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On the mass distribution of neutron stars

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ABSTRACT

The distribution of masses for neutron stars is analysed using the Bayesian statistical inference, evaluating the likelihood of the proposed Gaussian peaks by using 54 measured points obtained in a variety of systems. The results strongly suggest the existence of a bimodal distribution of the masses, with the first peak around 1.37 $M_\odot$ and a much wider second peak at 1.73 $M_\odot$. The results support earlier views related to the different evolutionary histories of the members for the first two peaks, which produces a natural separation (even if no attempt to 'label' the systems has been made here). They also accommodate the recent findings of $\sim M_\odot$ masses quite naturally. Finally, we explore the existence of a subgroup around 1.25 $M_\odot$, finding weak, if any, evidence for it. This recently claimed low-mass subgroup, possibly related to the O–Mg–Ne core collapse events, has a monotonically decreasing likelihood and does not stand out clearly from the rest of the sample.

Key words: stars: neutron.

1 INTRODUCTION

The measurements of masses and radii of neutron stars (NSs) have the potential to constrain stellar evolution and dense matter physics alike. In fact, matching stellar evolution results and arguments to actual NS observations is crucial to test the whole theory. As is well known, the standard stellar evolution theory suggests the mass at the main sequence (MS) to be the most important parameter for the final outcome of the massive stars. The lowest end of ∼8–11 $M_\odot$ is expected to produce very degenerate O–Mg–Ne cores which eventually collapse because of electron captures. Some possible systems in which the collapse can occur have been discussed in Siess (2007), Poelarends et al. (2008), Nomoto & Kondo (1991), Nomoto & Iben (1985) and Nomoto (1987), among other works. Podsiadlowski et al. (2005) elaborated on this problem and suggested that, due to the 'characteristic mass' expected for the core, the equation of state and the amount of ejected mass would produce low-mass NSs in the ballpark of ∼1.25 $M_\odot$, also expected to receive small natal kicks in their birth events and therefore showing a low orbital eccentricity. Further evidence in favour of this proposal has been presented by Schwab, Podsiadlowski & Rappaport (2010) after analysing a sample of 14 well-measured NSs. In addition, a group of ∼1.35 $M_\odot$ has also been identified and associated with the standard scenario of iron core collapse. This group features a much higher natal kick, and comprises some of the binary pulsar systems such as PSR 1913+16.

On the other hand, increasing evidence for massive NSs has been mounting, with several systems in the range ∼1.6–1.8 $M_\odot$ and the very recent report of a 1.97 ± 0.04 $M_\odot$ (Demorest et al. 2010) neutron star. Interestingly enough, most of these NSs typically have a white dwarf (WD) companion, and thus a distinct evolutionary history. However, systems in HMXRB and binary pulsar also exist. The mass could be the direct result of the existence of massive iron cores for $M \geq 19\,M_\odot$ in the MS (Timmes, Woosley & Weaver 1996), a view advocated by van den Heuvel (2010) and others.

The knowledge of this mass distribution is therefore fundamental to understand the mechanisms involved in the final stages of stellar evolution. In this work, we consider the sample of known NS masses. We applied a Bayesian analysis for all set of masses to overcome an a priori *distribution*. This work is motivated by a similar earlier approach by Finn (1994), who applied the Bayesian approach to estimate the upper and lower limit for the NS masses, using one small set of data with only four well-measured NS binary pulsar systems. He observed the coincidence that all binary pulsar systems have constrained the masses close to 1.35 $M_\odot$. Schwab et al. (2010) recently argued for the existence of two distinct NS populations, the first with high mass (∼1.35 $M_\odot$) and the second with low mass (∼1.25 $M_\odot$), in a work that analysed 14 well-measured objects with uncertainties of ≤0.025 $M_\odot$. They interpreted these two populations as to be result of distinct evolutionary formation scenarios: low-mass populations originate in electron-capture supernovae (SNe) and feature low kicks, while the high-mass population is the result of iron core collapse SNe. Work by Thorsett & Chakrabarti (1999) a decade ago concluded that a very narrow range of masses around 1.35 $M_\odot$ was found, analysing a sample of 50 objects, ruling out accretion at the level of $\Delta M \geq 0.1\,M_\odot$ for the binary pulsars known at that time. Very recently, Zhang et al. (2011) concluded that a

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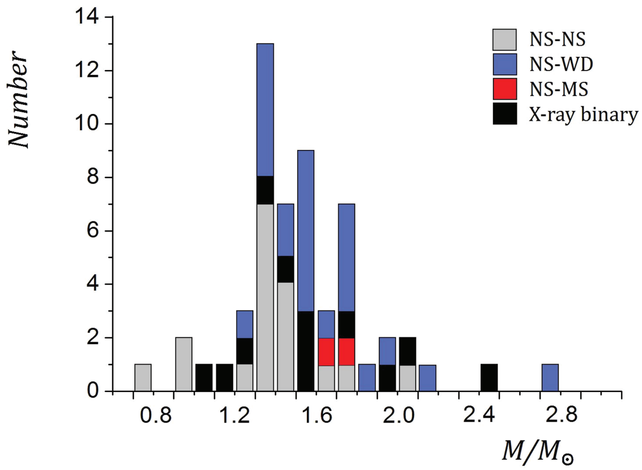

Figure 1. Neutron star mass sample. The plotted values correspond to the published central values of each determination. Each bin contains one or more NSs pertaining to one of the four classes in the sample (NS–NS, NS–WD, NS–MS and X-ray binary, marked with different colours, as indicated in the upper corner of the figure. The corresponding uncertainties vary widely and are not shown here, although they are central for the Bayesian analysis and have been included in it.

substantial accretion was present in recycled objects, using an enlarged sample. Clearly, a reanalysis of this subject is in order.

2 NEUTRON STAR SAMPLE

Our adopted sample is the compilation by Lattimer and collaborators, publicly available at http://stellarcollapse.org/nsmasses. After finding the central values for each source (Fig. 1), we included 55 NSs with error bars varying between 0.009 and 0.548 $\mathrm{M}_\odot$ in our work. The full references to the original works, including the label letter employed in the compilation are given in the reference list (van Kerkwijck, van Paradijs & Zuiderwijck 1995; Barziv et al. 2001; Lange et al. 2001; Nice, Splaver & Stairs 2001, 2003, 2004; Stairs et al. 2002; Freire et al. 2003, 2008b; Gelino, Tomsick & Heindl 2003; Jonker, van der Klis & Groot 2003; Quaintrell et al. 2003; Corongiu et al. 2004; Podsiadlowski et al. 2004; Champion et al. 2005; Ransom et al. 2005; Splaver et al. 2005; Weisberg & Taylor 2005; Bassa et al. 2006; Hotan, Bailes & Ord 2006; Jacoby et al. 2006; Kramer et al. 2006; Lorimer et al. 2006; Freire, Ransom & Gupta 2007; Steeghs & Jonker 2007; Bhat, Bailes & Verbiest 2008; Ferdman 2008; Freire, Jacoby & Bailes 2008a; Janssen et al. 2008; Nice, Stairs & Kasian 2008; Verbiest et al. 2008; Freire 2009; Casares et al. 2010; Mason et al. 2010). The uncertainties for each mass are quite different because the methods of measurement were distinct at different times, and the methods had been improved in many cases.

3 STATISTICAL METHODOLOGY

In this work the analysis of the sample of NS masses has been studied using Bayesian statistics based on conditional probabilities, usually stated as $p(H_i|D,I) = \frac{p(H_i|I)p(D|H_i,I)}{p(D|I)}$, where $p(H_i|I)$ is the probability *priori*, $p(D|H_i, I)$ is the *likelihood function*, $p(H_i|D, I)$ is the *posteriori probability* and $p(D|I)$ is the *predictive probability*. This approach has been shown to be particularly powerful for the treatment of scarce/inaccurate data, yielding none the less quite accurate estimate of the parameters in most cases. One of the main tools to evaluate the quality of the results is the Bayesian Information Criterion (BIC), which considers the ratio of the likelihood models, the available data and models, and explicitly penalizes the model having more parameters. A crucial (and often criticized) ingredient is the a priori expectation from theoretical inference which is weighed by the BIC. An earlier study by Finn (1994) used radio observations for four NS binary pulsar systems and employed Bayesian statistics, approximating each observed point by a Gaussian function (on mass and standard deviation). He used one flat a priori distribution between an assumed upper limit of mass m_u and the lower limit m_l. The values found were $1.01 < m_\mathrm{l}/\mathrm{M}_\odot < 1.34$ (lower limit) and $1.43 < m_\mathrm{u}/\mathrm{M}_\odot < 1.64$ (upper limit). We aimed to improve this kind of analysis by working with the much larger sample and exploiting the potential of the Bayesian formalism.

3.1 Likelihood

Our task in this section is to construct the likelihood function. The likelihood distribution is the key point of Bayesian analysis because it considers the data and the theoretical knowledge about the measurements together. Here, we assumed that the likelihood function is simply the product of independent probabilities for what was measured and what was expected to be measured:

$$L(\theta|D,M) = \left[\prod_i^N p(m_i|D,M)\right] \prod_j p(m_j|D,M),$$

where θ represents the space of parameters, D is the data set, M is the model, $p(m_i|D, M)$ is the probability of the data to be measured and $p(m_j|D, M)$ is the expected probability for the measured data. The likelihood weights the sampling probability of the given data (D) for model M. The likelihood in our case is given by

$$\begin{aligned} L(\theta|D,M) = &-\exp \int n_\mathrm{p}(M, M_1, M_2, a_\mathrm{p}, \sigma_1, \sigma_2, G)\mathrm{d}M \\ &\times \prod a_\mathrm{p}\, g(M_1, \sigma_1, M_i, \xi_i) + (1 - a_\mathrm{p} - a_0) \\ &\times g(M_2, \sigma_2, M_i, \xi_i) + a_0\, g(1.25, 0.07, M_i, \xi_i), \end{aligned}$$

where n_p is a function that involves the peak masses M_1 and M_2, a_p is the relative amplitude of the first peak, a_0[1] is the amplitude centred on the 1.25 $\mathrm{M}_\odot$, with assumed standard deviation $\sim$0.07, σ_1 and σ_2 are the standard deviations of the theoretical peaks and g is a Gaussian function (actually the product of two Gaussian distributions integrated):

$$g = \int_{a_1}^{a_2} \exp\left[-\frac{(u-x_1)^2}{2q_1^2}\right] \times \exp\left[-\frac{(u-x_2)^2}{2q_2^2}\right] \mathrm{d}u,$$

where a_1 and a_2 are given by

$$a_1 = \max[x_1 - H\,q_1, x_2 - H\,q_2]$$

and

$$a_2 = \max[x_1 + H\,q_1, x_2 + H\,q_2].$$

Here H is the scale parameter, q_1 and q_2 are the standard deviations of x_1 and x_2. Finally, n_p is given by

$$\begin{aligned} &n_\mathrm{p}(M, M_1, M_2, a_\mathrm{p}, \sigma_1, \sigma_2, g) \\ &\quad = a_\mathrm{p} \exp\left[-\frac{(M-M_1)^2}{2s_1^2}\right] + G \times \exp\left[-\frac{(M-1.25)^2}{2(0.07^2)}\right] \\ &\qquad + [1 - (a_\mathrm{p} + a_0)] \exp\left[-\frac{(M-M_2)^2}{2\sigma_1^2}\right]. \end{aligned}$$

[1] Here, $0 \le a_\mathrm{p} + a_0 \le 0$.

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3.2 The a priori distributions

The a priori distribution is the assumed knowledge about the phenomenon that is treated. In many previous works, notably those of Finn (1994) and Schwab et al. (2010), Gaussian distribution was employed, and is a 'natural' choice employed in our work (see Finn 1994 for a discussion of this Gaussian form within the Bayesian approach). We then assumed, to compare with the work of Schwab et al. (2010), a distribution peaked on two masses, around $M_1 = 1.35\,\mathrm{M}_\odot$ and $M_2 = 1.55\,\mathrm{M}_\odot$. Those authors restricted their analyses to a set of 14 well-measured NSs, and did not include the large error bar points of the X-ray binaries and several WD–NS systems, consistently with their frequentist approach. With the aim of exploring the full distribution, we have chosen a second, higher value of M_2 to match the plain mean value of the NS in WD–NS and X-ray binary systems of the sample first but, as we shall see below, the precise value is not too important at this point. We performed a first run within this two-value hypothesis, and compared it with the occurrence of a *single*-mass peak for all objects, including NS–NS binaries, WD–NS binaries, X-ray binaries and MS–NS systems. The motivation for this first bold comparison was to see whether a single-mass scale was still possible with the present data, as many works insisted on this till a few years ago.

After this 'first run', and still working within the two-peak hypothesis, and adopting the same values as Schwab et al. (2010) for M_1 and σ_1, we looked for evidence of a subgroup attributed by them to O–Mg–Ne cores producing low-mass NSs. In addition to the main peaks, we examined the distribution to identify the presence of this subgroup by defining a_0 as the peak amplitude of a $1.25\,\mathrm{M}_\odot$ relative to the two main identified peaks. Again, since the claimed masses lie at the low end, the calculation is not sensitive to the precise value of M_2. We defined and calculated the relevant likelihood of a third peak, physically related to the formation of light NS out of O–Mg–Ne cores of the lighter progenitors, of this second run.

In a third run we left the values of the masses M_1 and M_2 to be determined directly by the raw available data, together with their standard deviation values σ_1 and σ_2. That is, while still imposing the distribution to be composed of two Gaussian forms, we sought for the optimal values without restrictions as driven by the data sample. The purpose here is to let the Bayesian tools indicate which are the possible values given the full error bars within a definite Gaussian hypothesis.

4 RESULTS AND CONCLUSIONS

We first address the basic results provided by the first run: the likelihood of still a single-mass scale as an explanation of all the data points is much lower than (at least) two peaks in them, in spite of the introduction of extra parameters penalized by the Bayesian approach. This result may not be meaningful for some, since it has been known for years that the more massive systems should have accreted $\sim$0.1–0.2 $\mathrm{M}_\odot$ or more, and therefore detach from the original mass value. However, the first run is important to overcome the idea that a single value of the NS mass will be enough: even if the two peaks are quite close, this distribution is preferred to a single wide peak. This is somewhat expected, since the extremes of the determined masses, around 1 $\mathrm{M}_\odot$ [van der Meer et al. 2007 , see the recent work by Rawls et al. (2011) released after the completion of this work], at the lowest, and $1.97 \pm 0.04\,\mathrm{M}_\odot$ (Demorest et al. 2010), with a few more massive candidates (Clark et al. 2002 ; Freire et al. 2008c), are now separated by at least 1 $\mathrm{M}_\odot$.

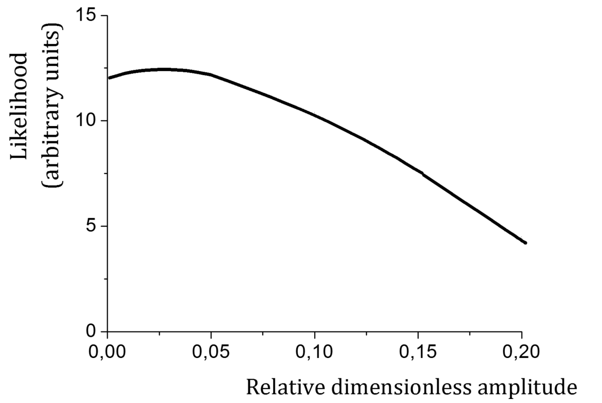

Figure 2. The likelihood of a third, low-mass peak. The dimensionless amplitude a_0 of this third peak has a monotonically decreasing likelihood (not normalized), except for a nearly constant *plateau* value near $a_0 \sim 0$. This is interpreted as the absence of evidence for a bump in the distribution at low masses $M \sim 1.25\,\mathrm{M}_\odot$.

The results of the second run are summarized in Fig. 2. The calculated likelihood of the third peak is a monotonically falling function of the amplitude, being maximal around zero amplitude (relative to the prominent main peaks). Therefore, we conclude that there is little evidence for the presence of a low-mass subgroup, and that the four objects in this range may be in fact members of the $1.35\,\mathrm{M}_\odot$ peak. However, the confirmation of this result would have important consequences, since the progenitor stars are quite abundant. The lack of strong evidence of a peak around $1.25\,\mathrm{M}_\odot$ could be due to still poor sample/bias, or it could alternatively mean that most of the 8–11 $\mathrm{M}_\odot$ become asymptotic giant branch, an issue that deserves serious consideration.

The results of the third run rendered two masses, as shown in Fig. 3. The first mass is not substantially different from the result of Schwab et al. (2010), a fact we interpret as the robustness of the distribution at this scale; while the second one is now around $1.73\,\mathrm{M}_\odot$. This is not surprising, since the known WD–NS and X-ray binary systems have not only large uncertainties but also high values of the central NS masses. The full analysis of the Bayesian techniques suggests here that masses around 2 $\mathrm{M}_\odot$ are not unexpected, even less when considering the obtained value of $\sigma_2 = 0.25$ (for comparison, the value of $\sigma_1 = 0.042$ is very narrow, as expected). The recently announced value of the object in the system, $1.97 \pm 0.04\,\mathrm{M}_\odot$, according to Demorest et al. (2010) (not included in the sample), is just an example of this higher figure for the systems of this kind, and suggests a mean accreted mass of several tenths of $\mathrm{M}_\odot$, although the precise value is model dependent and should be estimated for each individual case. This subgroup may also include members coming from $\geq$20 $\mathrm{M}_\odot$ masses in the MS (Timmes et al. 1996; van den Heuvel 2004), born with higher masses without suffering from any substantial accretion.

In summary, we have presented an analysis of an available NS mass sample which indicates (a) a bimodal distribution with a narrow peak at $M_1 = 1.37\,\mathrm{M}_\odot$ (fully compatible with the findings of Schwab et al. 2010), and a higher peak at $M_1 = 1.73\,\mathrm{M}_\odot$, the latter with a wide shape capable of accommodating $\geq$2 $\mathrm{M}_\odot$ masses, (b) little evidence for the expected low-mass NS descendants from the 8–11 $\mathrm{M}_\odot$ range in the MS and (c) the unsustainability of the 'one-mass-fits-all' picture, since the adopted Bayesian scheme properly weights the large uncertainties and extra parameters of the bimodal hypothesis applied to an imperfect data set. Given the potential implications for the stellar evolution, the need of further pursuing these

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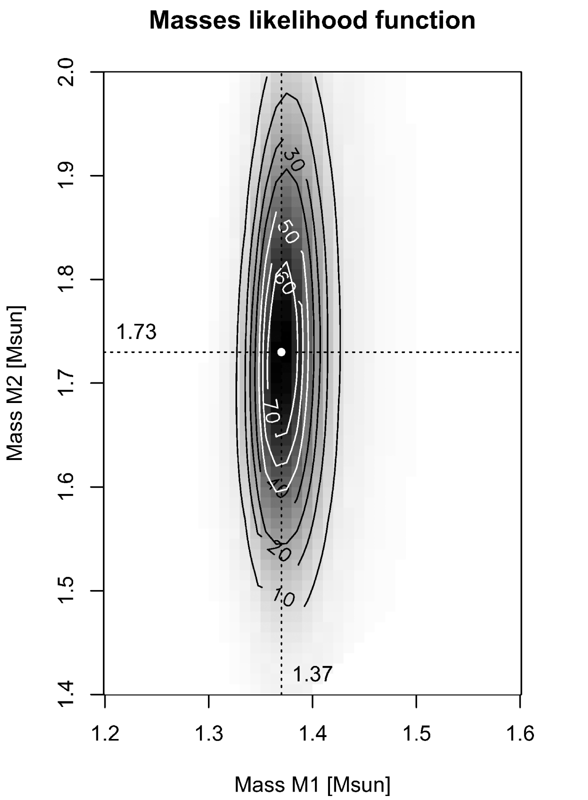

Figure 3. The values of masses at which the distribution peaks. The numbers on the contours indicate the decreasing probabilities of finding M_1 and M_2 there.

kinds of analyses and a continuous improvement by incorporating new data cannot be overstated.

After the completion of this work we noted the public release of a Bayesian analysis by Kiziltan, Kottas & Thorsett (2010), tackling the same problem with a very detailed treatment of calibration. Also their sample is restricted to avoid the inclusion of WD–NS and X-ray binary systems with large error bars. In this analysis, the authors find two peaks, one at $M = 1.35\,\mathrm{M}_\odot$, and another located at $M = 1.5\,\mathrm{M}_\odot$. Given the different sampling and their reliance on simulated distributions (not performed by us), it is fair to say that there is enough room for a convergence of the results. It is important to note that these authors warn against the inclusion of more uncertain points because of a possible contamination of the sample. While we agree with this judgement, we believe that unless the higher masses happen to be completely and systematically overestimated, the emergence of a bump at a mass even higher than $1.5\,\mathrm{M}_\odot$ is strongly expected. Our value for that 'second peak' should reflect to a large extent the difference of including these loose observational data as processed by the Bayesian formalism, acknowledged to handle this kind of situations better than the well-known frequentist approaches. In addition, the quest for a low-mass bump remains in that work, since the peak at the lower $M = 1.35\,\mathrm{M}_\odot$ hosts the low-mass systems attributed by Schwab et al. (2010) to the lower end of the progenitor masses.

Finally, we acknowledge the works of Steiner, Lattimer & Brown (2010) and Zhang et al. (2011), the first aimed to reveal the nuclear equation of state and the second focusing on the evolutionary features of the systems. Steiner, Lattimer & Brown found independently, from a re-analysis of a subset of X-ray bursters, that the maximum mass had to be quite high, as demanded by the $2\,\mathrm{M}_\odot$ determination by Demorest et al. (2010) released shortly after their paper. We did not attempt any specific inference about the nuclear equation of state here, although our results also demand a theoretical description capable to accommodate the objects in the second peak. Determinations of masses and radii were previously published by Özel, Baym & Güver (2010) using thermonuclear bursts, which resulted in tighter constraints for the masses. On the other hand, Zhang et al. used almost the same sample, but their calculations attempted to link the period to the mass, rather than discriminating between single-peak and multimodal distributions. Even their statements about the NS–NS systems alone does not allow a firm conclusion about the existence of the low-mass peak at $1.25\,\mathrm{M}_\odot$, since they focus just on the mean values and dispersions. In all cases the relatively high values of the latter dispersions seem to be a consequence of this methodology.

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