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ATMOSPHERE COMPOSITION OF QUIESCENT ACCRETING NEUTRON STARS IN GLOBULAR CLUSTERS

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Abstract. Through the study of the quiescent X-ray emission of neutron stars in low-mass X-ray binaries it is possible to constrain the equation of state of dense matter. However, the chemical composition of the neutron star atmosphere is still uncertain. Using deep *Chandra* observations, we report the detailed spectral analysis of a neutron star in the globular cluster M28. For the first time for this kind of object, different atmosphere models composed of hydrogen, helium or carbon are used. The carbon model can be ruled out, and the derived mass and radius are clearly distinct depending on the composition of the atmosphere, leading to different constraints on the equation of state. We compare those results with the other similar neutron stars studied with a hydrogen atmosphere model only and show that a helium model could be relevant in many cases. Measurements of neutron star masses/radii by spectral fitting should consider the possibility of heavier element atmospheres, which produce larger masses/radii for the same data, unless the composition of the accretor is known independently.

Keywords: equation of state, stars: neutron, globular clusters: individual (M28 or NGC 6626), X-rays: binaries, X-rays: individual (CXOGlb J182432.8-245208)

1 Introduction

Neutron stars (NS) are composed of the densest form of matter known to exist in our Universe, providing us with a unique laboratory to study cold matter at supra-nuclear density. In particular, it is still not well understood whether exotic condensates occur in the NS core. The chemical composition of the outer envelope is also uncertain, as well as the symmetry energy, the behavior of superfluidity among neutrons and protons, and the conductivity of the NS crust. Measuring the masses or radii of these objects can lead to useful constraints on the dense matter equation of state (EOS), and give insights of the composition of NSs (see Lattimer 2010 for a recent review).

The mass and radius of isolated NS or ones in transient low-mass X-ray binaries (LMXBs) can be inferred from spectral modeling if their distances are accurately determined. In the case of accreting NSs located in globular clusters (GCs), relatively accurate distances are known. It has been shown that the surface of a weakly magnetic ($B < 10^{10}$ G) NS should be chemically very pure and dominated by the lightest element present as the heavier elements settle out of the atmosphere within seconds to minutes (Alcock & Illarionov 1980; Brown et al. 2002). If there is accretion after the NS formation, the atmosphere could be composed of hydrogen –H– or helium –He– as heavier elements are expected to be destroyed via nuclear spallation reactions (Bildsten et al. 1992; Chang & Bildsten 2004). A fraction of the incident He also suffers spallation reactions and may reform through fusion reactions (Bildsten et al. 1993). The ratio of H to He is thus not well determined. If no accretion takes place or if all lighter elements are burned, heavy elements are expected (Chang et al. 2010, and references therein).

Different NS atmosphere models have been developed, but most recent work for low magnetic fields has focused on a pure H model, such as the ones developed by Zavlin et al. (1996), Gänsicke et al. (2002), or Heinke et al. (2006). The latter model, NSATMOS, was further developed to represent atmospheres of pure He, carbon, nitrogen, oxygen or iron (Ho & Heinke 2009). In particular, such models were used for the low magnetic field NS located at the center of the Cassiopeia A supernova remnant, which was shown to harbor a carbon atmosphere (Ho & Heinke 2009).

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2 Chandra observation of the quiescent accreting neutron star in M28

The GC M28 (NGC 6626) is located at a distance of $D = 5.5 \pm 0.3$ kpc (from Harris 1996, 2010, using measurements in Testa et al. 2001) at RA $= 18^h24^m32.81^s$ and Dec $= -24°52'11.2''$ (J2000). The reddening toward M28 is $E(B-V) = 0.42 \pm 0.02$ (Testa et al. 2001), implying a H column density of $N_{\rm H} = (2.33 \pm 0.12) \times 10^{21}$ cm^2 (using Predehl & Schmitt 1995 for conversion).

Becker et al. (2003) have previously reported on a set of ∼40 ks *Chandra* X-ray Observatory ACIS-S observations of M28 (ObsIds 2683, 2684, 2685). They suggested that the luminous, soft *Chandra* source numbered 26 in their work (IAU-approved source name CXOGlb J182432.8-245208) is a transiently accreting NS in a LMXB in quiescence (qLMXB). We keep the name source 26 throughout the text. Two additional long observations were acquired on 2008 August 7 (ObsId 9132) and 2008 August 10 (ObsId 9133) for 144 and 55 ks, respectively. Using all the available data, the qLMXB candidate is detected with a total of 10332 counts (∼0.043 cts s^{-1}) in the 0.3–6 keV energy band. The complete analysis of this dataset is presented in Servillat et al. (2012).

The source showed no significant variability in all Chandra observations. We thus fitted simultaneously the five spectra extracted from the five different epochs with Xspec 12.7.0e (Arnaud 1996), using the pure H atmosphere model NSATMOS (Heinke et al. 2006) and a photoelectric absorption $N_{\rm H}$ along the line of sight (TBABS, with abundances from Wilms et al. 2000). We fixed the distance to 5.5 kpc and the normalization to 1 (i.e. we assume that all the NS surface is emitting). We used the pile-up model component available in Xspec (Davis 2001) with a frame time set to 3.1 s and a free α parameter (related to the probability of events being retained as a good grade after filtering). The best fit model (χ^2_ν/dof = 0.87/141) is obtained for $\alpha = 0.41 \pm 0.15$, $N_{\rm H} = (2.5 \pm 0.3) \times 10^{21}$ cm^2, a temperature $kT_{\rm eff} = 125 \pm 40$ eV, a mass $M = 1.4^{+0.4}_{-0.9}$ $M_\odot$ and a radius $R = 9 \pm 3$ km. Errors are at 90% significance and we considered only masses higher than 0.5 $M_\odot$ and radii higher than 6 km. The 0.3–6 keV absorbed flux of the source (after removing the pile-up effect) is then $(1.8 \pm 0.2) \times 10^{-13}$ erg s^{-1} cm^{-2}, and the unabsorbed luminosity $\sim 1.6 \times 10^{33}$ erg s^{-1} (at 5.5 kpc). We then ran the command *steppar* and obtained confidence contours for the mass and radius of the NS, which are more instructive than the best fit parameter values and errors (see Figure 1, left).

We performed the same fitting procedure with an atmosphere model composed of pure He (using opacity tables computed by the Opacity Project[i]; see Ho & Heinke 2009 for details), and including the pile-up model. A similar good fit was obtained (χ^2_ν/dof = 0.88/142) with $N_{\rm H} = (2.65 \pm 0.25) \times 10^{21}$ cm^2, a temperature $kT_{\rm eff} = 170^{+50}_{-90}$ eV, a mass $M = 2.0^{+0.5}_{-1.5}$ $M_\odot$ and a radius $R = 14^{+3}_{-8}$ km. The confidence contours obtained with the *steppar* command are reported in Figure 1 (right). We note that the regions delimited by the contours are not consistent at the 80% confidence level with the contours obtained with the H model.

Finally, we performed a similar fit with a carbon atmosphere model (Ho & Heinke 2009). We obtain an acceptable fit (χ^2_ν/dof = 0.88/142) but the parameter values are excluded by causality (Rhoades & Ruffini 1974): $M > 2.6$ $M_\odot$ for $R = 10 \pm 2$ km.

3 Discussion

For both a H and a He model, we found good fits with an absorption consistent with the expected absorption from the GC reddening, suggesting that the source is located in the core of M28 with no or very low intrinsic absorption. The mass and radius are as expected for a typical NS (e.g. Lattimer 2010), and the temperature is in the expected range for qLMXBs.

The only striking difference is that H and He atmosphere models give distinct contour regions of masses/radii at the 80% confidence level (Figure 1). On the one hand, the H model gives a mass and radius consistent with the canonical value of 1.4 $M_\odot$ and 10 km, and allows for the presence of exotic matter inside NSs (hyperons, quarks). On the other hand, the He model provides solutions with higher masses/radii, consistent with the stiffest EOS for NS interiors, most of them composed of neutrons and protons.

The composition of the NS atmosphere depends on the accreting material, physical processes occurring during the accretion, and conditions on the NS surface. A non-evolved star will produce mostly H, which will quickly stratify to provide a pure H atmosphere. White dwarf donors (in so-called ultra-compact LMXBs) will provide mostly He, C/O, or O/Ne/Mg depending on the white dwarf. Ultra-compact LMXBs are observed to be much more common in GCs than in the rest of the Galaxy (Deutsch et al. 2000). Of 16 bright LMXBs in 13 clusters, we have 11 orbital period measurements, of which 5 indicate ultra-compact systems (e.g. Zurek et al.

[i]http://cdsweb.u-strasbg.fr/topbase/TheOP.html

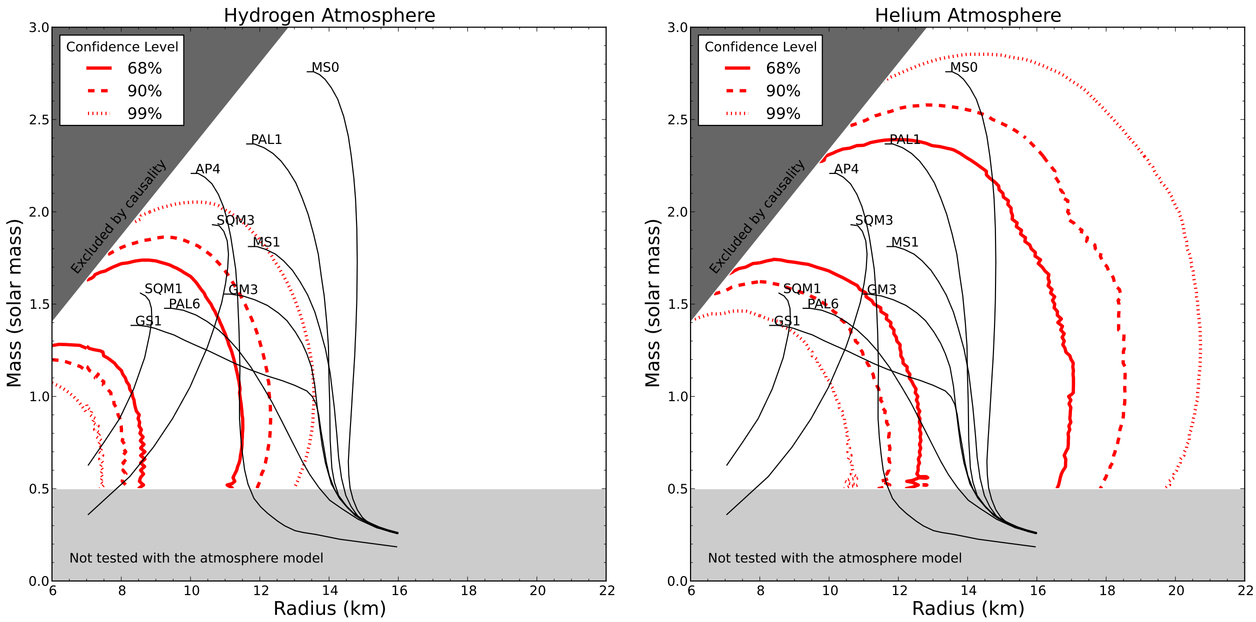

Fig. 1. Confidence levels for the mass and radius of the M28 NS *Chandra* source 26, using a H (**left**) or He (**right**) atmosphere model. A representative selection of EOS are reported (labelled as in Lattimer & Prakash 2001). The parameters were not allowed to vary in the area "Not tested with the atmosphere model". We report in dark gray the area excluded by causality (Rhoades & Ruffini 1974).

2009; Altamirano et al. 2010). In the rest of the Galaxy, only 9 ultra-compact systems are known among the ∼80 bright LMXBs with period measurements (Ritter & Kolb 2003, 2010). Dynamical formation of ultra-compact LMXBs in GC cores explains this difference (Verbunt 1987; Ivanova et al. 2005).

It is unclear whether spallation always produces H during accretion (Bildsten et al. 1992, 1993; Chang & Bildsten 2004). Theoretical work is needed to clarify the conditions for spallation. Also, obtaining a high-quality X-ray spectrum of an neutron star ultra-compact LMXB in quiescence at known distance would help clarify this question.

4 Comparison with other GC qLMXBs

Table 1. Results from spectral fits with NSATMOS for qLMXBs in GCs. Objects are ordered with decreasing radius. We give the absorption, the temperature, mass and radius of the NS, and error on R_∞. Brackets indicate that the value was frozen during the fit. References are [a] Heinke et al. (2006), [b] Lugger et al. (2007), [c] Webb & Barret (2007), [d] Guillot et al. (2011a), [e] Servillat et al. (2012), [f] Guillot et al. (2009b), [g] Guillot et al. (2011b), [h] Servillat et al. (2008b), [i] Servillat et al. (2008a).

source name	Distance kpc	Obs.	$N_{\rm H}$ 10^{21} cm^{-2}	$T_{\rm eff}$ eV	$M_{\rm NS}$ $M_\odot$	$R_{\rm NS}$ km	R_∞ error km
47 Tuc X7[a]	4.85 ± 0.18	Chandra	4.2 ± 1.8	100 to 160	[1.4]	$14.5^{+1.6}_{-1.4}$	± 2.5
M30 A1[b]	9.0 ± 0.5	Chandra	$2.9^{+1.7}_{-1.2}$	94^{+17}_{-12}	[1.4]	$13.4^{+4.3}_{-3.6}$	± 3
ω Cen X3[c]	5.3	XMM	$1.2^{+0.4}_{-0.2}$	82^{+28}_{-9}	$1.66^{+0.84}_{-1.16}$	$11.6^{+7.0}_{-5.0}$	± 2
M13 X7[c]	7.7	XMM	$0.12^{+0.04}_{-0.03}$	86^{+1}_{-8}	$1.30^{+0.06}_{-0.12}$	$9.8^{+0.1}_{-0.3}$	± 2
NGC 6397 U24[d]	2.5 ± 0.06	Chandra	[1.4]	76^{+2}_{-3}	$1.13^{+0.47}_{0.32}$	$9.7^{+0.9}_{-0.8}$	± 1
M28 #26[e]	5.5 ± 0.3	Chandra	2.5 ± 0.3	125 ± 40	$1.4^{+0.4}_{-0.9}$	9 ± 3	± 2.5
NGC 6304 #4[f]	5.97 ± 0.08	XMM+Ch	[2.66]	122^{+31}_{-45}	[1.4]	$8.1^{+4.2}_{-2.4}$	
NGC 6553 #3[g]	6.0	XMM+Ch	[3.5]	134^{+21}_{-34}	[1.4]	$6.4^{+2.1}_{-0.8}$	
NGC 2808 C2[c,h,i]	9.6	XMM	$1.6^{+1.4}_{-0.5}$	92^{+1}_{-23}	$0.9^{+1.6}_{-0.4}$	$6.1^{+11.5}_{-1.1}$	± 6

We list in Table 1 all the NS studied with the NSATMOS NS atmosphere model (Heinke et al. 2006) found in the literature. Those are the best studied cases, but there are further candidates with reported values using other models and lower quality data (see Heinke et al. 2003, Table 2, and Guillot et al. (2009a), Table 4). For NGC 6304, the model used was NSA (Zavlin et al. 1996), but we re-analysed the data with NSATMOS and checked that the results were consistent. We found $M_{\rm NS} < 1.4\ M_\odot$ and $R_{\rm NS} < 9.0$ km (90% error).

Due to the strong surface gravitational field, the observed radius is different from the physical radius, and linked to the NS mass: $R_\infty = R_{\rm NS} \times (1 - 2GM_{\rm NS}/c^2R_{\rm NS})^{-1/2}$. As the shape of the contours in Figure 1 show the degeneracy between the NS mass and radius, it is instructive to give the error on R_∞. This can be seen as the error along a line of constant $M_{\rm NS}/R_{\rm NS}$ ratio, and it is almost constant over the range of NS masses and radii. The error on R_∞ is around ± 2 using the best available data. This opens some discussions on the favored EOS, but cannot provide strong constraints on the equation of state. Combining all those results can give slightly better constraints (Steiner et al. 2010). We note that in some cases the absorption or the NS mass was frozen in the fit, which probably led to underestimated errors. Moreover, the distance error is generally not included in the error budget.

Among the qLMXBs in GCs that were used to derive constraints on the mass and radius of their NS using a H atmosphere models, some were reported to have a low mass or radius. Following our study of the qLMXB in M28, it is possible that some of those sources harbor a NS with a He atmosphere, rather than a H atmosphere. This would favor higher radii and masses for NS, and thus stiffer EOS, in agreement with the precise measurement of relatively high masses for some NS (e.g. $\sim 2\ M_\odot$, Demorest et al. 2010). We will thus try fitting other quiescent LMXBs with He (and carbon) atmospheres in future work.

Identifying the composition of the atmosphere of known quiescent LMXBs is clearly of key importance, and we suggest three means of doing so. i) Spectroscopy, or (less time-consuming) narrow-filter photometry of optical counterparts can identify Hα emission from LMXBs in quiescence or outburst and thus the presence of H; the LMXB in ω Cen (Haggard et al. 2004) and X4 and X5 in 47 Tuc (van den Berg et al., in prep) therefore possess H atmospheres. ii) Orbital periods differentiate between ultra-compact and longer period systems; we note that long periods are known for X5 and W37 in 47 Tuc (Heinke et al. 2005), suggesting a main-sequence companion and accretion of H. iii) Finally, thermonuclear bursts can distinguish between H-rich and H-poor environments, particularly at low ($< 0.01\ \dot{M}_{\rm Edd}$) accretion rates where H should burn unstably (e.g. Fujimoto et al. 1981; Galloway et al. 2008).

This last point is of particular interest for the M28 qLMXB, since a peculiar X-ray burst was observed from this GC (Gotthelf & Kulkarni 1997). This burst was unusually low-luminosity, suggesting burning on only one patch of the star. The short timescale of this burst (τ=7.5 s) requires He burning without the presence of H, and thus (given the quiescent state) pure He accretion and a pure He atmosphere. Unfortunately we cannot be certain that this burst originated from the known qLMXB, as other qLMXBs may be hidden among the fainter sources in this cluster.

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