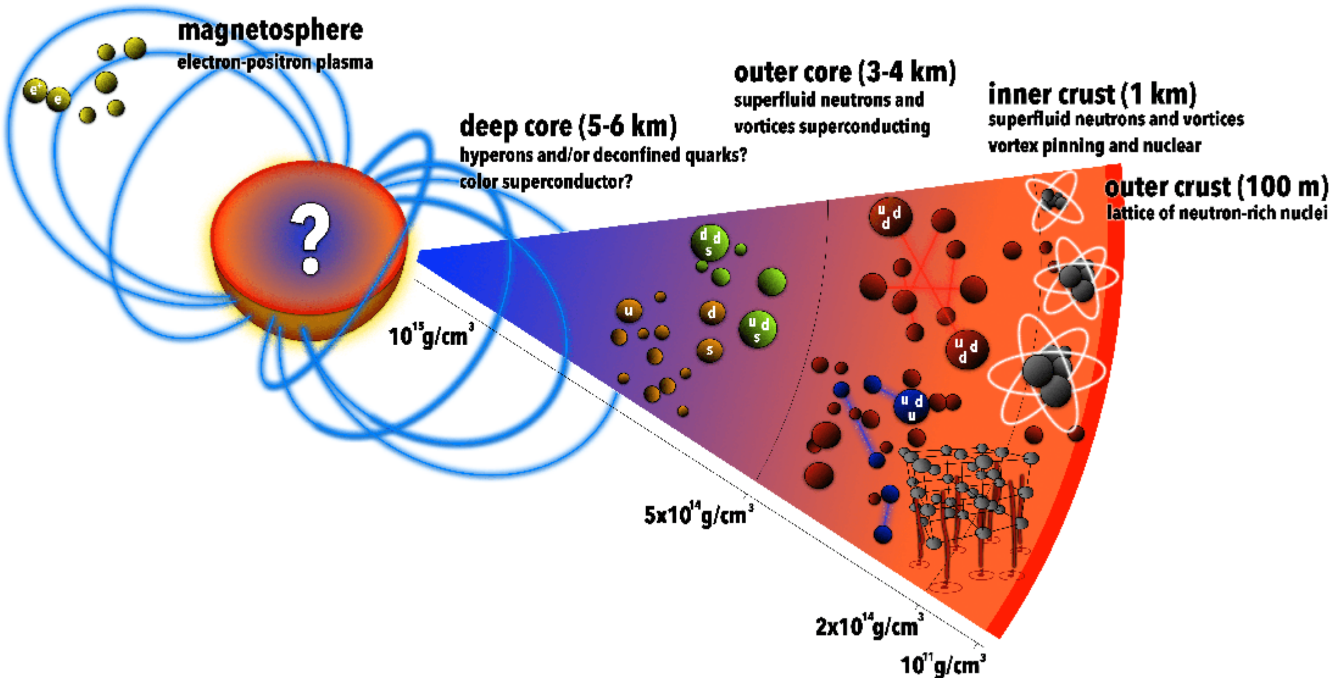
Astronomy & Astrophysics : An Introductory Survey

A lecture series by Prof. G. Srinivasan

A 'Golden Jubilee Celebration' Event of the Astronomical Society of India

Lecture 20 : Journey to the centre of a Neutron Star



[Figure : Watts, A. et al, 2015, arXiv:1501.00042]

A neutron star is like a gigantic atomic nucleus in the sky, weighing more than our Sun, but only ten kilometres in size; it is perhaps the most exotic celestial body we know of. In this lecture, Prof. Srinivasan takes us on a journey to the centre of a neutron star to explore its interior. Exotic nuclei, not found on earth, are encountered there as well as exotic phases of matter such as nucleonic superconductors and superfluids. The story does not end there because there could even be nuggets of quarks and gluons right near the centre of a neutron star.

It must be noted that this is an exceptionally opportune time for astrophysics when a number of next-generation mega-instruments are poised to observe the Universe across the entire electromagnetic spectrum with unprecedented data quality. In particular, the Square Kilometre Array (SKA) is expected to discover tens of thousands of new neutron stars likely heralding an entirely new era of neutron star research. India has a sizeable community of scientists working on different aspects of neutron star physics with immediate access to both the GMRT (Giant Meterwave Radio Telescope, an SKA pathfinder) and the recently launched X-ray observatory Astrosat.

There is no better to tell us about these very special objects other than Prof. Srinivasan, who has not only been instrumental in establishing the first neutron star research group in India (at Raman Research Institute, Bangalore) but has also played an important role in setting up GMRT as an international open-access facility.

16 September 2022

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2. S. D. Kawaler, I. Novikov, G. Srinivasan, 1997, ***Stellar Remnants (Chapter 2)***, Springer
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5. L. Rezzolla et al, 2018, ***The Physics and Astrophysics of Neutron Stars***, Springer

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2. A. J. Legget, 2006, ***Quantum Liquids: Bose Condensation and Cooper Pairing in Condensed-Matter Systems***, Oxford University Press
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2. A. Akmal, V. R. Pandharipande & D. G. Ravenhall, 1998, ***Equation of state of nucleon matter and neutron star structure***, Phys. Rev. C, 58, 1804
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4. D. Bhattacharya, K. S. Dwarakanath & S. Konar Eds., 2017, ***Physics of Neutron Stars and Related Objects***, Journal of Astrophysics & Astronomy, 38 (3), Indian Academy of Sciences
[Festschrift for Prof. G. Srinivasan - collection of articles reviewing the current status of neutron star research.]
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16 September 2022

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Suggested Problems

1. From the current spin-period, the period derivative and the age of a neutron star, the spin-period at birth can be estimated. Assuming the magnetic field to be constant, find an expression for the spin-period at birth (P_0) of a neutron star. Take any five pulsars from the ATNF Pulsar Catalog and find the P_0 for each of them.

2. Old, isolated neutron stars may have surface temperatures of 10^6 K. Why is it reasonable to treat the electron gas as degenerate, i.e., effectively at zero temperature (and hence in its ground state)?

   Also, this temperature is much higher than the boiling temperature of solid (atomic) iron (2500° C). Would iron atoms be partially or totally ionised at the surface? If it indeed gets completely ionised would it lead to greater compaction? By how much?

3. Neutron star crusts are supported against gravity by relativistic, degenerate electrons stripped from iron nuclei (A=56, Z=26). These free electrons constitute a fluid with zero shear modulus but finite bulk modulus. Find the bulk modulus K of the crust in terms of n_e and fundamental constants.

   The bare iron nuclei are not relativistic. They arrange themselves into a bcc lattice. This lattice can support shear. Estimate the shear modulus μ of the crust in terms of n_e, Z and fundamental constants.

4. Newton studied the equatorial bulge of a homogeneous fluid body of mass M that is rotating with angular velocity Ω. He showed that the equatorial radius R_e exceeds the polar radius R_p by an amount given by

$$\frac{R_e - R_p}{Rm} = \frac{5\Omega^2 R_m^3}{4GM} \tag{1}$$

   where $R_m = (R_e + R_p)/2$. Use this formula to estimate $R_e - R_p$ for a neutron star with M = 1.4M$_\odot$, R_m = 10 km, and a rotation period equal to twice the minimum period obtained in the previous problem.

   According to the dipolar model, a pulsar slows down because the energy of emission comes at the expense of its rotational energy. As it slows down the appropriate equatorial bulge must also change. But, being a solid, the crust does not automatically adjust to the 'correct' bulge as it slows down. Instead, the crust cracks and readjusts itself only when the stresses developed (because of the 'incorrectness' of the bulge) exceeds the shear stress. If a neutron star (having the above mentioned mass and radius) is born with $P_{\rm min}$, what would be the maximum spin-period it can slow down to before the crust must crack?

5. Show that the relation $n_e : n_p : n_n = 1 : 1 : 8$ in the limit of very large densities is a trivial consequence of charge neutrality, β-equilibrium, and extreme relativistic degeneracy (n_e, n_p, n_n - number densities of electrons, protons, neutrons).

6. Compute the maximum momentum of an electron emitted in the following reaction

$$n \rightarrow p + e + \bar{\nu}\,. \tag{2}$$

   Find the density above which p_F^e would always be greater than the maximum momentun calculated above. Convince yourself that as a consequence neutrons are stable against this mode of decay in the interior of neutron stars.