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The EOSs and the Blatant Discrepancy in Modelling Massive Neutron Stars: Origin and a Possible Solution Method

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Abstract

Exploring the state of ultra-cold supranuclear dense matter that makes up the cores of massive neutron stars is one of the greatest unresolved problems in modern physics. In this letter, we show that when the interiors of pulsars are made of compressible and dissipative normal matter, the commonly used solution procedures combined with the known EOSs yield widely scattered solutions and poorly determined radii. A remarkable agreement emerges, however, if pulsars harbour cores that are made of incompressible entropy-free superfluids (SuSu-matter) embedded in flat spacetimes. Such supranuclear dense matter should condensate to form false vacua as predicated by non-perterbative QCD vacuum. The solutions here are found to be physically consistent and mathematically elegant, irrespective of the object's mass. Based thereon, we conclude that the true masses of massive NSs may differ significantly from those revealed by direct observation.

Keywords

General Relativity, Pulsars, Neutron Stars, EOSs, QCD, Incompressibility, Superfluidity, Super-Conductivity

1. Cores of Massive Neutron Stars

Currently, there are dozens of nuclear EOSs that are used for numerically modelling the internal structures of ultra-compact objects[1] (UCDs) of moderate masses (see [1], and the references therein). Based on numerical calculation, the central densities, ρ_c, of UCOs with masses beyond $1.15M_{\odot}$ are generally higher than the saturation value ρ_0, whereas for $M_{UCB} \geq 2.1M_{\odot}$, most EOSs

[1]UCOs consist of pulsars, magnetars and neutron stars (NSs).

fail to provide physically consistent repulsive forces, which is interpreted as if the object collapses into a stellar black hole [2] [3].

Recently, it was proposed that pulsars should be born with embryonic cores made up of incompressible superfluids (SuSu-matter) and embedded in flat spacetimes [4] [5] [6]. The transitions between these flat and the surrounding curved spacetimes embedding normal matter are discontinuous, which renders the cores spatially and temporarily disconnected from the outside observers. Hence, the masses of UCOs revealed by observations are due to normal matter only, which solely dictates the topologies of the embedding spacetimes. However, the hidden SuSu-matter in the cores, or the tapped matter making up the false vacua at their centres, remains undetected. Also, due to incompressibility of SuSu-matter in the cores of glitching pulsars, the cores are set to abruptly grow during glitch-event, in accord with Onsager-Feynman analysis of superfluidity (see Eq. 3 in [5]). As UCOs cool down on cosmic times, the density of normal matter in the boundary layers (BLs) between SuSu-cores and overlaying shells of normal matter would surpass the maximum compressibility limit: $\rho_{cr} \approx 3\rho_0$ (see [7], and the references therein). When the other relevant conditions are met, the BLs and the cores merge to form larger and more massive cores.

2. Numerical Results

The study here is based on solving the TOV equation from outside-to-inside, using a large sample of verified EOSs. Unlike the standard solution procedure, where the central density and outer radius are unknown, here both the inner and our radii of the shell containing normal matter are sought. Hence, for a given M_{UCO} and an EOS, the TOV equation is then integrated inwards starting from an initial outer radius, until the critical density, ρ_{cr} is reached, which determines the inner radius of the shell, or equivalently, the radius of the SuSu-core, r_{core}. The central region, $[0 \le r \le r_{core}]$ is filled then with incompressible SuSu-matter and the embedding spacetime is taken to be flat [1].

It turns out that even for mid-mass pulsars, such as the Crab, the EOSs display widely scattered solutions (**Figure 1**). A possible measure for the discrepancy-range, is to introduce the following function:

$$\sigma_{dis} = \frac{\Delta R}{\langle R \rangle}, \quad \text{where } \Delta R = [R_{\max} - R_{\min}], \ \langle R \rangle = \frac{\sum_1^N R_i}{N}, \tag{1}$$

and where $R_{\max,\min}$ are the maximum and minimum radii predicated by the sample of EOS. Our calculations show that σ_{dis} stem its values mainly from the supranuclear density regime, where uncertainties in the EOSs peak and propagate outwardly through the integration procedure, hence rendering the determination of the true radius $r(P=0)$ impossible. These uncertainties don't appear to reasonably correlate with increasing the masses of UCOs as can be verified from (**Figure 1**). Here the procedure was employed to several well-studied pulsars, such as the Crab, Vela, the magnetar PSR J0740+6620 [8], and we even extended it, to include remnant-NS that formed during NS-merger in GW170817 (see [6] [9] [10], and the references therein) and to a hypothetical massive NS (SMNS) consisting of $M_{NM} = 5M_{\odot}$ of normal matter.

It turns out that this solution strategy yields much more elegant mathematical solutions compared to the classical ones: the scattering around most probable radii is significantly reduced, and the correlation between σ_{dis} and mass follows a reasonable track (see **Figure 2** and **Figure 3**). By mathematical elegancy here, we mean that the solutions are simple, reasonable and inherent a certain form of uniformity behaviour.

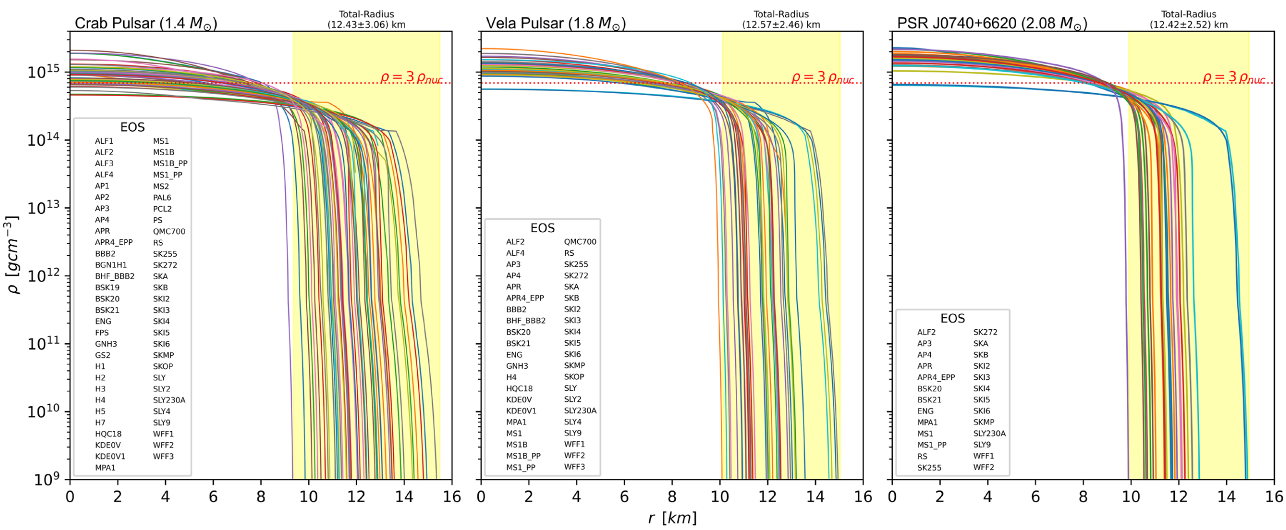

Figure 1. The density of normal matter versus radii for the three pulsars: Crab, Vela and PSR J0740+6620, using a large variety of EOSs. The matter making up the cores is taken to normal, *i.e.* compressible and dissipative matter. Here, the blatant discrepancies in predicting both the central densities and radii are significant and amount to almost 50% of the corresponding radii.

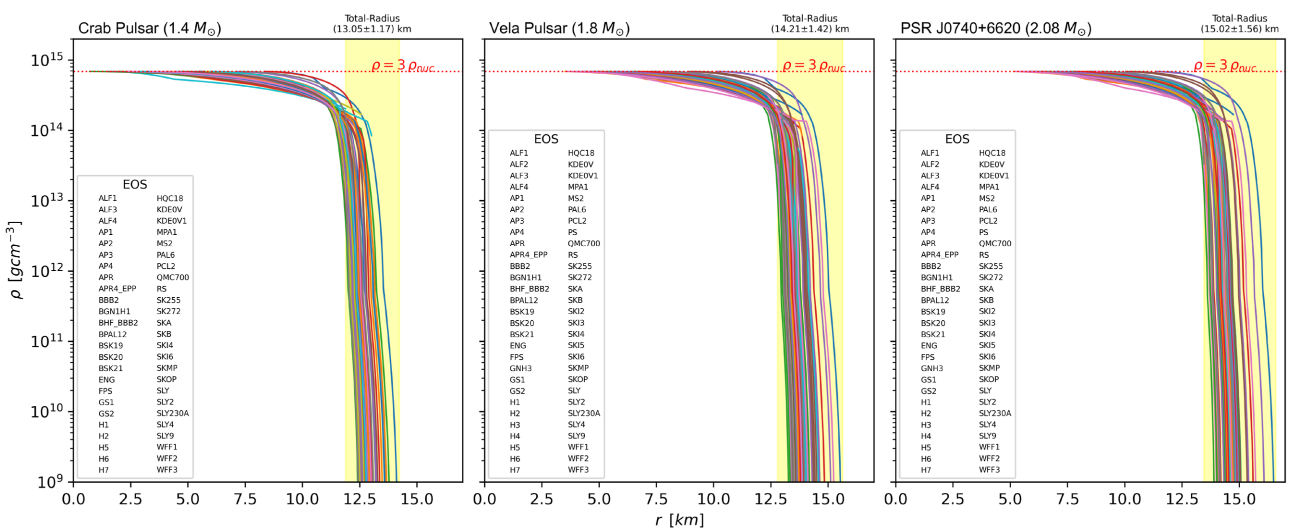

Figure 2. Similar to the previous figure, the density of normal matter versus radii for the three pulsars are plotted, using a large variety of EOSs. The objects here are set to harbour cores, in which their matter contents are trapped in false vacuums. The strong discrepancies shown in the previous Figure are now remarkably reduced, *i.e.* by almost 50%, therefore enhancing the prediction power significantly.

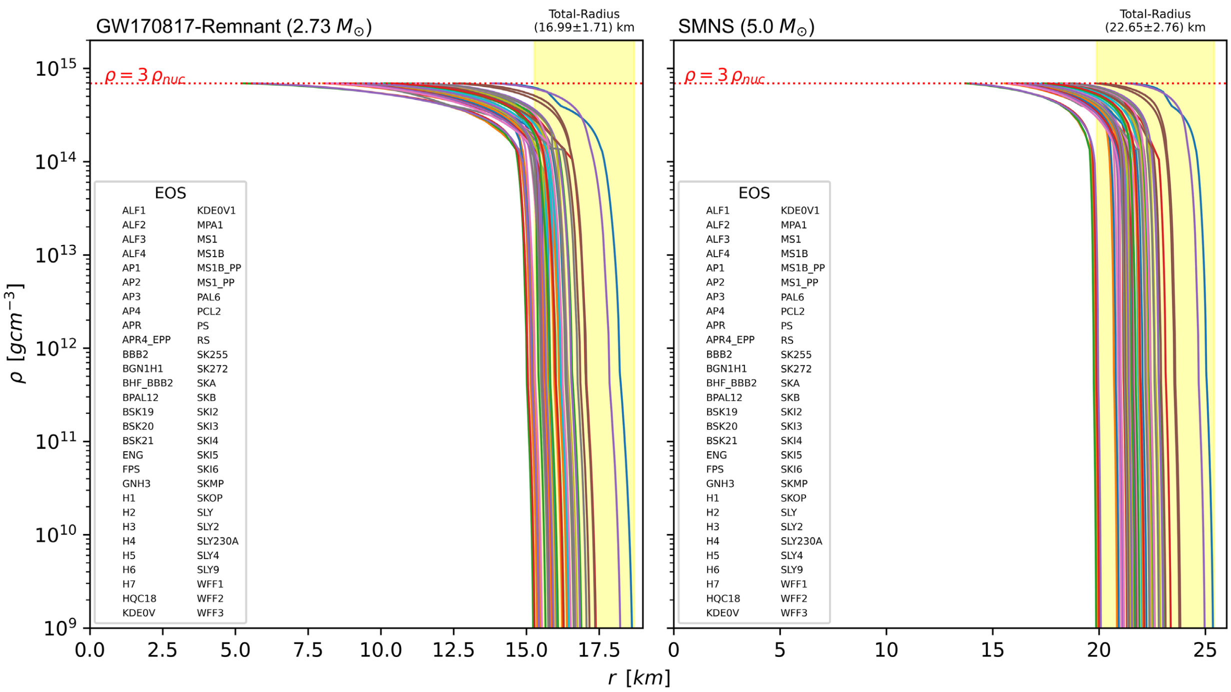

Figure 3. Similar to the previous figure, we show the internal structures of both the massive NS formed through the NS-merger in GW170817 and of hypothetical NS, whose normal matter content amounts to $5M_\odot$. Both objects are set to harbor SuSu-cores, whose mass-contents are trapped in false vacua and, therefore, cannot be communicated to the outside world.

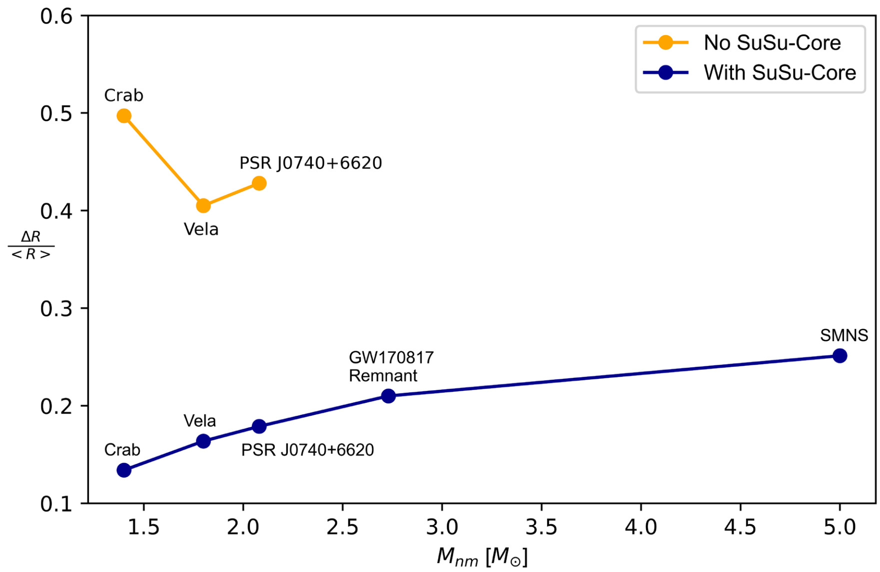

Figure 4. σ_{dis} versus masses of several UCOs, such as the Crab, Vela, PSR PJ0740+6620, with and without SuSu-cores. In the latter case (yellow connected-points) σ_{dis} attains much higher values than in the former case (blue-color connected points). The correlation is extended to include the remnant NS in GW170817 and a hypothetically massive NS of $5M_\odot$ normal matter.

3. Summary

The scenario presented here allows us to model the internal structures of UCOs that are much more massive than PSR J0740+6620. In **Figure 3**, we show the internal structure of the remnant of neutron star merger in GW170817 as well as of a hypothetically supermassive massive NSs, whose normal mass amounts to $M_{SMNS} = 5M_{\odot}$. Based on our calculations, the respective SuSu-cores of the Crab, Vela, PSR J0740+6620, the remnant of GW179817 and of a hypothetical SMNS read: $[0.15, 0.55, 0.66, 1.63, 7, 53]M_{\odot}$. This implies that the true masses should be modified to include the hidden matter in the cores, or equivalently, the trapped matter in the false vacua, so to yield $[1.55, 2.35, 2.81, 4.36, 12.53]M_{\odot}$, respectively.

In **Figure 4**, we show the relative discrepancy $\Delta R / \langle R \rangle$ versus mass of UCOs, using a variety of EOSs. Here two trends can be identified: UCOs without SuSu-cores yield $\Delta R / \langle R \rangle$ that does not correlate with mass in a physically reasonable manner, whereas UCOs harbouring SuSu-cores appear to correlate nicely and reasonably with normal masses of UCOs. Moreover, the uncertainty in the former case is roughly three to four times larger compared to the latter case.

Moreover, the correlation in the latter case is not only consistent with the cosmic evolution of UCOs, but it displays a certain form of mathematical elegancy.

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Conflicts of Interest

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

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