CHAPTER - I
INTRODUCTION
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This thesis is an attempt to find 'A variant in the explosive nuclear burning product in Astrophysics'. The word variant implies a different form of the same thing, a different reading, changeful or varying or diversified. In the present work, the variant is the temperature.

It has been realized in recent years that the coefficients in the semi empirical mass formula for atomic nuclei are temperature dependent. Therefore the variation of temperature will reflect a variation in mass also.

Massive stars and supernovae are generally believed to be the sites for explosive thermonuclear burning. Alpha capturing reactions are supposed to produce elements up to Ca in an explosive situation. It is expected that the abundance distribution of these elements can be reproduced in the premises of explosive burning situations.

Variation of the temperature can lead to new values of temperature dependent nuclear masses and hence new Q values for the alpha capturing reactions. This will allow a recalculation of all the reaction rates for explosive alpha capturing reactions, and so the calculation of the abundances of the reaction products.
The abundance of elements

The material universe around us is made of a bewildering variety of elements and their isotopes. Man has been very inquisitive to learn about the elements and their formations. Significant correlation has been established between the elemental abundances and the systematic properties of nuclear masses. The astrophysical studies revealed that our present universe has a definite age and in general the relative abundance of elements are universal in character.

For nucleosynthesis in stars the abundances of elements play a very definite role. Historically, it was the important early data on abundances of solar system matter compiled by Goldschmidt (1937), Brown (1949) and Suess and Urey (1956) that provides the basis upon which the nucleosynthesis studies of Burbidge et al., (1957) and Cameron (1959) were developed. We now have available a significant body of abundance data involving both galactic and extra galactic sources.

For cosmic abundances of elements and isotopes, the data sources can be classified into tangible, where samples can be directly handled and anaylysed by chemical and other laboratory methods, and intangible requiring spectroscopy or considerations from theoretical astrophysics Pagel, (1997).
Data Sources for Cosmic Abundance

<table>
<thead>
<tr>
<th>Tangible</th>
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<td>1. Earth (a) crust</td>
<td>Astrophysical objects</td>
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<td>(b) atmosphere</td>
<td>Sun, planets, stars, planetary</td>
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<td>(c) oceans</td>
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<td>2. Moon rocks (Apollo)</td>
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Abundances in stars in our galaxy were reviewed by Pagel (1971) and Baschek (1979). Abundances in interstellar matter were discussed by Spitzer (1975), Wannier (1980), York (1982) and Peimbert (1975). Abundances in stellar populations in our galaxy and other galaxies are surveyed by Pagel et al. (1981), Mould (1982) and van den Bergh (1975). Abundances in supernova ejecta and remnants are reviewed by Oke and Searle (1974) and Trimble (1982, 1983). Other useful reviews include those on the chemical composition of globular clusters (Kraft, 1979; Freeman, 1981) and gamma ray sources.

From these studies, it can be seen that hydrogen is the most abundant element in the universe. The next most abundant element is $^4$He. C, N and O make about one thousandth part of hydrogen. Beyond this iron group elements have large abundances.
Stellar studies have now established that the local variations in chemical compositions do occur.

Lithium has been found to be over abundant in T-Tauri stars.

Hydrogen is available in stars from the hottest to the coldest. But there are certain stars which are deficient in hydrogen. Such objects are HD 160641 (Bidelman, 1952), HD 168476 (Thackeray, 1954) and HD 135485 (Stewart, 1956).

They show presence of helium, carbon, oxygen, neon, etc. There are certain objects which are supposed to be pure helium stars, eg., the star Hz 29 (Aller, 1957).

Carbon over-abundance is observed in carbon stars and Wolf Rayet stars (Burbidge and Burbidge, 1957). Wolf Rayet Stars, which are hot stars of high luminosity like O stars but have peculiar spectra with broad emission bands of He$^+$, N$^{++}$(WN), C$^{+}$ and C$^{+++}$(WC) or O$^{+++}$(WO) and with hydrogen weak or absent. Many of the new abundance determinations show that certain W.C stars have no hydrogen and they have various metal to helium ratio. Some stars also show metal deficiencies (Wallerstein et al., 1963).
Studies of heavy primary Cosmic radiations show that the elements Fe is about one thousand times more abundant in cosmic rays than the value of Suess and Urey (1956).

**Stellar evolution and Nucleosynthesis**

Stellar evolution is characterised by a sequence of alternate stages of gravitational contraction to higher temperature and densities and the thermonuclear burning of the available fuel at these temperatures. Since these nuclear burning stages give rise to the production of successively heavier nuclei, it is clear that the question of stellar energy generation and nucleosynthesis is tied closely together. The various nuclear processes occurring in stars and supernovae, responsible for nuclear energy generation and for the formation of the heavier elements observed in nature were first defined in the now seminar papers by Burbidge et al. (1957) and by Cameron (1959).

On the basis of these processes enumerated in the above works above, the general trends of the abundance curve can be well explained.

There are some new experimental results obtained affecting the products of helium burning and alpha-capturing processes. In view of these experimental informations, some work has been undertaken in this area on helium burning and alpha capturing processes.
Helium burning and alpha capturing reactions:

During red giant evolution, the hydrogen exhausted core continues to contract in radius and heat up. Helium burning sets in at temperature of the order of $10^8$ K and densities ~ $10^4$ gm cm$^{-3}$ through the triple $\alpha$ reaction (Opik, 1951; Salpeter, 1952).

In massive and intermediate mass stars, the interior is still not degenerate when helium burning sets in; the new energy source causes the core to expand and the envelope to contract, and the star undergoes some loops in the H R diagram. In less massive stars the core is degenerate and a thermal runaway ensues known as the (core) helium flash.

Some other important alpha capturing reactions are the following.

$^{12}$C ($\alpha, \gamma$)$^{16}$O converts a substantial fraction of the carbon from triple $\alpha$ into oxygen. The rate is still somewhat uncertain because it is affected by the tails of subthreshold resonances (Fig. 1.1) and this uncertainty is significant for calculation of more advanced stages of nucleosynthesis (Pagel, 1997; Woosley and Weaver, 1995; Truran, 1984). This will enable one to set the initial core condition for pre supernova models.

More advanced alpha capturing reactions $^{16}$O($\alpha, \gamma$)$^{20}$Ne, $^{20}$Ne($\alpha, \gamma$)$^{24}$Mg upto $^{36}$Ar($\alpha, \gamma$)$^{40}$Ca may take place at temperatures ~ 1GK=$10^9$ K under some conditions, eg. shell burning in advanced stages and explosive nucleosynthesis.
The levels of $^{16}O$ near the $\alpha + ^{12}C$ threshold are shown above.
Helium capturing on CNO material previously converted into $^{14}\text{N}$ by hydrogen burning leads to the series of reactions:

$$^{14}\text{N}(\alpha,\gamma)^{18}\text{F} (\beta^+\nu)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$$

**Further burning stages: evolution of massive stars**

In stars below a certain initial mass $M_{up}$, core burning is halted by formation of a degenerate CO core which later becomes a white dwarf. Stars with initial mass about $10M_\odot$ or more ignite carbon in the core which remains nondegenerate. Owing to neutrino emission at the high temperatures involved, due to $e^\pm$ annihilation and other processes subsequent evolution is greatly accelerated, the nuclear time scale becoming shorter than the thermal time scale and nuclear evolution occurring before the envelope (blue or red supergiant) had the time to adjust. The main reactions are:

**Carbon burning** (T $\approx$ 1 GK; lifetime of reaction, $\tau$ = 600 years)

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{24}\text{Mg} + \gamma + 13.93\text{ MeV} \]
\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha + 4.6\text{ MeV} \]
\[ ^{23}\text{Na} + \gamma + 2.2\text{ MeV} \]
\[ ^{23}\text{Mg} + n + 2.6\text{ MeV} \]

**Neon burning**

\[ ^{20}\text{Ne} (\gamma,\alpha)^{16}\text{O}, \quad ^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}, \quad ^{24}\text{Mg}(\alpha,\gamma)^{28}\text{Si} \]
Schematic illustration (not to scale) of the onion skin structure in an interior of a highly evolved massive star $25M_\odot$. Numbers along the vertical axis show some typical values of the massive fraction, which those along the horizon axis indicate temperatures and densities (gm cm$^{-3}$). Adapted from R. Kippenhahn and A. Weigert, Stellar Structure and Evolution, Springer Verlag, 1990.
Oxygen burning \( (T \approx 2 \text{GK}, \tau = \frac{1}{2} \text{years}) \)

\[ ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{32}\text{S} + \gamma \]

\[ \rightarrow ^{28}\text{Si} + \alpha \] in partial degenerate condition. Core O burning is accompanied by shell C burning etc. leading to a concentric onion like structure with increasingly heavy nuclei towards the interior (Fig. 1.2). However convective zone caused by some of the shell sources will tend to complicate this picture by blurring the composition boundaries and the extent of this effect is obscured by uncertainties in nuclear reaction rates and in the influence of convective over-shooting silicon burning takes place at \( T \geq 3 \text{ GK} \).

The next stage in dynamical collapse of the core caused by electron capture and photodisintegration or / and \( e^± \) pair creation, for \( M \geq 100M_\odot \) caused by the increase of temperature following gravitational contraction when silicon fuel is exhausted.

According to standard picture the collapse leads to the formation of a neutron star, leading to copious neutrino emission and at bounce at nuclear density which causes a shock to propagate outwards. The shock reinforced by absorption of energetic neutrinos lead to expulsion of the outer layers in an explosion identified with supernova of type II (and related types Ib, etc). The gravitational energy released is of the order of \( 10^{53} \text{erg} \). 99% of which is carried away by neutrinos.
O, Ne, Mg originate mainly from hydrostatic burning shells and the amount synthesized and ejected rises sharply with progenitor mass (or strictly speaking the mass of the helium core) whereas S, Ar, Ca, Fe are mostly due to explosive burning and their ejected mass is assumed to vary much less.

However, there are uncertainties in the range of initial stellar masses where this standard picture applies, more massive stars may leave behind a black hole instead of a neutron star with or without a supernova explosion depending on the equation of state of nuclear matter and how much initially outgoing material falls back. Mass loss in the pre supernova stages can have drastic effects on the evolution of stars of 40\(M_\odot\) or more especially at higher metallicities (Maeder, 1992, 1993). A solar metallicity star of initial mass 40\(M_\odot\) (He core mass \(M_\alpha = 19M_\odot\)) in which the peeling away of the outer layers by stellar winds gradually exposes increasingly nuclear processed material that appear at the surface of Wolf Rayet star and reduce the total mass to 12\(M_\odot\) before the supernova explosion.

The most massive stars (above 50\(M_\odot\)) may lose their expected supernova ejecta in a black hole but still contribute lighter elements like C, N, O, and Ne (especially \(^{22}\)Ne) in winds during their prior evolution.

**Pre supernova core:**

The calculation of pre supernova structure of the massive stars were carried out mainly by two groups. One at California (Woosley and Weaver; 1984, 1988, 1993, 1995) and the other in Japan (Nomoto and Hashimoto 1988, Shigeyama et al, 1988) Supernova 1987A in the LMC provided us an excellent opportunity to test the theory of massive star evolution and nucleosynthesis.
Explosive burning process in star

The study of explosive nuclear burning process in stars necessitates data such as an understanding of the mechanism of the explosion and the time history of the temperature and density of the exploding matter during the ensuing expansions; knowledge of the composition and the state of matter before the explosion and the rates of a large number of thermonuclear reactions involved. Large body of theoretical and experimental data on a variety of thermonuclear reactions are presently available, (Fowler et al.,1967, 1975; Harris et al.,1983; Weiseher et al.,1986; Hoffman and Woosley,1992; Thielemann et al.,1996; Fuller, Fowler and Newman, 1982, Oda et al.,1994)

With the discovery of the effective cooling of evolved stellar interiors due to neutrino emission, it has become apparent that explosive nuclear fuel namely $^{12}\text{C}$, $^{16}\text{O}$, etc., may ignite in a degenerate electron core and the runaway reactions may disrupt the star completely (Arnett et al,1968; Arnett, 1970, 1995). The high temperature of explosion which lasts only a fraction of a second, produces such a high degree of nuclear processing that the expelled thermonuclear products are vastly different from that of the composition of mass zones before the explosion (Arnett,1970 and Truran et al.,1970).

The key thermonuclear feature of explosive burning is that, large amount of thermal energy is liberated within a short time. The star hardly has the time to compensate hydro-dynamically at this situation. As a result the entire star may be given a positive energy for the expansion. This time should be of the order of the hydrodynamic time scale for free fall or free expansion.
Here the mass density $\rho$ is expressed in CGS units. Although large amount of energy are liberated initially the subsequent expansion should be nearly adiabatic i.e.,

$$\tau_{H_D} = \frac{444}{\rho^{1/6}} \text{sec} \quad (1.1)$$

$$PT^{-3} = \text{constant} \quad (1.2)$$

The investigation so far have combined equation (1) and (2) with values of initial density and peak temperature of the explosion, to yield an estimate of the nuclear abundance. In the hydronamic calculaton of explosive nucleosynthesis in supernova, one chooses an initial composition consistent with helium burning and post helium burning configurations of stellar cores and then determines the range of temperature and density conditions consistent with the explosion of the matter in supernova event. The expansion time scale is to be equated with the hydro dynamic timescale. Calculations of explosive carbon, oxygen and silicon burning nucleosynthesis performed in this manner proved extremely successful is their prediction of detailed abundance features.

Explosive hydrogen burning and explosive $\alpha$ capturing reactions can play a crucial role in diverse astrophysical environment, with implication both for nucleosynthesis and for energy generation and dynamic evolution. These environments include super massive stars (Fricke et al., 1973; Morgan, 1980; Woosley et al., 1980) Supernova (Howard et al., 1971) novae (Gallagher et al., 1978) WC star, (Maeder, 1990, 1992) accreting neutron star (Hansen et al., 1975; Wallace et al., 1982).
**Motivation for present work:**

The two goals in nuclear astrophysics are the attempts to understand the energy generation of stars at all stages by stellar evolution and to explain, the abundances of the elements and their isotopes. Both goals are closely related as nuclear processes have been identified as the enormous energy source which stabilizes the stars and governs their evolution by transmuting nuclear species into other nuclear species thus creating new elements. It is therefore not surprising that studies of stellar evolution require as input the reaction rates for those nuclear processes which are part of the network of many reactions taking places at each stage of stellar evolution. Though both experimental and theoretical information are available for a number of reactions of hydrogen and helium burning occurring in stars, the data need constant improvisations for reliable analysis of nuclear burning processes. This will facilitate proper study of nucleosynthetic sites in Astrophysics. The presently available data are thus useful in re-examining the energy generation and nucleo synthetic processes in massive stars, supernovae, etc. This might explain some interesting features of certain element abundances.

In chapter II, assuming the volume and surface binding to be effective (because in present range of high temperature and density condition, these coefficients play the dominant role), all the nuclear masses are calculated from the measured values of masses of concerned nuclei. These new masses are used to obtain the Q values of the reaction. We have analysed in detail, the mass variations of different nuclei with different temperature and the nature of variations.
In chapter III we discuss the α capturing reactions. Special emphasis was given to the reaction $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$. Due to Pre supernova evolution of stars more massive than about $20\text{M}_\odot$, the core structure is very sensitive to the reaction rate of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction. (Woosley and Weaver, 1995; Langanke and Koonin 1983, 1985, 1992).

Again we have studied the alpha capturing rates in $^{16}\text{O}$, $^{20}\text{Ne}$, $^{24}\text{Mg}$, $^{28}\text{Si}$, $^{32}\text{S}$, $^{36}\text{Ar}$, $^{40}\text{Ca}$. At some stages of stellar evolution these reactions are believed to play a significant role. The $(\alpha,\gamma)$ reactions may proceed through a number of levels of the compound states. Recent measurement of energy level data have been used for these calculations. For the recalculation of reaction rates, the new masses and newly calculated $Q$ values are used.

We have also studied the $^{14}\text{N}(\alpha,\gamma)\, ^{18}\text{F}(\beta^+,\nu)^{18}\text{O}$ reaction extensively in the context of variation of mass with temperature in this chapter, which is also a very important α capturing reaction.

In the last part of this chapter, we have calculated the explosive temperatures for $^{12}\text{C} - ^{4}\text{He}$ fuel by equating the nuclear reaction time with the approximate explosive hydrodynamic time. We take the approximate time around this value to calculate the abundances distribution of $4\text{N}$ nuclei. We have also calculated the relative abundances of these elements for different explosive temperature dictated by the nuclear physics requirement. We have assumed a density $\rho = 10^2 - 10^6\text{ gm cm}^{-3}$ in conformity with conditions available for explosive burning (Arnett, 1969). It is believed that these conditions will be available during and after the hydrostatic carbon burning in massive stars.
In the chapter IV, we have studied the nucleosynthesis in explosive burning conditions of massive stars in pre supernova stages. As the Wolf Rayet stars, particularly W C stars are the progenitors of SNeIb, we have studied about them in details. An attempt is made to calculate and compare the abundances of elements in those conditions.

In the chapter V the energy generation rates in highly evolved massive stars are considered. In pre supernova stages Fowler and Hoyle (1960) examined the stellar energy generation due to $^{12}\text{C} + ^{12}\text{C}$ and $^{16}\text{O} + ^{16}\text{O}$, etc, reactions. When the temperature goes on increasing, energy generation rates also increase. Energy generation rates at those physical situations are re-examined for some crucial reactions considering the mass change with temperature. The new Q values and the new reaction rates are taken into account. The neutrino emission rates are also considered. Two approximate power laws are developed for new temperature dependent energy generation rates for these two reactions in question.

The energy generation for an exploding material of 2.6 $\text{M}_\odot$ core of type II supernova is calculated. An effort is made to explain the observed radiation in supernova with the results obtained from the calculations.

A brief outline of some future scope of studies relevant to the present problem is given in the concluding chapter (Chapter VI).
References

- Baschek, B. Les Elements et leur isotopes dans l' univers;
  Liege Univ. Liege Press. (1979)