Sensitivity of radius of massive neutron stars to their exotic cores

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Introduction

The constituents of neutron star (NS), especially at its core remain as an intriguing subject for several decades. Precise measurement of neutron star masses and radius is of importance for better understanding of matter at high density. The recent high precision observation of the pulsar J1614-2230 with mass (1.97 ± 0.04) solar mass $(M_{\odot})$ was reported with a suggestion that many nuclear models which consider exotic particles in the core could be ruled out. However, many recent calculations could explain this star with various exotic particles, rendering the precise mass measurements insufficient to conclude on exotic cores. We examine the sensitivity of the radius of a $2M_{\odot}$ neutron star to the details of its core.

E-RMF results with antikaons

We have chosen few representations of E-RMF model, which signify as extrema with and without antikaons $(K^-, \bar{K}^0)$, that can yield $2M_{\odot}$ as the maximum mass of NS. The model Lagrangian and details of calculation are explicitly explained elsewhere[1, 2]. Using the Lagrangian density, we obtain the energy density and pressure (EoS) with or without antikaons. Once the EoS is defined, we use the Tolman-Oppenheimer-Volkoff equations to get the mass-radius relation of a NS.

The mass-radius relation, thus obtained, using the parameters NL3[3], G1, G2[1], and FSU2.1[4] are shown in Fig. 1. Among these chosen parameters, G2 yields the softest EoS and represents one extremum where exotic particles cannot be accommodated. The other extremum should correspond to an EoS with reasonably extreme value of U_K, yielding a $2M_{\odot}$ NS. NL3 represents this extremum and its EoS is the stiffest among the chosen parameters. The other parameters G1 and FSU2.1 fall in between the extrema and have similar EoS but significantly different symmetry energy contribution.

From Fig. 1, one can observe a general trend that the radius (R) corresponding to maximum mass is lower for a softer EoS. However, this scenario can change in the presence of antikaons. These results suggest that a $2M_{\odot}$ NS can be explained with different quantity of antikaons and the radius corresponding to $2M_{\odot}$ NS, is different with different parameter sets. In our calculations exotic core is restricted to antikaons, but these calculations should be extended to include hyperons and quarks. In Table I, along with the summary of E-RMF results, we have summarized the compilation of radii calculated with different models and compositions as quoted in recent literature for a NS with mass (1.97 ± 0.04) $M_{\odot}$. With these results, the scenario is completely different that NS with exotic cores can have lower radii than that of those without exotic cores. In other words we can say for $R \lesssim 11$ km, exotic cores must be present.

Results from parabolic EoS

To strengthen our claim, we look more into the systematics, beyond relying on few theoretical results available till date. For this purpose we construct a fiducial EoS comprising two parabolas, one at the lower energy density representing the nucleonic matter and other representing exotic matter which can occur at higher densities. With EoS from one parabola and two parabolas, we calculate the radius for a NS with mass $(1.97 \pm 0.04)M_{\odot}$. With one parabola, the resulting radius is almost a linear function of slope of the parabola. While

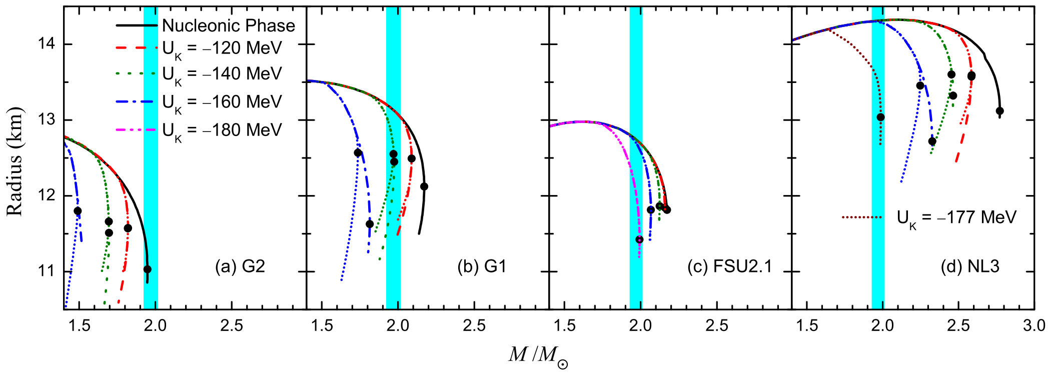

FIG. 1: The mass-radius relation from RMF models. For each parameter set, solid black line represents nucleonic (non-kaonic) phase, lines with different patterns and colors represent the phase with K^- and the corresponding small dotted lines represent the phase with both antikaons ($K^-, \bar{K}^0$). The different patterns and colors represent the strength of the kaon optical potential U_K ($|U_K|$ quantifies the influence of kaons). The solid circles represent the maximum mass in every case. Mass is given in units of solar mass ($M_\odot$). The shaded region correspond to the recent observation of $(1.97 \pm 0.04)M_\odot$ neutron star.

Model	Radius (km)	
	Without exotic core	With exotic core
RMF (Fig. 1)	11.03	$11.43 \leq R \leq 13.04$
Parabolic EoS	$10.87 \leq R \leq 11.27$	$9.79 \leq R \leq 13.22$
From literature	$11.0 \leq R \leq 11.2$	$10.6 \leq R \leq 13.2$

TABLE I: Radius of a neutron star of mass $(1.97 \pm 0.04)M_\odot$ at their maximum mass configuration, obtained from different models.

considering two parabolas, the variation in onset and slope of second parabola leads to a change in radius up to ~ 2.5 km. A complete range for all allowed values of slopes and onsets are given in Table I, where we summarize all of our results.

Our fiducial model suggests that without exotic core, we have a narrow allowed range of radius. If the radius of such massive star is observed beyond this range, then an exotic core must be present. From Table I we clearly see that the radius given by our fiducial model comprise the ranges obtained from our RMF calculations and other recent results. Hence safer conclusions could be drawn from these broader ranges of radius.

For a static neutron star of mass $(1.97 \pm 0.04)M_\odot$, at its maximum mass configuration, we conclude that a pure nucleonic star can have only a narrow range of radius (10.87 km $\lesssim R \lesssim$ 11.27 km) and the presence of exotic cores widen this range. Beyond the above-mentioned range, exotic cores must be present. However, the observed $2M_\odot$ NS need not be at its maximum mass configuration. If more massive stars are observed, our conclusions could change.

References

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