CHAPTER I

 STELLAR EVOLUTION OF NEUTRON STAR
1.1 INTRODUCTION

The stellar evolution of a stable or quasistable stellar object is the story of the competition between other physical effects and the universal pull of gravity. Opposition to gravity may be provided by kinetic effects or by the other fundamental interactions of physics, i.e. electromagnetic and nuclear forces. Angular momentum is a kinematic effect which can prevent gravitational collapse. Other kinematic processes opposing gravity are provided by the normal hydrodynamic pressure and radiation pressure in a main sequence star and neutrino pressure in neutron stars. Kinematic effect provided by the fermion nature of matter is also important. Fermions obey the Pauli exclusion principle, and thus no two fermions can be in the same state i.e. even at absolute zero temperature, there is a distribution of non-zero momentum states occupied by the Fermi pressure or degeneracy pressure, which will oppose the pull of gravity.

Thus angular momentum can be lost through the action of normal hydrodynamic viscous forces or be radiated away gravitationally, or in the case of magnetic system it may be lost into electromagnetic radiation. Hot systems in general will radiate away their free energy in the form of photons or neutrinos. But how the temperature
of a stellar object responds to the struggle against gravitational collapse depends on the equation of state for the material of which it is composed.

The sequence of collapses is a dynamical process. As the object collapses the gravitational forces become stronger, and if the collapse is not to become catastrophic the pressure gradient must rise at least as rapidly. The collapse may be extremely violent resulting in processes in which much of the original mass of the star may be blown off. If a main sequence star is too large, the radiation pressure may rise to rapidly, leading to an instability, which may result in thermonuclear explosions or degenerate stars may be so massive that neutrino pressure may drive off the outer layer of the star. For a gravitationally selfbound object, if these same forces are sufficient to halt the gravitational collapse, the endpoint is a planet. If the mass is too great, a planet will collapse under its own weight; but this process may be halted by the electron degeneracy pressure, in which the endpoint is a cold white dwarf. If the mass is even greater, the electron Fermi pressure may not be sufficient and the collapse may continue until halted by the strong nuclear forces or the baryonic Fermi pressure; in this case the endpoint is a neutron star. If the mass is too great for a stable neutron star to form, then the collapse to a blackhole is predicted.
Fig 1.1 Mass radius relationships for various astrophysical objects

\[ M = \text{Mass of the collapsing object having radius } R' \]
\[ \mathcal{R} = \text{The Schwarzschild radius or blackhole radius} \]

\( R < \mathcal{R} \) no stable objects
Thus, the important is that the resultant stable stellar objects are the products of the dynamics of the collapse, and hence it is not implying that all blackholes are more massive than all neutron stars, which in turn are more massive than all white dwarf. So, the collapse may be so explosive, resulting in processes in which much of the original mass of the star may be blown off and the resulting core, which becomes the neutron star may be only a small fraction of the initial mass of the star. The exact dynamical process by which the neutron star is formed is still obscure. What fraction of the original stellar mass finishes up in the neutron star core is not clear.

1.2 HISTORICAL BACKGROUND

The possibility that neutrons may play an important role in astrophysics had been recognised almost from the beginning of neutron physics. The notion that neutron production and neutron star formation might be significant in supernovae was speculated by Baade and Zwicky (1934a, b, c, d) very soon after Chadwick's discovery of the neutron. They first discussed the concept of a neutron star — an object consisting primarily of neutrons, with mass about equal to that of the sun but radius of only about 10 km. Oppenheimer and Volkoff in 1939 made first the model of a neutron star giving the
TABLE 1.1: Various parameters of a Neutron Star with
radius $R = 10^6$ cm and Effective Surface
Temperature $T_e = 10^6$ K

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>$10^6$ cm</td>
</tr>
<tr>
<td>Surface Area</td>
<td>$1.3 \times 10^{13}$ cm$^2$</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>$10^6$ K</td>
</tr>
<tr>
<td>Wavelength of the maximum of the spectrum (on the frequency scale)</td>
<td>$40$ Å</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$7 \times 10^{32}$ ergs. sec$^{-1}$</td>
</tr>
<tr>
<td>Absolute bolometric magnitude (mag)</td>
<td>6.5</td>
</tr>
<tr>
<td>Fraction of the radiated energy in the interval 3000 – 10,000 Å</td>
<td>$5.4 \times 10^{-6}$ ergs</td>
</tr>
<tr>
<td>Luminosity in the interval 3000 – 10,000 Å</td>
<td>$3.8 \times 10^{27}$ ergs. sec$^{-1}$</td>
</tr>
</tbody>
</table>
structure of such an object. According to their model a neutron star is composed of non-interacting neutrons. At the enormous densities encountered in the interior of such stars, about $10^{14}$ g. cm$^{-3}$, the neutrons form a degenerate fermi gas; the pressure associated with this degeneracy is sufficiently large to prevent further collapse of the star. The neutron core of the star is surrounded by a shell consisting of nuclei and degenerate electrons; the outermost surface layer consists of an ordinary plasma. Regardless of the processes occur inside the neutron star, the temperature of its interior, as pointed out by Chiu (1964), cannot long remain greater than several billion degrees. Since at such temperature intensive creation of neutrino-antineutrino pairs (which instantaneously leave the star) rapidly cool it. In all inner portions of the star, where the electron gas is degenerate, the thermal conductivity is extremely high. Therefore, the core of a neutron star is isothermal and only in the outermost shell there is a temperature gradient. Various parameters of a neutron star with radius $R = 10^6$ cm and effective surface temperature $T = 10^6$ K are shown in the table 1.1 (Wheeler 1966).

The details of neutron star structure are quite sensitive to the still imperfectly understood neutron matter equation of state at densities greater than
Fig 1.2. Cross section of a neutron star having a total gravitational mass of $1.33\,M_\odot$

(Pandharipande et al 1976)
the density of nuclear matter ($\rho = 2.8 \times 10^{14} \text{ g cm}^{-3}$). But subsequent analysis have considered more realistic compositions and equations of state for the various density regimes. A schematic model of the structure of a neutron star is shown in fig 1.2.

Beneath an atmosphere only a few meter thick one finds an outer crust, 0.5 km thick, of increasing density. In this outer most region ( outer crust ) the structure of a neutron star is expected to be $^{56}$Fe nuclei ( since $^{56}$Fe is the most stable terrestrial nucleus ) surrounded by a sea of degenerate electrons and a density at the surface of about $10^4 \text{ g cm}^{-3}$. Because of their mutual electrostatic repulsion, the iron nuclei are expected to form a body centered crystalline lattice ( provided the temperature is below about $10^{10}$ K ), thereby giving the neutron star a solid outer crust. As the coulomb interaction energy is of the order of 1 MeV per nucleus ( very high ), the outer crust will have a large shear modulus and hence be very rigid.

Beneath the outer crust of iron nuclei the density increases. This layer therefore consists of neutron rich nuclei, forming another crystalline lattice known as the inner crust and surrounded by a sea of degenerate electrons. The inner crust begins at $\rho \sim 4.3 \times 10^{11}$ g. cm$^{-3}$ and extends a few km until a mass density
\( f \sim 2.4 \times 10^{14} \text{ g.cm}^{-3} \) is reached. At the interface with the outer crust, where the density is about \( 4.3 \times 10^{11} \text{ g.cm}^{-3} \), the electron fermi energy is about 25 MeV and the nuclei begin to release free neutrons — the neutron drip point. As the density increases inward, the number of free neutrons increases rapidly until, at about \( 2 \times 10^{14} \text{ g.cm}^{-3} \), the nuclei completely dissolve into a neutron sea. As the electron fermi energy at this point is of the order of 100 MeV, the interaction between two neutrons within the inner crust is probably sufficiently attractive for the neutrons to form a superfluid. At densities higher than \( 2 \times 10^{14} \text{ g.cm}^{-3} \), the material is thought to form a uniform sea of electrons, protons, and neutrons. It is called quantum liquid interior. It is expected that in this quantum liquid interior the neutrons will again be superfluid and that the protons will be superconducting. There may be a zone of normal neutrons between the crustal and interior superfluid region, the behaviour of electrons remains normal throughout the star.

The constituents of neutron star at densities well in excess of \( 10^{15} \text{ g.cm}^{-3} \) in the core of the star are uncertain. Electron and neutron fermi energies become so great in such a core that new particles, such as muons, hyperons are created. Calculations suggest that the first heavy particles to appear are the \( \Xi^- \) and \( \Lambda^0 \) hyperons. Canuto and Chitre (1973) have suggested that at this
Fig 1.2.2 A cross section of a 1.33 M⊙ Neutron Star calculated using a moderately stiff equation of state proposed by Bethe and Johnson (1973)
densities the neutrons solidify into a crystalline lattice. But Takemari and Guyer (1975) have shown that no stable solid state can be found. Migdal (1973) has suggested that a solid state involving neutral pion may exist at these densities. The recent works of Takatsuka (1981, 84), Tamagaki (1981), Tatsumi (1983) suggest that in this region an alternating layer structure involving pion condensate is possible.

For better understanding the structure of this core it is needed first to know more details about the role played by core superfluidity. The recent observations of surface temperature, rapid cooling, etc for Crab pulsar and Vela pulsar create argument in favour of pion condensation, but more work will need to know the definite structure of neutron star.

Pines and Alpar (1985) have argued that although a convincing case has been made for crustal neutron superfluidity, there is little observational evidence for core neutron superfluidity, as the calculated rapid coupling of the core superfluid to the crust rules out post glitch behaviour as a way to observe core superfluids.

With average densities in excess of that of nuclear matter ($\rho = 2.8 \times 10^{14} \text{g/cm}^3$), neutron stars are the highest density observable matter. They contain
the lowest temperature superfluid. On the other hand, the neutron superfluid which coexists with a periodic lattice of neutron rich nuclei in the inner crust of the neutron star is the ultimate high temperature superfluid. Moreover, the neutron superfluid in the crust and core of neutron stars are also by far the most abundant superfluids we encounter in the universe. Relatively speaking, we can say neutron stars act as a cosmic physics laboratory where we can study the matter under extreme conditions, superfluidity, superconductivity at high temperature, etc. So, the study of neutron star will light on the internal structure as well as on the various astrophysical behaviours of neutron star.

1.3 PREVIOUS WORKS ON NEUTRON STAR

The dense nucleon matter equation of state (E.O.S.) plays an important role in neutron star structure. In 1939 Oppenheimer and Volkoff gave a detailed treatment of the equilibrium configuration of neutron star. Their assumptions were very clear:

1) Describe the microphysical structure of a neutron star by an equation of state obtained from the quantum mechanical treatment of a degenerate (T = 0) relativistic gas of neutrons fulfilling fermi statistics.

2) Describe the macroscopic structure of a neutron
Fig 1.2.1. Masses of the equilibrium configuration of neutron stars plotted as a function of the central density for selected equation of state (E.O.S.)

Pandharipande E.O.S. based on strong interaction between nucleons

Harrison Wheeler E.O.S. based on free particle approximation

Hagedorn E.O.S. based on thermodynamic approach
star (mass, radius, density distribution) by the use of Einstein equation as applied to a perfect fluid distribution of matter. The two major conclusions were:

a) stable equilibrium configuration of neutron stars can only exist in a finite range of masses and densities

\[ 0.1 \, M_\odot \leq M \leq 0.7 \, M_\odot \]

\[ 1.0 \times 10^{14} \leq \rho \leq 3.6 \times 10^{15} \, \text{g/cm}^3 \]

b) there is a critical value of the mass of a neutron star over which no equilibrium configuration can possibly exist. If the initial mass of a star is large enough unless fission due to rotation, or ejection of mass reduces the star to a mass smaller than this critical value, then, after the exhaustion of thermonuclear sources of energy, the star will gravitationally collapse and contract indefinitely, never reaching true equilibrium.

But much works to calculate equation of state and masses of equilibrium configuration of neutron star from the variational frame work have done. A summary of some of different masses of the equilibrium configuration of neutron star have shown in fig 1.2.1 & 1.2.2.

The Pandharipande (1973) equation of state takes into account the strong interaction between
Fig 1.2.3 Neutron Star Mass (in solar mass units, \( M_\odot = 1.99 \times 10^{33} \text{gm} \)) as a function of central mass density \( \varepsilon_c \) for various models. The TI and Pandharipande hyperon \( \Lambda \) models are also shown. The solid line at 1.55 \( M_\odot \) represents the lower mass limit for X-ray pulsar 4U0900 - 40.
nucleons. The Harrison-wheeler equation of state neglects all the nuclear interactions and uses substantially a 'free particle' approximation. The Hagedorn (1965, 68, 70) equation of state is based on thermodynamic approach derived from the theoretical analysis of high energy collision between elementary particles and applies asymptotically for $\rho \geq 5 \times 10^{15}$ g cm$^{-3}$. Their works showed that neutron stars can still reach stable equilibrium configuration only in a finite range of masses (Ruffini 1975, 1973)

$$0.1 \, M_\odot \leq M \leq 1.45 \, M_\odot$$

Using the average matter density on the boundary surface of a neutron star Rhoades and Puffini (1974) calculated the maximum mass limit 3.2 $M_\odot$. In 1982 Vaidya and Tikekar have increased this maximum mass limit from 3.2 $M_\odot$ to 3.575 $M_\odot$, using the same average mass density.

Recent work of Wiringa, Fiks and Fabrocini (1988), based on Hamiltonians: Argonne V14 and Urbana V14 (i.e. AV14 & UV14) two nucleon potentials, both alone and with the Urbana VII three nucleon potential, and the density dependent Urbana V14 plus three nucleon interaction (TNI) model of Lagaris, Friedman and Pandharipande, argues that the AV14 plus UVII and UV14 plus UVII models both give maximum neutron star masses above 2.1 $M_\odot$ while UV14 plus TNI model gives 1.8 $M_\odot$.

They have calculated the lower limit which is = 1.55 $M_\odot$ [fig 1.2.3]
The phenomena of neutron sources for astrophysical nucleosynthesis had been studied extensively by many physicists. Burbidge et al. (1957) gave a clear picture in this matter. Iben (1975) and Ulrich (1982) suggested that $^{13}\text{C} \left(\alpha, n\right) ^{16}\text{O}$ reaction and $^{22}\text{Ne} \left(\alpha, n\right) ^{25}\text{Mg}$ are the most important neutron sources for the nucleosynthesis. The recent theoretical studies of Bigbang nucleosynthesis, done by Kossionides et al. (1990), suggest that $^{8}\text{Li} \left(\alpha, n\right) ^{11}\text{B}$ reaction is more significant to take into account the possible inhomogeneities in baryon densities arising from the quark hadron phase transition. Based on reaction rate Drotleff et al. (1990) showed that the neutron producing reaction $^{22}\text{Ne} \left(\alpha, n\right) ^{25}\text{Mg}$ has a great contribution in nucleosynthesis.

One of the important parameters of neutron star models for various equation of state is dragging of inertial frames on rotation axis. Bethe, Borner and Sato (1971) first pointed out that near the center of the uniformly rotating neutron star, the inertial frames can rotate with angular velocity $\sim 70\%$ that of the star, dropping to $\sim 30\%$ near the surface (fig 1.2.4). Ruderman (1971) and Müller et al. (1971) made clear that because of the extremely strong magnetic fields near the surface of a neutron star, the gradient of the density becomes much steeper.
Fig 1.2.4 Angular Velocity of inertial frames on Rotation Axis (i.e. Dragging) vs Neutron Star Radius for model based on the Bethe, Borner, Sato (BBS) equation of state.

A = Log Central Density 15.5
B = Log Central Density 15.0
C = Log Central Density 14.7
↓ indicates surface
The present observations on Vela pulsar PSR 0833-45 and Crab pulsar PSR 0531-21 show a sudden increase in frequency (glitch) followed by the usual slowing down. Also, observations on X-ray bursts, Gamma ray bursts, Accretion effect on binary systems, coherent radiation emission showed that neutron star surface magnetic field plays an important role (Radhakrishnan, Manchester 1969, Lohsen 1971, Zeldovich and Shakura 1971, Pines and Alper 1987).

1.4 SCOPE OF PRESENT INVESTIGATION

The studies of Doppler delays of the pulsed radiation for binary radiopulsar PSR 1913 + 16 gives the best determined neutron star mass $1.42 \pm 0.03 \, M_\odot$ (Weisberg and Taylor 1984) whereas observation for 4U0900 - 40 gives the largest minimum mass at $1.85 \pm 0.35 \, M_\odot$

It is also observed that observation data are fit for some very stiff and for some very soft equation of state. The vortex creep theory describes the motion of pinned vortex lines in the crustal superfluid and fits to the observational data provided constraints on the portion of the star that is crust (Pines et al 1987). Periodicity observation in X-ray source Her X-1 argues for a relatively large crust. The density profiles for $1.4 \, M_\odot$ neutron star models using
pure neutrons matter and beta stable matter without muons argue for larger radii, crusts and momenta of inertia for the same gravitational mass (Wiringa et al. 1988).

In pion condensate phenomena two types of pion condensate have been identified: a charged or pionic mode that corresponds to the appearance of physical in the medium, and a neutral or sound mode that corresponds to long range NN correlations with pion quantum numbers. Recently Tatsumi and Moto (1990) have proposed that there exists the spin-isospin branch responsible to pion condensation at the same time. So, the questions of the density, at which condensation takes place; what type of condensation takes place are important. Øvergaard and Østgaard (1991) suggest for hypothetical quark stars and hybrid star i.e. quarks exist in the core of the neutron star.

Thus, the problems of stable mass, soft equation of state, density distribution, pion condensation of neutron star, the problem of the coupling of strong gravity and rapid rotation, the existence of quark stars, possible hybrid stars, the various features introduced by the strong magnetic field of the neutron star seem to be still open questions.
The scope of the present investigation is on the stellar neutron sources, minimum mass of a stable neutron star, and the characteristic surface magnetic field of a rotating neutron star i.e. radiopulsars. It is found that the stability begins in a neutron star when the density variation parameter ($\lambda$) attains the maximum permissible value 0.68 with the corresponding mass $m = 1.5707 \, M_\odot$. It is also found that radiopulsars having almost same age form a group though their period, first and second time derivative of periods are different.
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