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

A. I. Chugunov1⋆, M. E. Gusakov1,2† E. M. Kantor1‡
1Ioffe Institute, St Petersburg, Russia
2St.-Petersburg State Polytechnical University, Polytekhnicheskaya 29, 195251 St.-Petersburg, Russia

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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 neutron stars. 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 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 indirect evidences in favor 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 analyzed.

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

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., Viganò et al. 2013; Papitto et al. 2013). Detailed observations of NSs from each class together with their accurate theoretical modeling 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; Shsternin et al. 2011). 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 reli-

1Observations of this NS have been recently reanalyzed 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 Shsternin et al. (2011). If these new results are correct, parameters of the superfluid model of Shsternin 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).
able measurements of NS masses (see, e.g., Demorest et al. 2011; Antoniadis et al. 2013), while observations of hot NSs in 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 $T_{\text{eff}} \sim 10^6$ K, internal redshifted temperatures $T_{\infty} \sim 10^9$ K) nonaccreting rapidly rotating (spin frequencies $\nu \gtrsim 200$ Hz) NSs, whose temperature stays high during $\sim 10^9$ yrs because of the $r$-mode instability. Such stars can be descendants of NSs in LMXBs (see, e.g., Reisenegger & Benz 2003; Bondarescu & Wasserman 2013; Gusakov et al. 2014a and Sec. 2) and, as we will show here, they form a new class of NSs with very specific physical properties and observational features (see Sec. 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 $L_{\text{cool}} \sim 10^{36}$ 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, $E \sim L_{\text{cool}} t \sim 10^{41}$ erg. In a nonaccreting NS only rotation can afford such a huge energy budget. In addition, rotation energy should be deposited into thermal energy with very high efficiency ($\sim 30\%$), which is achievable with $r$-mode instability [see Eq. (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 twenty years ago by Andersson (1998) and Friedman & Morsink (1998). It is a particular case of the instability analysed by Chandrasekhar (1970) and Friedman & Schutz (1979a,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 1979a,b; Levin & Ushomirsky 2001; Ho & Lai 2000]. As a result, gravitational waves emitted by $r$-modes excite (rather than damp) $r$-modes at arbitrary spin frequency $\nu$ (Andersson 1998; Friedman & Morsink 1998; Lindblom, Owen, & Morsink 1998). An account for dissipation suppresses instability at low $\nu$. 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 spontaneouly and their dissipation becomes an important source of stellar heat-energy (Friedman & Schutz 1978a,b; Levin & Ushomirsky 1999). An account for dissipation suppresses instability at low $\nu$ and is briefly described here for completeness. Corresponding evolutionary tracks in the plane “rotation frequency $\nu$ — red-shifted internal temperature $T_{\infty}$” 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 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 $M = 1.4M_\odot$ and radius $R \sim 10$ 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_{\text{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 (Bondarescu & Wasserman 2013). 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 Brown, Bildsten, & Rutledge (1998). That model allows one to explain all observations.

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); Gusakov et al. (2014a,b). 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 $\nu$ — red-shifted internal temperature $T_{\infty}$” 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 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 $M = 1.4M_\odot$ and radius $R \sim 10$ 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).

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Footnote 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.
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 \( M = 1.4 M_\odot \). The accretion rate, averaged over long period of time, involving both quiescent and active phases, is chosen to be \( \dot{M} = 3 \times 10^{-10} M_\odot/\text{yr} \). Such \( M \) 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 \( T_{\text{eq}}^\infty \approx 1.08 \times 10^8 \text{ K} \), 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). Ascending the stability peak can be terminated at \( T_{\text{eq}}^\infty \approx 1.08 \times 10^8 \text{ K} \), at which the spin up accretion torque balances the joint torque produced by the magnetodipole 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 continues, and the star cools down to the temperature \( T_{\text{eq}}^\infty = T_{\text{eq}}^\infty \). Then the evolution cycle repeats. A typical period of the cycle is about \( 10^8 \) years (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. 2014a). 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; Gusakov et al. 2014b; Bondarescu & Wasserman 2013). 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 \( \nu_{\text{eq}} \) (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 2004; 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 \( \nu_{\text{eq}} \) 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. 1993; Ho & Lei 2000; Gusakov et al. 2014b]. The corresponding evolutionary paths are shown in Fig. 1(b) by the thick dashes. In model (a) the end of accretion epoch does not lead to reduction of $T^\infty_r$, because this would amplify the NS instability [see Fig. 1(a)]. 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 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 $\nu$ in the beginning of the ”hot widow”/HOFNAR phase is determined by the frequency $\nu$ at the end of LMXB stage 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,

$$\tau_\text{GR} = \tau_\text{Diss},$$

where $\tau_\text{GR}$ and $\tau_\text{Diss}$ are gravitational-wave and damping timescales, respectively. In the case of model (a) this condition is fulfilled because of marginal stability of r-mode (see Gusakov 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 $\tau_\text{Diss}$ includes also dissipation due to these processes (Gusakov et al. 2014b). Using Eq. (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 ($E_{\text{rot}}$) loss because of the instability of $m = 2$ r-mode is given by

$$\frac{dE_{\text{rot}}}{dt} = 3L_{\text{cool}}.$$

Thus, the total NS thermal emissivity $L_{\text{cool}}$ (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, $E_{\text{th}} \sim E_{\text{rot}}/3 \sim 10^{51}$ erg, while the life time of an NS at this stage constitutes $E_{\text{rot}}/(3L_{\text{cool}}) \sim 10^9$ years. 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.

Notice that in the model (a), depending on the value of $T^\infty_r$, 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. 2014b). 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 centered at $T^\infty_r \approx 4.5 \times 10^7$ K if $T^\infty_\text{eq} \lesssim 4 \times 10^7$ 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) analyzed 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 timescale $\tau_r$ for the crustal magnetic field,

$$\tau_r \approx \frac{4\pi l^2}{c^2} \sim 4 \times 10^6 \frac{\sigma}{10^{24} \text{s}^{-1}} \left( \frac{l}{10^9 \text{cm}} \right) \text{yr},$$

is three orders of magnitude lower than the ”hot widow”/HOFNAR life time due to relatively low electrical conductivity $\sigma$ at high temperature ($\sigma \sim 10^{24} \text{s}^{-1}$ at $T \sim 10^8$ K and density $\sim 10^{13} \text{g cm}^{-3}$; see, e.g., Gnedin, Yakovlev & Potekhin 2001; Chugunov 2012). In Eq. (3) $c$ is the speed of light, and $l$ is the typical length scale $\sim 10^9$ cm. This simple estimate agrees with much more sophisticated calculations (e.g., Urpin & Konenkov 2003; Vigelius & Melatos 2006). 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 nontrivial, 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”/HOFNARSs are hot NSs, with the internal temperatures $T^\infty_r \sim 10^9$ K corresponding to the effective redshifted surface temperatures $T^\infty_{\text{eff}} \sim 10^6$ K (Potekhin et al. 1997). Therefore “hot widows”/HOFNARSs should exhibit thermal X-ray emission.

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 two (or even more). This effect can reduce amount of NSs that stay unstable (and thus become “hot widows”/HOFNARSs) after the end of LMXB stage.

Accurate evaluation of the time required to brake the star from rotation frequency 600 Hz down to the frequency when it becomes stable gives: $\sim 10^7$, $4 \times 10^9$, and $8 \times 10^{10}$ yrs 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 et al. 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 $T^\infty_{\text{eff}} \sim 5 \times 10^5$ K.
from their whole surface, and as they do not accrete matter (and have low magnetic field), the contribution of the non-
thermal component should be small. Exactly these pro-
erties of X-ray spectrum have been required for the selec-
tion of candidates to LMXBs in quiescent state (qLMXBs)
among various X-ray sources in GCs (Rutledge et al. 2004;
Heinke et al. 2003b; Guillot et al. 2011). Thus, qLMXB-
candidates, which: (i) have never been observed in outbursts
[i.e. no signatures of strong accretion have been detected; ap-
proximately 30 of such qLMXB candidates are known at the
present time, see Wijnands et al. 2013 and (ii) have thermal
X-ray spectra, can be considered as candidates to “hot wid-
ows” /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 hence, as
a result, NS does not accrete significantly. This fact allows us to for-
mulate identification criteria for “hot widows” /HOFNARs
based on optical observations (see Sec. 4.1).

4 EVIDENCES FOR THE “HOT
WIDOWS” /HOFNARs EXISTENCE

4.1 A possibility to reliably identify “hot
widows” /HOFNARs

Detection of a hot (\( T_{\text{eff}} \sim 10^6 \) 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 instance, observations
show that the source X5 in GC 47 Tuc is a hot NS (\( T_{\text{eff}} = 1.06^{+0.16}_{-0.46} \times 10^6 \) K, Heinke et al. 2003a) in the eclipsing binary
with the orbital period 8.666 ± 0.008 hours (Heinke et al.
2002). Optical observations with the Hubble Space Tele-
scope by Edmonds et al. (2002) have identified the optical
companion as a red main-sequence star and have revealed
the presence of an accretion disk. 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
(\( \text{Homer} et al. 2006, \text{Bogdanov} et al. 2011 \). 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. 4(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. 2003), whose X-ray
spectrum agrees with the redshifted surface temperature \( T_{\text{eff}} \sim (4 \pm 5) \times 10^6 \) K (see table 1 of Bogdanov et al. 2014).

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.

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

\section{Indirect evidences}

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 analyzed 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 hypo-
thesis we list them here as an indirect evidences in its favour.

\begin{itemize}
\item 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 1608-52, SAX J1750.8-2900, MXB 1659-28= (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 oscillation 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.

- 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. 2003a; Guillot et al. 2011], although the selection criteria for qLMXBs, applied, e.g., by Heinke et al. (2003a), allows for the contribution of up to 40% 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 2012a). 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.

- 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 et al. 2005a). However, only $N_{\text{qLMXB}} \sim 8$ of them have been observed in outburst for over $t_{\text{obs}} \sim 40$ yrs of satellite observations. This leads to the following estimate for an average recurrence time, $\sim N t_{\text{obs}}/N_{\text{qLMXB}} \sim 1000$ yrs (Heinke 2010). However, 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 case of GRS 1741.9-2853 this is because its thermal emission is strongly absorbed by the high hydrogen column density (Degenaar et al. 2012b); 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, Degenaar, & Ho 2012).

- $^8$ At the moment of publication of Heinke (2010) only 7 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. 2003a and as CX2 in Heinke et al. 2006a) 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. 2006a; Bahramian et al. 2014) and its X-ray spectrum had a considerable [28±8%], see table 3 of Heinke et al. 2006a] contribution of power-law component. Thus, it could not be classified as “hot widow”/HOFNAR candidate even in 2006.

5 RESULTS, CONCLUSIONS AND OUTLOOK

We study a hypothesis about a new possible class of hot rapidly rotating non-accreting neutron stars (“hot widow”/HOFNAR objects), whose high temperature is maintained for a long time ($\sim 10^9$ years) by instability of r-modes. In Sec. 2 we show that these objects should inevitability 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 to classify them as qLMXB candidates, can equally well be considered as candidates for “hot widows”/HOFNARs (Sec. 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 indirect evidences in favour of the “hot widow”/HOFNAR existence (Sec. 3).

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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