Does Submillisecond Pulsar XTE J1739–285 Contain a Weak Magnetic Neutron Star or Quark Star?

C. M. Zhang, H. X. Yin, Y. H. Zhao, Y. C. Wei, and X. D. Li

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Abstract. The possible detection of the fastest spinning nuclear-powered pulsar XTE J1739–285, of frequency 1122 Hz (0.8913 ms), arouses us to constrain the mass and radius of its central compact object and to infer the stellar matter composition: neutrons or quarks. Spun up by the accreting materials to such a high rotating speed, the compact star should have either a small radius or short innermost stable circular orbit. By the empirical relation between the upper kilohertz quasi-periodic oscillation frequency and star spin frequency, a strong constraint on mass and radius is obtained of 1.51 \( M_\odot \) and 10.9 km, respectively, which excludes most equations of state (EOSs) of normal neutrons and strongly hints the star promisingly to be a strange quark star. Furthermore, the star magnetic field is estimated to be about 4 \( \times \) \( 10^7 \) G < \( B < 10^9 \) G, which reconciles with those of millisecond radio pulsars, revealing the clues of the evolution linkage of two types of astrophysical objects.

Online material: color figures

1. INTRODUCTION

It has recently been announced that the most rapid spinning rate, 1122 Hz, has been detected in the accreting X-ray binary system XTE J1739–285 (Kaaret et al. 2007). This is the first submillisecond pulsar (spin period 0.89 ms) coming into our view since the discovery of the first radio pulsar by J. Bell and A. Hewish 40 years ago (Hewish et al. 1968) if the 1122 Hz is a spin frequency.

However, it is stressed that the 1122 Hz burst oscillation frequency is detected in only one burst but not the whole set of bursts (Kaaret et al. 2007), so this frequency still needs further confirmation in future burst detections. At the present time we take this 1122 Hz frequency as a tentative case and proceed with our investigations of its applications on that basis. If the declared spin frequency 1122 Hz is fully confirmed, then this compact object breaks the record of the fastest radio pulsar with a spinning frequency of 716 Hz (1.39 ms) discovered recently (Hessels et al. 2006). Strikingly, such a high spin rate makes the edge velocity at the radius of 42.6 km the speed of light, which quantitatively constrains the star size and its emission region. If this announced spin detection is true, it is interesting that such a high spin rate does not break up the star, which provides us a unique opportunity to explore the matter composition of the central object, neutrons or their constituent quarks that have never been seen as free particles to date. No doubt, such a high rotating frequency, 1122 Hz, should influence the EOS of the compact object and its mass-radius relation (Lavagetto et al. 2006; Bejger et al. 2007). In fact, the importance of detecting a submillisecond rotating pulsar as a way of discriminating star nuclear compositions has been proposed by several authors (Phinney & Kulkarni 1994; Burderi & D’Amico 1997; Burderi et al. 1999, 2001). The formation of a very fast spinning pulsar, however, depends sensitively on the history of the compact object in the binary and on the evolution of its magnetic field (Possenti et al. 1998).

The source XTE J1739–285, exhibiting as a transient X-ray burst source, first discovered in 1999 by the satellite Rossi X-Ray Timing Explorer (RXTE), is recently reported to have a burst oscillation frequency detected at 1122 Hz (Kaaret et al. 2007), which is identified as a spin frequency because in the accretion-powered pulsar SAX J1808.4−3658 both a pulsation frequency and a burst frequency are detected at 401 Hz (Chakrabarty et al. 2003; van der Klis 2006; Yin et al. 2007). The central object of XTE J1739–285 lies in a low-mass X-ray binary (LMXB) and is believed to be a dense star with incredible density, like what would exist if \( 1 \times 10^{12} \) G were trapped in an area of 10 km as a result of the supernova explosion of some massive star. The magnetic field of this type of object is about \( 10^6 \)–\( 10^9 \) G, which experiences reduction from the original value \( 10^{12} \) G by sucking the accreting materials from the disk fed by its companion (e.g., Bhattacharya & van den Heuvel 1991). The rotating of such a magnetic object will be responsible for its pulsation.

The measured mass and radius of a compact object can be used to study the strong nuclear force of matter or the relation between the matter pressure and density, i.e., the equation of state (EOS; Lattimer & Prakash 2001, 2004, 2006; Glendenning 2000). Understanding the behavior of matter at superhigh density...
binary radio pulsar system (e.g., Kaspi et al. 1994), for instance, the masses of double pulsar PSR J0737−3039, \( M = 1.337 \pm 0.005 \) and \( 1.250 \pm 0.005 \) \( M_\odot \) (Lyne et al. 2004). Until now, around 50 NS masses have been measured with an average value of \( \sim 1.4 \) \( M_\odot \) (Lattimer & Prakash 2004, 2006), from the possible minimum mass \( 0.97 \pm 0.24 \) \( M_\odot \) (Jonker et al. 2003) to the maximum value \( 2.1 \pm 0.2 \) \( M_\odot \) (Nice et al. 2005). Unlike the situation of NS mass measurement, there is no effective way of acquiring an accurate NS radius directly; thus, the star EOS can be only estimated by some measurements with errors (Zhang et al. 2007). Then some \( M-R \) relations can be measured to derive the \( M \) and \( R \) constraints (Özel 2006; Miller 2002), for instance, the apparent radius estimated from the thermal emission of a perfect blackbody (Trümper et al. 2004; Burwitz et al. 2001, 2003; Rutledge et al. 2001; Haensel 2001), the gravitational redshift of the spectral lines (Cottam et al. 2002), and the star magnetosphere limit of SAX J1808.4−3658 (Burderi & King 1998), etc. As stated, it is important to confine the challenging attempts to measure the NS radius to the most reliable data and methods; otherwise, we will continue to produce radius values with uncertainties of a factor of 2 or so, which is not enough to constrain the EOS of NS matter (J. E. Trümper 2007, private communication).

2. MASS AND RADIUS ESTIMATION OF XTE J1739−285

2.1. Constraints on Mass and Radius by the Spin Frequency

Located about 35,000 lt-yr away from Earth, the burst source XTE J1739−285 lies in an accreting binary system, where the orbital materials in the star inner disk of radius \( r \) proceed with a circular motion with Keplerian frequency \( \nu_K \) (van der Klis 2006; Stella & Vietri 1999; Miller et al. 1998),

\[
\nu_K = \sqrt{\frac{GM}{4\pi^2 r^3}} = 1833 \text{ (Hz)} \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{R}{10 \text{ km}} \right)^{-3/2},
\]

which should be bigger than the spin frequency \( \nu \) because the star in the LMXB is experiencing the spin-up phase (e.g., van der Klis 2006).

The Keplerian motion will end at the innermost stable circular orbit (ISCO) if the star surface is inside the ISCO, so the spin-up process will be invalid there. The formation of the spin frequency of a star in an LMXB is due to the spin-up of the accreted matter in the Keplerian motion; thus, the Keplerian orbital frequency in the inner magnetosphere-disk boundary must exceed the spin frequency (e.g., Bhattacharya & van den Heuvel 1991; Cheng & Zhang 2000; Lamb & Boutloukos 2007). Therefore, it is usually believed that the maximum Keplerian frequency occurs at the ISCO with the radius \( R_{\text{ISCO}} = 6GM \) (e.g., Miller et al. 1998; Zhang et al. 1998; see the illustration diagram Fig. 1), or the ISCO lies inside the corotation radius.
radius $R_{\text{co}}$ at which the Keplerian frequency equals the star rotation spin frequency, i.e., $R_{\text{ISCO}} \leq R_{\text{co}}$,

$$
\frac{R_{\text{co}}}{10 \text{ km}} = \left( \frac{M}{M_\odot} \right)^{1/3} \left( \frac{1833}{\nu_s} \right)^{2/3}.
$$

Thus, one has a mass constraint in the following (Miller et al. 1998):

$$
\frac{M}{M_\odot} \leq 2200 \left( \frac{\text{Hz}}{\nu_s} \right).
$$

As stated, for a given star mass and radius, the permitted maximum spin frequency is as follows (Lattimer & Prakash 2004, 2006):

$$
\nu_s \leq 1045 \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{R}{10 \text{ km}} \right)^{-3/2}.
$$

Therefore, from equations (3) and (4) the mass-radius constraints can be obtained, which are plotted in Figure 2.

For comparison, several EOS curves are plotted in Figure 2 as well. In the shaded area of Figure 2 with $M < 1.96 M_\odot$ and $R < 11.9 \text{ km}$, for which the meanings of its boundaries are indicated in the figure legend, we find that the EOSs that are too stiff are strongly excluded.

### 2.2. More Stringent Constraints on M and R by the Kilohertz QPOs

However, if the higher twin kilohertz quasi-periodic oscillations (QPOs) are detected in XTE J1739$-285$, as derived from the other twin kilohertz QPO sources, we could even give a stronger constraint on the star mass upper limit. In theory, the Keplerian frequency of orbital matter, to which the upper kilohertz QPO frequency is identified, should be greater than the spin frequency because of the spinning up of the star by accretion (Shapiro & Teukolsky 1983). From RXTE detections, the twin kilohertz QPOs, the upper and lower frequencies, are often found in the Fourier power spectra (van der Klis 2006), and it is also noticed that, for the known nuclear-powered millisecond pulsars with simultaneously detected twin kilohertz QPO frequencies shown in Table 1, their upper kilohertz QPO frequencies, usually identified as the Keplerian orbital frequency (van der Klis 2006; Stella & Vietri 1999; Miller et al. 1998), are all at least 1.3 times bigger than their spin frequencies (see Table 1; Yin et al. 2007), which implies the inner orbital accreting matter to enter into the region enclosed by the corotation radius. If this empirical relation is also valid for XTE J1739$-285$ although no twin kilohertz QPOs have been simultaneously detected in this source (Kaaret et al. 2007), one

### Table 1

| Sources | $\nu_{\text{lower}}$ (Hz) | $\nu_{\text{upper}}$ (Hz) | $\nu_{\text{max}}/\nu_s$ | Reference |
|---------|--------------------------|---------------------------|--------------------------|-----------|
| 4U 1608−52 | 802−1099 | 619 | 1.3 | 1 |
| 4U 1636−53 | 971−1192 | 581 | 1.7 | 2 |
| 4U 1702−43 | 1055 | 330 | 3.2 | 3 |
| 4U 1728−34 | 582−1183 | 363 | 1.6 | 4 |
| KS 1731−265 | 1169 | 524 | 2.2 | 5 |
| 4U 1915−05 | 514−1055 | 270 | 1.9 | 6 |
| XTE J1807−294 | 353−587 | 191 | 1.8 | 7 |
| SAX J1808.4−3658 | 694 | 401 | 17.0 | 8 |

* On the QPO data, see Belloni et al. (2005), van der Klis (2006), and Zhang et al. (2006). * On the spin frequency, see also Chakrabarty (2004), Strohmayer & Bildsten (2006), van der Klis (2006), Lamb & Boutloukos (2007), Yin et al. (2007), and the original references therein. * The ratio between the minimum upper kilohertz QPO frequency and spin frequency.

### References

—(1) Hartman et al. 2003; (2) Wijnands et al. 1997; (3) Markwardt et al. 1999; (4) Strohmayer et al. 1996; (5) Smith et al. 1997; (6) Galloway et al. 2001; (7) Markwardt et al. 2003; (8) Wijnands & van der Klis 1998.
can conclude that the minimum upper frequency of twin kilohertz QPOs of XTE J1739−285 is bigger than about 1439 (= 1.3 × 1122) Hz. Henceforth, the upper limit of the mass constraint by equation (3) is changed to \( M = 1.51 M_\odot \). Interestingly, in the shaded area of Figure 2 with \( M < 1.51 M_\odot \) and \( R < 10.9 \text{ km} \), almost all plotted EOSs of normal neutrons and pion condensation transition are excluded, and only the model SS1 for quark matter (Dey et al. 1998) is possible. Accordingly, the compact object in XTE J1739−285 is more probably composed of quark matter if the stated higher kilohertz QPO frequency is detected. Put in perspective, these results shed light on the study of subnuclear physics. In addition, it would be meaningful to detect the higher kilohertz QPOs than 1500 Hz in XTE J1739−285, revealing a smaller mass value than 1.47 \( M_\odot \) inferred from equation (3), which will indispensably exclude EOSs of normal neutron matter. Furthermore, the \( M-R \) constraints would be considerably improved if the star mass or some \( M-R \) relations, e.g., the gravitational redshift and thermal emission, were known. In any case, XTE J1739−285 is a dramatically particular probe of exotic matter in extreme environments that cannot be achieved on Earth. Meanwhile, in conclusion, the submillisecond pulsar will definitely exclude the EOSs that are too stiff, implying that the star matter is highly incompressible or the big stars cannot endure spin frequencies that are too fast without breaking apart.

3. ON THE MAGNETIC FIELD CONSTRAINTS OF XTE J1739−285

The magnetic field of the NS in the binary system can be measured directly by the cyclotron lines in the magnitude order of \( \sim 10^{15} \text{ G} \) (Trümper et al. 1978); however, the radio pulsars and weak magnetic NSs in LMXBs have no such priorities. The magnetic field strength of a radio pulsar is estimated by the assumption of magnetic dipole radiation accounting for its spin-down, so the approximation is derived by exploiting the presumed star parameters, i.e., \( M = 1.4 M_\odot \) and \( R = 15 \text{ km} \) (e.g., Manchester & Taylor 1977). As for the estimation of the star magnetic field strength \( B \) in an LMXB, it is derived by the definition of the magnetosphere radius, which is also inaccurate because of the unknown star mass and radius (e.g., Shapiro & Teukolsky 1983; Burderi et al. 1996). This situation will be improved if one can infer the star mass and radius of XTE J1739−285. In an accreting binary system, the magnetosphere radius \( R_M \) is \( \sim 0.5 \text{ Alfvén radius} \) and can be conventionally written as (Shapiro & Teukolsky 1983)

\[
R_M = 0.43 \times 10^6 [\text{cm}] \left( \frac{B}{10^5 \text{ G}} \right)^{4/7} \left( \frac{\dot{M}}{10^{18} \text{ g s}^{-1}} \right)^{-2/7} \times \left( \frac{M}{M_\odot} \right)^{-1/7} \left( \frac{R}{10 \text{ km}} \right)^{12/7},
\]

or, equivalently,

\[
B = \left( \frac{R_M}{R} \right)^{7/4} B_j,
\]

where \( \dot{M} \) is the accretion rate and \( B_j \) is a field strength when \( R_M = R \) (\( B \) is designated as a bottom field; see, e.g., Zhang & Kojima 2006; Burderi et al. 1996). With the inequality \( R < R_M < R_{\text{co}} \), we obtain the magnetic field constraint as follows,

\[
B_j < B < \left( \frac{R_{\text{co}}}{R} \right)^{7/4} B_j.
\]

For XTE J1739−285, by means of the approximated conditions \( 2.9GM < R < 11.9 \text{ km}, M < 1.96 M_\odot \), and equation (4), where the radius \( 2.9GM \) is given by the causality condition of general relativity (Lattimer & Prakash 2004, 2006), we obtain lower and upper limits of the magnetic field of XTE J1739−285 of

\[
B > 4.2 \times 10^4 (G) \left( \frac{\dot{M}}{10^{18} \text{ g s}^{-1}} \right)^{1/2},
\]

\[
B < 9.97 \times 10^9 (G) \left( \frac{M}{M_\odot} \right)^{-13/6} \left( \frac{\dot{M}}{10^{18} \text{ g s}^{-1}} \right)^{1/2}
\]

respectively. XTE J1739−285 is identified as a less luminous atoll source (Kaaret et al. 2007), so its long-term accretion rate should be as low as those of the usual atoll sources, i.e., \( \dot{M} \sim 10^{-6} \text{ g s}^{-1} \) (for the definition of “atoll source,” see Hasinger & van der Klis 1989). In addition, if the star mass of XTE J1739−285 is set to be about \( \sim 1 M_\odot \), then the lower and upper limits of its magnetic field strength are approximately given, \( 4 \times 10^3 G < B < 10^9 G \), which is compatible with the approximately derived field strength \( \sim 10^6 \text{ G} \) of millisecond radio pulsars (Bhattacharya & van den Heuvel 1991; van den Heuvel & Bitzaraki 1995). Therefore, the similar magnetic
fields and spin frequencies of both the compact objects in LMXBs and millisecond pulsars in binary systems strongly hint at their relevant evolutionary linkage (van den Heuvel 2004). However, a magnetic field strength as low as $\sim 4 \times 10^7$ G has not yet been discovered. In the accreting binary system, it has long been believed that NS spin is accelerated by the accretion (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982) and its field decays (Bhattacharya & van den Heuvel 1991; van den Heuvel & Bildikar 1995). The spin and magnetic field of XTE J1739−285 strongly reveal the evidence that the compact object in the LMXB is the progenitor of a millisecond radio pulsar, which strengthens our understanding of the formation and evolution of such a striking spinning object. On the other hand, the evolutionary linkage also means that some millisecond pulsars are involved in the quark matter inside stars. Clearly, the confirmation of the spin frequency and the detection of the higher kilohertz QPO frequency of XTE J1739−285 are the most important priorities for setting stringent limits on the physical parameters of its compact object.

4. CONSEQUENCES AND DISCUSSION

In this paper, we take the burst oscillation frequency of 1122 Hz of XTE J1739−285 to be the NS spin rate; however, it still needs further confirmation (e.g., Galloway 2007). First, it is detected in the brightest burst with significance at the 99.96% confidence level, not in a whole set of six bursts (Kaaer et al. 2007). Second, from a statistical point of view, the frequency of 1122 Hz is far outside the range of the previously known spin frequencies of LMXBs, from the minimum value of 45 Hz (Villarreal & Strohmayer 2004) to the maximum of 619 Hz (Hartman et al. 2003), centered at $\sim 400$ Hz (Yin et al. 2007), and it is much higher than the fastest spin frequency of radio pulsars, 716 Hz (Hessels et al. 2006). Therefore, we take this spin frequency of 1122 Hz as a tentative detection, or the possibility might be considered that the signal of 1122 Hz is merely a candidate burst oscillation (e.g., Galloway 2007). In addition, we emphasize that this spin frequency is not yet totally verified and the present observation is not statistically as sound as for those of other LMXBs (see, e.g., Strohmayer & Markward 2002 for 4U 1636−536; Strohmayer et al. 2003 for XTE J1814−338).

By means of this assumed highest spin frequency, we can constrain the NS mass and radius, which indicates the frequency of 1122 Hz to be close to the centrifugal breakup limit for some equations of state of nuclear matter (e.g., Burgio et al. 2003). Furthermore, if the empirical relation on the kilohertz QPO frequency and spin frequency is presumed to be possible (see Table 1), then we can infer a higher kilohertz QPO frequency than 1500 Hz, which will exclude the EOSs of normal neutrons and just leave those of strange quark matter possible. Therefore, the motivations for the physical properties of superdense nuclear matter are enhanced (e.g., Page & Reddy 2006; Watts & Reddy 2007).

With the known spin frequency, combined with the constrained NS mass and radius, the corotation radius of the NS in XTE J1739−285 is inferred, by which the constraints of the NS magnetic field strength are derived with the observationally estimated mass accretion rate. A similar estimate of NS magnetic field has been obtained for SAX J1808.4−3658 (Wijnands & van der Klis 1998), where the NS mass and radius are assumed; however, in this paper we exploit the constrained mass and radius of the NS to derive the range of the NS magnetic field of XTE J1739−285, which presents the upper and lower limits of the magnetic field.

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