THEORIES OF NUCLEOSYNTHESIS

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Abstract. A review is presented of current theories of nucleosynthesis. The predicted contributions from (1) cosmological nucleosynthesis, (2) super-massive stars, (3) non-violent (quasi-static) stellar evolution, (4) supernova explosions, (5) cosmic ray interactions with the interstellar medium and (6) nova explosions to the observed solar system abundances are summarized. Recent studies of 'explosive nucleosynthesis' in supernovae and of the production of lithium, beryllium and boron by the interaction of cosmic rays with interstellar gas are emphasized. Observations of stellar spectra which either impose limitations upon or provide confirmation of various aspects of these theories are noted, as are several critical nuclear experiments. The general picture which emerges is encouraging in that most of the major abundance features appear to be at least qualitatively understood, but significant further research is required.

1. Introduction

Theories of nucleosynthesis have been guided, historically, by the prevailing knowledge of element abundances. The earliest spectral studies of the Sun and stars were able to establish only that the elements of which they and the Earth are composed are qualitatively the same. It was therefore quite reasonable to assume a universe of uniform chemical composition and to search within the framework of cosmology for a set of physical conditions which would account for the present abundance distribution (see for example the review article by Alpher and Herman, 1950). Difficulties associated with 'bridging' the gaps at masses $A=5$ and 8 (no stable nuclear species exist with these mass numbers) soon made it clear that universal 'big-bang' synthesis (Alpher et al. 1948) could not have been responsible for the formation of the bulk of the nuclear species heavier than helium ($A=4$). The current status of the big-bang theory of nucleosynthesis, emphasizing its promising role in the production of $^2$D, $^3$He, $^4$He and $^7$Li, is reviewed in Section 2.

The essential role played by thermonuclear processes in providing an energy source sufficient to account for stellar lifetimes of billions of years was established in the late 1930s by the calculation of Bethe (1939) and von Weizsacker (1938). The fusion of four protons to one helium nucleus ('hydrogen burning') taking place in 10% of the Sun's mass releases several orders of magnitude more energy than is available as gravitational potential energy. It was not immediately recognized, however, that subsequent thermonuclear burning phases in stellar interiors might account for the formation of many of the heavier nuclei observed in nature. The recognition that nucleosynthesis is a continuing process in stellar interiors followed the discovery by Merrill (1952) of the presence of the element technetium in the atmospheres of red giant stars. As technetium has no stable isotopes (the longest lived isotope, $^{98}$Tc, having a half life $\tau=1.5 \times 10^6$ y), its presence confirms that thermonuclear processes involving heavy nuclei have very recently taken place in the interior.

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This conclusion has been confirmed by many subsequent spectroscopic analyses which have revealed that pronounced abundance variations occur in certain broad classifications of stars. 'Carbon stars', for example, showing anomalous atmospheric abundances of $^{13}\text{C}/^{12}\text{C} \sim 4$ and nitrogen $(\text{N}/\text{C} \sim 35)$ compared to the solar values, are interpreted as stars in which hydrogen burning by means of the CNO cycles has taken place in the interior with the resulting materials being mixed to the surface by convection.

The broader classifications of stars in our Galaxy into disc (Population I) and halo (Population II) populations is reinforced by considerations of their relative metal contents $Z$ ($Z$ being the fraction by mass in the form of all elements heavier than $^4\text{He}$). Disc population stars typically show heavy element concentrations within a factor three of the Sun ($Z_\odot = 0.015$), while halo stars may have somewhat lower metal contents and a few extreme halo population stars are known to have metal contents $Z \sim 10^{-3} - 10^{-2} Z_\odot$. As the halo stars are generally assumed, for dynamic reasons, to constitute an earlier galactic generation, these abundance variations suggest that the heavy elements observed in solar system matter represent the integrated effects of stellar or supernova nucleosynthesis over the lifetime of the Galaxy. The fact that relatively few stars are observed with extremely low metal contents ($Z < 10^{-4} Z_\odot$) suggests that the net rate of heavy element synthesis during the earliest phases of galactic history may have been somewhat greater than at present and certainly that relatively few stars of lifetimes greater than ten billion years (masses $\lesssim$ one solar mass ($M_\odot$)) were formed at this epoch (Schmidt, 1963; Truran and Cameron, 1971). The possible role of nucleosynthesis in supermassive stars in the earliest stages of galactic history is briefly discussed in Section 3, and the contributions predicted as a consequence of the non-violent (quasi-static) evolution of normal stars throughout galactic history are reviewed in Section 4.

Recent theoretical calculations regarding two specific mechanisms – supernova nucleosynthesis and cosmic-ray-induced nucleosynthesis – are elaborated in Sections 5 and 6, respectively. As will become clear, the final catastrophic supernova phase of evolution characteristic of stars in certain mass ranges seems the most promising site for the synthesis of the bulk of the heavy elements observed in nature. The interaction of high energy protons and $\alpha$-particles in the cosmic radiation with the more abundant heavy constituents of the interstellar medium (carbon, nitrogen, oxygen and neon) has recently been demonstrated to produce significant abundances of the isotopes of lithium, beryllium and boron – nuclei which had previously presented severe difficulties. Finally, in Section 7 a brief discussion of the possible role of nova explosions in nucleosynthesis is presented.

The major boundary conditions with which we are provided for theories of nucleosynthesis are shown in Figure 1 – the solar system abundances (Cameron, 1968). It may be useful at this stage to scan the important abundance features and to keep these in mind in our subsequent discussions. The two most abundant nuclei, hydrogen and $^4\text{He}$, together with their isotopes deuterium and $^3\text{He}$, seems most likely to have emerged from the cosmological big-bang (Section 2). Lithium, beryllium and