Impact of PREX-II and Combined Radio/NICER/XMM-Newton’s Mass–radius Measurement of PSR J0740+6620 on the Dense-matter Equation of State

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Abstract

In this paper, we discuss the impact of the following laboratory experiments and astrophysical observation of neutron stars (NSs) on their equation of state (EoS): (a) the new measurement of neutron skin thickness of $^{208}\text{Pb}$, $R_{\text{skin}}^{208} = 0.29 \pm 0.07$ fm by the PREX-II experiment; (b) the mass measurement of PSR J0740+6620 has been slightly revised down by including additional $\sim1.5$ yr of pulsar timing data. As well as the radius measurement of PSR J0740+6620 by joint NICER/XMM-Newton collaboration, which has a similar size to PSR J0030+0451. We combine this information using Bayesian statistics along with the previous LIGO/Virgo and NICER observations of NS using a hybrid nuclear+piecewise-polytrope EoS parameterization. Our findings are as follows. (a). Adding PREX-II result yields the value of empirical parameter $L = 69^{+21}_{-19}$ MeV, $R_{\text{kin}}^{208} = 0.20^{+0.05}_{-0.05}$ fm, and radius of a $1.4 \ M_\odot$, $(R_{1.4}) = 12.75^{+0.42}_{-0.54}$ km at 1$\sigma$ confidence interval. We find these inferred values are mostly dominated by the combined astrophysical observations as the measurement uncertainty in $R_{\text{kin}}^{208}$ by PREX-II is much broader. Also, a better measurement of $R_{\text{kin}}^{208}$ might have a small effect on the radius of low-mass NSs but, for the high masses, there will be almost no effect. (b) After adding the revised mass and radius measurement of PSR J0740+6620, we find the inferred radii of NSs are slightly pushed toward the larger values and the uncertainty on the radius of a 2.08 $M_\odot$ NS is moderately improved.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Gravitational wave astronomy (675); Nuclear astrophysics (1129); Pulsars (1306)

1. Introduction

Throughout the last few decades, understanding dense-matter equations of state (EoS) has been one of the most key challenges to multiple physics and astrophysics communities. Observation of macroscopic properties of a neutron star (NS) such as mass, radius, tidal deformability, and moment of inertia could provide us fascinating information about the dense-matter EoS. Thanks to the LIGO/Virgo collaboration (Aasi et al. 2015; Aceernese et al. 2015), we have now entered into a multi-messenger era, in which we have already observed gravitational wave (GW) signals from multiple likely binary neutron star merger systems (Abbott et al. 2017, 2018, 2020). In 2019, NICER collaboration (Gendreau et al. 2016) for the first time reported a very accurate measurement of mass and radius of PSR J0030+0451 (Miller et al. 2019; Riley et al. 2019) by observing X-ray emission from several hot spots of the NS surface. Additionally, very accurate mass measurement of an NS by radio observations, particularly the heaviest one (Cromartie et al. 2019), also helps us to constrain the high-density EoS. In a recent work (Biswas et al. 2021) (also see other works (Dietrich et al. 2020; Jiang et al. 2020; Landry et al. 2020; Raaijmakers et al. 2020; Traversi et al. 2020; Al-Mamun et al. 2021) using different EoS parameterization), using Bayesian statistics we have already combined the aforementioned observations based on a hybrid nuclear + piecewise-polytrope (PP) EoS parameterization and placed a stringent constraint on the NS EoS. This hybrid parameterization is constructed by combining two widely used EoS models: near the saturation density ($\rho_0$) nuclear empirical parameterization (Piekariewicz & Centelles 2009; Margueron et al. 2018) is used based on a parabolic expansion of energy per nucleon and, at higher densities, a nuclear-physics-agnostic PP parameterization (Read et al. 2009), as the high-density EoS could not be probed by the current nuclear physics understanding. This hybrid parameterization is also used recently to investigate the nature of the “mass-gap” object in GW190814 (Biswas et al. 2020).

In recent times, laboratory experiments such as PREX-II have shown promise to put further constraint (Reed et al. 2021; Essick et al. 2021b) on the NS EoS. They have reported (Adhikari et al. 2021) the value of neutron skin thickness of $^{208}\text{Pb}$ to be, $R_{\text{skin}}^{208} = 0.29 \pm 0.07$ fm (mean and 1$\sigma$ standard deviation). Such a measurement can give us crucial information about the nuclear EoS around the saturation density. In particular, our hybrid nuclear+PP model directly allows us to include the result obtained from the PREX-II experiment as the empirical parameter like $L$ shows a strong correlation with $R_{\text{skin}}^{208}$ (Viñas et al. 2014; Reinhard & Nazarewicz 2016). The aim of this paper is to improve our knowledge of dense-matter EoS using hierarchical Bayesian statistics by including this newly obtained result from PREX-II experiments (combining with other aforementioned observations) under the hybrid nuclear +PP EoS parameterization.

Finally, this is to note that very recently the mass measurement of PSR J0740+6620 has been revised down by including an additional $\sim1.5$ yr of pulsar timing data (Fonseca et al. 2021). Interestingly, NICER collaboration has also been taking data of this object using X-ray pulse profile modeling and they are able to measure the radius of this object as well. Additionally, to improve the total flux measurement of the star, they also include X-ray multi mirror (XMM)-Newton telescope (Strüder et al. 2001; Turner et al. 2001) data, which have a far smaller rate of background counts than NICER. Two independent analyses using this joint NICER/XMM-Newton data have estimated the radius to be $12.39^{+1.30}_{-1.03} \text{ km}$ (Riley et al. 2021) and $13.71^{+2.61}_{-1.80} \text{ km}$ (Miller et al. 2021). In this paper, we use the mass–radius estimate of PSR J0740+6620 from both (Riley
et al. 2021) and Miller et al. (2021), and study its impact on the dense-matter EoS.

2. Hybrid Nuclear+PP EoS Inference Methodology

Hybrid nuclear+PP is an EoS model which connects a nuclear-physics-informed EoS parameterization in the vicinity of $\rho_0$ with a high-density nuclear-physics-agnostic PP EoS parameterization. Since the crust has a very minimal impact on NS macroscopic properties (Biswas et al. 2019; Gamba et al. 2020), standard BPS EoS (Baym et al. 1971) is used in this model for the low-density regime and joined with the core EoS in a thermodynamically consistent fashion (Xie & Li 2019). EoS around $\rho_0$ is well described via parabolic expansion of energy per nucleon and can be divided into two parts:

$$e(\rho, \delta) \approx e_0(\rho) + e_{\text{sym}}(\rho)\delta^2,$$

the term $e_0(\rho)$ corresponds to the energy of symmetric nuclear matter for which the number of neutrons is equal to the number of protons, $e_{\text{sym}}(\rho)$ is the energy of the asymmetric nuclear matter or widely named as symmetry energy, and $\delta = (\rho_n - \rho_p)/\rho$ is known as symmetry parameter where $\rho_n$, $\rho_p$ and $\rho$ are, respectively, the number density of neutrons, protons, and the total number density. Around $\rho_0$, these two energies can be further expanded in a Taylor series:

$$e_0(\rho) = e_0(\rho_0) + \frac{K_0}{2}\chi^2 + \ldots,$$

$$e_{\text{sym}}(\rho) = e_{\text{sym}}(\rho_0) + L\chi + \frac{K_{\text{sym}}}{2}\chi^2 + \ldots,$$

where $\chi \equiv (\rho - \rho_0)/3\rho_0$ quantifies deviation from saturation density which must be always much smaller than unity. In this work, we truncate the Taylor expansion up to the second-order in $\chi$. As the lowest-order parameters are experimentally well determined, we fix them in this analysis, such as $e_0(\rho_0) = -15.9\text{ MeV}$, and $\rho_0 = 0.16\text{ fm}^{-3}$. The symmetry energy at $\rho_0$, curvature ($K_0$) of symmetric matter, slope ($L$), and the curvature ($K_{\text{sym}}$) of symmetry energy are the four free parameters in the model. Above 1.25$\rho_0$ density, the nuclear empirical parameterization is no longer taken to be reliable (for details, see Biswas et al. 2021) and joined with three-segment PP EoS parameterization ($\Gamma_1$, $\Gamma_2$, and $\Gamma_3$ be the three polytropic indices). The prior ranges for all the free parameters in this hybrid nuclear+PP model are shown in Table 1. One notable difference from Biswas et al. (2021) is now we have taken a broader prior for the high-density parameters to avoid a situation where priors could work against the posteriors. However, the priors for the nuclear-physics-informed parameters such as $K_0$, $e_{\text{sym}}$, and $L$ remains to be same as the previous work.

Then the posterior of the EoS parameters (denoted as $\theta$) are computed through nested sampling algorithm implemented in Pymultinest (Buchner et al. 2014):

$$P(\theta|d) \propto P(\theta) P(d|\theta),$$

where $d = (d_1, d_2, \ldots)$ is the set of data from different types of experiments and observations, $P(d|\theta)$ are corresponding likelihood distribution, and $P(\theta)$ are the priors on the EoS parameters $\theta$. For astrophysical observations, likelihood distributions are modeled in the following fashion: (a) Old mass measurement of PSR J0740+6620 (Cromartie et al. 2019) is modeled with a Gaussian likelihood of $2.14M_\odot$ mean and $0.1M_\odot$ $1\sigma$ standard deviation; (b) mass and tidal deformability measurement from GW170817 (Abbott et al. 2017) and GW190425 (Abbott et al. 2020) are modeled with Gaussian kernel density estimator (KDE); (c) similarly, mass and radius measurement of of PSR J0030+0451 (Miller et al. 2019; Riley et al. 2019) and PSR J0740+6620 (Miller et al. 2021; Riley et al. 2021) are also modeled with Gaussian KDE. For the PREX-II experiment, the likelihood function is taken to be a Gaussian distribution of skin thickness with $0.29 \pm 0.07$ fm (mean and $1\sigma$ standard deviation). Similar to Essick et al. (2021b) for the likelihood computation of PREX-II, we use the following universal relation obtained from Viñas et al. (2014) between $r_{\text{skin}}$ and empirical parameter $L$:

$$L(r_{\text{skin}}) = 0.101 + 0.00147 \times L(\text{MeV}).$$

3. Results

In the left panel of Figure 1, the posterior distribution of the empirical parameters $L$ and $K_{\text{sym}}$ and their correlation with $R_{1.4}$ are shown after combining astrophysical observations (old mass measurement of PSR J0740+6620, GWs, and PSR J0030+0451) and PREX-II experiment results. In the marginalized one-dimensional plot corresponding prior, median, and 1σ confidence intervals (CIs) are also given. Posterior distributions of $K_0$ and $e_{\text{sym}}$ are not shown here as the current data are unable to provide any significant information about them. However, the constraint on $L$ and $K_{\text{sym}}$ is improved. Before adding PREX-II results, the bound on $L$ was $54^{+21}_{-20}$ MeV at 1σ CI and now it becomes $69^{+21}_{-19}$ MeV. Constraint on $K_{\text{sym}}$ is not as strong as $L$, but data suggests the negative value of $K_{\text{sym}}$. We find a very weak correlation between $R_{1.4}$ and $L$ (the value of Pearson correlation coefficient between them is only 0.27), and therefore the PREX-II data has very marginal effect on $R_{1.4}$. Reference (Reed et al. 2021) has extracted a much larger ($106 \pm 37$ MeV) value of $L$ compared to using the PREX-II result and they also obtain a strong correlation between $R_{1.4}$ and $L$. Because of this strong correlation, they find the radius and tidal deformability of the NS have to be large which reveals tension with the GW170817 result. The reasons for this discrepancy are as follows: (a) To deduce the properties of NS one must combine all the available information using hierarchical Bayesian statistics. Reference (Reed et al. 2021) deduce a larger radius for NS based on PREX-II result alone using a correlation-based study and later they find the result is in tension with GW170817. (b) Reference (Reed et al. 2021) also use a handful number of EoSs that can introduce model

| Parameter                       | Prior                  |
|---------------------------------|------------------------|
| $K_0$ (MeV)                     | $\mathcal{N}(240, 30)$ |
| $e_{\text{sym}}$ (MeV)          | $\mathcal{N}(31.7, 3.2)$ |
| $L$ (MeV)                       | $\mathcal{N}(58.7, 28.1)$ |
| $K_{\text{sym}}$ (MeV)          | uniform($-1000,500$) |
| $\Gamma_1$                     | uniform(0.2,8) |
| $\Gamma_2$                     | uniform(0.2,8) |
| $\Gamma_3$                     | uniform(0.2,8) |

Note. A Gaussian prior on $K_0$, $e_{\text{sym}}$ and $L$ is considered here indicating their mean and 1σ CI. For the other four parameters, wide uniform priors are assumed.

Gaussian likelihood of $2.14M_\odot$ mean and $0.1M_\odot$ $1\sigma$ standard deviation; (b) mass and tidal deformability measurement from GW170817 (Abbott et al. 2017) and GW190425 (Abbott et al. 2020) are modeled with Gaussian kernel density estimator (KDE); (c) similarly, mass and radius measurement of of PSR J0030+0451 (Miller et al. 2019; Riley et al. 2019) and PSR J0740+6620 (Miller et al. 2021; Riley et al. 2021) are also modeled with Gaussian KDE. For the PREX-II experiment, the likelihood function is taken to be a Gaussian distribution of skin thickness with $0.29 \pm 0.07$ fm (mean and $1\sigma$ standard deviation). Similar to Essick et al. (2021b) for the likelihood computation of PREX-II, we use the following universal relation obtained from Viñas et al. (2014) between $r_{\text{skin}}$ and empirical parameter $L$: $R_{\text{skin}}^{208}$ [fm] = $0.101 + 0.00147 \times L(\text{MeV})$. 

**Table 1**

| Parameter Prior                  |
|---------------------------------|------------------------|
| $K_0$ (MeV)                     | $\mathcal{N}(240, 30)$ |
| $e_{\text{sym}}$ (MeV)          | $\mathcal{N}(31.7, 3.2)$ |
| $L$ (MeV)                       | $\mathcal{N}(58.7, 28.1)$ |
| $K_{\text{sym}}$ (MeV)          | uniform($-1000,500$) |
| $\Gamma_1$                     | uniform(0.2,8) |
| $\Gamma_2$                     | uniform(0.2,8) |
| $\Gamma_3$                     | uniform(0.2,8) |

Note. A Gaussian prior on $K_0$, $e_{\text{sym}}$ and $L$ is considered here indicating their mean and 1σ CI. For the other four parameters, wide uniform priors are assumed.
dependence as mentioned by Essick et al. (2021b). On the other hand, our result is robust as we sample the posterior distribution of EoS parameters directly using the data by employing a nested sampling algorithm.

In Figure 2, the inferred posterior distribution of \( R_{208}^{\text{skin}} \) (purple), which is obtained after combining astro+PREX-II data is compared with the PREX-II measured distribution (blue). Though the uncertainties of these two distributions overlap with each other within the 1\( \sigma \) CI, we find the inferred value of \( R_{208}^{\text{skin}} = 0.20^{+0.05}_{-0.05} \) fm is relatively smaller than PREX-II measured value. This smaller inferred value of \( R_{208}^{\text{skin}} \) is consistent with Reference (Xu et al. 2020; Li et al. 2021; Tang et al. 2021; Essick et al. 2021b) using different assumption of EoS parameterization. This suggests that there is a mild tension between astrophysical observations and PREX-II data. Currently astrophysical observations dominate over the PREX-II measurement. The uncertainty in the measurement of \( R_{208}^{\text{skin}} \) by PREX-II is still much broader. If the high value of \( R_{208}^{\text{skin}} \) persists with lesser uncertainty then this tension will be revealed. To support this statement, we consider a hypothetical measurement of \( R_{208}^{\text{skin}} = 0.29 \pm 0.02 \) fm (median and 1\( \sigma \) CI) and combined with the existing astrophysical observations. With this lesser uncertainty in the measured \( R_{208}^{\text{skin}} \), we find the inferred values of \( L = 110^{+11}_{-10} \) MeV and \( R_{208}^{\text{sym}} = 0.26^{+0.03}_{-0.02} \) fm. These inferred values would pose a challenge to the current theoretical understanding about the nuclear matter near the saturation densities. In the right panel of Figure 1, the posterior distributions of \( L \) and \( R_{\text{sym}} \), and their correlation with \( R_{1.4} \) are shown for this hypothetical case. This time we find a slightly higher value (~0.2 km) of \( R_{1.4} \) compare to the predicted \( R_{1.4} \) by combined astro+PREX-II data. We further check how the skin thickness measurement affects the radius of different NS masses. In Figure 3, the distribution of radius of 1.1, 1.4, and 1.8 \( M_{\odot} \) NSs are shown using three (astro, astro+PREX-II, and astro+hypothetical \( R_{208}^{\text{skin}} \)) different types of data. We see virtually no change in \( R_{1.4} \) and \( R_{1.8} \) when PREX-II measurement is added to other astrophysical observations.

\( R_{1.1} \) is slightly increased by the addition of PREX-II data. This increment gets moderately higher when the hypothetical measurement of \( R_{208}^{\text{skin}} \) is added. For \( R_{1.4} \), we see only a slight increment even after adding the hypothetical measurement of \( R_{208}^{\text{skin}} \) and almost no change for \( R_{1.8} \). Therefore, a better measurement of \( R_{208}^{\text{skin}} \) might have a small effect on the radii of low-mass NSs, but for the high-mass NSs there will be almost no effect. A similar conclusion has also been achieved recently in Essick et al. (2021a) using their nonparametric equation of state representation based on Gaussian processes.

Finally, we discuss the impact of the radius measurement of PSR J0740+6620 by joint NICER/XMM-Newton data. Since the uncertainties in the radius measurement of PSR J0740+6620 by Miller et al. (2021) is larger than the Riley et al. (2021) due to a conservative treatment of the calibration error, we analyze both data separately and compare the results. In Figure 5, 68\% (blue) and 90\% CI (purple) of mass–radius posterior is shown adding successive observations. In the upper left panel, constraints coming from the GW170817 observation are shown. The
corresponding various macroscopic properties such as the posterior distribution of $R_{1.4}$, $R_{2.08}$, $\Lambda_{1.4}$, and $M_{\text{max}}(M_\odot)$ are also shown Figure 4 and their median and 90% CI are quoted in Table 2. Interestingly, the LIGO-Virgo published GW170817 posterior of $\Lambda$ has a bimodality: the primary mode peaks at $\Lambda \sim 200$ and the secondary one peaks at $\Lambda \sim 600$. We also see the inferred posterior of $\Lambda_{1.4}$ peaks around $\sim 200$ using the GW170817 observation alone. After adding the mass measurement of PSR J0740+6620 ($2.14 \pm 0.1 M_\odot$), GW190425, and PSR J0030+0451, we find the combined data no longer favors the primary mode of GW170817 but it only favors the secondary mode (see Figure 3). In panels c and d of Figure 5, we show the resulting

Figure 3. The posterior distributions of radius are shown for three different NS masses: 1.1 (left), 1.4 (middle), and 1.8 $M_\odot$ (right).

Figure 4. Inferred posterior distributions of various macroscopic properties such as $R_{1.4}$, $\Lambda_{1.4}$, $R_{2.08}$, and $M_{\text{max}}$ are shown adding successive observations.

| Quantity | GW170817 | +2.14 M_\odot | +PSR GW190425 | +PSR J0740 | +PSR J0740 |
|----------|-----------|----------------|----------------|------------|------------|
|          |           | Pulser         |                |            | (Miller+)  |
|          |           | +PSR J0030     |                |            |            |
| $R_{1.4}$ (km) | 11.61±1.45 | 12.49±0.69     | 12.64±0.71     | 12.75±0.68 | 12.75±0.68 |
| $R_{2.08}$ (km) | 12.66±1.58 | 12.91±0.97     | 12.70±1.25     | 12.92±0.97 | 12.92±0.97 |
| $\Lambda_{1.4}$ | 322±39    | 602±284        | 538±289        | 575±282    | 575±282    |
| $M_{\text{max}}(M_\odot)$ | 1.71±0.25 | 2.52±0.31      | 2.17±0.15      | 2.16±0.19  | 2.16±0.19  |

Table 2

Median and 90% CI of $R_{1.4}$, $R_{2.08}$, $\Lambda_{1.4}$, and $M_{\text{max}}(M_\odot)$ are quoted here after adding successive observations.
mass–radius posterior due to the addition of PSR J0740+0620 using the data from Riley et al. (2021) and Miller et al. (2021), respectively. We find for the low-mass NSs, both data result in similar bound of radius. There is only $\sim 0.07(0.36)$ km difference in $R_{1.4}(R_{2.0})$ toward the stiff EoSs when we add data from Miller et al. (2021) instead of Riley et al. (2021). Also it can be noticed the estimated $M_{\text{max}}$ is slightly lower after adding PSR J07400+0620 due to its revised mass estimate.

A direct comparison between our results and other studies (Legred et al. 2021; Miller et al. 2021; Pang et al. 2021; Raaijmakers et al. 2021) can be done due to the different model assumptions and choice of different combinations of data sets. Raaijmakers et al. (2021) reports $R_{1.4} = 12.33^{+0.76}_{-0.81}$ km and $M_{\text{max}} = 2.23^{+0.24}_{-0.21} M_{\odot}$ at the 95% CI based on piecewise-polytrope parameterization, which is informed by chiral-effective theory calculations at lower densities. Legred et al. (2021)
In summary, we have investigated the impact of the recent PREX-II experimental results, the revised mass measurement of PSR J0740+6620, and as well as its radius measurement on the dense-matter EoS based on a hybrid nuclear+PP EoS parameterization. The PREX-II data combined with astrophysical observations predict a slightly larger value of $L$ compared to when we only use astrophysical observations. However, the value of $L$ is in good agreement with other experimental determinations and theoretical expectation (Margueron et al. 2018). We find a very weak correlation between $L$ and $R_{1.4}$, which does not change the radius much. We also argue that the dominant contribution to the inferred EoS posterior comes from the combined astrophysical observations as the measurement uncertainty in $R_{2.08}^{\text{kin}}$ by PREX-II is still much broader. It is also shown that a better measurement of $R_{2.08}^{\text{kin}}$ could have a small effect on the radius of low-mass NSs, but the effect on the radius of high-mass NSs will be almost negligible. Finally, we discuss the effect of the revised mass and radius measurement of PSR J0740+6620 using the data from both Riley et al. (2021) and Miller et al. (2021). Inferred radii using both data sets are broadly consistent with each other with a maximum of ~0.36 km difference in $R_{2.08}$ toward the stiff EoSs using the data from (Miller et al. 2021). The estimated $M_{\text{max}}$ also gets slightly lower after adding PSR J0740+6620 mainly due to its revised mass measurement.

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4. Conclusion

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