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Neutron stars in globular clusters as tests of nuclear physics

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Abstract. I present a re-analysis of the X-ray spectra of quiescent low-mass X-ray binaries hosted in globular clusters. Because their distances are known, and because these neutron stars (NSs) are non-variable on long time scales and display purely thermal emission from their surface, they have been routinely used to measure the radii of NSs as a way to constrain the equation of state of dense matter. In this re-analysis, I used updated measurements of globular cluster distances which changes significantly the resulting measured radius of NSs, under the assumption that all NSs have the same radius. This assumption corresponds to a toy-model representation of most nucleonic dense matter equations of state. The value found, $R_{\rm NS}$=$10.3^{+1.2}_{-1.1}$ km, is about ~10% higher than previously measured.

Key words. Stars: neutron

1. Introduction

More than fourty years after the observational discovery of neutron stars, their interior composition still eludes nuclear physicists and astrophysicists alike. It is unknown whether matter in their core is purely nucleonic or whether exotic components (kaons/pions condensates or hyperons), or even deconfined quarks, appear at densities above nuclear saturation density $\rho_0 = 2.8{\times}10^{14}\,{\rm g\,cm^{-3}}$. Many theories of dense nuclear matter are proposed by nuclear physics (for a review, see Lattimer & Prakash 2001), with no possibility to test them experimentally due to our inability to reproduce such dense matter in laboratories. Determining the dense matter equation of state (dEoS, the relation between pressure and density above ρ_0) therefore relies on observations of NSs.

One method to constrain the dEoS consists in measuring the radius of NSs, $R_{\rm NS}$. Several observational techniques have been used to this purpose, including the lightcurve modelling of the pulsed X-ray emission from millisecond pulsars (e.g., Bogdanov et al. 2008), the analysis of the emission from Type I X-ray bursts (e.g., Özel et al. 2016), and the surface emission of quiescent low mass X-ray binaries (qLMXBs, Rutledge et al. 2001; Guillot et al. 2011, 2013). This work focuses on the latter by combining the X-ray spectra of six qLMXBs to measure the $R_{\rm NS}$ and place constraints on the dEoS.

LMXBs consist of a compact object (NS or black hole) in orbit with a low-mass star (generally $\lesssim 1\,M_{\odot}$). The Roche-lobe filling companion star tranfers matter onto the compact object, which results in an increase of the X-ray emission from the hot accretion disk and possibly a hot corona (in the case of NS LMXBs) surrounding the compact object.

Transient NS LMXBs alternate between states of X-ray bright active accretion and quiescent states during which the accretion rate onto the NS is suppressed or sufficiently reduced that the faint NS surface emission become the dominant source of X-ray emission (for a review on transient LMXBs, see Lewin et al. 1997).

This thermal emission from the NS surface visible during quiescence originates from the NS deep crust, radiating through the outermost layer (atmosphere). This internal heat has been deposited in the NS crust during previous episodes of accretion by a series of nuclear reactions when accreted matter pushed deeper nucleons to higher densities and temperatures environments. In this interpretation, called deep crustal heating (Brown et al. 1998), these nuclear reactions release $\sim$1–2 MeV per accreted nucleon (Haensel & Zdunik 2008).

The resulting thermal spectrum is well described by hydrogen (H) atmoshere models for NSs. Radiative transfer calculations of the radiation re-processed by a NS atmosphere composed of fully ionized H are used to generate the expected spectra (e.g., Zavlin et al. 1996; Heinke et al. 2006; Haakonsen et al. 2012). Fitting such models to observed spectra gives emission areas consistent with that of a $\sim$10 km NS (e.g. Rutledge et al. 2001, 2002). In such models, the peak of the spectrum is shifted to energies higher than for a Planck spectrum of the same effective temperature. In other words, using a blackbody to fit the surface emission from a NS that has a H atmosphere results in an over-estimated temperature and consequently, an under-estimated emission area (that would correspond to $R_{\rm NS} \lesssim 1$ km).

The atmosphere of NSs in qLMXBs is thought to be composed of the lightest element in the material accreted from the companion star; generally H in the case of low-mass stars. This is due to the fast 10–100 sec gravitational settling of elements in the upper layers of NSs due to the intense surface gravity (Bildsten et al. 1992). Furthermore, the amount of H necessary to fully cover the NS (with optical depth of $\sim$ unity) is on the order of $10^{-20}\,M_\odot$ (Özel 2013). Therefore, it is reasonable to assume a pure-H NS atmosphere, unless the donor star is completely H-depleted.

Employing a NS atmosphere model to fit the soft X-ray spectra of qLMXBs (obtained with *XMM-Newton* or the *Chandra X-ray Observatory*) therefore provides the NS surface temperature and the flux $F_{\rm X} \propto (R_\infty/D)^2$, where D is the source distance, and R_∞ is the radiation radius, seen by an observed at ∞ and defined as $R_\infty = R_{\rm NS}\left(1 - 2GM_{\rm NS}/R_{\rm NS}c^2\right)^{-1/2}$. Therefore, if the distance is know, one can measure the NS mass $M_{\rm NS}$ and radius $R_{\rm NS}$, in a highly correlated way. Unfortunately, distances to LMXBs in the field of the Galaxy have $\sim$30–50% uncertainties, which contributes to $\sim$30–50% uncertainties in the extracted R_∞.

A solution to this problem consists in observing qLMXBs located inside globular clusters (GCs) since their typical distances are measured with $\sim$5–10% uncertainties. Furthermore, GCs contain an over-abundance of X-ray binaries compared to the field of the Galaxy, due to the large amount of interactiong in their core (Hut et al. 1992; Pooley et al. 2003). Finally, NS LMXBs in GCs likely possess a relatively low ($\sim 10^{8-9}\,G$) magnetic field, due to its burial by numerous accretion episodes during their lifetime. Overall, GC qLMXBs are useful objects to measure $R_{\rm NS}$.

2. Obtaining useful measurements of the neutron star radius

As mentioned above, fitting the spectra of GC qLMXBs with a NS atmosphere model provides measurements of R_∞. However, these measurements from individual qLMXBs can only place moderate constraints on the dEoS because of the degeneracy between $M_{\rm NS}$ and $R_{\rm NS}$ (see above). To remedy this, one can combine X-ray observations of a sample of qLMXBs, and make some assumptions to break the degeneracy between $M_{\rm NS}$ and $R_{\rm NS}$. One such assumption consists in imposing that all NSs have the same radius (Guillot et al. 2013). While it may seem arbitrary at first, this assumption is equivalent to a simple representation of the $M_{\rm NS}$–$R_{\rm NS}$ relations of proposed nucleonic dEoS (those with $R_{\rm NS}$ variation of $< 10\%$ for $M_{\rm NS} > 0.5\,M_\odot$). In other words, this constant-$R_{\rm NS}$ assumption corresponds to a toy-model parameterization of the dEoS. It had initially been prompted by two precise measurements of massive $M_{\rm NS} \sim 2\,M_\odot$ NSs (Demorest et al. 2010; Antoniadis et al. 2013), which favors proposed dEoS that appear quasi-vertical in $M_{\rm NS}$–$R_{\rm NS}$ space (see Fig. 1).

In this approach, the simultaneous fitting of the X-ray spectra of qLMXBs is performed via a Markov-Chain Monte-Carlo (MCMC) method. This allows an efficient sampling of the complicated parameter space (1 $R_{\rm NS}$ parameter common to all NSs, and 5 other spectral parameters for each NS), as well as the inclusion of Bayesian priors for the source distance. In addition, MCMC sampling makes the evaluation of the parameters posterior distributions robust and convenient. This method was used to measure $R_{\rm NS}$, given the assumptions listed above: $R_{\rm NS} = 9.1^{+1.3}_{-1.9}$ km (90% confidence, Guillot et al. 2013). An updated measurement was published with additional data for the qLMXB in ω Cen and adding a qLMXB in M30, finding $R_{\rm NS} = 9.4 \pm 1.2$ km (90% confidence, Guillot & Rutledge 2014). From a nuclear physics point of view, such low radii are somewhat difficult to reconcile with theoretical models of nucleonic equations of state. Specifically, it is challenging to produce an equation of state that is both consistent with $\sim$ 9–10 km radii and $\sim 2\,M_\odot$ masses (e.g., Chen & Piekarewicz 2015).

As mentioned above, analyzing the spectra from qLMXBs in GC relies on independently measured distances. While they are generally known to 5–10%, it is not uncommon that different distance measurement methods result in different values (for example, see Woodley et al. 2012). Using recently published distance measurements, I re-analyzed the spectra of the same 6 qLMXBs in the constant-$R_{\rm NS}$ assumption described above. Specifically, for two of the host GCs, the revisited distances were larger by up to ~10% (for NGC 6397 and ω Cen, Watkins et al. 2015). In particular, the larger distance for the GC NGC 6397, means that larger R_∞ values (i.e., larger $R_{\rm NS}$ values) can be accommodated by the simulateneous spectral fit. This relaxes part of the tension of the qLMXB in NGC 6397 with the other qLMXBs that was initially found (Guillot et al. 2013). As a consequence, this results in a larger common radius. Specifically, the constraints from the measured radius, $R_{\rm NS}$=$10.3^{+1.2}_{-1.1}$ km, are shown in Fig. 1.

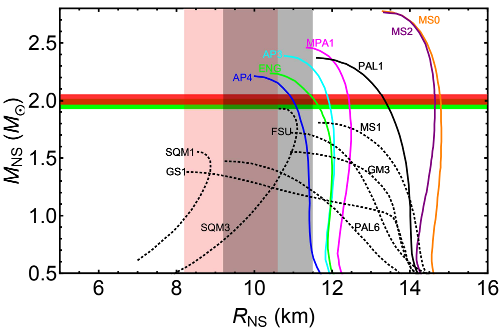

Fig. 1. This $M_{\rm NS}$–$R_{\rm NS}$ diagram shows a selection of proposed dEoS and the measurements of two $M_{\rm NS}$ (green and red horizontal bands, Demorest et al. 2010; Antoniadis et al. 2013) that favor nucleonic dEoSs (solid lines). The light red vertical band shows the 90% radius measurement of Guillot et al. (2013), and the vertical grey band shows the radius measurement presented in this work.

Even if GCs have relatively well-measured distances, their uncertainties can still affect significantly the $R_{\rm NS}$ measurements obtained from NSs hosted in GCs. Nonetheless, the amount of absorption of soft X-rays, which is difficult to constrain from moderate signal-to-noise ratio (S/N) data, still domintates the uncertainty on R_∞, and therefore on the common $R_{\rm NS}$. Another source of uncertainty that can affect the measurements (to a lesser extent) is linked to the calibration of the X-ray instruments (see discussion in Bogdanov et al. 2016).

3. Possible systematic biases on neutron star radius measurements

In addition to the sources of uncertainty mentioned in the previous paragraph, there are sources of systematic bias in the $R_{\rm NS}$ measurement that can emerge from analysis assumptions made in this work. These include:

1) The use of non-magnetic atmosphere models which requires assuming that the NS magnetic field (B) is low enough. Large magnetic fields ($\gtrsim 10^{10}\,G$) affect the radia-

tive transfer and modify the surface emission. While there are no B-field measurements available for qLMXBs in GC, it is expected that the B-field has been buried by the numerous episodes of matter accretion from the companion star.

2) The assumption that the NSs are slowly rotating. The atmosphere models used here have been calculated without considering the possibility of fast rotators (with $P \gtrsim 3$ ms). However, faster spin period could cause a broadening of the observed spectra and could also make the NS oblate. Both effects could bias the $R_{\rm NS}$ measurements by several percents (Bauböck et al. 2015).
3) The assumption that the NS surface emits isotropically. Since the source of the radiation originates from the deep crust that is in thermal equilibrium with the core, it is reasonable to assume that this heat is transfered isotropically. However, some configurations of the B-field inside the crust could favor the propagation of the radiative transfer in a prefered direction toward the surface, resulting in an anisotropic emission (see Elshamouty et al. 2016).
4) The assumption that the atmosphere is composed of pure H. In LMXBs, the alternative would be a NS with an atmosphere composed of pure helium (possible in the case of binaries where the donor star is a helium white dwarf). Because the X-ray spectra of these two possible atmospheres are indifferentiated, we assume a given composition for the NS atmosphere model used to fit the spectra. Using the wrong atmospheric composition can result in R_∞ that are 30–50% larger or smaller (e.g. Servillat et al. 2012). Searching for the presence of H in qLMXB systems (Haggard et al. 2004), or identifying the companion star to the NS (Edmonds et al. 2002), can help choose the atmosphere model to be used for the spectral analysis presented in this work.

4. Conclusions

In this work, I have re-analyzed the X-ray spectra of six qLMXBs (the same as in Guillot & Rutledge 2014) with the constant-$R_{\rm NS}$ assumption, using recently published distances to the GC hosting these sources. Some of these distances, larger by ∼10% in one case, relaxed some of the tension existing between sources in the previous analysis (Guillot et al. 2013). As a result, the radius measured was increased by ∼10% compared to the previous analyses. I found that $R_{\rm NS} = 10.3^{+1.2}_{-1.1}$ km, when the dEoS is parameterized by a vertical line in $M_{\rm NS}$–$R_{\rm NS}$ space. One can improve the constraints on the dEoS from GC qLMXBs by (1) using more precise distance measurements to the GCs, as will be made possible by Gaia (Pancino et al. 2013); (2) identify the presence of H in the qLMXB system to ensure that the proper NS atmosphere models are used; (3) use more realistic parameterizations of the dEoS instead of the constant-$R_{\rm NS}$ toy-model, and (4) obtain higher S/N spectra for the qLMXB X-ray spectra.

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