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NEUTRON STARS - UNIQUE COMPACT OBJECTS OF THEIR OWN

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ABSTRACT

This paper outlines the study of neutron stars right from the early theoretical predictions and observations by various astrophysicists which gradually aroused huge interests among the scientific community, to the latest developments in the scientific analysis of the behavior of the different categories of compact objects. Although white dwarfs, neutron stars, brown dwarfs, Black Holes etc.fall under the category of compact objects, each of them is unique in its own way.

I. INTRODUCTION

Neutron stars are compact objects containing supra-nuclear 10^{12} density matter in their interiors, comprising a large fraction of neutrons. They possess masses typically of the order of M ~ 1.4 solar masses Radii R ~10km. Hence, their masses come closer to the solar mass which is equivalent to 1.98 x 10^{33} kg and the radii turn out to be 10 times smaller than the radius of the Sun which is nearly 6.96 x 10^8 m.

Neutron stars possess an enormous gravitational energy given by

$$E_{grav} \sim GM^2/r \sim 5 \times 10^{47} \text{ joules} \sim 0.2\, MC^2$$

Surface gravity

$$g \sim GM/R^2 \sim 2 \times 10^{12} \text{ m/sec}^2$$

where G is the Universal gravitational constant and c is the speed of light in free space. This clearly shows that neutron stars are highly dense objects.

The mean linear mass density is around

$\rho = 3M/4\pi R^3$ which is nearly 7 X10^{11} kg/m³ or 2 to 3 times the normal nuclear density, which is the mass density of nucleon matter in heavy nuclei. The internal densities can reach up to 10 to 20 times the normal nuclear density.

II. A BRIEF HISTORY OF NEUTRON STARS

A. *Landau's Anticipation of dense stars*

James Chadwick announced his discovery of the neutron in a paper in NATURE on February 27th , 1932. But Landau had written a paper devoted to dense stars a year before Chadwick 's discovery. Landau was a graduate student of the Leningrad Physico- Technical Institute (now, the Ioffe Physico – Technical Institute, St. Petersburg, Russia). The paper was completed in 1931 in Zurich. Landau had calculated the maximum mass of white dwarfs, a little later than Chandrasekhar (1931) and independently of him. But in the second part of his paper, Landau speculated on a possible existence of stars more compact than white dwarfs. During that period, it was a little difficult to construct nuclei without neutrons from protons and electrons as the uncertainty principle of Heisenberg forbids localizing the electrons within the nuclei. Landau had no other option, but to violate the laws of quantum mechanics. Hence he suggested that " all stars heavier than 1.5 times solar mass certainly possess regions in which the laws of Quantum mechanics are violated". He also made a significant conclusion that in such stars , " The density of matter is so huge that nuclei come into contact resulting in one gigantic nucleus. The paper was submitted to " Physikalische Zeitschrift der sowjetunion" on February 7, 1932 and was published in the February issue of the Journal (landau 1932).

B. The Prediction of Zwicky and Baade

The actual theoretical prediction of neutron stars was made by W. Baade of Mount Wilson Observatory and F. Zwicky of Caltech, who had analyzed the various observations of supernova explosions and proposed an explanations of the release of enormous energy in these explosions. The results were presented at the meeting of the 'American Physical Society 'at Stanford (Dec 15-16 1933) and was Published in the January issue of the Physical Review (Baade and Zwicky, 1934a). They had written "With all reserve, we advance the view that the supernovae represent the transitions from ordinary stars to neutron stars which consist of extremely closely packed neutrons in their final stages."

In the next publication, Baade and Zwicky (1934b) further elaborated that "a neutron star ....may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the gravitational packing energy in a cold neutron star may become very large and under certain circumstances may exceed the ordinary nuclear packing fractions. In the consecutive paper (Baade and Zwicky, 1934c), they had stated the transition process of an ordinary star into a neutron star as follows: "If neutrons are produced on the surface of an ordinary star, they will rain down towards the center, if we assume that the light pressure on neutrons is practically zero".

C. Theoretical progress during the Pre - 2nd world war era

(a) Development of Equation of State : The most crucial ingredient of the theory of neutron stars is the ' Equation of State ' (EOS) of densely packed matter in the interiors of a neutron star. EOS is often referred to the dependence of the pressure p and linear mass density ρ and temperature T of the matter. Since neutron stars are mainly composed of strongly degenerate Fermions (particles like protons, electrons etc..Which obey Fermi- Dirac Statistics), the temperature dependence is mostly negligible and the equation of state is calculated at T=O.

When an ordinary star transforms to a neutron star, the stellar matter undergoes strong compression force, which are further accompanied by the generation of neutrons from the beta captures of atomic nuclei. A preliminary attempt to construct the EOS of nuclear matter in equilibrium was made by Sterne in 1933. He considered the matter composed of electrons, protons, several species of nuclei at T-> 0. He had actually predicted the neutronization of matter with increasing density.

Interest in neutron stars aroused during 1937-38 mainly due to the problem of stellar energy with the source of energy being unknown. Landau (1937) and Gamow (1938) had independently suggested that any normal star could contain a neutron star in its core region. This certainly would have initiated a slow ' accretion ' of stellar matter within the normal star unto its neutron star core, so that the stellar energy would have been supplied by the gravitational energy release in the course of accretion. However Hans Bethe and Critchfield in 1938 proved that the energy of normal stars is provided by thermonuclear reactions.

Now in a paper (1938), Zwicky estimated the maximum binding energy of a neutron star of mass M and obtained as 0.42 Mc^2. One must certainly distinguish between the so called Baryon mass (the sum of baryon masses in the interior of a neutron star) and gravitational mass M obtained from Baryon mass by subtracting the gravitational binding energy. Zwicky (1938) also noticed that on the surface of the star " ....the acceleration of gravity should be indeed high and light coming from this surface must be subjected to huge ***gravitational red shifts (*** of wavelengths). " he later developed the idea of red shifts in a subsequent paper elaborately" (Zwicky 1939).

The next most important step was done by Richard C. Tolman from Caltech and by Robert Oppenheimer and G.M. Volkoff from university of California, Berkeley. Their papers (Tolman 1939; Oppenheimer and Volkoff, 1939) had been received in the Physical Review on January 3rd 1939 and were published in the same February issue. Both the papers contained the mathematical derivation of the equation of Hydro-static equilibrium for a spherically symmetric star in the framework of General relativity. This was the basic equation for building up the different models of neutron stars. It is popularly known as " Tolman - Oppenheimer - Volkoff " equation. The gravitational neutron star energy is a sizeable fraction of its rest mass energy; neutron stars are so compact that Space- Time is curved around and the effects of General Relativity play a significant role.

Tolman (1939) had obtained eight exact solutions of the new equation. They do not correspond to any realistic EOS of the neutron star matter, although they enable one (Oppenheimer & Volkoff, 1939) to understand the existence of a maximum mass of neutron stars. Oppenheimer & Volkoff (1939) used their equation for solving the most important problem. They had numerically calculated various neutron star models for the simplest EOS of stellar matter composed of a non interacting strongly degenerate relativistic gas of neutrons. They had showed that ***stable static neutron stars have the maximum (gravitational) mass,*** which is nearly 0.71 times the mass of Sun, which is popularly known as ***Oppenheimer- Volkoff mass limit.*** They had understood the simplicity of their model of non interacting neutrons and discussed a possible repulsive component of neutron-neutron interaction which might stiffen the EOS and thereby increase the maximum mass. They concluded "It *seems likely that our limit of 0.71 solar masses is near the truth."* their conclusion has turned out to be wrong, although their mass limit is extremely important. Combined with accurate measured masses (1.25 - 1.44) times mass of the sun, of some neutron stars, this limit gives a direct astrophysical evidence of strong repulsive interaction in dense matter at supra-nuclear density.

It is really worth mentioning that Von Neumann and Chandrasekhar had obtained the same General Relativistic equation of hydro-static equilibrium several years before in 1934 to study collapsed stars, but their results were not published (Baym, 1982). This was done at the Trinity College (Cambridge, England) after Chandrasekhar had constructed models of white dwarf stars. More realistic Equations of state could not be worked out during the Pre 2nd world war time, because the properties of strong interactions and nuclear matter were poorly known. The theoretical basis was supplemented by the idea that neutron stars should be born in supernova explosions. With the outbreak of the 2nd world war however, interest in neutron stars gradually faded.

D. Theoretical progress during the Post 2nd world war era

Until the beginning of the 1960s, neutron stars had been treated as the work of imagination of some weird theoreticians. The situation started changing later, with the hope to discover neutron stars in observations. Let us outline four main themes of theoretical studies.

(a) *EOS of Dense matter:* The main field of neutron star theory prior to the discovery was concerned about constructing a model EOS of dense stellar matter. Wheeler and his collaborators in the 1950s contributed significantly. They had constructed a model of the crust of a neutron star and calculated the EOS of neutron star cores composed of free neutrons, protons and electrons in beta equilibrium. It was Cameron (1959) who emphasized the utmost significance of nuclear forces for the structure of neutron stars. He also had shown that the inclusion of nuclear forces can certainly stiffen EOS. This can increase the maximum mass of neutron stars from the Oppenheimer-Volkoff limit of 0.7 solar masses to about 2 solar masses, making the formation of neutron stars in Supernova explosions more realistic. Zeldovich in 1961 used a model of Baryon interaction through a massive vector field and constructed a stiff EOS with the sound speed lower than the speed of light c, and tending to c in the extreme high density limit. Eventually, it was understood that besides neutrons, protons, electrons the cores of neutron stars might contain particles such as muons, mesons, hyperons etc. The First arguments regarding hyperons was put forward by Cameron (1959) and Salpeter (1960); some EOS s of hyperonic matter and associated neutron star models were calculated by several authors like Ambartsumyan & Saakyan (1960) and Tsuruta & Cameron (1966b). Ivanenko & Kurdgelaidze (1965, 1969) considered hypothetical quark cores of neutron stars.

(b) *Super-fluidity of neutron star matter:* Another striking aspect was the theoretical prediction of Super-fluidity in the interiors of neutron stars. This was actually initiated by the BCS theory of Superconductivity of metals (Bardeen, Cooper and Schrieffer -1957). The electron Superconductivity is explained by cooper pairing of electrons under a weak attraction force which is induced by electron - phonon interaction. A Superconducting state appears with decreasing temperature as a result of a second order phase transition; the typical critical temperatures being of the order of (1-10) K. On a microscopic scale, the phenomenon consists in the appearance of an energy gap Δ in the electron energy spectrum near the Fermi level. Migdal (1959) was one of the first persons who applied the BCS theory to atomic nuclei. He had also remarked that neutron Super fluidity could occur in the interiors of neutron stars; he predicted the Super fluid gap $\Delta \sim 1$ MeV and the associated critical temperature $T_c \sim 10^{10}$ Kelvin. Five years later Ginzburg and Kirzhnits (1964) estimated the gap produced by the singlet state pairing of neutrons at the densities of nearly 10^{13} - 10^{15} g/cm^3 and obtained Δ~ (5- 20) MeV. A serious step was also made by Wolf (1966) in this regard. He showed that the singlet state neutron pairing operates at sub nuclear densities in the inner neutron star crust, but disappears in the core, since the singlet state neutron-neutron interaction becomes highly repulsive at supra nuclear densities. The number density of protons in the core is smaller than that of neutrons. Accordingly, the singlet state proton- proton interaction is mostly attractive there and it leads to proton pairing. The possibility of neutron pairing in the core of the neutron star due to the attractive part of the triplet state neutron-neutron interaction was understood quite later.

It is thought that Super fluidity is quite important for explaining pulsar glitches. It also affects the heat capacity and neutrino emission of neutron stars. The effect of neutron Super- fluidity on the neutrino emission was first studied by Wolf (1966).

(c) *Emission of neutrinos from Neutron stars:* Another line of theoretical studies was inspired by the expectations at the beginning of the 1960s to discover neutron stars by detecting the thermal radiation from their surfaces. Born hot in Supernova explosions, neuron stars get cooled down by the thermal emission of photons from stellar surfaces and the emission of neutrinos from their interiors. This certainly makes the neutrino processes quite significant. In this regard, we must mention a paper by Chiu & Salpeter (1964) who had suggested the modified Urca process and estimated the emissivity of neutrinos. It is the leading neutrino process in the cores of not too massive neutron stars. The detailed calculations were performed particularly by Bahcall and Wolf (1965a). They also studied a model of dense matter which contains free Pions. They had also considered the neutrino process which consists of two reactions; neutron beta decay followed by beta capture in the presence of Pions. The neutrino emissivity appeared to be much higher than in the modified Urca process. Similar enhancement in a more realistic model of Pion- Condensed matter was analyzed much later by Maxwell et al. (1977). More references to earlier papers on the neutrino emission from neutron stars can be found in Yakovlev et al. (2001).

(d) *Thermal Evolution of Neutron stars:* The first estimates of the thermal emission from cooling neutron stars were most probably done by Stabler (1960). Four years later Chiu (1964) repeated the estimates and theoretically proved the possibility to discover neutron stars from their thermal emission. Simplified calculations of the neutron star cooling were done by Morton (1964), Chiu & Salpeter (1964) and Bahcall & Wolf (1965a, b). The latter authors emphasized the strong dependence of the cooling rate on neutrino emission processes and pointed out that this dependence can be used to explore the EOS of dense matter by comparing theoretical cooling models with observations of thermal radiation from neutron stars. The foundation of the strict cooling theory was made by Tsuruta & Cameron (1966a). They had formulated the main elements of the cooling theory such as the neutrino and photon cooling stages, the relation between the internal and surface temperatures. More detailed description of the history of the neutron star cooling is given by Yakovlev et al. (1999).

III. THE SEARCH AND THE DISCOVERY

Serious attempts were made to discover neutron stars when the era of practical X - ray astronomy began in the 1960s. It was expected to detect the thermal radiation from the surfaces of cooling neutron stars. A star with the surface temperature of ~ 10^6 K would mainly emit soft X- rays which cannot be detected by ground based facilities.

The first Cosmic X- ray source of non solar origin, Sco X-1 (in the Scorpius constellation), was discovered in rocket experiments by Giacconi et al...(1962). The discovery generated a huge interest in neutron stars but the first attempts had failed to prove the relation between neutron stars and newly discovered compact X-ray sources. Bowyer et al (1964) measured the size of the X ray source in the crab nebula from observations during a lunar occultation on July 7, 1964. Their result indicated that the source was much larger than a neutron star should be. Ironically, the crab nebula turned out to be an exception: there was a neutron star there, the famous Crab Nebula, but it was hidden within a compact plerion pulsar Nebula. The Crab Nebula is actually the archetype of a plerion - a supernova remnant with an active pulsar at its centre, powering the nebula expansion and radiation. At the same time, Kardashev (1964) considered a collapse of a magnetized rotating star into a compact object (collapsar) with the appearance of a surrounding envelope (nebula). He emphasized that the collapsar can gain rapid rotation during its birth and its spin energy can be transferred to the surrounding nebula by the magnetic field. He assumed that this mechanism can power the crab Nebula.

Many scientists proposed various methods of discovering neutron stars (as described by Zeldovich & Novikov 1971, Shapiro & Teukolsky 1983 and Lyne & Graham Smith 1998). For instance, Zeldovich & Guseynov (1966) suggested observing some selected binary stars with optical primary components and invisible secondary components. Pacini (1967) , in a paper published in Nature, showed that a rapidly rotating neutron star with a strong dipole magnetic field could efficiently transform its rotational energy into electromagnetic radiation and subsequently accelerate particles to high energies. He suggested that the rotational energy loss rate is the same as produced by a magnetic dipole rotating in vacuum. Like Kardashev, he anticipated that such a star could obviously power a surrounding nebula, particularly the crab nebula.

It was quite important that Sandage et al. (1966) had identified Sco X-1, the first detected and the brightest X – ray source as an optical object of 13th magnitude. Analyzing those observations, Scklovsky (1967) had concluded that the source "…. Corresponds to a neutron star in a state of accretion …and…..the natural and very efficient supply of gas for such a accretion is a stream of gas, which flows from a secondary component of a close binary system toward the primary component which is a neutron star". Now, we know that Sco X-1 is indeed an X-ray binary system consisting of an accreting neutron star, but Shklovsky's arguments were mostly ignored by the astrophysical community. In 1965 Antony Hewish (Cavendish laboratory, Cambridge, England) started to construct a new radio telescope. Its wavelength was 3.7m; it was an array of 2048 dipole antennae that covered an area of about 18,000 square meters. It was designed to study the scintillations of radio sources while their radiation passes through in homogeneities of solar wind in the interplanetary space. On August 6th, 1967, Jocelyn Bell – a graduate student supervised by Hewish since 1965 discovered a weak variable radio source (Hewish 1975). It was observed at night time, whereas the scintillations of ordinary radio sources are stronger at day time, when a telescope is directed closer to the sun. it took several weeks to understand that the rapidly spinning or pulsating source, ***the pulsar*** was well outside the solar system. The discovery was announced on 24th February 1968 issue of Nature (Hewish et al. ...1968) and produced a sensation. White dwarf stars could not sustain such a rapid rotation; they would be destroyed by centrifugal forces. Hence, pulsars are spinning neutron stars with their magnetic moments inclined to spin axes. Their radio emission is generated outside a star, in the ***magnetosphere***. It is beamed along the magnetic axis. The beamed radiation rotates with the star, and a pulsar is detected if its beam crosses the Earth. The emitted electromagnetic radiation carries away the rotational energy and momentum, producing a slow but regular spinning down of the pulsar which results in the increase of the pulse period.

IV. CONCLUSION

The Neutron stars certainly prove themselves to be unique of their kind generating huge interests in the scientific community with respect to the magnetic fields, pulsations, emission of electromagnetic radiation etc…The internal core processes are still quite complicated and lots of phenomena need to be understood in this regard. Super fluidity plays a key role in understanding the interiors of compact objects.

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