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Review

# Frontiers in nuclear astrophysics

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ABSTRACT

The synthesis of nuclei in diverse cosmic scenarios is reviewed, with a summary of the basic concepts involved before a discussion of the current status in each case is made. We review the physics of the early universe, the proton to neutron ratio influence in the observed helium abundance, reaction networks, the formation of elements up to beryllium, the inhomogeneous Big Bang model, and the Big Bang nucleosynthesis constraints on cosmological models. Attention is paid to element production in stars, together with the details of the pp chain, the pp reaction, $^3$He formation and destruction, electron capture on $^7$Be, the importance of $^8$B formation and its relation to solar neutrinos, and neutrino oscillations. Nucleosynthesis in massive stars is also reviewed, with focus on the CNO cycle and its hot companion cycle, the rp-process, triple-$\alpha$ capture, and red giants and AGB stars. The stellar burning of carbon, neon, oxygen, and silicon is presented in a separate section, as well as the slow and rapid nucleon capture processes and the importance of medium modifications due to electrons also for pycnonuclear reactions. The nucleosynthesis in cataclysmic events such as in novae, X-ray bursters and in core-collapse supernovae, the role of neutrinos, and the supernova radioactivity and light-curve is further discussed, as well as the structure of neutron stars and its equation of state. A brief review of the element composition found in cosmic rays is made in the end.



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## 1. Introduction

Nuclear astrophysics is the science behind the synthesis of nuclei in temperature and pressure conditions existing within stars. It encompasses the synthesis and time evolution of nuclear abundances occurring through thermonuclear reactions from the Big Bang to the present date. Although the temperatures during the Big Bang were very high, the densities were low compared to typical stellar environments and only elements up to helium were produced appreciably. Hydrogen (75%) and helium (25%) remained as the source elements from which stars were formed long after the Big Bang Nucleosynthesis (BBN) stopped. Small traces of other elements such as Be and Li isotopes were also produced in the BBN. The oldest stars (population III stars) were formed from these and few other light primordial nuclei. One theorizes that population III stars with large masses exhausted their nuclear fuel quickly and ejected heavier elements synthesized in their cores in very energetic supernovae explosions. Population II stars, found in the bulge and halo of galaxies, are the next generation of stars and very metal poor stars, but can form elements such as carbon, oxygen, calcium and iron. These elements were dredged up from the core of stars and ejected by means of stellar winds to the interstellar medium. A few of these stars, much heavier than our Sun, have also exploded, ejecting heavier elements. This stardust gave rise to a new generation of stars, population I stars, usually found in the disk of galaxies and with the highest metallicity content of all three populations.

BBN is of impressive success, and has been used as a test of many new theories in physics, ranging from cosmology to particle and nuclear physics. In this review article we will discuss the state-of-the-art understanding of the physics of element production in the Universe and the challenges we face in nuclear astrophysics. In Section 2 we discuss the physics of the Big Bang both from the point of view on how particles, matter, and space evolve, and also on how nuclei are formed from the pre-existing nucleons during the BBN. In this section we discuss the physics of the early Universe, the proton to neutron ratio influence in the observed helium abundance, reaction networks, the formation of elements up to beryllium, the inhomogeneous Big Bang model, and the BBN constraints on cosmological models. In the following Section 3 we discuss the physics of element production in stars, starting with the Sun which belongs to population I stars. The Sun is burning hydrogen into helium slowly for about 4.5 Gyr and will continue to do it for 5 Gyr more. Nuclear reactions are responsible for the evolution and life-cycle of the stars, not only yielding internal heat, but also synthesizing heavier elements than those manufactured in the early Universe. Stars with masses small compared with the solar mass did not evolve and may be still burning hydrogen, and some have already ended up as dwarf stars. In Section 3 we present the general concepts in stellar nucleosynthesis, the pp chain, the pp reaction, $^3$He formation and destruction, electron capture on $^7$Be, the importance of $^8$B formation and its relation to solar neutrinos, and neutrino oscillations.

The metallicity of a star is defined as the proportion of chemical elements heavier than helium. E.g., the Sun has a metallicity of about 1.8% of its mass. Metallicity is often denoted by "[Fe/H]", the logarithm of the ratio of iron abundance compared to the iron abundance in the Sun. Iron is used a reference because it is easy to identify with spectral data in