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Letter to the Editor

On the unpulsed radio emission from J0737-3039

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Abstract. The double pulsar system J0737-3039 appears associated with a continuous radio emission, nearly three times stronger than that of the two pulsars together. If such an emission comes from a transparent cloud its spatial extent ($\gtrsim 10^{13}$ cm) should be substantially larger than the orbital separation. Assuming homogeneity and equipartition, the cloud magnetic field is ~0.03 G and the electron characteristic energy ~60 MeV. This is consistent with supposing that relativistic electrons produced in the shock formed by the interaction of the more luminous pulsar wind with the magnetosphere of the companion flow away filling a larger volume. Alternatively, the unpulsed emission may directly come from the bow shock if some kind of coherent mechanism is at work. Possible observational signatures that can discriminate between the two pictures are shortly discussed.

Key words. pulsars: individual: PSR J0737-3039A/B – radiation mechanisms: non-thermal – stars: neutron

1. Introduction

The double pulsar system J0737-3039 (Burgay et al. 2003; Lyne et al. 2004) is unique in many respects. Out of the eight known double neutron star (NS) systems, it is the only one where both neutron stars (A and B) manifest themselves as radio pulsars. The pulsars periods are $P_{\rm A} = 0.02$ s, $P_{\rm B} = 2.77$ s with period derivatives $\dot{P}_{\rm A} = 1.74 \times 10^{-18}$ ss^{-1}, $\dot{P}_{\rm B} = 0.88 \times 10^{-15}$ ss^{-1}. The orbital period $P_{\rm orb} = 0.10$ d is the shortest of the eight, and makes the system an ideal laboratory to observe general relativistic effects. The simultaneous, unprecedented measurement of several Post-Newtonian parameters allows to place stringent constraints on the NS masses ($M_{\rm A} \simeq 1.34\ M_\odot$, $M_{\rm B} \simeq 1.25\ M_\odot$) even if the system has been monitored for less than a year. The orbital separation of the two stars is typically $d \sim 9\times10^{10}$ cm and the estimated distance of J0737-3039 is $D \sim 600$ pc (Lyne et al. 2004). Very recently, a faint X-ray source ($L_{\rm X} \approx 2\times10^{30}$ erg s^{-1}) has been observed with *Chandra* at the position of J0737-3039 (Mc Laughlin et al. 2004).

The total flux detected at 1390 MHz from J0737-3039 is ~7 mJy. The time-averaged pulsed flux from the two pulsars is ~1.8 mJy indicating that the largest part of the system radio emission is unpulsed (Lyne et al. 2004). This is the first time that a continuous radio-source appears associated to an old pulsar (with the possible exception of nearly aligned rotators, see e.g. Hankins et al. 1993). As suggested by Lyne et al. (2004), the continuous radio emission might be associated with the interaction of the two pulsar winds, a situation realized in J0737-3039 alone. Assuming isotropic emission, an unpulsed flux of $F_{\rm C} \sim 5$ mJy at 1390 MHz corresponds to a luminosity $L_{\rm C} \sim 3 \times 10^{27}$ erg s^{-1} in the same band at the given distance of 0.6 kpc.

In this letter we investigate in more detail the nature of the continuous radio emission from J0737-3039. Two possible scenarios to account for the observed unpulsed flux are presented in Sect. 2 and observational signatures that can discriminate between them briefly discussed in Sect. 3.

2. Continuous radio emission models

Because of the large difference in the spin-down luminosity of the two pulsars ($\dot{E}_{\rm A} \sim 5.8 \times 10^{33}$ erg s^{-1}, $\dot{E}_{\rm B} \sim 1.6 \times 10^{30}$ erg s^{-1}), the relativistic wind of A penetrates deep into the magnetosphere of B. A bow shock should be produced where the energy density associated with the wind of A equals that of the magnetic field of B. A simple calculation assuming a dipole field for pulsar B with surface strength $B_{\rm B} \sim 1.6\times10^{12}$ G shows that this happens at a distance $r_{\rm s} \sim 6\times10^{9}$ cm from B. Since B's light cylinder radius is $r_{\rm c,B} \sim 1.3 \times 10^{10}$ cm, the shock is well within $r_{\rm c,B}$ (Lyne et al. 2004).

The magnetic field of pulsar B at the shock is $B_{\rm s} \approx 7$ G. Assuming that the linear dimension of the shock is $\approx r_{\rm s}$, and its width is $\eta r_{\rm s}$ with $\eta \ll 1$, it is easy to show that the synchrotron depth is larger than unity at radio frequencies if the density of relativistic electrons produced in the shock itself exceeds $n_{\rm e} \approx 10^2$ cm^{-3} (see Sect. 2.2). As noted by Kaspi et al. (2004), such an opaque plasma sheath is probably responsible for the eclipses of pulsar A at certain phases (see also Demorest et al. 2004).

Despite the magnetosheath is definitely the site of particle acceleration and hence of synchrotron emission, the fact that it is thick to radio photons implies that the released power is *prima facie* orders of magnitude below $L_{\rm C}$. This brings in the question of how and where the continuous radio emission is produced. In the following we discuss two possible scenarios for explaining the continuous flux. The first is based on the assumption that the radio-source is transparent (or quasi-transparent) to radiation at 1390 MHz. The second considers the possibility that the radio emission comes from the bow shock but it is coherent.

2.1. The transparent scenario

First we consider a homogeneous spherical cloud and derive the basic physical parameters in the hypothesis that the cloud is transparent at radio frequencies ($\nu \approx 1400$ MHz), and that the magnetic and relativistic electron energy densities are in equipartition. We further assume that there is a characteristic electron Lorentz factor γ, and that the energy spectrum around γ has a slope $p = 2$. Let N_e denote the total electron number, R the cloud radius, and B the magnetic field strength. From the condition that the typical frequency is of the order of the synchrotron frequency $\nu_c \sim 4.2 \times 10^6 B\gamma^2$ Hz, it follows

$$\gamma \sim 18B^{-1/2}. \tag{1}$$

Equipartition between magnetic and relativistic particles energy density is

$$\frac{B^2}{8\pi} \sim \left(\frac{3N_e}{4\pi R^3}\right)\gamma m_e c^2 \tag{2}$$

from which it follows

$$B \sim 0.02 N_e^{2/5} R^{-6/5} \text{ G}. \tag{3}$$

The total synchrotron power emitted by a single electron is

$$P_e \sim 10^{-15}\gamma^2 B^2 \sim 4 \times 10^{-13} B \text{ erg s}^{-1}. \tag{4}$$

By equating the total luminosity $N_e P_e$ to that of the continuous radio emission, $L_C \sim 3 \times 10^{27}$ erg s^{-1}, we get

$$N_e \sim 5 \times 10^{29} R^{6/7}. \tag{5}$$

The monochromatic synchrotron absorption coefficient for electrons with a power-law energy distribution of index p is (e.g. Rybicki & Lightman 1979)

$$\alpha_\nu \sim 2 \times 10^{17} \frac{3N_e}{4\pi R^3} B^{(p+2)/2} \nu^{-(p+4)/2} \text{ cm}^{-1}. \tag{6}$$

Using expressions (3) and (5), taking $\nu = 1400$ MHz and $p = 2$, Eq. (6) becomes

$$\alpha_{1.4 \text{ GHz}} \sim 3 \times 10^{39} R^{-27/7} \text{ cm}^{-1}. \tag{7}$$

The condition for marginal transparency is $\tau_\nu \sim \alpha_\nu R \sim 1$ from which a minimum cloud size can be derived

$$R \approx 5 \times 10^{13} \text{ cm}. \tag{8}$$

Correspondingly, the other parameters take the values

$$N_e \approx 3 \times 10^{41}, \quad B \sim 0.03 \text{ G},$$
$$n_e \approx 0.6 \text{ cm}^{-3}, \quad \gamma \approx 100.$$

A homogeneous cloud model is obviously far from giving a realistic description of the source, and the parameters given above should be taken just as terms of reference.

If we assume that the magnetic field decays like $1/r^3$ inside r_c and as $1/r$ in the radiation zone, it is noticeable that at $r \approx 10^{13}$ cm the field expected from pulsar A is $B \sim 7 \times 10^{-2}$ G, comparable to the equipartition value employed above. It is then reasonable that the field generated by pulsar A itself accounts for the synchrotron emission.

Since a continuous radio flux does not appear in isolated pulsars, but it is a unique characteristic of this system, the relativistic electrons responsible for the synchrotron emission are most probably produced at the shock. In this respect we note that the unpulsed radio luminosity is only a small fraction of the wind luminosity of A intercepted by the bow shock, $L_S \approx [r_s/(d - r_s)]^2 \dot{E}_A \approx 3 \times 10^{31}$ erg s^{-1}, so there will be plenty of energy to accelerate the electrons. If we refer again to the parameters of the homogeneous model, supposing an isotropic distribution of pitch angles and a typical particle energy $\sim\gamma m_e c^2 \sim 60$ MeV, the timescale for synchrotron losses is $\tau_{\rm synch} \approx m_e c^2 \gamma / P_e \approx 10^{10}$ s. This means that electrons accelerated at the shock continuously flow to larger distances. An effective drift distance of $\sim 10^{13}$ cm is consistent with a mean free path (taken to coincide with the Larmor radius) of $\sim 10^7$ cm. Zhang & Loeb (2004) have recently estimated the total rate at which particles are deposited in the bow shock by the wind of A to be $\dot{N} \approx 10^{35}$ s^{-1} under typical conditions; the rate at which particles leak from the shock into the magnetosphere of B is ten times smaller and is neglected here. The total number of particles injected during a synchrotron timescale is $\approx \dot{N}\tau_{\rm synch} \approx 10^{45} \gg N_e$. This should ensure that enough relativistic particles are present even if the pair multiplicity of A is below $\sim 10^6$ (see again Zhang & Loeb 2004) or only a fraction of the particles are actually accelerated in the bow shock.

2.2. The coherent scenario

Since we now refer to particles populating the magnetosheath, we take $B \sim 7$ G, the field strength of pulsar B at the shock position r_s. Now the typical volume of the emitting region is ηr_s^3, where ηr_s is the shock width. The limiting frequency for synchrotron self-absorption can be computed as a function of the electron number N_e from the condition $\tau_\nu \sim \alpha_\nu \eta r_s \sim 1$. Using for the absorption coefficient the expression given in Eq. (6), with $4\pi R^3/3$ replaced by ηr_s^3 and again $p = 2$, we get

$$\nu_{\rm th} \sim 5 \times 10^5 r_s^{-2/3} B^{2/3} N_e^{1/3} \sim 0.6 N_e^{1/3} \text{ Hz}. \tag{9}$$

We note that, having expressed $\nu_{\rm th}$ in terms of the electron number N_e, Eq. (9) is independent of η.

The spectrum of a self-absorbed synchrotron source is peaked around $\nu_{\rm th}$ (e.g. Rybicki & Lightman 1979), so, as a first approximation, we can assume that the total luminosity is given by

$$L \approx \nu_{\rm th} L_{\nu_{\rm th}}, \tag{10}$$

where $L_{\nu_{\rm th}}$ is the monochromatic luminosity at $\nu_{\rm th}$. The latter can be found multiplying the synchrotron emission coefficient times the volume of the emitting region

$$L_\nu \sim \eta r_s^3 P_\nu \sim 5 \times 10^{-19} N_e B^{3/2} \nu^{-1/2} \text{ erg s}^{-1} \text{ Hz}^{-1}. \tag{11}$$

Inserting Eqs. (9) and (11) into Eq. (10), we get

$$L \approx 2 \times 10^{-19} B^{11/6} N_e^{7/6} \sim 7 \times 10^{-18} N_e^{7/6} \text{ erg s}^{-1}. \quad (12)$$

From the energetics it follows that the total luminosity produced by the magnetosheath is $L \lesssim L_S \approx 3 \times 10^{31}$ erg s^{-1}. The total particle number required to produce such a power is $N_e \approx 5 \times 10^{41}$ (Eq. (12)). The emitted flux is peaked at $\approx \nu_{th} \approx 5 \times 10^{13}$ Hz, four orders of magnitude above the radio frequencies at which the continuous emission has been detected. The luminosity in the GHz range will be $\approx L_S (10^9/\nu_{th})^{5/2} \approx 6 \times 10^{19}$ erg s^{-1}, many orders of magnitude below L_C. For the limiting frequency given by Eq. (9) to fall into the radio domain, $\nu_{th} \approx 10^9$ Hz, it has to be $N_e \approx 10^{28}$ which gives a total luminosity $L \approx 4 \times 10^{15}$ erg s^{-1}. This shows that synchroton emission from the optically thick layer can not be responsible for the observed unpulsed luminosity.

The brightness temperature associated with the unpulsed flux is

$$T_b \sim 10^{34} \left(\frac{F_C}{1 \text{ Jy}}\right) \left(\frac{D}{1 \text{ kpc}}\right)^2 \left(\frac{\nu}{1 \text{ GHz}}\right)^{-2} R^{-2} \text{ K} \approx 2 \times 10^{15} \eta^{-2} \text{ K} \quad (13)$$

where $R \approx \eta r_s$ is the size of the emitting region. Would the unpulsed emission came from a population of relativistic electrons, particles with a typical Lorentz factor $\gamma \sim k_B T_b / m_e c^2 \gtrsim 10^5$ should be present. These electrons should be confined in outermost layers of the magnetosheath and their number is not to exceed $N_e \approx 10^{28}$ to avoid severe synchrotron absorption. If the main radiative losses are through curvature radiation, the luminosity in the radio range is given by

$$L_C \approx L_S \left(\frac{\nu_{1 \text{ GHz}}}{\nu_{crit}}\right)^{4/3} \quad (14)$$

where $\nu_{crit} = c\gamma^3 / 2\pi\rho$ and ρ is the curvature radius of the trajectory (see e.g. Pacini & Rees 1970). By setting $\rho \approx \eta r_s$, it is $\nu_{crit} \gtrsim 1 \times 10^7$ GHz from which it follows from Eq. (14) that $L_C \lesssim 10^{-9} L_S \sim 10^{22}$ erg s^{-1}.

It seems therefore that the only possibility left to explain the unpulsed emission in terms of emission from the magnetosheath is to invoke a coherent mechanism. Coherent emission has been extensively investigated in connection with radio pulsars and comes into three types: maser, reactive and "coherent", or emission by bunches (e.g. Ruderman & Sutherland 1975; Melrose 1978; Zhang et al. 1999, and references therein). In the latter case particles in a bunch with spatial scale smaller than a wavelength radiate in phase and the total power emitted by a single particle is enhanced by a factor N, the number of particles in a bunch. Despite applications of the bunching mechanism to pulsars' radio emission have been criticized in the past (e.g. Melrose 1978), recent investigations have shown that a free-electron laser (FEL) can indeed be operating high up in the pulsar magnetosphere, where the background magnetic field is $\lesssim$100 G (Fung & Kuijpers 2004, and references therein). Although the proposed scenario for the FEL is quite different from the present one, one may speculate that the same basic mechanism is at work in the two cases. A further possibility to achieve coherent emission, as recently suggested by Zhang & Loeb (2004), is the two-stream instability which may develop between the downstream wind of pulsar A and the upstream wind of B.

3. Discussion

While the transparent scenario is rather conventional, the second scenario postulates the presence of electron bunching and of some coherence in the radio emission. The only argument we can quote for the latter situation is that coherence needs to be required for explaining pulsars radio emission, as it follows from elementary considerations on the radio brightness temperature. The geometric and physical conditions where the pulsed and continuous emission described in Sect. 2.2 arise may be somehow similar, although we are aware that the analogy is only tentative and that electron bunching is just one of the possible mechanisms.

The two pictures proposed above lead to rather different observational expectations. The transparent radio source has an apparent diameter $\gtrsim$1 mas at the putative distance of $\sim$600 pc and could be, in principle, resolved by radio telescopes like VLBA. In the coherent model variability on timescales $\sim$0.1 s is expected together with some degree of orbital modulation, produced by the change in the bow shock aspect ratio with phase. No modulation at all should be present in the transparent picture. It is worth noting that the transparent cloud can not be responsible for the X-ray emission detected by *Chandra* (Mc Laughlin et al. 2004). In fact, for a typical energy of primary photons $\approx h\nu_c \approx 6 \times 10^{-6}$ eV, inverse Compton on electrons with $\gamma \approx 130$ will produce at most IR radiation. On the other hand, the X-ray luminosity could be produced at the shock or by pulsar A itself.

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