

IS THE BURSTING RADIO-SOURCE GCRT J1745-3009 A DOUBLE NEUTRON STAR BINARY ?

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ABSTRACT

GCRT J1745-3009 is a peculiar transient radio-source in the direction of the Galactic Center. It was observed to emit a series of ~ 1 Jy bursts at 0.33 GHz, with typical duration ~ 10 min and at apparently regular intervals of ~ 77 min. If the source is indeed at the distance of the Galactic Center as it seems likely, we show that its observational properties are compatible with those expected from a double neutron star binary, similar to the double pulsar system J0737-3039. In the picture we propose the (coherent) radio emission comes from the shock originating in the interaction of the wind of the more energetic pulsar with the magnetosphere of the companion. The observed modulation of the radio signal is the consequence of an eccentric orbit, along which the separation between the two stars varies. This cyclically drives the shock inside the light cylinder radius of the less energetic pulsar.

Subject headings: Radio continuum: stars — Radiation mechanisms: non-thermal — Stars: neutron

1. INTRODUCTION

Recently Hyman et al. (2005) announced the remarkable discovery of a powerful bursting radio-source located about 1 deg south of the Galactic Center (GC). GCRT J1745-3009 was detected in 2002 during a radio transient monitoring of the GC region at 0.33 GHz, and appears to emit a series of bursts of typical duration ~ 10 min. The flux in a single burst is ~ 1 Jy and no emission is detected between the events to an upper limit of 75 mJy. The bursts seem to follow a regular pattern, with a time separation of ~ 77 min. The bursting source is unresolved and no counterparts are found thus far in other spectral bands.

The quite high radio flux, combined with the limited spatial extent of the emitting region derived from the decay time of the bursts, implies a brightness temperature of $T_b \sim 10^{16}$ K placing the source at the GC distance. If this is the case, a coherent mechanism is required to power the observed radio emission (Hyman et al. 2005).

A number of possible interpretations for the peculiar properties of GCRT J1745-3009 have been examined by Hyman et al. (2005). Their main conclusion is that, although the option that this is a close-by radio-source (a very cold dwarf, or an extrasolar planet) can not be dismissed, it appears much more likely that GCRT J1745-3009 is indeed located close to the GC. Along this line, they consider both a radio-pulsar and a neutron star-neutron star binary as possible options. The case for a pulsar nature of GCRT J1745-3009 is more thoroughly discussed in a recent paper by Zhu & Xu (2005).

If one interprets the interburst time as due to orbital motion, according to the original suggestion by Hyman et al. (2005), the system may be similar to the double pulsar J0737-3039 (Burgay et al. 2003; Lyne et al. 2004). In this *Letter* we further explore the possibility that GCRT J1745-3009 is a double neutron star system, following the

proposal by Turolla & Treves (2004, hereafter TT04), that the continuous emission from J0737-3039 could be due to coherent radiation, produced at the shock formed by the interaction of the relativistic wind of the more energetic pulsar with the magnetosphere of the companion.

2. THE MODEL

We develop a simplified model for GCRT J1745-3009 by assuming that: i) the source is at the distance of the GC, $D = 8.5$ kpc, ii) the interval between the bursts is an orbital period, $P = 77$ min, and iii) the binary system consists of two neutron stars (NS). Eight examples of NS+NS binaries in which one of the star is a radio pulsar are presently known. Among these J0737-3039 is unique since both its components are detected as pulsars. Moreover J0737-3039 is the only NS+NS binary ($P_{orb} = 2.4$ h, $a \sim 9 \times 10^{10}$ cm, $e \sim 0.09$; Lyne et al. 2004), which exhibits a continuous radio emission ($F_{1.4\text{GHz}} \sim 5$ mJy) about two times stronger than the emission from the two pulsars (Lyne et al. 2004). The fact that unpulsed radio emission occurs in a double neutron star binary is of particular relevance in connection with GCRT J1745-3009 and is at the basis of the scenario we are proposing. So far it has not been possible to establish if the continuous radio flux from J0737-3039 exhibits an orbital modulation. Were the continuous radio emission steady or weakly modulated, despite the alleged analogies, the two systems must differ in some respects, as discussed further on.

The origin of the continuous emission from J0737-3039 is still uncertain. The starting point is assumed to be the interaction of the wind of the most luminous pulsar A ($P_A = 0.02$ s, $\dot{E}_A \sim 6 \times 10^{33}$ erg s⁻¹, $B_A \sim 6 \times 10^9$ G) with the magnetosphere of pulsar B ($P_B = 2.77$ s, $\dot{E}_B \sim 2 \times 10^{30}$ erg s⁻¹, $B_B \sim 10^{12}$ G⁴). A shock is produced when the energy density of the relativistic wind of A equals the magnetic energy density of B. Since $\dot{E}_A \gg \dot{E}_B$, the wind penetrates deep into the magnetosphere of B and the shock

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⁴ Actually, the magnetic field of pulsar B could be somewhat smaller than this value, see Lyutikov (2004)

is well within B's light cylinder radius at $r_S \sim 6 \times 10^9$ cm from B (Lyne et al. 2004; TT04). Under the reasonable assumption that the shock is the site of particle acceleration, TT04 suggested two possible scenarios for the continuous emission. If the relativistic electrons originating in the shock fill a large volume (size $\approx 10^{13}$ – 10^{14} cm corresponding to $\approx 1''$ at the estimated distance of J0737-3039, ~ 0.6 kpc), optically thin synchrotron radiation is able to account for the observed flux. On the contrary, in case the size of the emitting region is comparable to that of the shock itself, the only way to circumvent severe self-absorption is to consider coherent emission.

In the picture we propose for GCRT J1745-3009 the coherent emission is activated when the relativistic wind of one component (which we call A) penetrates the magnetosphere of the other (B), in analogy with what likely occurs in J0737-3039. However, as already noticed and at variance with the case of J0737-3039, the strong radio emission has a finite duration, $T \sim 10$ min. A possible explanation is that the two NSs in GCRT J1745-3009 are in rather eccentric orbits, so that the shock is inside B's light cylinder only when the separation between the two stars drops below a limiting value. Clearly such a situation will occur only close to periastron, as illustrated in Figure 1.

The orbit semi-major axis follows from Kepler's law

$$a = 3.5 \times 10^{10} \left(\frac{M_{tot}}{M_\odot} \right)^{1/3} \left(\frac{P}{1\text{h}} \right)^{2/3} \text{ cm} \\ \sim 5.7 \times 10^{10} \text{ cm} \quad (1)$$

where $M_{tot} = M_A + M_B \sim 2.6M_\odot$ is the total mass. The area swept by the radius in a time T is simply $S = \pi a^2 \sqrt{1-e^2} (T/P)$, where e is the orbit eccentricity. From this it follows that the portion of the orbit centered at the periastron and travelled in a time T is limited by the values of the phase angle ϕ and $2\pi - \phi$, where ϕ as a function of e is implicitly given by

$$\int_\phi^\pi \frac{1}{(1-e\cos\phi)^2} d\phi = \frac{\pi}{(1-e^2)^{3/2}} \frac{T}{P}. \quad (2)$$

The solutions of eq. (2) for different values of e and $T/P = 10 \text{ min}/77 \text{ min} = 0.13$ are shown in Figure 2 (full line).

The distance of the shock from B, r_S , is given by

$$\frac{B_B^2}{8\pi} = \frac{\dot{E}_A}{4\pi\chi_A(r-r_S)^2c} \quad (3)$$

where $B_B = B_B(R_B)(R_B/r_S)^3$ assuming a dipole field, $R_B = 10^6$ cm is the radius of star B, $B_B(R_B)$ is the polar surface field, \dot{E}_A is the wind luminosity emitted by A in a solid angle $4\pi\chi_A$ and $r = a(1-e^2)/(1-e\cos\phi)$ is the orbital separation.

The burst radio luminosity at $\nu = 0.33$ GHz is

$$L_R \sim 4\pi\chi_R F_\nu \nu D^2 \sim 2.7 \times 10^{31} \chi_R \text{ erg s}^{-1} \quad (4)$$

where χ_R is the fraction of the total solid angle covered by the coherent radio beam. We take L_R to be proportional to the fraction of \dot{E}_A intercepted by the shock

$$\chi_R L_R(\phi) = \frac{\pi\xi\dot{E}_A r_S^2}{4\pi\chi_A(r-r_S)^2}; \quad (5)$$

ξ represents the efficiency for the production of (coherent) radio photons. Note that the radio luminosity which appears in the previous equation depends on the orbital phase through r and r_S . To derive an estimate of \dot{E}_A , we evaluate eqs. (3) and (5) at the periastron, where $\phi = \pi$, $r = a(1-e) \sim 3 \times 10^{10}$ cm, and we take $L_R(\pi) = L_R$, the latter as given by eq. (4). This results in

$$\dot{E}_A \sim 1.8 \times 10^{35} \left[\frac{B_B(R_B)}{10^{12} \text{ G}} \right]^{-1} \left(\frac{\chi_A}{0.1} \right) \left(\frac{\chi_R}{0.1} \right)^{3/2} \\ \times \left(\frac{\xi}{10^{-3}} \right)^{-3/2} \text{ erg s}^{-1}. \quad (6)$$

Inserting the previous expression for \dot{E}_A into eq. (3) and imposing that the shock is at the light cylinder radius of B, $r_S = r_{c,B} = cP_B/2\pi \sim 4.8 \times 10^9 P_B$ cm, results in a further relation between the phase ϕ and e

$$\frac{1-e^2}{1-e\cos\phi} = 8.4 \times 10^{-2} P_B + 20 P_B^3 \left[\frac{B_B(R_B)}{10^{12} \text{ G}} \right]^{-3/2} \\ \times \left(\frac{\chi_R}{0.1} \right)^{3/4} \left(\frac{\xi}{10^{-3}} \right)^{-3/4}. \quad (7)$$

The request that $r_S = r_{c,B}$ at a given point P guarantees that $r_S < r_{c,B}$ at all points along the orbit which are closer than P to periastron.

In order for our model to work, conditions (2) and (7) must be satisfied together. Only in this case the shock is inside the light cylinder radius of B for the observed duration of the burst T . The values of ϕ solutions of eq. (7) are shown in Fig. 2 as a function of the eccentricity and for different values of P_B and $B_B(R_B) = 10^{12}$ G; all other parameters have been taken equal to their reference values. As it can be seen from Fig. 2, the simultaneous fulfillment of both conditions is possible only in a quite restricted range of spin periods of star B, $0.31 \text{ s} \lesssim P_B \lesssim 0.35 \text{ s}$. The corresponding values of the eccentricity are in the range ~ 0.3 – 0.6 . In an even tighter interval of periods, around $P_B = 0.32$ s, a second solution for ϕ is present at higher values of the eccentricity. The allowed periods increase with B_B ; however, for $5 \times 10^{11} \text{ G} < B_B(R_B) < 3 \times 10^{12} \text{ G}$ they are still in the 0.3–0.4 s range. Increasing (decreasing) the beaming factor χ_R (the efficiency ξ) results in shorter periods. The shock distance from star B, as derived from eq. (3), is shown in Figure 3 (left panel) for $e = 0.4$. By combining eqs. (3) and (5) it is easy to see that $L_R(\phi) \propto r_S^4$. The corresponding light curve is shown in Figure 3 (right panel); no radio emission occurs when star B phase angle is outside the range for which $r_S \leq r_{c,B}$. In Figure 3 the orbital variation of r_S and L_R is shown for the parameters typical of J0737-3039 for comparison. In this case it is always $r_S < r_{c,B}$. The shock distance changes only slightly along the orbit because of the lower eccentricity and the orbital modulation of the unpulsed flux is $\sim 10\%$.

The wind luminosity of pulsar B can be estimated as

$$\dot{E}_B \sim 3 \times 10^{32} \left[\frac{B_B(R_B)}{10^{12} \text{ G}} \right]^2 \left(\frac{P_B}{0.35 \text{ s}} \right)^{-4} \text{ erg s}^{-1}. \quad (8)$$

Although the ratio of the wind luminosities \dot{E}_A/\dot{E}_B is somewhat smaller than that inferred in J0737-3039, it is

still $\dot{E}_B \ll \dot{E}_A$ and the energy density of the wind of A exceeds that of B by a factor ~ 10 at B light cylinder. This ensures consistency with our starting assumption about the shock forming as the result of the interaction of the wind of A with the magnetosphere of B.

3. DISCUSSION

The scenario outlined in the previous section shows that if one chooses for the model parameters values close to those introduced above, the main observational features of GCRT J1745-3009 can be successfully reproduced. Although the general picture we propose resembles that of J0737-3039, the two binary systems differ in more than one respect. In particular, the shock radiative efficiency needs to be higher in GCRT J1745-3009, $\sim 10^{-3}$ as compared to $\sim 10^{-4}$ in J0737-3039 (TT04). Lower values of ξ , in fact, result in smaller periods for pulsar B: this produces a steep increase of \dot{E}_B which soon would become $\sim \dot{E}_A$ at B's light cylinder radius. Albeit coherence seems indeed to be required in both systems, no detailed model for coherent radio emission has been put forward so far. In TT04 some possibilities were suggested but the very model of coherent radio emission should be revisited possibly in the light of most recent studies on this topic (e.g. Fung & Kuijpers 2004; Zhang & Loeb 2004).

Hyman et al. (2005) reported that GCRT J1745-3009 was not detected in two ~ 6 hr images obtained in 1996–1998 and in ~ 1 hr observations in 2002–2003. While no conclusive evidence can be drawn from the shorter observations which have duration less than the orbital period, the lack of activity in 1996–1998 might pose a difficulty to the NS+NS binary model, as the same authors state. Here we only mention that an “on”–“off” state may be achieved if star A precesses. For $\chi_A \sim 0.1$, the wind beam is $\sim 70^\circ$ wide and even a moderate precession angle can prevent the beam from A from intercepting the magnetosphere of B which subtends an angle $\lesssim 10^\circ$. Interestingly, the characteristic time $1/\Omega \sim 116P^{5/3}M^{-2/3}(1-e^2)s$ (Damour & Ruffini 1974) for changing the system geometry due to geodetic precession of the spin axis of pulsar A is ~ 3 yr, assuming equal masses ($M = 1.3M_\odot$) for the two stars.

The range of P_B and $B_B(R_B)$ for which our model holds implies that neutron star B may be an active radio-pulsar. The required spin down luminosity of neutron star A (see eq. [5]) is also compatible with it being a canonical radio-pulsar with $B_A \sim 10^{12} - 10^{13}$ G and $P_A \sim 0.1 - 1$ s or a mildly recycled pulsar with $B_A \sim 5 \times 10^9 - 5 \times 10^{10}$ G and $P_A \sim 10 - 20$ ms. The latter possibility fits better with the standard scenario for the formation of a double neutron

star binary (e.g. van den Heuvel & de Loore 1973), which predicts that the system should include a relatively young neutron star (the one resulting from the second supernova explosion) and a recycled pulsar (the first born neutron star), spun up to tens of millisecond period by the short phase of mass transfer from the evolving companion.

Detectability of the pulsed signal from these two sources depends on the radio luminosity and favorable orientation of their beams. Given the position in galactic coordinates ($l = 358.9^\circ$, $b = -0.5^\circ$) and for a distance in the range 6–12 kpc, the available models for the distribution of the ionized components in the interstellar medium (Taylor & Cordes 1993; Cordes & Lazio 2001) indicate that scattering would prevent detection of any pulsating radio signal with P shorter than few seconds at the frequency of 330 MHz. However, observations at frequencies higher than 1 GHz would preserve the possibility of discovering a ~ 0.3 s pulsar, while observing at frequency $\gtrsim 2$ GHz is required for detecting a ~ 10 ms pulsar.

An X-ray luminosity coincident with the shock of $L_X \approx 10^{32}$ erg s $^{-1}$ should be present, assuming that $\sim 10\%$ of the wind luminosity intercepted by the magnetosphere is converted into X-rays. However, the expected flux is extremely low, $\approx 10^{-4}$ cts s $^{-1}$ for XMM-EPIC and Chandra-ACIS, assuming a power-law spectrum with index 2 and $N_H \sim 10^{22}$ cm $^{-2}$. We do not expect substantial emission in other energy bands, as in the case of J0737-3039, although the younger NS may be associated with a supernova remnant.

Indirect support in favor of a double NS system for GCRT J1745-3009 could come from further radio observations of J0737-3039. In fact, evidence that the continuous source is unresolved at the arcsec level would rule out the transparent scenario (TT04), leaving coherent emission from the shock as the only viable option. If the picture of GCRT J1745-3009 proposed here will be confirmed, one should consider that other similar systems may exist in the Galaxy. Their search among radio transients with programs analogous to that of Hyman et al. (2005), may be of the paramount importance for estimating the coalescence rate on NS+NS systems, a vital issue in connection with the response of new generation gravitational wave detectors like VIRGO and LIGO.

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REFERENCES

- Burgay, M., et al. 2003, *Nature*, 426, 531
 Damour, T., & Ruffini, R. 1974, *Comptes Rendus Acad. Sci. Ser. A*, 279, 971
 Cordes, J.M., & Lazio, T.J.W. 2001, *ApJ*, 549, 997
 Fung, P.K., & Kuijpers, J. 2004, *A&A*, 422, 817
 Hyman, S.D., et al. 2005, *Nature*, 434, 50
 Lyne, A.G., et al. 2004, *Science*, 303, 1153
 Lyutikov, M. 2004, *MNRAS*, 353, 1095
 Taylor, J.H., & Cordes, J.M. 1993, *ApJ*, 411, 674
 Turolla, R., & Treves, A. 2004, *A&A*, 426, L1 (TT04)
 van den Heuvel, E.P.J., & de Loore, C. 1973, *A&A*, 25, 387
 Zhang, B., & Loeb, A. 2004, *ApJ*, 614, L53
 Zhu, W.W., & Xu, R.X. 2005, preprint (astro-ph/0504251)

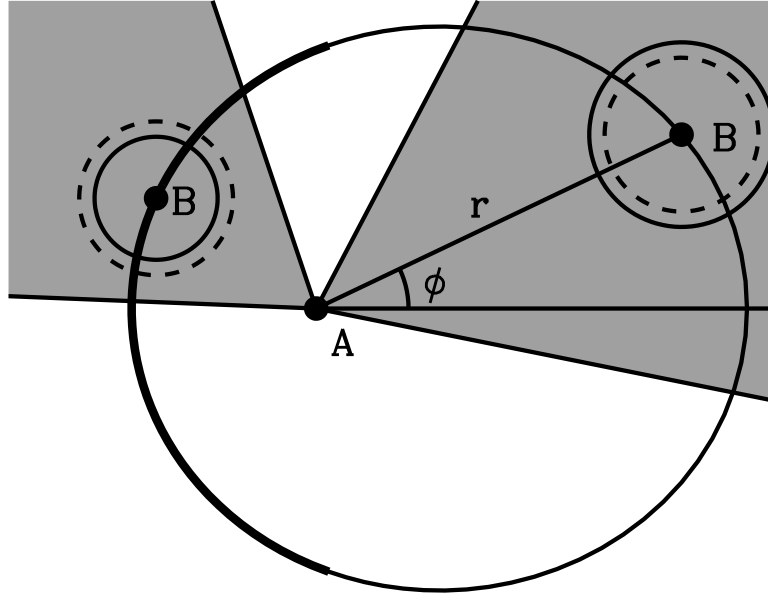


FIG. 1.— A cartoon of the putative double NS system in GCRT J1745-3009. The orbit of star B relative to star A has $e = 0.4$. The dashed and full circles represent the position of B’s light cylinder and of the shock, respectively (not to scale). Along the portion of the trajectory close to periastron and marked with a heavy line the shock is inside the light cylinder. The shaded areas show the wind of A (for illustrative purpose only).

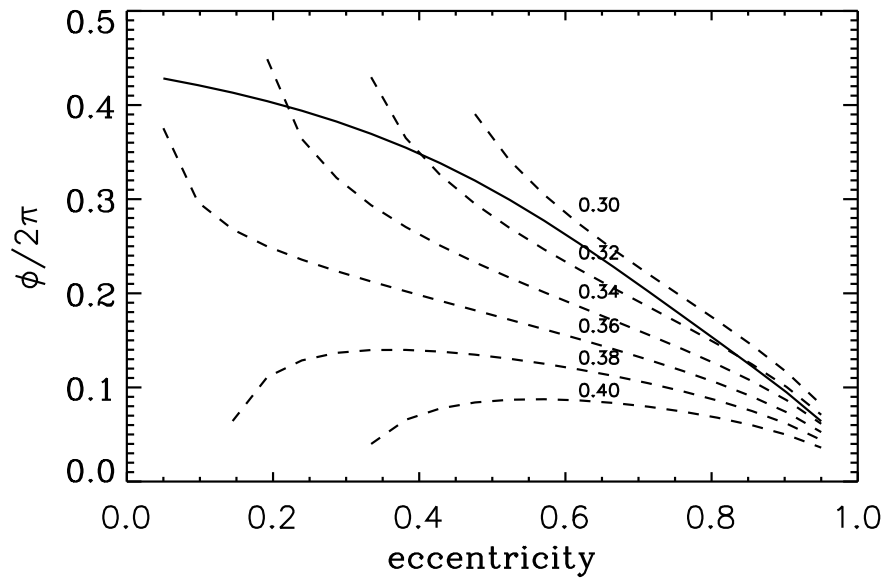


FIG. 2.— The solutions of eqs. (2) (full line) and (7) (dashed lines) as a function of the eccentricity. Each dashed curve is labelled by the corresponding value of the spin period P_B in seconds.

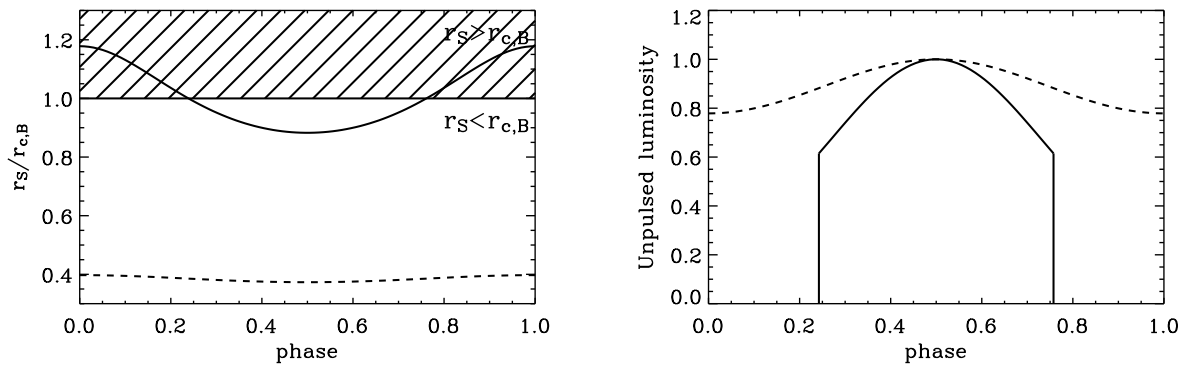


FIG. 3.— Left: The variation of the shock radius with the orbital phase. Actually, a shock can form only outside the hatched region, where $r_S < r_{c,B}$. Right: Same for the unpulsed radio luminosity (in arbitrary units; see text for details). The dashed lines show the same quantities for J0737-3039.