Open Access Library Journal
2020, Volume 7, e6022
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Neutron Star and Its Properties

Fred Wekesa Masinde[1], Abel Mukubwa[2]

[1]Department of Physical Sciences, South Eastern Kenya University, Kitui, Kenya
[2]Department of Science, Technology and Engineering, Kibabii University, Bungoma, Kenya
Email: fmasinde@seku.ac.ke, abelmuwa@gmail.com

How to cite this paper: Masinde, F.W. and Mukubwa, A. (2020) Neutron Star and Its Properties. *Open Access Library Journal*, **7**: e6022.
https://doi.org/10.4236/oalib.1106022

Received: December 23, 2019
Accepted: July 6, 2020
Published: July 9, 2020

Abstract

Neutron stars are created due to the cataclysmic merger of two superdense stellar corpses. It is now evident that neutron-star smash-ups are the source of much of the universe's gold platinum, uranium and other heavy elements. Heavy elements contain large neutron excess and thus, neutron energy pairing will play a very important role in the creation of such heavy element. Using theoretical considerations and the results of experimental observations, some important properties of neutron stars such as radius (R), the speed of sound inside the neutron star (C_s), the surface speed (V_s) and the most stable isotopes in the neutron star have been determined. The calculated values are compared with the values known so far.

Subject Areas

Classical Physics

Keywords

Neutron Star, Radius of Neutron Star, Surface Speed, Speed of Sound in Neutron Star

1. Introduction

For the first time ever, the scientists spotted both gravitational waves and light coming from the same cosmic event that led to cataclysmic merger of two superdense stellar corpses known as neutron stars [1]. This work revealed that some of the observed light was the radioactive glow of heavy elements such as gold, platinum and uranium which were produced when two neutron stars collided. The heaviest elements in the periodic table whose origin was not known until today are made in mergers of neutron stars [2]. Each merger can produce up to ten times the earth's mass of precious metals like gold, platinum and many of the rare elements. It will, however, be impossible to recover such precious metals from the neutron stars. Such heavy elements compose the crust of the neutron star [3]. Proceeding inwards, we can encounter nuclei with ever-increasing number of neutrons but such nuclei will decay easily on earth, but are kept stable in neutron stars due to tremendous pressures.

Neutron stars are the smallest and most dense stars known so far [4]. The radius of the neutron star could be of the order of 10 km, or a little more. They are as close as you can get to the black hole without themselves actually being black holes. The supernova explosions of the massive star combined with gravitational collapse that compresses the core past the white dwarf star density, leads to a density that exists in the atomic nuclei or even higher.

In general neutron stars are composed of neutrons only, with very small percentage of electrons and protons. They are supported against further collapse by neutron degeneracy pressure, a phenomenon described by the Pauli Exclusion Principle. If the size of the neutron star is in excess of 2 - 3 solar masses, it will continue collapsing to form a black hole. The upper limit on the size of the neutron star is 2 - 3 solar masses and in this case, the density of the neutron star becomes very large. A 10 m star will collapse into a black hole.

Neutron stars that can be observed are exceptionally hot and have a surface temperature of around 600,000 K [5] [6]. They are so dense that the normal-sized match-box containing neutron-star material would have a mass of around 3 billion tonnes or 0.5 cubic kilometre chunk of the earth (a cube with edges of about 800 metres) [7]. The magnetic fields of the neutron stars are between 10^8 and 10^{15} times as strong as that of the earth. The gravitational fields at the neutron star's surface are about 2×10^{11} times that of the earth.

When the star core collapses its rotation rate increases due to conservation of angular momentum. Consequently, the newly formed neutron star rotates up to several hundred times the rotation rate of the collapsing star per second. Some neutron stars emit beams of electromagnetic radiations that make them detectable as pulsars. In fact, the discovery of pulsars in 1967 [8] [9] was the first observational suggestion that the neutron stars exist. The radiation from pulsars is thought primarily emitted from the regions near their magnetic poles. if the magnetic poles do not coincide with the rotational axis of the neutron star, the emission beam will sweep the sky and when seen from a distance, and if the observer is somewhere in the path of the beam, it will appear as pulses of radiations coming from a fixed point in a space (the so-called light house effect). The fastest spinning neutron star is known as PSRTJ17482446 ad rotating at the rate of 716 times per second or 43,000 revolutions per minute (about a quarter of the speed of light) [10].

A neutron star has a mass of at least $1.1M_\oplus$ and perhaps up to $3M_\oplus$ ($M_\oplus$ = solar mass) [4]. The maximum observed mass of the neutron stars is about $2.1M_\oplus$. However, in general, compact stars of less than $1.39M_\oplus$ (the Chadrasekhar limit) are white dwarfs, whereas compact stars with a mass between $1.49M_\oplus$ and $3M_\oplus$ should be neutron stars. When the neutron star mass is more than $10M_\oplus$, the stellar remnant will overcome the neutron degeneracy pressure and gravitational collapse will occur to produce a black hole. Recently, gravitational waves from neutron star crash have been detected. It was the cataclysmic merger of two superdense stellar corpses known as neutron stars [1] [11]. This proves the existence of gravitational waves predicted by Albert Einstein in 1916 when he proposed his theory of general relativity.

The temperature of a newly formed star is from around 10^{11} to 10^{12} K. Such a star emits huge number of neutrons that carry away so much energy that the temperature of an isolated neutron star falls to around 10^6 K.

Neutron star densities vary between 3.7×10^{17} kg·m^{-3} and 5.9×10^{17} kg·m^{-3} (which are 2.6×10^{14} and 4.1×10^{14} times the density of the sun). These are closer to the densities of the atomic nuclei that is 3×10^{17} kg·m^{-3}. Nearer the crust of the neutron star, the density is 1×10^9 kg·m^{-3} and it increases with depth until when it is about $(6 - 8) \times 10^{17}$ kg·m^{-3}. Similarly, the pressure increases from 3×10^{33} Pato 6×10^{35} Pa from inner crust to the centre [12].

2. Theoretical Formulations

1) Properties of the Neutron Star

a) *Velocity of sound* (C_s) *of the Neutron Star*

The velocity of sound of a neutron star (C_s) is given by

$$C_s^2 = \frac{Y}{P} \tag{1}$$

b) *Surface Speed* (V_s) *of the Neutron Star*

To start with, we take a look at the spin rate of the neutron star which varies from one point in the neutron star to another. The maximum spin rate of a neutron star is a point at which the surface gravity is equal to the centrifugal force, which yields

$$V_s = \left(\frac{M_n G}{R}\right)^{\frac{1}{2}} \tag{2}$$

c) *Radius of the Neutron Star*

The radius of the neutron star is obtained from the Tolman-Oppenheimer-Volkoff (TOV) equation [1], whose solution leads to

$$R = \frac{2GM_n}{C^2} = 17.69 \times 10^{14}\ \text{m} \tag{4}$$

Some calculations give

$$R = \frac{3GM_n}{C^2} \tag{5}$$

2) Neutron Paring Energy in Neutron Stars

The heaviest elements in the periodic table are made in mergers of neutron stars [2]. The latest event [1] shows that the bulk of the neutron star may be composed of heavy elements such as Gold, platinum and Uranium. It is possible that there could exist some other stable heavy elements as well. To have some idea of the stable existence of heavy elements such as gold, platinum and uranium, we have calculated the neutron pairing energy for the isotopes of these elements, to understand as to which isotopes could be most abundant in the neutron star. As a rule, elements with the largest neutron pairing energy should be the most abundant merger of the stars. As a first step, it may be advisable to calculate the pairing energy of a neutron in the neutron star since the very heavy nuclei will have large neutron excess. The neutron-neutron interactions within the nucleus are strongly attractive. Thus, it can lead to huge attractive force resulting in collapse or merger. The expression for neutron pairing energy has been provided by Masinde (2019) as

$$P_n(A,Z) = B(A+1,Z) - 3B(A,Z) + 3B(A-1,Z) - B(A-2,Z) \tag{6}$$

where A is the mass number and Z is the atomic number.

3. Discussions

The Young's modulus $Y = 5.3\times10^{30}$ and the density P of the neutron star is 5.9×10^{17} kg·m^{-3}. Thus, the velocity of sound in the neutron star, according to Equation (1) becomes

$$C_s \cong \sqrt{\left(\frac{Y}{P}\right)} = 3.0\times10^{6}\,\mathrm{m\cdot s^{-1}}$$

which is very large.

In determining the radius of the neutron star, we take $M_n = 2M_\oplus = 3.978\times10^{33}\,\mathrm{g}$, $G = 6.67\times10^{-8}\,\mathrm{cm^3\cdot g^{-1}\cdot s^{-1}}$. Therefore Equation (4) yields

$$R = \frac{2GM_n}{C^2} = \frac{2\times6.67\times10^{-8}\,\mathrm{cm^3\cdot g^{-1}\cdot s^{-1}}\times3.9782\times10^{33}\,\mathrm{g}}{\left(3.0\times10^{10}\,\mathrm{cm\cdot s^{-1}}\right)^2} = 5.89\,\mathrm{km}$$

while Equation (5) yields

$$R = \frac{3GM_n}{\left(3.0\times10^{7}\,\mathrm{m\cdot s^{-1}}\right)^2} = 8.84\,\mathrm{km}$$

Equation (2) has been used to determine the surface speed of the neutron star. The radius R = 12 km, and thus, the surface velocity for the star becomes,

$$V_s = \left(\frac{2\times6.67\times10^{-8}\,\mathrm{cm^3\cdot g^{-1}\cdot s^{-1}}\times3.9782\times10^{33}\,\mathrm{g}}{12\times10^{3}\,\mathrm{m}}\right)^{\frac{1}{2}}$$

$$V_s = 1.5\times10^{8}\,\mathrm{m\cdot s^{-1}} = 0.5C$$

where C is the velocity of light.

Neutron Paring Energy in Neutron Stars

To calculate the neutron pairing energy, Equation (6) was used. The binding energy value for gold uranium and platinum has been shown in Table 1.

Table 1. Binding energy values for gold, uranium and platinum.

Atomic Number Z	Nucleus	A	N	Binding Energy
79	Au	197	118	−3.709

Continued

78	Pt	190	112	−4.933
78	Pt	192	114	−4.597
78	Pt	194	116	−4.335
78	Pt	195	117	+4.064
78	Pt	196	118	−3.924
79	Au	198	119/120	−3.709
92	U	234	142	−2.632
92	U	235	143	+2.795
92	U	238	146	−2.374

From the table, the most stable isotopes at the core of the neutron star are Au-197, Pt-195 and U-235.

Acknowledgements

We acknowledge Professor K. M. Khanna in the Department of Physics in the University of Eldoret for his professional input in this research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Ligo's Two Detectors Located in Louisiana and Worshington State (2017).

[2] Berger, E. (2017) Harvard Smithsonian Centre for Astrophysics, Cambridge. Massachusetts, USA. https://www.youtube.com/watch?v=rEwrfqoMnvQ

[3] Pons, J.A. (2013) Too Much Pasta for Pulsars to Spindown. *Nature Physics*, **9**, 431-434.

[4] Kiziltau, B. (2011) Reassessing the Fundamentals on the Evolution, Ages and Mass of the Neutron Stars. https://doi.org/10.1063/1.3629483

[5] Ozel, F., Psaltis, D., Narayan, R. and Villarreal, A.S. (2012) On the Mass Distribution and Birth Masses of the Neutron Stars. *The Astrophysical Journal*, **757**, 13. https://doi.org/10.1088/0004-637X/757/1/55

[6] Chamel, N., Haensel, P., *et al.* (2013) On the Maximum Mass of the Neutron Stars. *International Journal of Modern Physics E*, **22**, Article ID: 1330018. https://doi.org/10.1142/S021830131330018X

[7] Mohr, P.J., Newell. D.B. and Taylor, B.N. (2014) CODATA Recommended Values of the Fundamental Physical Constants.

[8] Shkolovsky, I.S. (1967) On the Nature of the Source of X-ray Emission. *Astrophysics Journal*, **148**, L1-L4. https://doi.org/10.1086/180001

[9] Ghosh, P. (2007) Rotation and Accretion Powered Pulsars. World Scientific, Singapore. https://doi.org/10.1142/4806

[10] Astro-Ph/0601337. A Radio Pulsar Spinning at 716 Hz.

[11] Nadia, D. (2017) In a First Gravitational Waves Linked to Neutron Star.

[12] Niven, C.L. (2017) Neutron Star.