gravity, but it also changes the composition and produces new elements as a by-product.

The reader is referred to the Chapters on “The Physics of Stars” and “Single Stars” as introductions to this section.

When we are concerned with the structure and evolution of a star, we must consider the main nuclear reactions, meaning those that produce the most energy or the largest compositional changes. However for our purposes we are interested in reactions that will produce changes in the observable composition of a star, even if they are not important to the energy production. Hence we will consider not only the main reactions occurring in stars, but we will need to look at some of the reactions that produce new species even though they are unimportant from a structural viewpoint.

2.1. Hydrogen Burning

The longest phase in a star’s life is the time it spends burning hydrogen into helium in its core on the Main Sequence, also known as the Hydrogen burning phase. These reactions are fundamental to the lives of stars and we discuss them first.

2.1.1. The pp Chains

The most elementary reactions involve burning hydrogen by fusing two protons together (A proton is simply a hydrogen nucleus; we will use the terms interchangeably. Similarly, a ^{4}He nucleus is also known as an α particle.) . These are the start of the “pp chains” for hydrogen burning, and are shown in Figure 1. These reactions can occur in a gas that is composed initially of pure hydrogen, and are thus important for the first stars to form after the Big Bang. We will see below that other hydrogen burning reactions use heavier species as catalysts and hence can not have been active (at least initially) in the first stars, which were composed entirely of hydrogen and helium. Also, because the Coulomb barriers for protons are the lowest available, these reactions will start at the lowest temperatures of all hydrogen burning reactions. They are the main source of energy in stars with masses less than about a solar mass ($M_\odot$), or composed entirely of hydrogen and helium.

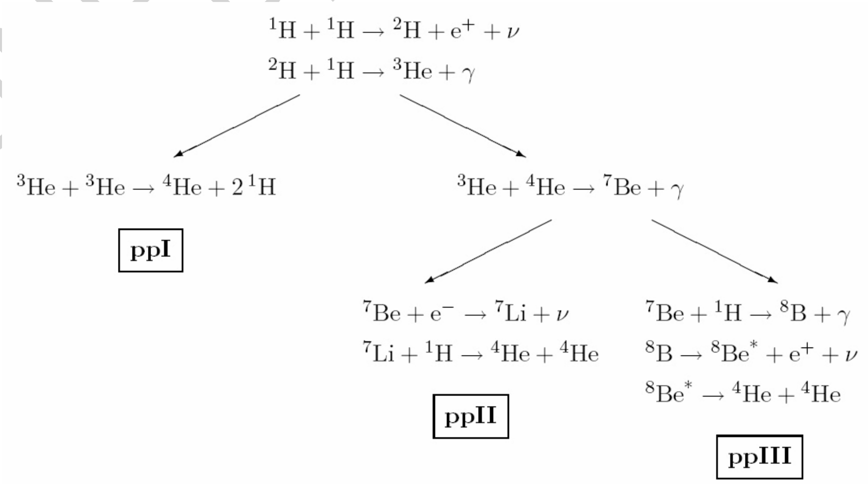

Figure 1. The proton-proton chains for hydrogen burning. An asterisk denotes an excited state of the nucleus.

From the viewpoint of someone interested in nucleosynthesis, the pp chains are not very interesting. They turn protons into ^{4}He and in the process they produce very small amounts of ^{2}D and ^{3}He. Deuterium is often referred to as ^{2}D but since it is simply an isotope of hydrogen is also correct to write it as ^{2}H. We will use both terms interchangeably. (A deuterium nucleus is also sometimes called a "deuteron" and is often written as simply d.) The only other item of note in the pp chains is the destruction of ^{7}Li and ^{7}Be. Although these are both produced and destroyed in the pp chains, any of these species initially present will be destroyed very easily, at quite low temperatures (a few million K). The main effect of the pp chains is summarized in Table 1.

Species	**Effect**	**Note**
^{1}H	destroyed	
^{2}D	produced	very low levels
^{3}He	produced	
^{4}He	produced	
^{7}Li	destroyed	
^{7}Be	destroyed	

Table 1. The main results of pp chains.

2.1.2. The CNO Cycles

The next important set of reactions for hydrogen burning are the CNO cycles. Here various CNO nuclei play the role of catalysts, being consumed at the start of the cycle but being returned again later in the cycle. There are four main CNO cycles, as illustrated in Figure 2. The higher nuclear charge here means that higher temperatures are required to initiate these reactions. They are the dominant energy source for hydrogen burning in stars more massive than the Sun, and also in shell hydrogen burning of all stars (Except those comprised purely of hydrogen and helium.).

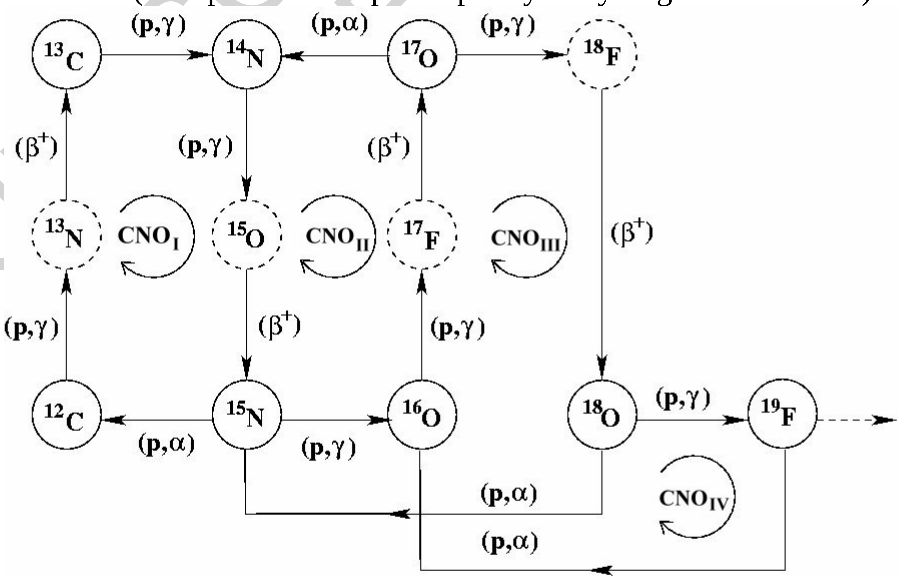

Figure 2. The CNO cycles for hydrogen burning. Unstable species are shown in dotted circles.

Clearly there is much going on here, but fortunately a simple understanding is possible. The timescales are such that we can consider the various cycles as largely separate. First consider just CNO_I in Figure 2. This is usually referred to as "the CN cycle." Despite all the species involved, remember that the main result is the burning of protons into ^{4}He. Within the CNO species, the main results are the destruction of ^{12}C and the production of ^{13}C and ^{14}N. The slowest reaction is $^{14}N(p,\gamma)^{15}O$ so the result is that most of the CNO nuclei accumulate in ^{14}N. When the CN cycle operates in equilibrium the resulting ratio of carbon isotopes is $^{12}C/^{13}C = 3-5$, depending on the temperature. Hence one can use observations of this ratio to indicate that the CN cycle has been active in the star.

Moving to CNO_{II} in Figure 2, which is usually referred to as "the ON cycle", we have very analogous behavior. Again, do not be confused by the large number of species involved: the main effect is burning hydrogen into helium. This is achieved through cycling ON nuclei through the reactions in the figure. The slowest reaction is still the proton capture on ^{14}N so most species eventually end up as ^{14}N, with destruction of ^{16}O and the production of small amounts of ^{17}O if the temperature is below about 25 million K, or the destruction of ^{17}O if the temperature is higher.

The CNO_{III} and CNO_{IV} cycles produce small amounts of ^{18}O and ^{19}F for temperatures below about 25 million K, but destroy these species at higher temperatures. This raises an important point, however. Some species, and ^{19}F is a good example, owe their fate not to a single nuclear reaction chain, such as the CNO cycles, but to the interplay of various reactions with the structural behavior of a star. This will be discussed further in Section 3.

Species	Effect	Note
^{1}H	destroyed	
^{4}He	produced	
^{12}C	destroyed	
^{13}C	produced	$^{12}C/^{13}C$ = 3-4 in equilibrium
^{14}N	produced	Almost all CNO nuclei end up as ^{14}N
		if cycle runs to hydrogen exhaustion
^{15}N	produced	in small quantities
^{16}O	destroyed	
^{17}O	produced	if burnt at $T < 25$ million K
	destroyed	if burnt at $T > 25$ million K
^{18}O	produced	in small quantities,
		if burnt at $T < 25$ million K
	destroyed	if burnt at $T > 25$ million K
^{19}F	produced	in small quantities,
		if burnt at $T < 25$ million K
	destroyed	if burnt at $T > 25$ million K

Table 2. The main results of CNO cycling.

Finally we discuss the "hot" CNO cycles. A careful examination of Figure 2 will show that the unstable species are all assumed to undergo β-decay. However at very high temperatures we must allow for the possibility that proton capture may occur on a similar timescale to the decay. Hence the unstable species may suffer two fates: a β-decay or a proton capture. There are some environments where these reactions are important, such as X-ray bursts, but we will not discuss these any further here. A summary of the action of the CNO cycles is given in Table 2.

2.1.3. The Ne-Na Chain

The Ne-Na chain is shown in Figure 3 and is quite analogous to the individual CNO cycles. Compare Ne-Na with CNO_I for example. The Ne-Na chain is directly linked to the CNO cycles by the fate of ^{19}F; a proton capture will produce ^{20}Ne and open the Ne-Na reactions. Whether these behave as a *chain* or a *cycle* depends on the relative rates of the (p,γ) and (p,α) reactions occurring on ^{23}Na. If the (p, γ) channel dominates then the Ne-Na reactions operate as a chain that sends species through to the Mg-Al chain (see below). If the (p, α) dominates then the reactions behave as a cycle, very much in analogy with the CN and ON cycles discussed earlier. In practice the reactions are a cycle for $T < 50$ million K and a chain for higher temperatures. Note, of course, that all of these values are subject to revision as we determine the reaction rates more accurately.

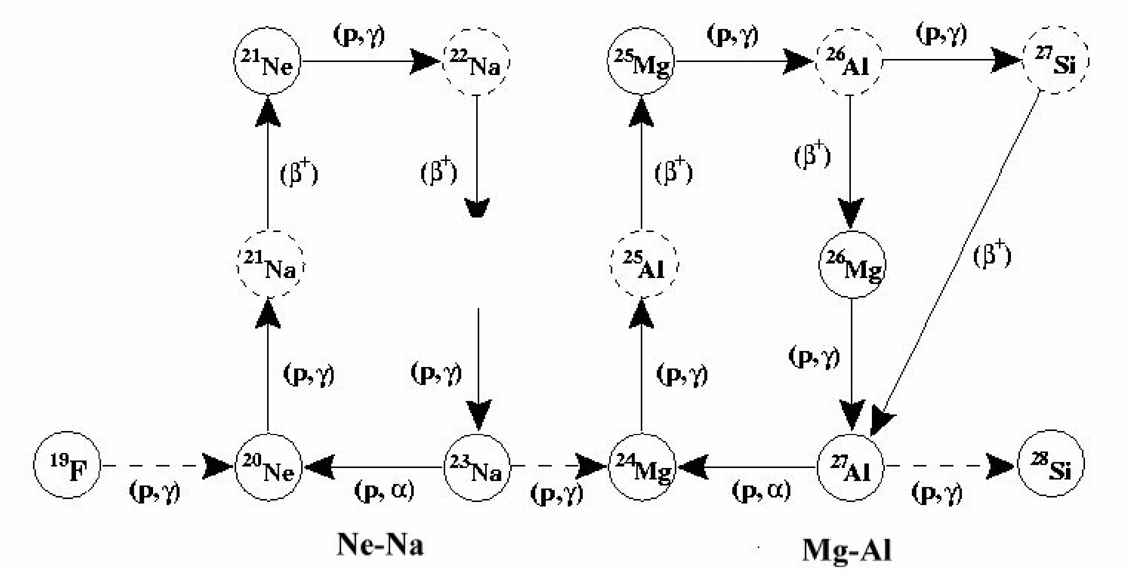

Figure 3. The Ne-Na and Mg-Al reactions for hydrogen burning. The Ne-Na reactions are on the left and the Mg-Al are on the right. The two are linked via the reaction ^{23}Na(p, γ)^{24}Mg.

There are three stable isotopes of Ne, being ^{20}Ne, ^{21}Ne and ^{22}Ne. Of these, the lighter isotope is by far the most common and it takes only a tiny decrease in this isotope to provide a significant increase in the amount of the heavier isotopes, especially ^{21}Ne. Further burning destroys ^{22}Ne via proton capture to produce ^{23}Na. The details depend on the burning temperature and whether you burn until all the hydrogen is consumed, for example. We can summarize by saying the ^{21}Ne is produced for temperatures below about 40 million K but destroyed at higher temperatures. A modest amount of ^{23}Na is produced at most temperatures through the destruction of ^{22}Ne.

Species	Effect	Note
^{1}H	destroyed	
^{4}He	produced	
^{20}Ne	destroyed	by a negligible amount
^{21}Ne	produced	below 40 million K
	destroyed	above 40 million K
^{22}Ne	destroyed	partially
^{23}Na	produced	

Table 3. The main results of the Ne-Na reactions.

2.1.4. The Mg-Al Chain

This is shown in the right hand side of Figure 3. It is fed by proton captures on ^{23}Na, which provides a link to the Ne-Na reactions. For temperature below about 1GK, which covers all non-explosive hydrogen burning situations, the $^{27}Al(p,\gamma)^{28}Si$ reaction dominates over the $^{27}Al(p,\alpha)^{24}Mg$ reaction, so the result is a chain rather than a cycle.

We meet a new complication here. The isotope ^{26}Al has an isomeric state that is not in thermal equilibrium with the ground state at the temperatures of most hydrogen burning. Hence it must be considered as a separate species in detailed calculations. The entire chain is comprised of the three stable isotopes of magnesium (the most common being ^{24}Mg) and two isotopes of aluminum, the stable ^{27}Al and the unstable ^{26}Al, with a half-life of some 700,000 years.

The main results of the Mg-Al chain are that significant increases in the amount of ^{26}Mg can be produced with only small decreases of ^{25}Mg. Quite high temperatures are needed ($T > 60$ million K) to decrease the ^{24}Mg content and to produce the aluminum isotopes. Note that since ^{26}Al is unstable, there is initially none present so the increase is quite noticeable. Of course, any ^{26}Al produced will later β-decay into ^{26}Mg.

Species	Effect	Note
^{1}H	destroyed	
^{4}He	produced	
^{24}Mg	destroyed	by a small amount
		above 60 million K
^{25}Mg	destroyed	
^{26}Mg	produced	in small amounts
^{26}Al	produced	radioactive; initially none, decays to ^{26}Mg
^{27}Al	produced	in small amounts a high T

Table 4. The main results of the Mg-Al chain.

2.2. Helium Burning

Helium burning usually occurs after all of the hydrogen in the core has been exhausted during the earlier evolution (The exception is for stars composed purely of hydrogen and helium, who will experience hydrogen and helium burning simultaneously; these stars will not be considered further in this article.). Hence we will discuss helium burning with an initial composition appropriate to a gas that has undergone complete hydrogen burning. This means that the initial composition will be mostly helium (since all hydrogen has earlier burned into helium) but that the initial CNO nuclei will have been processed into mostly ^{14}N nuclei by the actions of the CNO cycles. Thus ^{14}N is the second most abundant species in such a region. There is also a small amount of ^{13}C from the CNO cycles. Hence the main phase of helium burning begins with helium or ^{14}N as the initial seeds, but with ^{13}C providing a complication we must deal with.

2.2.1. Pure Helium Burning

If the initial gas is pure helium then we have helium as the initial seed for the subsequent reactions. In this case the single most important reaction is the triple-α reaction which we write as

$$^{4}\mathrm{He}(2\alpha,\gamma)^{12}\mathrm{C}\,.$$

Here we have effectively combined three ^{4}He nuclei into one ^{12}C nucleus. Once a reasonable amount of ^{12}C is produced then a competing reaction becomes

$$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$$

which has a notoriously uncertain reaction rate, although this uncertainty has dropped in recent years due to the combined work of many people. Analogously, once some ^{16}O is present then

$$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$$

can produce ^{20}Ne.

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Biographical Sketch

John Lattanzio was born in Cowes, the main town on Australia's glorious Phillip Island. This memorable event took place in the same year that the field of nuclear astrophysics was put on a secure footing by Geoffrey Burbidge, Margaret Burbidge, Willy Fowler and Fred Hoyle as well as Alistair Cameron. He is proud of having met each of those extraordinary people.

Lattanzio was first schooled on Phillip Island but then traveled to Wonthaggi for his high school education and then to Monash University as an undergraduate. He completed his PhD there prior to post-doctoral positions at the Canadian Institute for Theoretical Astrophysics (in Toronto) and the Lawrence Livermore National Laboratory in California. He spent a year at the Institute of Astronomy, at Cambridge, before settling into civilian life at Monash University. He has published almost 200 research articles on stellar astrophysics.

Lattanzio is a Fellow of the Royal Astronomical Society and an Honorary Fellow of the Astronomical Society of Australia.