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Millisecond radio pulsars with known masses: Parameter values and equation of state models

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HIGHLIGHTS

- The work characterizes a group of millisecond pulsars at an unprecedented level.
- The work provides the first detailed catalogue of some compact star properties.
- The uncertainties of computed parameter values can be used to constrain EoS models.
- The density is not much higher than six times the nuclear density for most stars.
- Stellar spinning configuration is important to reduce bias on EoS model constraints.

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ABSTRACT

The recent fast growth of a population of millisecond pulsars with precisely measured mass provides an excellent opportunity to characterize these compact stars at an unprecedented level. This is because the stellar parameter values can be accurately computed for known mass and spin rate and an assumed equation of state (EoS) model. For each of the 16 such pulsars and for a set of EoS models from nucleonic, hyperonic, strange quark matter and hybrid classes, we numerically compute fast spinning stable stellar parameter values considering the full effect of general relativity. This first detailed catalogue of the computed parameter values of observed millisecond pulsars provides a testbed to probe the physics of compact stars, including their formation, evolution and EoS. We estimate uncertainties on these computed values from the uncertainty of the measured mass, which could be useful to quantitatively constrain EoS models. We note that the largest value of the central density ρ_c in our catalogue is $\sim$5.8 times the nuclear saturation density ρ_{sat}, which is much less than the expected maximum value $13\rho_{sat}$. We argue that the ρ_c-values of at most a small fraction of compact stars could be much larger than $5.8\rho_{sat}$. Besides, we find that the constraints on EoS models from accurate radius measurements could be significantly biased for some of our pulsars, if stellar *spinning* configurations are not used to compute the theoretical radius values.

1. Introduction

Compact stars, commonly known as "neutron stars", are possibly the densest objects in the universe apart from black holes. A class of such compact stars, pulsars, show periodic variation of intensity in their electromagnetic emission. In fact, compact stars were discovered from such periodic radio pulses (Hewish et al., 1968). The first reported fast spinning pulsar, i.e., the millisecond (ms) pulsar, was PSR B1937 + 21 (Backer et al., 1982). It was immediately proposed that such pulsars could be spun up by accretion-induced angular momentum transfer in low-mass X-ray binaries (LMXBs; Radhakrishnan and Srinivasan, 1982; Alpar et al., 1982). This model was strengthened by the discovery of an accretion-powered X-ray ms pulsar SAX J1808.4-3658 (Wijnands and van der, 1998; Chakrabarty and Morgan, 1998). This is because this X-ray pulsar showed that compact stars could be spun up in

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LMXBs. However, a clear evolutionary connection between radio ms pulsars and LMXBs would be established if a compact star had shown both LMXB phase and radio pulsations possibly in a non-accreting phase. Recently, three such sources, called transitional pulsars, have been discovered (Archibald et al., 2009; Papitto et al., 2013; de Martino et al., 2013). These findings strongly show that ms pulsars are spun up in LMXBs. However, the detailed mechanism of this spin evolution, which depends on accretion processes and the interaction between the accretion disc and the stellar magnetosphere, is somewhat poorly understood. Testing the models of these physical processes against the precisely measured parameter values of observed ms pulsars will be very useful to understand the physics of compact star evolution.

Another poorly understood aspect of compact stars is their internal composition, especially the physics of their cores. The densities of these degenerate cores are well above the nuclear saturation density $\rho_{\rm sat} \approx 2.6 \times 10^{14}$ g cm^{-3}. Consequently (see, e.g., Bombaci, 2007) various particle species (apart from neutrons, protons, electrons and muons) and phases of dense matter are expected in the stellar interior. Thus different types of compact stars (nucleonic, hyperonic, strange matter, hybrid) are hypothesized to exist. Therefore compact stars can be considered as natural laboratories that allow us to investigate the constituents of matter and their interactions under extreme conditions that cannot be reproduced in any terrestrial laboratory. Understanding the nature of supra-nuclear core matter remains a fundamental problem of physics, even after almost 50 years since the discovery of the first pulsar.

The standard way attempted to solve this problem is the following. Assuming the constituents of the stellar matter and the interactions among them, an equation of state (EoS) is computed using different many-body approaches. The EoS is given by the thermodynamical relation between the matter pressure P, the mass density ρ and the temperature T. The temperature could be considered equal to zero a few minutes after the compact star birth (Burrows and Lattimer, 1986; Bombaci et al., 1995; Prakash et al., 1997). Many such EoS models exist in the literature.

In order to understand the superdense matter of compact star cores, it is required to identify the "correct" EoS model. How can one do that? For a proposed EoS model, one can compute the stable stellar structure. For doing this, one needs to solve the Tolman-Oppenheimer-Volkoff (TOV) equations (Oppenheimer and Volkoff, 1939; Tolman, 1939) for nonspinning compact stars. For fast spinning stars, however, one needs to follow a numerical formalism described and used in this paper. Once the stable stellar structure is computed, it is possible to calculate the values of various stellar parameters, such as mass, radius, spin rate, etc. One needs to compare these computed values with the measured values to reject some proposed EoS models. By rejection of many EoS models, one can attempt to identify the "correct" EoS model as accurately as possible. In order to achieve this goal, one needs to measure three independent parameters of the same ms pulsar.

So far, for no compact star three parameters have been precisely measured. However, precise measurements of two parameters, mass and spin rate, have been done for a fast growing population of ms pulsars in recent years. This, for the first time, provides a unique opportunity to characterize a number of observed ms pulsars with an unprecedented accuracy. Note that previous authors explored the stable structure of compact stars, which provided general information about the fast spinning compact star parameters (e.g., Cook et al., 1994). Some authors went a step further, considered the measured spin rate of an ms pulsar, and computed a constant spin sequence for that pulsar (e.g., Datta et al., 1998; Bhattacharyya et al., 2016). But such a sequence gives large ranges of other parameter values for a given EoS model. Therefore, while this sequence gives an insight about the general properties of ms pulsars, it does not give very useful additional information about the parameters of the considered ms pulsar. Furthermore, since these large ranges of parameter values overlap for various EoS models, such spin sequences are not very useful to constrain EoS models. With two parameters known, we can now accurately estimate the other parameter values of observed ms pulsars for a given EoS model. In this paper, we do this estimation for 16 ms pulsars and eight diverse EoS models from four different classes, and make a catalogue. This catalogue not only will be useful to constrain EoS models, but also will provide a testbed to probe the physical processes of compact star evolution. We also discuss the ways to constrain EoS models using measured radius values.

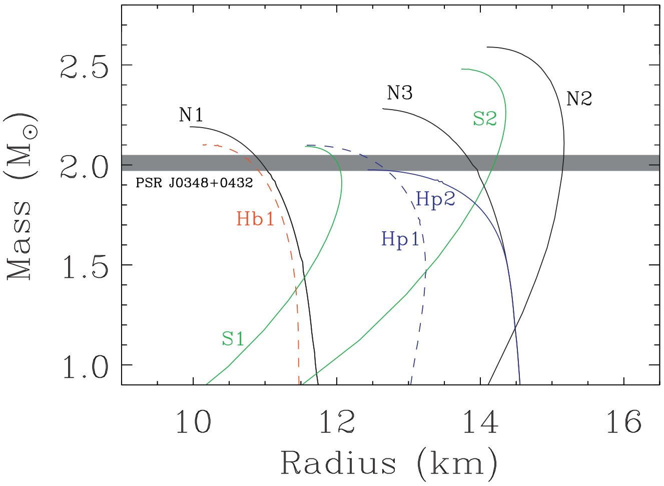

Fig. 1. Compact star gravitational mass versus radius curves. Eight curves for non-spinning stars (Section 3) are for eight EoS models (marked by names given in Table 2). The horizontal band shows the mass ($2.01 \pm 0.04 M_\odot$) of the relatively slowly spinning (spin period = 39 ms) pulsar PSR J0348 + 0432. This figure shows that all our EoS models can support the mass of this massive pulsar (see Section 2).

In Section 2, we mention and discuss the ms pulsars and EoS models we consider. In Section 3, we describe the procedure to compute stable fast spinning compact star structure. Section 4 includes our catalogue of computed ms pulsar parameters and a detailed discussion on their implications. In Section 5, we summarize our results and conclusions.

2. Pulsars and equations of state

As mentioned in Section 1, in this work we use a special sample of ms pulsars, that is those with precisely measured mass values. Here we define pulsars with spin periods less than 10 ms as ms pulsars. Masses of these pulsars in binary stellar systems were measured from the estimation of post-Keplerian parameters or the spectroscopic observations of the companion white dwarf stars (see Özel and Freire, 2016 and references therein). We choose ms pulsars with quoted mass error less than a quarter of a solar mass. We list the spin rates, measured masses with errors and the references on spin and mass measurements for these pulsars in Table 1. It is interesting to see that masses of all these pulsars are distributed within the $1 - 2M_\odot$ range.

In this paper, we consider eight EoS models from four different classes (Table 2). We carefully chose these EoS models keeping various points in mind. For example, three of our EoS models are nucleonic, two are hyperonic, two are strange quark matter and one is hybrid, and hence the set is truly diverse. Moreover, the discovery of the massive pulsar PSR J0348 + 0432 with a precisely measured mass ($2.01 \pm 0.04 M_\odot$; Antoniadis et al., 2013) demands that the "correct" EoS must be able to support this high mass. All our EoS models pass this test (Figs. 1, 2 and Table 2). We