ON THE FORMATION OF THE PECULIAR LOW-MASS X-RAY BINARY IGR J17480−2446 IN TERZAN 5

LONG JIANG1,2 AND XIANG-DONG LI1,2
1 Department of Astronomy, Nanjing University, Nanjing 210093, China; lixd@nju.edu.cn
2 Key laboratory of Modern Astronomy and Astrophysics, Nanjing University, Ministry of Education, Nanjing 210093, China
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ABSTRACT

IGR J17480−2446 is an accreting X-ray pulsar in a low-mass X-ray binary harbored in the Galactic globular cluster Terzan 5. Compared with other accreting millisecond pulsars, IGR J17480−2446 is peculiar for its low spin frequency (11 Hz), which suggests that it might be a mildly recycled neutron star at the very early phase of mass transfer. However, this model seems to be in contrast with the low field strength deduced from the kilo-Hertz quasi-periodic oscillations observed in IGR J17480−2446. Here, we suggest an alternative interpretation, assuming that the current binary system was formed during an exchange encounter either between a binary (which contains a recycled neutron star) and the current donor, or between a binary and an isolated, recycled neutron star. In the resulting binary, the spin axis of the neutron star could be parallel or anti-parallel with the orbital axis. In the latter case, the abnormally low frequency of IGR J17480−2446 may result from the spin-down to spin-up evolution of the neutron star. We also briefly discuss the possible observational implications of the pulsar in this scenario.

Key words: stars: evolution – stars: neutron – X-rays: binaries – X-rays: stars

1. INTRODUCTION

Millisecond pulsars are thought to be old neutron stars that have been recycled in low-mass X-ray binaries (LMXBs; Aplar et al. 1982). According to this scenario, material is transferred to the neutron star from its companion when it fills its Roche lobe, spinning up the neutron star to a millisecond period, and reducing the surface magnetic field by several orders of magnitude, from $\sim 10^{11}–10^{12}$ G to $\sim 10^8–10^9$ G (see Bhattacharya & van den Heuvel 1991 for a review).

Currently, there are 14 accreting millisecond pulsars (Patruno & Watts 2012). The first accreting millisecond pulsar is SAX J1808.4−3658, which rotates at a frequency of 401 Hz (Wijnands & van der Klis 1998). Spectral modeling of the iron line constrained its magnetic field to be $\sim 3 \times 10^8$ G at the poles (Cackett et al. 2009; Papitto et al. 2009), similar to the value of $\sim 2 \times 10^8$ G derived from the spin-down rate measured between outbursts (Hartman et al. 2008, 2009). With a spin frequency of 599 Hz, IGR J00291 + 5934 is another source showing both spin-up and spin-down during and between outbursts, respectively, suggesting the magnetic field to be $\sim 2 \times 10^9$ G (Hartman et al. 2011). Both SAX J1808.4−3658 and IGR J00291 + 5934 are composed of an accreting pulsar and a brown dwarf companion. The 435 Hz accreting pulsar XTE J1751−305 has a helium white dwarf companion. Its magnetic field was derived from its spin-down to be $\sim 4 \times 10^8$ G, while its spin-up during the 2005 outburst was strongly affected by timing noise (Papitto et al. 2009). From the aforementioned examples, one sees that the spin frequencies and magnetic fields reported are consistent with the prediction of the recycling scenario.

A new accreting pulsar, IGR J17480−2446, was detected with the International Gamma-Ray Astrophysics Laboratory in 2010 October (Bordas et al. 2010). This system is located in the core of Terzan 5, one of the densest globular clusters in the Galaxy. It looks like a typical LMXB, with an orbital period of 21.3 hr. The binary mass function was estimated to be $\sim 0.021275(5) \ M_\odot$, indicating a companion star with a mass larger than 0.4 $M_\odot$ (Papitto et al. 2011). The most remarkable feature of IGR J17480−2446 is that its rotating frequency is only 11 Hz (Strohmayer & Markwardt 2010), too slow compared with the known spin frequencies ($\sim 185–600$ Hz) of accreting millisecond pulsars.

Estimating the magnetic field of IGR J17480−2446 is not straightforward. Assuming that the inner radius of the accretion disk lies between the neutron star’s radius and the corotation radius when the source shows pulsations, Papitto et al. (2011) and Cavecchi et al. (2011) evaluated the magnetic field in the range from $\sim 2 \times 10^{9}$ to $\sim 2 \times 10^{10}$ G. Miller et al. (2011) used the results of a relativistic iron line fit to estimate the magnetic field at the poles to be $B \sim 10^9$ G. Papitto et al. (2012) estimated the magnetic field in the range between $\sim 5 \times 10^9$ and $\sim 1.5 \times 10^{10}$ G from the spin-up rate during outbursts. Finally, assuming the kilo-Hertz quasi-periodic oscillation (kHz QPO) frequency as an orbital frequency at the inner disk radius, one can place a lower limit on the radius. If the disk is truncated at the magnetospheric radius, then the upper limit of the magnetic field of the neutron star can be derived. Barret (2012) detected highly significant QPOs soon after the source had moved from the atoll state to the Z state at frequencies between 800 and 870 Hz, and suggested that the surface magnetic field is less than $5 \times 10^8$ G (see also Altamirano et al. 2012).

The above investigations indicate that there is a possibility that the magnetic field of IGR J17480−2446 is similar to other accreting millisecond pulsars. If this is the case, then there is an interesting implication for its magnetic field evolution. It is controversial whether there is long-term evolution of the magnetic fields of rotation-powered neutron stars. However, magnetic field decay in accreting neutron stars has been widely accepted, and the mechanisms include accelerated Ohmic decay, vortex–fluid interactions, and magnetic burial or screening (Payne et al. 2008, for a review). Shibazaki et al. (1989) proposed a phenomenological form relating magnetic field evolution with accreted mass $\Delta m$ (see also Romani 1990),

$$B = \frac{B_0}{1 + \frac{\Delta m}{m_\ast}},$$  \hspace{1cm} (1)

where $B_0$ is the initial magnetic field and $m_\ast$ is a constant. By fitting to observations of LMXBs, Shibazaki et al. (1989) found $m_\ast \sim 10^{-4} \ M_\odot$. van den Heuvel & Bitzaraki (1995)
showed that there is a remarkable correlation between the magnetic fields and the orbital periods of binary radio pulsars with nearly circular orbits and low-mass helium white dwarf companions. This relation is consistent with an increasing decay of the neutron star magnetic field with an increasing amount of accreted material of \( \lesssim 10^9 \) G have accreted material of \( (0.5 f) M_\odot \), where \( f \sim 0.5-1 \) is the accretion efficiency. From the measured masses of neutron stars in binary systems, Zhang et al. (2011) also found that the average mass of millisecond radio pulsars is indeed \( \sim 0.2 M_\odot \), which is heavier than that of other long-period pulsars.

The anomalously low rotation frequency suggests that IGR J17480–2446 could be exactly in the process of becoming an accreting millisecond pulsar. Indeed, observations show that it is spinning-up at a rate \( \dot{v} \approx 1.4 \times 10^{-12} \) Hz s\(^{-1}\) (Cavecchi et al. 2011; Patruno et al. 2012). Patruno et al. (2012) proposed that IGR J17480–2446 is a mildly recycled pulsar which has started a spin-up phase lasting less than a few \( 10^5 \) yr. This means that IGR J17480–2446 is in an exceptionally early RLOF phase. A potential problem of this scenario is that the incipient RLOF mass transfer may cause little field reduction according to Equation (1) (see discussion in Section 3). To account for this, Patruno et al. (2012) assumed that the neutron star underwent two phases of evolution, i.e., the magneto-dipole spin-down and the wind accretion spin-down before the current RLOF spin-up phase. During the wind accretion phase, the neutron star magnetic field \( B \) decayed to \( \sim 10^{10} \) G, in proportion to the rotation rate, due to the flux-line–vortex-line coupling (Srinivasan et al. 1990). However, this model of magnetic field decay does not seem to be compatible with observations. For example, the symbiotic X-ray pulsar GX 1+4 is believed to possess a very strong magnetic field \( B \sim 3 \times 10^{13} \) G with a very low spin frequency \( 6.3 \times 10^{-3} \) Hz (Cui 1997). Other long-period X-ray pulsars such as 4U 2206+54 (Finger et al. 2010; Reig et al. 2012), GX301–2 (Doroshenko et al. 2010), and SXP 1062 (Fu & Li 2012) are even thought to be accreting magnetars with \( B > 10^{14} \) G.

Alternatively, if the magnetic field of IGR J17480–2446 is \( \sim 10^8-10^9 \) G, then Equation (1) implies that it should have accreted a sufficient amount of mass (at least \( 0.1 M_\odot \)), and it will be difficult to explain its slow spin in the traditional recycling scenario. Considering the fact that Terzan 5 is one of the densest and most metal-rich clusters in our Galaxy (Cohn et al. 2002; Ortolani et al. 2007), with 35 rotation-powered millisecond pulsars discovered so far (Ransom et al. 2005; Hessels et al. 2006; Pooley et al. 2010), we suggest that the companion star of IGR J17480–2446 is the original one in its primordial binary, and that the neutron star has undergone a close encounter during which the primordial binary system broke up and formed a triple system. In the end of the short-interval triple phase, the neutron star captured the current companion and lost its first donor, which had spun up to a spin of milliseconds (along with the magnetic field having decayed to \( \sim 10^8-10^9 \) G). When the second mass transfer occurred, if the spin angular momentum of the neutron star was reversed to the orbital angular momentum of the current companion, then the neutron star was spun-down first. This phase lasted \( \sim 10^8 \) yr until the spin angular momentum reduced to zero, and was succeeded by the current spin-up. Since the second spin-up epoch started just recently, it is not abnormal to detect the system with slow spin.

The structure of this paper is as follows. In the following section, we briefly review the exchange encounter processes in the globular cluster and estimate the formation rate of neutron stars that have evolved from the reversed-to-parallel accretion channel. In Section 3, we describe the possible evolution of IGR J17480–2446 in some detail. The observational implications are discussed in Section 4.

2. THE CHANCE OF EXCHANGE ENCOUNTERS IN TERZAN 5

Terzan 5 is reported as the densest globular cluster, with a central mass density \( \sim (1-4) \times 10^6 M_\odot \) pc\(^{-3}\) (Lanzoni et al. 2010). It is composed of two different populations of stars with sub-solar metallicity (\( Y = 0.26 \) and \( Z = 0.011 \)) and an age of 12(±1) Gyr, and with supra-solar metallicity (\( Y = 0.29 \) and \( Z = 0.03 \)) and an age of 6(±2) Gyr. Given the high density and old age of Terzan 5, its X-ray binaries are likely to have formed during close encounter processes: a neutron star was captured tidally during a close encounter with a single star or took the place of one member of a binary star in an exchange encounter. In our case, we assume that the current donor of IGR J17480–2446 has exchanged its original companion in the progenitor binary. We set \( m_1 \) as the mass of the first donor, which has lost most of its matter and was ejected after the encounter, \( m_2 \) as the mass of the neutron star, and \( m_3 \) as the mass of the incoming object, assumed to be a main-sequence star (all the masses are in the units of \( M_\odot \)). Following Heggie et al. (1996), we write the semi-analytical exchange cross section as follows:

\[
\sigma_{\text{ex}} = (1.39 \times 10^3 \text{AU}^2) \bar{v}_\infty^{-2} m_1^{7/2} m_2^{1/6} m_3^{1/6} M_\odot^{-5/2} M_\odot^{-1/3} \bar{v}_\text{ek}^2 \approx (1.39 \times 10^3 \text{AU}^2) \bar{v}_\infty^{-2} m_1^{7/2} m_2^{1/6} m_3^{1/6} M_\odot^{-5/2} M_\odot^{-1/3} \bar{v}_\text{ek}^2 \ (\text{2})
\]

where

\[
M_{12} = m_1 + m_2, \quad M_{13} = m_1 + m_3,
\]
\[
M_{23} = m_2 + m_3, \quad M_{123} = m_1 + m_2 + m_3,
\]
\[
k = 3.70 + 7.49 \mu_1 - 1.89 \mu_2 - 15.49 \mu_1^2 - 2.93 \mu_1 \mu_2 - 2.92 \mu_2^2 + 3.07 \mu_1^3 + 13.15 \mu_1^2 \mu_2 - 5.23 \mu_1 \mu_2^2 + 3.12 \mu_2^3,
\]
\[
\mu_1 = m_1/M_{12}, \quad \mu_2 = m_3/M_{123}.
\]

Here \( \bar{v} \) is the average orbital separation of the binary in units of \( \text{AU} \), and \( \bar{v}_\infty \) is the velocity dispersion of the cluster in \( \text{km s}^{-1} \). This exchange process results in a binary system consisting of a main-sequence companion and a recycled neutron star. The encounter rate is roughly

\[
\Gamma \approx n_\text{bin} \sigma_{\text{ex}} \bar{v}_\infty
\]
\[
\approx (3.35 \times 10^{-14} \text{pc}^{-3} \text{yr}^{-1}) n_\text{bin} n_\text{bin} \bar{v}_\infty^3 M_\odot^{7/2} M_\odot^{1/6} M_\odot^{-5/2} \bar{v}_\text{ek}^{1/3} \bar{v}_\text{ek}^2
\]

\[
\times M_{12}^{1/6} M_{23}^{1/3} M_{123}^{-1/3} \bar{v}_\text{ek}^2,
\]

where \( n_\text{bin} \) and \( n_\text{bin} \) are the number densities (in units of \( \text{pc}^{-3} \)) of the target stars and the original binaries, respectively.

We first discuss the number density of the target objects. We assume that all the stars in the globular cluster were formed more or less simultaneously, and the initial mass distribution is given by a power-law function: \( dN = C_0 m^{-1.5} \text{dm} \) (Salpeter 1955; Verbunt 1988), where both the normalization constant \( C_0 \) and the power index \( x \) need to be derived from the observational data. For Terzan 5, we set the value of \( x \) to be in the range of 1–2 (cf. Verbunt & Hut 1987; Verbunt 1988). The normalization constant \( C_0 \) is dependent on the total stellar mass in the globular

\[
5 \text{ Alternatively, an isolated millisecond pulsar may capture a main-sequence star, or exchange with a less massive star in a normal binary, to form an LMXB.}
\]
where \( m_{\text{up}} \) and \( m_{\text{low}} \) are the upper and lower mass limits of the target stars, respectively, while \( m_{\text{max}} \) and \( m_{\text{min}} \) are for all stars in the globular cluster. We take the turnoff mass as the upper limit of the stellar mass in the cluster, which can be calculated from the main-sequence lifetime of a star with mass \( m \) (Eggleton 2006),

\[
t_{\text{MS}}(\text{Myr}) = \frac{m^7 + 146m^{5.5} + 2740m^4 + 1532}{0.3432m^2 + 0.0397m^2}
\]

(4)

for \( 0.25 \leq m \leq 50 \).

Setting \( m_{\text{min}} = 0.1 \) and \( m_{\text{max}} = 1.2 \) (i.e., the turnoff mass of stars with age of 6 Gyr), with the reported central mass density of Terzan 5 \( \sim (1-4) \times 10^6 M_\odot \text{ pc}^{-3} \) (Lanzoni et al. 2010), we calculate the number density of stars of mass \( 0.5-1.2 M_\odot \) to be \( n_1 \sim (1.8-7.2) \times 10^5 \text{ pc}^{-3} \) for \( x = 2 \), and \( \sim (4.7-18.8) \times 10^5 \text{ pc}^{-3} \) for \( x = 1 \). So in the following, we take \( n_1 \sim 5 \times 10^5 \text{ pc}^{-3} \) as a rough estimate. The number density of the binaries \( n_{\text{bin}} \) can be estimated by using the total number of binaries with millisecond pulsars (\( N_b \)) divided by the volume \((V)\) of the cluster core.

The number of binary systems that have undergone exchange encounters with a reversed-spinning neutron star is

\[
N \sim \frac{1}{2} \Gamma_T p V \sim 2.5 \times 10^{-4} n_1 a N_b f(m) v_{\infty}^{-1},
\]

(5)

where \( f(m) = m^{7/2} M_1^{1/6} M_2^{1/6} M_3^{5/2} M_4^{-1/3} \), and \( \Gamma_T \) is the time interval between the formation of the original binary and the encounter, which can be roughly set as \( \sim 3 \times 10^9 \text{ yr} \), i.e., the half age of the metal-rich population in Terzan 5. A factor of \( 1/2 \) is added to account for the fact that the orbit angular momentum of the later binary can be either parallel or anti-parallel with the spin of the neutron star.

Taking typical values for the parameters in Equation (5), i.e., \( m_1 \sim 0.3 \), \( m_2 \sim 1.4 \), \( m_3 \sim 0.8 \), \( v_{\infty} \sim 10 \), and \( \tilde{a} \sim 0.02 \), we obtain \( N \sim 0.5 N_b \), suggesting that a considerable fraction of the millisecond binary pulsars in Terzan 5 may have experienced the specified dynamical interaction. There are 35 known millisecond pulsars (Ransom et al. 2005; Hessels et al 2006; Pooley et al. 2010) in this globular cluster, and the total number of millisecond pulsars may be \( \sim 150 \) (Bagchi et al. 2011). It is not surprising that all the binary pulsars may have been formed by dynamical interactions, and probably half of them might have experienced exchange encounters that leave a reversed-spinning neutron star in the new binary.

We expect that other globular cluster also harbor systems like IGR J17480–2446. For example, in the globular cluster NGC 6440, the central density is \( \sim 5 \times 10^5 M_\odot \text{ pc}^{-3} \) (Webbink 1985), and so around 5% of the millisecond pulsars might have undergone the exchange evolution.

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4 We assume that the second donor has transferred at least \( \sim 0.1 M_\odot \) to the neutron star (see Equations (9) and (10)), so the lower limit of its initial mass is taken to be \( \sim 0.5 M_\odot \).

5 We assume that the neutron star magnetic field does not decay further when it has reached the so called bottom field \( \sim 10^8-10^9 \text{ G} \) (e.g., Zhang & Kojima 2006).
where $P_{100} = P/100$ ms. The real value of $t_{\text{rup}}$ could be even larger, since IGR J17480$-$2446 currently appears as a transient source (Papitto et al. 2011; Patruno et al. 2012). The typical evolutionary lifetime of an LMXB is roughly $t_{\text{ev}} \sim \Delta m/\dot{m} \sim 3 \times 10^9 m_{17}^{-1}$ yr for an average accreted mass of $\sim 0.3 M_{\odot}$. The observed number of IGR J17480$-$2446-like systems can then be roughly estimated as

$$N_{\text{obs}} = \frac{t_{\text{rup}}}{t_{\text{ev}}} N \sim (0.007 N) I_{\text{str}} B_8^{-2/7} P_6^{-6/7} P_{10}^{-1} m_3^{-3/7} m_{17}^{1/7},$$

or $N_{\text{obs}} \sim 0.6$ for $N \sim 0.5 N_b \sim 75$, which suggests there could be at most one such system in Terzan 5. Obviously, the rarity of IGR J17480$-$2446 originates from the very short duration of its current spin-up phase, and it will become a millisecond pulsar again a few $10^7$ yr later.

We also note that according to Equation (10), the accreted mass to accomplish the spin-up to 11 Hz is $\sim 0.002 M_{\odot}$. With this amount of mass, Equation (1) suggests that the magnetic field would have decayed only from $\sim 10^{12} \text{ G}$ to $\sim 5 \times 10^{10} \text{ G}$ if this were the first phase of mass accretion. Specifically, there was enough accreted matter to spin up the neutron star, but it would be insufficient to substantially reduce the magnetic field to $\sim 10^9$ G. In our proposed scenario, this problem does not occur since the neutron star had already been recycled before the exchange encounter.

### 4. DISCUSSION AND CONCLUSIONS

The newly discovered accreting millisecond pulsar IGR J17480$-$2446 in the globular cluster Terzan 5 has a surprisingly low spin frequency, and has been suggested to be a mildly recycled pulsar that started a spin-up phase exceptionally recently. Here we propose an alternative explanation if the magnetic field of IGR J17480$-$2446 is as low as other accreting millisecond pulsars, taking into account the dense environment of IGR J17480$-$2446. In dense globular clusters, when a single star interacts with a binary (the neutron star could either be a member of the binary or the single object), the most probable result is that one of the binary components is replaced by the single star if it is the lightest one (Krolik et al. 1984). In our case, the resulting binary will be composed of a recycled neutron star and a relatively massive companion star. The high density of the globular cluster Terzan 5 supports the possibility of such a triple-object close encounter. The low spin frequency of IGR J17480$-$2446 may be explained as the result of reversed-to-parallel evolution of the neutron star’s spin.

In Patruno et al. (2012), the system is assumed to be in its incipient mass transfer process, while in this work, since the donor has transferred some more material through RLOF, the mass of the companion may be $\sim 0.1$--$0.2 M_{\odot}$ less than its initial mass. Accordingly, the neutron star has experienced accretion phases twice, so its mass may be considerably higher than its initial value. However, it seems difficult to distinguish our model from that of Patruno et al. (2012) in these respects, since detailed calculations (e.g., Lin et al. 2011) show that the evolutions of LMXBs are rather complicated, depending on the initial masses of the component stars, the initial orbital periods, and the processes of mass and orbital angular momentum transfer and loss. The neutron star magnetic field may serve as a distinct feature. We assume that the neutron star has experienced a long accretion time, so its magnetic field has reached the bottom field, $\sim 10^8$--$10^9$ G, which is considerably lower than the expected value of Patruno et al. (2012). Both the spin evolution and the kHz QPO frequencies can place constraints on the magnitude of the magnetic field if the mass accretion rate of the neutron star can be accurately determined.

Finally, we point out that this work is based on the specified relation between the magnetic field and the accreted mass described by Equation (1), as we know that the mechanism for accretion-induced field decay is still uncertain and there may be other forms. For example, in Kiel et al. (2008), it is assumed that the magnetic field decays exponentially with the amount of mass accreted:

$$B = B_0 \exp(-k \Delta M/M_{\odot}),$$

where $k$ is a scaling parameter that determines the rate of decay. For choices of $k = 3000$ and $10,000$, as suggested by Kiel et al. (2008), an accretion of only $\sim 0.002 M_{\odot}$ can decrease the magnetic field to $\sim 2 \times 10^9 \text{ G}$ or $< 10^8 \text{ G}$. Thus, with Equation (12), the small amount of accretion required to spin-up the neutron star to 11 Hz would also be sufficient to highly suppress the magnetic field. If it can someday be established, via other means, that the capture by the neutron star of a second companion is necessary, or possibly not needed for IGR J17480$-$2446, then this might indicate either Equation (1) or Equation (12) as the more valid expression of field decay in accreting neutron stars.

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### REFERENCES

Alpar, M. A., Cheng, A. F., Ruderman, M. A., & Shaham, J. 1982, *Natur*, 300, 728
Aaltomirano, D., Ingram, A., van der Klis, M., et al. 2012, *ApJL*, 759, L20
Bagchi, M., Lorimer, D. R., Chennamangalam, J. 2011, *MNRAS*, 418, 477
Barret, D. 2012, *ApJ*, 753, 84
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, *PhR*, 203, 1
Bordas, P., Kuulkers, E., Alfonso-Garzón, J., et al. 2010, *A&A*, 521, 91
Cackett, E. M., Aaltomirano, D., Patruno, A., et al. 2009, *ApJL*, 694, L21
Cavecchi, Y., Patruno, A., Haskell, B., et al. 2011, *ApJ*, 740, L8
Cohn, H., Lugger, P. M., Grindlay, J. E., & Edmonds, P. D. 2002, *ApJL*, 571, 818
Cui, W. 1997, *ApJL*, 482, L163
Doroshenko, V., Santangelo, A., Suleimanov, V., et al. 2010, *A&A*, 515, 10
Eggleton, P. 2006, *Evolutionary Processes in Binary and Multiple Stars* (Cambridge: Cambridge Univ. Press), 36
Finger, M. H., Ikhsanov, N. R., Wilson-Hodge, C. A., & Patel, S. K. 2010, *ApJ*, 709, 1249
Fu, L., & Li, X.-D. 2012, *ApJL*, 757, 171
Hartman, J. M., Galloway, D. K., & Chakrabarty, D. 2011, *ApJL*, 726, 26
Hartman, J. M., Patruno, A., Chakrabarty, D., et al. 2008, *ApJ*, 675, 1468
Hartman, J. M., Patruno, A., Chakrabarty, D., et al. 2009, *ApJL*, 702, 1673
Heggie, D. C., Hut, P., & McMillan, S. L. W. 1996, *ApJ*, 467, 359
Hessels, J. W. T., Ransom, S. M., Stairs, I. H., et al. 2006, *Sci*, 311, 1901
Kiel, P. D., Hurley, J. B., & Murray, J. R. 2008, *MNRAS*, 388, 393
Krolik, J. H., Meiksin, A., & Joss, P. C. 1984, *ApJL*, 282, 466
Lanzoni, B., Ferraro, F. R., Dallessandro, E., et al. 2010, *ApJ*, 717, 653
Lin, J., Rappaport, S., Podsidiakovski, Ph., et al. 2011, *ApJL*, 732, 70
Miller, J. M., Maitra, D., Cackett, E. M., et al. 2011, *ApJL*, 731, L7
Ortolani, S., Barbuy, B., Bica, E., et al. 2007, A&A, 470, 1043
Papitto, A., D’Aì, A., Motta, S., et al. 2011, *A&A*, 526, L3
Papitto, A., Di Salvo, T., Maitra, D., et al. 2012, *MNRAS*, 423, 1178
Papitto, A., Di Salvo, T., Aì, A., et al. 2009, *A&A*, 493, L39
Papitto, A., Menna, M. T., Burderi, L., et al. 2008, *MNRAS*, 383, 411
Patruno, A., Alpar, M. A., van der Klis, M., & van den Heuvel, E. P. J. 2012, *ApJL*, 752, 33
Patruno, A., & Watts, A. L. 2012, in Timing Neutron Stars: Pulsations, Oscillations and Explosions, ed. T. Belloni, M. Mendez, & C. M. Zhang (ASSL, Berlin: Springer), in press
Payne, D. J. B., Vigelius, M., & Melatos, A. 2008, in AIP Conf. Proc. 1068, A Decade of Accreting Millisecond X-ray Pulsars, ed. R. Wijnands, D. Altamirano, P. Soleri et al. (Melville, NY: AIP), 144
Pooley, D., Homan, J., Heinke, C., et al. 2010, ATel, 2974, 1
Ransom, S. M., Hessels, J. W. T., Stairs, I. H., et al. 2005, Sci, 307, 892
Reig, P., Torrejón, J. M., & Blay, P. 2012, MNRAS, 425, 595
Romani, R. W. 1990, Natur, 347, 741
Salpeter, E. E. 1955, ApJ, 121, 161s
Shibazaki, N., Murakami, T., Shaham, J., & Nomoto, K. 1989, Natur, 342, 656
Srinivasan, G., Bhattacharya, D., Muslimov, A. G., & Tsygan, A. J. 1990, CSci, 59, 31
Strohmayer, T. E., & Markwardt, C. B. 2010, ATel, 2929, 1
van den Heuvel, E. P. J., & Bitzaraki, O. 1995, A&A, 297, L41
Verbunt, F. 1988, AdSpR, 8, 529
Verbunt, F., & Hut, P. 1987, in IAU Symp. 125, The Origin and Evolution of Nutron Stars, ed. D. J. Helfand & J.-H. Huang (Dordrecht: Reidel), 187
Wang, J., Zhang, C.-M., Zhao, Y.-H., et al. 2011, A&A, 526, A88
Webbink, R. F. 1985, in IAU Symp. 113, Dynamics of Star Clusters, ed. J. Goodman & P. Hut (Dordrecht: Reidel), 341
Wijnands, R., & van der Klis, M. 1998, Natur, 394, 344
Zhang, C.-M., & Kojima, Y. 2006, MNRAS, 366, 137
Zhang, C.-M., Wang, J., Zhao, Y.-H., et al. 2011, A&A, 527, A83