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New possible class of neutron stars: hot and fast non-accreting rotators

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ABSTRACT

A new class of neutron stars (NSs) – hot rapidly rotating non-accreting NSs, which we propose to call HOFNARs (HOt and Fast Non-Accreting Rotators) or '*hot widows*' (in analogy with 'black widow' pulsars) – is suggested. We argue that such stars should originate from the low-mass X-ray binaries (LMXBs) provided that they were unstable with respect to excitation of r modes at the end of accretion epoch (when their low-mass companions ceased to fill the Roche lobe). High temperature of 'hot widows'/HOFNARs is maintained by r-mode dissipation rather than by accretion. We analyse observational properties of 'hot widows'/HOFNARs and demonstrate that these objects form a specific separate class of NSs. In particular, some of the most stable X-ray sources among the candidates to quiescent LMXB systems (qLMXBs), can, in fact, belong to that new class. We formulate observational criteria which allow us to distinguish 'hot widows'/HOFNARs from qLMXB systems, and argue that available observations of X-ray sources 47 Tuc X5 and X7 satisfy (or, at least, do not contradict) these criteria. In addition, we discuss pieces of indirect evidence in favour of 'hot widows'/HOFNARs existence, following from the analysis of observations and predictions of population synthesis theories. If that new class of NSs does exist, it would prove the possibility to emit gravitational waves by mass–current multipole. Various applications of our results, such as prospects for constraining superdense matter properties with 'hot widows'/HOFNARs, are analysed.

Key words: instabilities – stars: neutron – stars: oscillations – X-rays: binaries – X-rays: stars.

1 INTRODUCTION

Neutron stars (NSs) are usually divided into various classes according to their diverse observational manifestations (e.g. Harding 2013), although, to all appearances, the equation of state in their interiors is universal (e.g. Haensel, Potekhin & Yakovlev 2006). Furthermore, it is generally believed that, depending on the evolution stage, the same star can belong to different classes (e.g. Papitto et al. 2013; Viganò et al. 2013). Detailed observations of NSs from each class together with their accurate theoretical modelling may shed light on still poorly known properties of superdense matter. For example, it is very hard to explain pulsar glitches without invoking nucleon superfluidity in their interiors (e.g. Pines & Alpar 1985), while comparison of the theory with observations of cooling isolated NSs allowed us to put tight constraints on the parameters of nucleon superfluidity in the NS core (e.g. Gusakov et al. 2004; Page et al. 2004). These constraints have been subsequently confirmed by recent observations of a real-time cooling NS in Cassiopeia A supernova remnant (Page et al. 2011; Shternin et al. 2011).[1] As shown by Kantor (2011) and Ho & Andersson (2012), the dependence of superfluid properties of matter on temperature can reveal itself in a deviation of the pulsar braking index from the standard value 3, predicted by the magneto-dipole model. Binary systems with pulsars serve as the excellent targets for reliable measurements of NS masses (see e.g. Demorest et al. 2010; Antoniadis et al. 2013), while observations of hot NSs in low-mass X-ray binaries (LMXBs) can be used to estimate both mass and radius for these stars (see e.g. Guillot et al. 2013) and, possibly, can reveal resonance features in their oscillation spectra (Gusakov, Chugunov & Kantor 2014a,b).

In this paper, we consider a hypothesis of existence of hot (effective redshifted surface temperatures $T_{\rm eff}^{\infty} \sim 10^6$ K, internal

[1] Observations of this NS have been recently reanalysed by Posselt et al. (2013), who argued that its cooling may not be so strong, as it was reported previously by Heinke & Ho (2010) and Shternin et al. (2011). If these new results are correct, parameters of the superfluid model of Shternin et al. (2011) should be slightly modified, which does not exclude superfluidity per se (for example, similar model of Gusakov et al. (2004) predicts slower cooling for this NS).

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redshifted temperatures $T^{\infty} \sim 10^8$ K) non-accreting rapidly rotating (spin frequencies $\nu \gtrsim 200$ Hz) NSs, whose temperature stays high during $\sim 10^9$ yr because of the r-mode instability. Such stars can be descendants of NSs in LMXBs (see e.g. Reisenegger & Bonačić 2003; Bondarescu & Wasserman 2013; Gusakov et al. 2014a and Section 2) and, as we will show here, they form a new class of NSs with very specific physical properties and observational features (see Section 3). Following Gusakov et al. (2014a), we suggest to call these NSs 'HOFNARs' (from HOt and Fast Non-Accreting Rotators) or 'hot widows' (similar to 'black widow' pulsars).

High internal temperature $T^{\infty} \sim 10^8$ K of 'hot widows'/HOFNARs, and hence their high luminosity $L_{\rm cool} \sim 10^{34}$ erg s^{-1} (in the form of neutrino and thermal radiation from the atmosphere) during $\tau \sim 10^9$ yr, requires a lot of energy, $E \sim L_{\rm cool} t \sim 10^{51}$ erg. In a non-accreting NS, only rotation can afford such a huge energy budget. In addition, rotation energy should be deposited into thermal energy with very high efficiency ($\sim$30 per cent), which is achievable with r-mode instability (see equation 2 below), but hardly possible for other mechanisms. As a result, existence of 'hot widows'/HOFNARs is impossible without unstable r modes.

An instability of NSs with respect to excitation of r modes was discovered less than 20 years ago by Andersson (1998) and Friedman & Morsink (1998). It is a particular case of the instability analysed by Chandrasekhar (1970) and Friedman & Schutz (1978a,b) [Chandrasekhar–Friedman-Schutz (CFS) instability]; it is related to the fact that excitation of r mode decreases stellar angular momentum and rotation energy (Friedman & Schutz 1978a,b; Ho & Lai 2000; Levin & Ushomirsky 2001). As a result, gravitational waves emitted by r modes excite (rather than damp) r modes at *arbitrary* spin frequency ν (Andersson 1998; Friedman & Morsink 1998; Lindblom, Owen & Morsink 1998). An account for dissipation suppresses instability at low ν. However, at high enough temperature and spin frequency an NS still stays unstable (see e.g. Lindblom et al. 1998; Andersson & Kokkotas 2001; Ho, Andersson & Haskell 2011; Haskell, Degenaar & Ho 2012; Andersson et al. 2013). A corresponding region of temperatures and frequencies is known as the 'instability window'. For NSs inside the instability window r modes excite spontaneously and their dissipation becomes an important source of stellar heating (Levin 1999; Heyl 2002; Gusakov et al. 2014a,b; Haskell, Glampedakis & Andersson 2014). It allows NSs to stay hot (i.e. to become 'hot widows'/HOFNARs) even after the end of accretion epoch, until their spin frequencies become sufficiently small to make them stable with respect to excitation of r modes. We discuss evolution and properties of such 'hot widows'/HOFNARs, as well as their observational manifestations.

2 SCENARIOS OF THE NS EVOLUTION RESULTING IN 'HOT WIDOW'/HOFNAR FORMATION

In this section, we will demonstrate that 'hot widows'/HOFNARs appear in all scenarios of NS evolution in LMXBs, in which the r-mode instability plays essential role (that is, the probability to observe an NS with excited r mode is not small). For this purpose, we will analyse three models of r-mode instability: (i) model (a), whose characteristic feature is the resonance interaction of superfluid inertial modes with the r mode (for more details see Gusakov et al. 2014a,b); (ii) model (b), for which the saturation of r mode is defined by the first parametric instability due to non-linear interaction of r mode with the higher order (principal mode number $n \sim 100$) inertial modes, freely penetrating the crust (Bondarescu & Wasserman 2013); (iii) widely used model (c), for which the saturation amplitude of r modes (i.e. the maximum achievable r-mode amplitude) is independent of the oscillation frequency and temperature.

NS evolution at the stage of active accretion in an LMXB is driven by the equations formulated by Owen et al. (1998), Ho & Lai (2000), and Gusakov et al. (2014b). For the models listed above, the evolution was studied in detail by Gusakov et al. (2014a,b) [model (a)], by Bondarescu & Wasserman (2013) [model (b)], by Levin (1999), Heyl (2002), and Gusakov et al. (2014b) [model (c)], and is briefly described here for completeness. Corresponding evolutionary tracks in the plane 'rotation frequency ν – redshifted internal temperature T^{∞}' are shown by thick solid lines in Fig. 1 (evolution direction is indicated by arrows). Fig. 1 also shows boundaries of the stability region for the most unstable oscillation mode[2] with multipolarity $m = 2$ (thin solid line) and r mode with multipolarity $m = 3$ (dot–dashed line). These curves are calculated in Gusakov et al. (2014a,b) for a canonical NS with the mass $M = 1.4\,{\rm M}_{\odot}$ and radius $R = 10$ km. Filled circles with error bars in Fig. 1 correspond to the observed spin frequencies and temperatures of NSs (see Gusakov et al. 2014a, and references therein).

In the region where all oscillation modes are stable (filled grey in the figure), a star is spun up by accretion. Its temperature $T^{\infty} = T^{\infty}_{\rm eq}$ (see vertical dashes in the figure) is determined by the balance of stellar cooling and internal heating caused by nuclear transformations in the accreted NS crust (deep crustal heating model of Brown, Bildsten & Rutledge 1998). For the range of temperatures considered in this paper, an NS cools down mostly due to neutrino emission from its core, which is calculated by employing a microphysical model from Gusakov et al. (2004). That model allows one to explain *all* observations of cooling isolated NSs within minimal assumptions on the NS core composition and properties. In what follows, in our calculations we consider an NS with the mass $M = 1.4\,{\rm M}_{\odot}$. The accretion rate, averaged over long period of time, involving both quiescent and active phases, is chosen to be $\dot{M} = 3 \times 10^{-10}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$. Such $\dot{M}$ agrees with the estimates of accretion rates for the hottest NSs in LMXBs (see Heinke et al. 2007, 2009; Gusakov et al. 2014a and references therein) and corresponds to the equilibrium temperature $T^{\infty}_{\rm eq} \approx 1.08 \times 10^8$ K, which does not depend on the r-mode instability model. When a star reaches the instability region, the amplitude of $m = 2$ r mode rapidly grows up, and its dissipation becomes a powerful source of stellar heating. Subsequent stellar evolution slightly differs for the model (a) and models (b) and (c).

In model (a) temperature increase is limited by the stability peak arising from the resonance interaction of oscillation modes. Having reached the peak, a star spins up due to accretion, moving along the left edge of the stability peak. The stellar temperature is maintained by dissipation of r mode, which is marginally stable and shown to have the required average amplitude (Gusakov et al. 2014a).

[2] For models (b) and (c) the most unstable mode, at any temperature, is the quadrupolar ($m = 2$) r mode. Model (a) accounts for the avoided crossings between the superfluid and normal modes which means that, strictly speaking, different modes can be the most unstable ones at different temperatures. However, it can be shown that far from the resonances (stability peaks) the most unstable oscillation mode is very similar to r mode of a non-superfluid NS (for more details see Gusakov et al. 2014a,b). In what follows, for brevity, the most unstable mode will be referred to as r mode for all the models.

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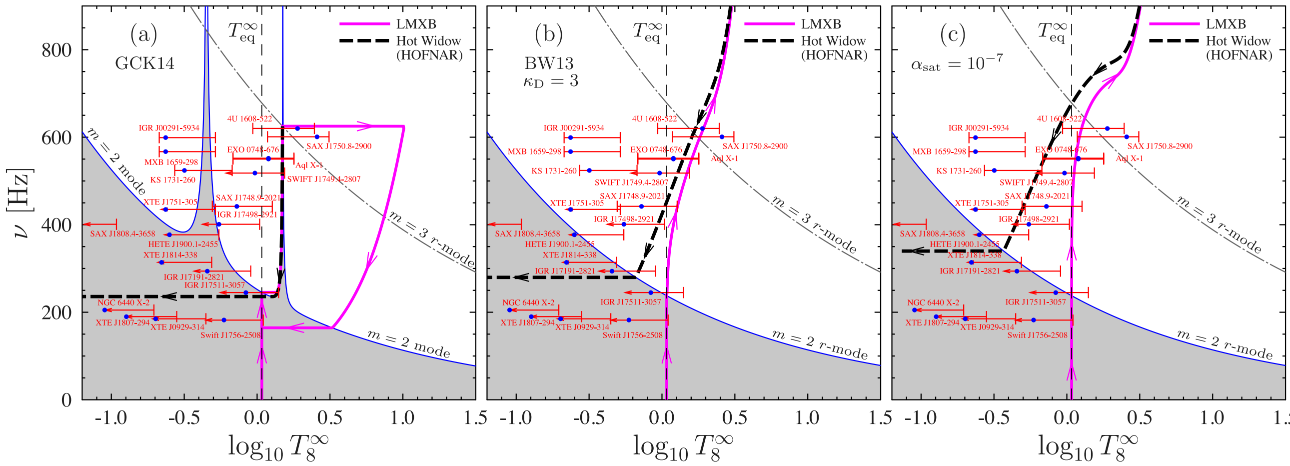

Figure 1. Evolution of frequency ν and internal redshifted temperature T^∞ for an accreting NS in LMXB (thick solid line) and for non-accreting NS with exhausted low-mass companion (thick dashed line), for three models of r-mode instability: (a) model of resonant interaction of superfluid inertial modes with r mode (Gusakov et al. 2014a,b, GCK14); (b) model of Bondarescu & Wasserman 2013 (BW13) with non-linear mode coupling parameter $\kappa_D = 3$; (c) widely used model in which the r-mode saturation amplitude is constant and is taken to be $\alpha_{sat} = 10^{-7}$. Arrows in the curves demonstrate direction of the NS evolution. Thin solid lines show instability curves for the most unstable (at a given temperature) mode with $m = 2$; the dot–dashed line demonstrates instability curve for $m = 3$ r mode. The stability region is shaded in grey; in the white region at least one of the oscillation modes is unstable. Vertical dashed line indicates T^∞_{eq}. Temperatures and frequencies of the NSs observed in LMXBs are shown by filled circles, error bars show uncertainties due to unconstrained NS envelope composition (see Gusakov et al. 2014a, and references therein).

Ascending the stability peak can be terminated at *equilibrium* rotation frequency ν_{eq}, at which the spin-up accretion torque balances the joint torque produced by the magneto-dipole losses and gravitational wave emission. If the accretion torque is sufficiently large, a star reaches the instability region of $m = 3$ r mode, where that mode excites and rapidly heats the star up. Gravitational wave emission then is so strong that the star spins down (despite ongoing accretion) and returns into the stability region, where all oscillation modes damp out very fast and the star cools down to the temperature $T^\infty = T^\infty_{eq}$. Then the evolution cycle repeats. A typical period of the cycle is about 10^8 yr (i.e. less than the typical duration of intensive accretion in LMXBs; see e.g. Chen et al. 2013) and depends on a spin-up rate of an NS in the course of accretion (Gusakov et al. 2014b). A star spends a major part of the period climbing up the stability peak. Thus, a probability to find it at the peak at the end of the LMXB stage (when accretion ceases, e.g. due to depletion of the low-mass companion) is high.

In models (b) and (c), NS evolution in an LMXB is a bit different. Once entering the instability region, an NS rapidly reaches the curve where stellar heating (due to nuclear reactions in the accreted crust and dissipation of the saturated r mode) is compensated by neutrino cooling. Then the star evolves along this curve (Levin 1999; Heyl 2002; Bondarescu & Wasserman 2013; Gusakov et al. 2014b). The observed NS temperatures within these models can only be explained if one assumes extremely low saturation amplitude $\alpha \lesssim 10^{-7}$ (see e.g. Mahmoodifar & Strohmayer 2013). The maximum allowable NS spin frequency for such models is limited by the *equilibrium* frequency ν_{eq} (see e.g. Bondarescu & Wasserman 2013).

The LMXB stage does not last forever: as a result of its own evolution and/or the evolution of orbital period of LMXB, the low-mass companion eventually ceases to fill the Roche lobe (see Tauris 2011; Tauris & van den Heuvel 2006 and references therein). This leads to an abrupt termination of accretion, and switching off heating due to nuclear reactions in the crust. An NS can then cool down rapidly and become a millisecond pulsar (MSP). However, if a star was at the left edge of the stability peak [which is quite probable in model (a), see above] or in the instability window [which occurs naturally in models (b) and (c) if ν_{eq} is not too small], then it continues to be heated by dissipation of NS oscillations even after the end of accretion epoch. As a consequence, an NS stays hot (and rapidly rotating) for a long time, i.e. it becomes a 'hot widow'/HOFNAR. Subsequent evolution of an NS with the excited r mode is described by the same model as that proposed to study NSs at the LMXB stage (Owen et al. 1998; Ho & Lai 2000; Gusakov et al. 2014b). The corresponding evolutionary paths are shown in Fig. 1 by the thick dashes. In model (a), the end of accretion epoch does not lead to reduction of T^∞, because this would amplify the NS instability (see Fig. 1a). Instead, after accretion stops, oscillation amplitude automatically adjusts itself (increases) so as to keep the star at the edge of the stability peak by means of heating exclusively due to r-mode dissipation. In the case of models (b) and (c), the saturated r mode cannot further increase its amplitude so that absence of accretion results in a reduction of temperature which is then determined by the balance between the neutrino luminosity and viscous r-mode heating [see Fig. 1(b,c)].

The spin frequency ν in the beginning of the 'hot widow'/HOFNAR phase is determined by the frequency ν at the end of LMXB stage;[3] during that phase an NS simply slows down due to magneto-dipole losses and gravitational wave emission by excited oscillation modes. Along the evolutionary track the following condition is satisfied,

$$|\tau_{GR}| = |\tau_{Diss}|, \qquad (1)$$

where τ_{GR} and τ_{Diss} are gravitational-wave and damping time-scales, respectively. In the case of model (a), this condition is fulfilled because of marginal stability of r mode (see Gusakov

[3] Note that in the final stage of LMXB evolution an NS can accrete matter being in the so-called propeller regime (Illarionov & Sunyaev 1975). As shown by Tauris (2012), this can lead to a rapid spin-down of an NS and to corresponding decreasing of its rotation energy by a factor of 2 (or even more). This effect can reduce amount of NSs that stay unstable (and thus become 'hot widows'/HOFNARs) after the end of LMXB stage.

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et al. 2014b), while for the models (b) and (c) it determines a 'saturation' of r-mode oscillations due to non-linear processes; in this case the quantity $\tau_{\rm Diss}$ includes also dissipation due to these processes (Gusakov et al. 2014b). Using equation (1), one can show (e.g. by means of equations 16, 19, and 20 of Gusakov et al. 2014b), that the rate of NS rotation energy ($E_{\rm rot}$) loss because of the instability of $m = 2$ r mode is given by

$$\frac{{\rm d}E_{\rm rot}}{{\rm d}t} = -3L_{\rm cool}. \qquad (2)$$

Thus, the total NS thermal emissivity $L_{\rm cool}$ (in the form of neutrinos from the whole star and thermal emission from its atmosphere) constitutes $1/3$ of the rate of rotation energy loss due to r-mode instability. It is easy to estimate that, during its life, a 'hot widow'/HOFNAR emits huge amount of thermal energy, $E_{\rm th} \sim E_{\rm rot}/3 \sim 10^{51}$ erg, while the lifetime of an NS at this stage constitutes $\sim E_{\rm rot}/(3L_{\rm cool}) \sim 10^9$ yr.[4] After an NS enters the stability region oscillation modes rapidly damp out and the star cools down along the horizontal part of the evolutionary path.

Note that in the model (a), depending on the value of $T^\infty_{\rm eq}$, NS evolution at the LMXB stage can be associated with different stability peaks resulting from the interaction of r mode with different superfluid modes (Gusakov et al. 2014a,b). For instance, in the case shown in Fig. 1(a), evolutionary track for an NS in LMXB will follow the left (low-temperature) stability peak centred at $T^\infty \approx 4.5 \times 10^7$ K if $T^\infty_{\rm eq} \lesssim 4 \times 10^7$ K. Model (a) explains in this way colder sources, such as IGR J00291−5934. If accretion ceases in such system, the produced 'hot widow'/HOFNAR will descend the low-temperature stability peak being not so hot.

The analysis presented in this section allow us to conclude that if some of the observed NSs in LMXBs are indeed r-mode unstable, then the new class of objects – 'hot widows'/HOFNARs – should emerge along with MSPs. This conclusion is almost insensitive to the actual model employed to describe the NS instability and is valid for the models (a)–(c) analysed here.

3 'HOT WIDOWS'/HOFNARS: OBSERVATIONAL SIGNATURES

In contrast to MSPs, it can be difficult to measure large spin frequencies of 'hot widows'/HOFNARs because they might not display any noticeable pulsed fraction in their electromagnetic emission. This is because the resistive relaxation time-scale $\tau_{\rm r}$ for the crustal magnetic field,

$$\tau_{\rm r} \approx \frac{4\pi\sigma l^2}{c^2} \sim 4 \times 10^6 \frac{\sigma}{10^{24}\,{\rm s}^{-1}} \left(\frac{l}{10^5\,{\rm cm}}\right)\ {\rm yr}, \qquad (3)$$

is three orders of magnitude lower than the 'hot widow'/HOFNAR lifetime due to relatively low electrical conductivity σ at high temperature ($\sigma \sim 10^{24}\,{\rm s}^{-1}$ at $T \sim 10^8$ K and density $\sim 10^{13}\,{\rm g\,cm}^{-3}$; see e.g. Gnedin, Yakovlev & Potekhin 2001; Chugunov 2012). In equation (3) c is the speed of light, and l is the typical length-scale $\sim 10^5$ cm. This simple estimate agrees with much more sophisticated calculations (e.g. Urpin & Konenkov 2008; Vigelius & Melatos 2009). However, one should bear in mind that the problem of magnetic field relaxation in NSs is a very complicated one, and depends on the magnetic field configuration (which can be non-trivial; see e.g. Priymak, Melatos & Payne 2011), crust conductivity and composition, etc., and deserves a special consideration. Yet, in what follows we assume that the resistive relaxation leads to decay of the magnetic field in the very beginning of 'hot widow'/HOFNAR stage making thus unlikely to measure their frequencies by observing them as radio pulsars.

On the other hand, 'hot widows'/HOFNARs are hot NSs, with the internal temperatures $T^\infty \sim 10^8$ K corresponding to the effective redshifted surface temperatures $T^\infty_{\rm eff} \sim 10^6$ K (Potekhin, Chabrier & Yakovlev 1997).[5] Therefore 'hot widows'/HOFNARs should exhibit thermal X-ray emission from their whole surface[6] and, as they do not accrete matter (and have low magnetic field), the contribution of the non-thermal component should be small. Exactly these properties of X-ray spectrum have been required for the selection of candidates to LMXBs in quiescent state (qLMXBs) among various X-ray sources in GCs (Rutledge et al. 2000; Heinke et al. 2003b; Guillot et al. 2011).[7] Thus, qLXMB-candidates, which (i) have never been observed in outbursts (i.e. no signatures of strong accretion have been detected; approximately 30 of such qLMXB candidates are known at the present time; see Wijnands, Degenaar & Page 2013) and (ii) have thermal X-ray spectra, can be considered as candidates to 'hot widows'/HOFNARs. It is worth noting, however, that there is a principal difference between the 'hot widows'/HOFNARs and real LMXB systems: 'Hot widow'/HOFNAR's low-mass companion does not fill the Roche lobe and, as a result, NS does not accrete significantly. This fact allows us to formulate identification criteria for 'hot widows'/HOFNARs based on optical observations (see Section 4.1).

4 PIECES OF EVIDENCE FOR THE 'HOT WIDOWS'/HOFNARS EXISTENCE

4.1 A possibility to reliably identify 'hot widows'/HOFNARs

Detection of a hot ($T^\infty_{\rm eff} \sim 10^6$ K) NS in a system, where low-mass companion does not fill the Roche lobe and hence NS cannot accrete intensively, would allow one to identify such NS as a 'hot widow'/HOFNAR. In fact, in that case the only way to explain its high temperature is to assume that it is permanently heated by an excited r mode. Search for such objects is a realistic task. For

[4] Accurate evaluation of the time required to brake the star from rotation frequency 600 Hz down to the frequency when it becomes stable gives $\sim 10^9$, 4×10^9, and 8×10^{10} yr for models (a), (b), and (c), respectively.

[5] This is an additional property that differs them from MSPs which are also formed as a result of LMXB evolution, but, as a rule, have lower surface temperatures (except for the hot spots; see Zavlin 2007; Bogdanov, Grindlay & Rybicki 2008, for example). However, one cannot exclude a situation that a (young) 'hot widow'/HOFNAR can be, at the same time, classified as MSP. For example, the 'missing link' binary PSR J1023+0038 ($\nu = 592.4$ Hz; as reported by Archibald et al. 2009) has a relatively high-redshifted surface temperature $T^\infty_{\rm eff} \sim 5 \times 10^5$ K (Homer et al. 2006; Bogdanov et al. 2011). It is believed that this pulsar is in a binary system, which leaves the LMXB stage (Patruno et al. 2014). In a model (a), it will become a young 'hot widow'/HOFNAR, attached to the *low-temperature* stability peak [see Fig. 1(a)]. Thus, it can keep its magnetic field and work as MSP as well. Another example is the pulsar PSR J1723−2837 ($\nu = 539$ Hz; Faulkner et al. 2004), whose X-ray spectrum agrees with the redshifted surface temperature $T^\infty_{\rm eff} \sim (4-5) \times 10^5$ K (see table 1 of Bogdanov et al. 2014).

[6] Because there are no reasons for any noticeable inhomogeneity, the surface temperature of 'hot widows'/HOFNARs should be uniform, making it difficult to measure their spin frequencies with X-ray observations.

[7] The only difference is that a non-thermal contribution of up to 40 per cent is allowed for qLMXB candidates (see e.g. Heinke et al. 2003b). However, significant ($\gtrsim$10 per cent) non-thermal emission is not necessary for describing most of the qLMXB candidates (see e.g. table 2 of Heinke et al. 2003b).

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instance, observations show that the source X5 in GC 47 Tuc is a hot NS ($T_{\rm eff}^{\infty} = 1.06^{+19}_{-16} \times 10^6$ K; Heinke et al. 2003a) in the eclipsing binary with the orbital period 8.666 ± 0.008 h (Heinke et al. 2002). Optical observations with the *Hubble Space Telescope* by Edmonds et al. (2002) have identified the optical companion as a red main-sequence star and have revealed the presence of an accretion disc. However, they also showed, that the companion star considerably underfills the Roche lobe (according to estimates of Edmonds et al. 2002 the ratio of the companion radius to the size of the Roche lobe is about $F = 0.5$–0.6), and thus is detached from the disc. In that case accretion can be very small (Edmonds et al. 2002) and not sufficient to explain the source's high temperature. Thus, we treat 47 Tuc X5 as a good candidate to 'hot widows'/HOFNARs. Another candidate – the object X7 in GC Tuc 47 – is a persistent source with the purely thermal X-ray emission (Heinke et al. 2005b, 2006a). Although optical observations do not allow us to identify its companion reliably, they also do not contain any indications of the presence of the accretion disc (Edmonds et al. 2002). Moreover, according to Edmonds et al. (2002), if the 5.5 h period identified in X-ray observations is real and the companion underfills its Roche lobe by about the same amount as X5, then the absolute magnitude of the companion is $M_V \sim 10.6$, and apparent visual magnitude is $V \sim 24.1$, which is just slightly below the observational upper limit $V \sim 23$. Thus, this source is also a good candidate to 'hot widows'/HOFNARs. Among the other sources, we would select five qLMXB candidates in GCs M28, M13, NGC 5139, NGC 6304, and NGC 6397, studied by Guillot et al. (2013), for which X-ray observations with good signal-to-noise ratio are available. Except for NGC 6397 U24, all of them can be described with the purely thermal hydrogen atmosphere spectrum, while for the source NGC 6397 U24 the contribution of non-thermal emission in the energy range 0.5–10 keV is only $\lesssim 2.6^{+1.7}_{-1.7}$ per cent (Guillot et al. 2013). Moreover, for the source NGC 6397 U24 rather strict constraints can be set on the companion luminosity in the visible spectral range, $M_V > 11$ (Grindlay et al. 2001), which indicates that the companion fills its Roche lobe only if its orbital period is sufficiently small (e.g. for $M_V \sim 10.6$ and orbital period 5.5 h the companion underfills its Roche lobe; see Edmonds et al. 2002). Further studies of the sources mentioned above, as well as other qLMXB candidates, can allow one to identify some of them as 'hot widows'/HOFNARs.

4.2 Pieces of indirect evidence

A possibility of existence of 'hot widows'/HOFNARs has not been previously accounted for in the analysis of observational data and in population synthesis calculations. If these objects do exist, they should help to clarify some inconsistencies between the predictions of the LMXBs/MSPs evolution theory and observations. We analysed the literature on this subject and found a few such inconsistencies.

Although at least some of those inconsistencies can be resolved without appeal to the 'hot widow'/HOFNAR hypothesis we list them here as pieces of an *indirect evidence* in its favour.

(i) The spin frequencies of accreting NSs in LMXBs are generally larger than the frequencies of MSPs, which are thought to be their descendants.

This fact cannot be explained just by NS spin-down at the MSP stage. Possible explanation of this phenomenon was suggested by Tauris (2012) who assumed that the difference between the spin frequencies of both populations could be related with the fast deceleration of an NS in a binary at the moment when the companion star decouples from its Roche lobe. In our scenario a complimentary mechanism is possible. It consists in the formation of 'hot widows'/HOFNARs from the most rapidly rotating hot NSs in LMXBs. Hence, it favours the selection of more slowly rotating (stable) NSs as progenitors of MSPs. A more detailed analysis of MSP spin distribution by Papitto et al. (2014) provides an additional evidence that this mechanism is relevant. The latter authors showed that the frequency distribution of the so-called nuclear-powered MSPs (a subclass of accreting NSs in LMXBs), whose quasi-coherent oscillations are observed exclusively during the thermonuclear type-I X-ray bursts (see e.g. Watts 2012), differs most strongly from the frequency distribution of MSPs. Note that the most rapidly rotating nuclear-powered MSPs [4U 1608−522, SAX J1750.8−2900, MXB 1659−298(=X 1658−298), EXO 0748−676, KS 1731−260] are unstable (or marginally stable in the model of resonance interaction of modes) with respect to r-mode oscillations[8] and should become 'hot widows'/HOFNARs (rather than MSPs) in the models (a)–(c) (see Fig. 1). Thus, in our scenario, spin distribution of nuclear-powered MSPs can differ significantly from the spin distribution of MSPs, in agreement with observations.

(ii) Low-level non-thermal emission from most of the qLMXB candidates.

Most of the observed qLMXB candidates do not require a power-law component for the interpretation of their spectra (Heinke et al. 2003b; Guillot et al. 2011), although the selection criteria for qLMXBs, applied, e.g. by Heinke et al. (2003b), allows for the contribution of up to 40 per cent of non-thermal emission. At the same time, many reliably identified LMXB systems, which have been observed in outbursts, require a non-thermal component for the description of their quiescent state (see e.g. table 2 of Degenaar, Patruno & Wijnands 2012b). A purely thermal spectrum is a distinguishing feature of 'hot widows'/HOFNARs. That is why the fact that many qLMXB candidates do have such spectrum can implicitly indicate that some of them are 'hot widows'/HOFNARs.

(iii) Recurrence time for qLMXB candidates.

An assumption that all the qLMXB candidates are LMXBs in quiescence leads to an estimate $N \sim 200$ of the total number of LMXB systems in GCs (Heinke, Grindlay & Edmonds 2005a). However, only $N_{\rm a} = 8$ of them have been observed in outburst for over $t_{\rm obs} \sim 40$ yr of satellite observations. This leads to the following estimate for an average recurrence time, $\sim N t_{\rm obs}/N_{\rm a} \sim 1000$ yr (Heinke 2010).[9] However, theoretical estimates, based on the disc instability model, predict much smaller recurrence times $\lesssim 180$ yr (see e.g. section 6.4

[8] The slowest nuclear-powered MSP IGR J17191−2821, is, most probably, stable (see Fig. 1). The question of stability is still open for a majority of other nuclear-powered MSPs (GRS 1741.9−2853, 4U 1636−536, 4U 1728−34, 4U 1702−429) since it is very difficult to extract their internal temperature from observations. In the case of GRS 1741.9−2853 this is because its thermal emission is strongly absorbed by the high hydrogen column density (Degenaar et al. 2012a); the reason for other sources is that they are persistent accretors, while we need to observe them in quiescent state to determine their internal temperature (Haskell et al. 2012).

[9] At the moment of publication of Heinke (2010), only seven systems have been observed in active state. However, recently, the qLMXB candidate X-3 in the GC Ter 5 (classified as Ter 5, W3 in Heinke et al. 2003b and as CX2 in Heinke et al. 2006b) has been observed in outburst (Bahramian et al. 2014), confirming thus that it is indeed an LMXB system. In this respect, it is interesting to note that this source showed a variability (Heinke et al. 2006b; Bahramian et al. 2014) and its X-ray spectrum had a considerable (28^{+8}_{-7} per cent; see table 3 of Heinke et al. 2006b) contribution of power-law component. Thus, it could not be classified as 'hot widow'/HOFNAR candidate even in 2006.

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in Lasota 2001 and references therein). Possible resolution of this problem, related to the low-level accretion on to NSs, is indicated by Heinke (2010). Still, if some qLMXB candidates are 'hot widows'/HOFNARs, this reduces an observational estimate for a total number of LMXB systems in GCs and, as a consequence, makes the recurrence time smaller.

(iv) Total number of MSPs in GCs.
Ivanova et al. (2008) showed that account for all channels of formation and spin-up of NSs in GCc leads to overproduction of MSPs, although all these channels are necessary for explanation of the observed number of LMXB systems. Ivanova et al. (2008) suggested that the formation of MSPs with large magnetic fields, leading to their fast deceleration, could serve as a possible way out of that paradox. However, almost all the observed MSPs have low spin-down rates (see e.g. Tauris 2012). An existence of 'hot widows'/HOFNARs can help to resolve the paradox because of the following two reasons: (i) if some of qLMXB candidates are indeed 'hot widows'/HOFNARs this should reduce an observational estimate for the total number of LMXBs in GCs; (ii) a possibility that 'hot widows'/HOFNARs originate from LMXBs should result in a lower production rate of MSPs.

Detailed population synthesis calculations, taking into account a possibility of 'hot widow'/HOFNAR formation, can reveal additional pieces of evidence for the existence of these objects.

5 RESULTS, CONCLUSIONS AND OUTLOOK

We study a hypothesis about a new possible class of hot rapidly rotating non-accreting NSs ('hot widow'/HOFNAR objects), whose high temperature is maintained for a long time ($\sim 10^9$ yr) by instability of r modes. In Section 2, we show that these objects should inevitably be produced in LMXBs, provided that the r-mode instability operates for NSs with the spin frequencies 300–600 Hz (which means that at least some of the observed NSs are unstable). The X-ray sources, whose spectra allow us to classify them as qLMXB candidates, can equally well be considered as candidates for 'hot widows'/HOFNARs (Section 3). Combined analysis of X-ray and optical observations of any such candidate can exclude the possibility of Roche lobe overflow in a binary system and hence prove that this NS is indeed a 'hot widow'/HOFNAR. Even observations, available at the present time, indicate that this condition is met for the sources X5 and X7 in GC 47 Tuc (Edmonds et al. 2002). This makes them promising candidates for 'hot widows'/HOFNARs. In addition, a statistical analysis of observational data and the results of population synthesis calculations provide pieces of indirect evidence in favour of the 'hot widow'/HOFNAR existence (Section 4.2).

A confirmation of the 'hot widow'/HOFNAR hypothesis opens interesting new ways for studying NSs. If these objects are real, this would provide a strong evidence for the CFS-instability in NSs and hence the possibility of gravitational wave generation by *mass–current* multipole (rather than by *mass* multipole, as is usually the case, see e.g. Andersson et al. 2013). Moreover, 'hot widows'/HOFNARs have stable purely thermal emission spectra and thus can be used, together with qLMXBs (Guillot et al. 2013), to constrain mass and radius of NSs from their X-ray observations. Furthermore, in the model of resonance interaction of oscillation modes [Fig. 1(a) and Gusakov et al. 2014a] 'hot widow'/HOFNAR temperatures should coincide with the resonance temperatures in oscillation spectrum of rotating NSs. The resonance temperatures are sensitive to the equation of state, critical temperature profiles etc. Therefore, confronting theoretically calculated resonance temperatures with observations can serve as a unique seismological tool to study microphysical properties of NS interiors. The fact that the very same objects allow, in principle, to measure their masses and radii with X-ray spectra (Guillot et al. 2013) makes this method even more promising.

At the present time, all known 'hot widow'/HOFNAR candidates are localized in GCs. The situation can change with SRG X-ray observatory, which will perform all-sky survey with high spatial and spectral resolution. It will make possible to identify hot NSs (see e.g. Merloni et al. 2012), which can be considered as qLMXB candidates, 'hot widows'/HOFNARs, or young NSs. Detailed analysis of these candidates would be a very interesting task. It could help to solve the MSP birthrate problem (Kulkarni & Narayan 1988; Levin et al. 2013), and present one more evidence for the 'hot widow'/HOFNAR existence.

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REFERENCES

Andersson N., 1998, ApJ, 502, 708
Andersson N., Kokkotas K. D., 2001, Int. J. Mod. Phys. D, 10, 381
Andersson N. et al., 2013, Class. Quantum Gravity, 30, 193002
Antoniadis J. et al., 2013, Science, 340, 448
Archibald A. M. et al., 2009, Science, 324, 1411
Bahramian A. et al., 2014, ApJ, 780, 127
Bogdanov S., Grindlay J. E., Rybicki G. B., 2008, ApJ, 689, 407
Bogdanov S., Archibald A. M., Hessels J. W. T., Kaspi V. M., Lorimer D., McLaughlin M. A., Ransom S. M., Stairs I. H., 2011, ApJ, 742, 97
Bogdanov S., Esposito P., Crawford F., III, Possenti A., McLaughlin M. A., Freire P., 2014, ApJ, 781, 6
Bondarescu R., Wasserman I., 2013, ApJ, 778, 9
Brown E. F., Bildsten L., Rutledge R. E., 1998, ApJ, 504, L95
Chandrasekhar S., 1970, Phys. Rev. Lett., 24, 611
Chen H.-L., Chen X., Tauris T. M., Han Z., 2013, ApJ, 775, 27
Chugunov A. I., 2012, Astron. Lett., 38, 25
Degenaar N., Wijnands R., Cackett E. M., Homan J., in't Zand J. J. M., Kuulkers E., Maccarone T. J., van der Klis M., 2012a, A&A, 545, A49
Degenaar N., Patruno A., Wijnands R., 2012b, ApJ, 756, 148
Demorest P. B., Pennucci T., Ransom S. M., Roberts M. S. E., Hessels J. W. T., 2010, Nature, 467, 1081
Edmonds P. D., Heinke C. O., Grindlay J. E., Gilliland R. L., 2002, ApJ, 564, L17
Faulkner A. J. et al., 2004, MNRAS, 355, 147
Friedman J. L., Morsink S. M., 1998, ApJ, 502, 714
Friedman J. L., Schutz B. F., 1978a, ApJ, 221, 937
Friedman J. L., Schutz B. F., 1978b, ApJ, 222, 281
Gnedin O. Y., Yakovlev D. G., Potekhin A. Y., 2001, MNRAS, 324, 725
Grindlay J. E., Heinke C. O., Edmonds P. D., Murray S. S., Cool A. M., 2001, ApJ, 563, L53
Guillot S., Rutledge R. E., Brown E. F., Pavlov G. G., Zavlin V. E., 2011, ApJ, 738, 129
Guillot S., Servillat M., Webb N. A., Rutledge R. E., 2013, ApJ, 772, 7
Gusakov M. E., Kaminker A. D., Yakovlev D. G., Gnedin O. Y., 2004, A&A, 423, 1063

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Gusakov M. E., Chugunov A. I., Kantor E. M., 2014a, Phys. Rev. Lett., 112, 151101
Gusakov M. E., Chugunov A. I., Kantor E. M., 2014b, Phys. Rev. D, 90, 063001
Haensel P., Potekhin A., Yakovlev D., 2006, Astrophysics and Space Science Library, Vol. 326, Neutron Stars 1: Equation of State and Structure. Springer-Verlag, Berlin
Harding A. K., 2013, Frontiers Phys., 8, 679
Haskell B., Degenaar N., Ho W. C. G., 2012, MNRAS, 424, 93
Haskell B., Glampedakis K., Andersson N., 2014, MNRAS, 441, 1662
Heinke C. O., 2010, in Kologera V., van der Sluys M., eds, AIP Conf. Proc. Vol. 1314, International Conference on Binaries: In Celebration of Ron Webbink's 65th Birthday. Am. Inst. Phys., New York, p. 135
Heinke C. O., Ho W. C. G., 2010, ApJ, 719, L167
Heinke C. O., Grindlay J. E., Lloyd D. A., Edmonds P. D., 2002, in Slane P. O., Gaensler B. M., eds, ASP Conf. Ser. Vol. 271, Neutron Stars in Supernova Remnants. Astron. Soc. Pac., San Francisco, p. 349
Heinke C. O., Grindlay J. E., Lloyd D. A., Edmonds P. D., 2003a, ApJ, 588, 452
Heinke C. O., Grindlay J. E., Lugger P. M., Cohn H. N., Edmonds P. D., Lloyd D. A., Cool A. M., 2003b, ApJ, 598, 501
Heinke C. O., Grindlay J. E., Edmonds P. D., 2005a, ApJ, 622, 556
Heinke C. O., Grindlay J. E., Edmonds P. D., Cohn H. N., Lugger P. M., Camilo F., Bogdanov S., Freire P. C., 2005b, ApJ, 625, 796
Heinke C. O., Rybicki G. B., Narayan R., Grindlay J. E., 2006a, ApJ, 644, 1090
Heinke C. O., Wijnands R., Cohn H. N., Lugger P. M., Grindlay J. E., Pooley D., Lewin W. H. G., 2006b, ApJ, 651, 1098
Heinke C. O., Jonker P. G., Wijnands R., Taam R. E., 2007, ApJ, 660, 1424
Heinke C. O., Jonker P. G., Wijnands R., Deloye C. J., Taam R. E., 2009, ApJ, 691, 1035
Heyl J. S., 2002, ApJ, 574, L57
Ho W. C. G., Andersson N., 2012, Nat. Phys., 8, 787
Ho W. C. G., Lai D., 2000, ApJ, 543, 386
Ho W. C. G., Andersson N., Haskell B., 2011, Phys. Rev. Lett., 107, 101101
Homer L., Szkody P., Chen B., Henden A., Schmidt G., Anderson S. F., Silvestri N. M., Brinkmann J., 2006, AJ, 131, 562
Illarionov A. F., Sunyaev R. A., 1975, A&A, 39, 185
Ivanova N., Heinke C. O., Rasio F. A., Belczynski K., Fregeau J. M., 2008, MNRAS, 386, 553
Kantor E. M., 2011, in Baiko D. A., Uvarov Y. A., Yakovlev D. G., eds, Proc. Int. Conf. on the Physics of Neutron Stars: Book of Abstracts. Publishing house of Polytechnical Univ., St. Petersburg, p. 64
Kulkarni S. R., Narayan R., 1988, ApJ, 335, 755
Lasota J.-P., 2001, New Astron. Rev., 45, 449
Levin Y., 1999, ApJ, 517, 328
Levin Y., Ushomirsky G., 2001, MNRAS, 324, 917
Levin L. et al., 2013, MNRAS, 434, 1387
Lindblom L., Owen B. J., Morsink S. M., 1998, Phys. Rev. Lett., 80, 4843
Mahmoodifar S., Strohmayer T., 2013, ApJ, 773, 140
Merloni A. et al., 2012, preprint (arXiv:1209.3114)
Owen B. J., Lindblom L., Cutler C., Schutz B. F., Vecchio A., Andersson N., 1998, Phys. Rev. D, 58, 084020
Page D., Lattimer J. M., Prakash M., Steiner A. W., 2004, ApJS, 155, 623
Page D., Prakash M., Lattimer J. M., Steiner A. W., 2011, Phys. Rev. Lett., 106, 081101
Papitto A. et al., 2013, Nature, 501, 517
Papitto A., Torres D. F., Rea N., Tauris T., 2014, A&A, 566, A64
Patruno A. et al., 2014, ApJ, 781, L3
Pines D., Alpar M. A., 1985, Nature, 316, 27
Posselt B., Pavlov G. G., Suleimanov V., Kargaltsev O., 2013, ApJ, 779, 186
Potekhin A. Y., Chabrier G., Yakovlev D. G., 1997, A&A, 323, 415
Priymak M., Melatos A., Payne D. J. B., 2011, MNRAS, 417, 2696
Reisenegger A., Bonačić A., 2003, Phys. Rev. Lett., 91, 201103
Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., 2000, ApJ, 529, 985
Shternin P. S., Yakovlev D. G., Heinke C. O., Ho W. C. G., Patnaude D. J., 2011, MNRAS, 412, L108
Tauris T. M., 2011, in Schmidtobreick L., Schreiber M. R., Tappert C., eds, ASP Conf. Ser. Vol. 447, Evolution of Compact Binaries. Astron. Soc. Pac., San Francisco, p. 285
Tauris T. M., 2012, Science, 335, 561
Tauris T. M., van den Heuvel E. P. J., 2006, in Lewin W. H. G., van der Klis M., eds, Compact Stellar X-ray Sources. Cambridge Univ. Press, Cambridge, p. 623
Urpin V., Konenkov D., 2008, A&A, 483, 223
Viganò D., Rea N., Pons J. A., Perna R., Aguilera D. N., Miralles J. A., 2013, MNRAS, 434, 123
Vigelius M., Melatos A., 2009, MNRAS, 395, 1985
Watts A. L., 2012, ARA&A, 50, 609
Wijnands R., Degenaar N., Page D., 2013, MNRAS, 432, 2366
Zavlin V. E., 2007, Ap&SS, 308, 297

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