NUCLEOSYNTHESIS IN NEUTRON RICH SUPERNOVA EJECTA

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Abstract. A nuclear reaction network of 903 different, strong and electromagnetic reactions, linking 107 chemical constituents is used to study the elements synthesized in the neutron rich material, ejected in supernova explosions. A large number of three body reactions virtually eliminates the usual bottle neck at the $A = 5$ mass gap.

For initially high temperatures and densities, $T = 10^{10}$ K and $\rho = 7 \times 10^8$ gm/cm$^3$, with expansion time scales of $10^{-3}$-$10^{-2}$ sec, three different n to p ratios, $n/p = 4$, $n/p = \frac{2}{3}$, and $n/p \sim 1$, are considered for the ejected matter. In all three cases, the material synthesized is preponderantly heavy. For the $n/p = 4$ model, the conditions at the charged particle freeze-out are ideal for the 'r-process'. The onset of this rapid neutron capture phase is explicitly shown with a sequence of time lapse abundance plots.

1. Introduction

Recent observational work, locating pulsars at the sites of supernova remnants, along with theoretical arguments suggesting the identification of neutron stars with pulsars, have emphasized the importance of having reliable models for supernova explosions. However, supernova calculations, with little observational data to guide them, have proceeded mainly along theoretical lines. As a consequence they have been plagued by many uncertainties and contradictions. One of these is the apparent disparity between the amount and rate of supernova ejected mass in the galaxy and the observed solar system abundances of the heavy chemical elements (Truran et al., 1968).

The present work is an in depth study of the elements synthesized by thermonuclear reactions in these explosions. The preliminary investigations of Truran et al. (1968), which studied supernova nucleosynthesis with a bare skeleton chain of $(n, \gamma)$ and $(\alpha, \gamma)$ reactions, suggested that the physical conditions in current models would favor a break through past carbon to the heavier elements. With a complete network of reactions up through the silicon isotopes and a bare $(n, \gamma)$ and $(\alpha, \gamma)$ extension network from silicon to the nickel isotopes, we confirm this and are able to give some estimates for the time scales involved. Furthermore, the observation of Truran et al. (1968), that the rapid neutron capture process of heavy element production will occur in these models, is actually seen to be underway at the termination of one of the presented calculations.

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We also find that the lightest elements, Li, Be and B, stand very little chance of surviving these model explosions. Some limits on the explosive conditions that might produce them are given.

While no attempt has been made here to resolve the discrepancy between these models and the heavy element abundances, recent work by Colgate (1970), indicates that the calculated amount of neutron rich ejecta, in these explosions, is an over-estimate, thus making them more compatible with observation.

In Section 2 a brief discussion of the hydrodynamic calculations for supernova explosions, summarizes the work of Colgate and White (1966), Arnett (1966, 1967) and Schwartz (1967). Section 3 presents the nuclear reactions linking the 107 nuclei considered. This is accomplished by a series of graphical displays called network diagrams, the construction of which are detailed in a set of formal rules. Emphasizing the importance of three body reactions in bridging the mass gap at $A=5$, the overall reliability of the network is also briefly touched upon. The nucleosynthesis products for the three $n$ to $p$ ratios, $n/p=4$, $n/p=\frac{3}{2}$, and $n/p \approx 1$, are given in Section 4 and the time scales for the establishment of nuclear statistical equilibrium are examined. In Section 5, the conditions most favorable to the onset of the $r$-process are investigated. They are compared with those suggested by other workers. The appendix presents the numerical techniques used to integrate the network equations.

2. The Supernova Model

Studied in detail by Colgate and White (1966), Arnett (1966, 1967) and Schwartz (1967), the hydrodynamic models for supernova explosions have encountered computational difficulties in handling neutrino transport properties (Colgate, 1968; and Arnett, 1968). These models investigated the behavior of highly evolved massive stars, undergoing gravitational collapse. The supporting pressure of the initial configuration was removed either by the decrease in the thermal photon pressure due to the photo-disintegration of nuclei or by the decrease in degeneracy pressure, resulting from the capture of high Fermi energy electrons on nuclei.

Essentially free falling onto itself, the stellar material is compressed to enormously high temperatures ($\sim 10^{11} - 10^{12}$ K) and densities ($\sim 10^{14}$ gm/cm$^3$) in the central regions. A hot, dense core of degenerate neutrons is formed, with the envelope of the star still raining down on it. Opaque to all forms of radiation, this neutron core radiates away its thermal energy as a black body neutrino emitter, with an energy flux of $\sim 10^{54}$ erg/sec at its surface. These neutrinos will be absorbed by, and consequently will heat up, the colder exterior mass, which has not yet fallen to nuclear densities. Some of the details of the fate of the still infalling material are in dispute (Colgate, 1968; Arnett, 1968).

The formation of a strong shock front in the models of Colgate and White (1966) and the weak to none in those of Arnett (1966, 1967) are primarily due to different methods in treating the deposition of the neutrino energy in the stellar envelope. The important point in either case, however, is that the outer layers of the star are