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A MODEL FOR THE FLARING RADIO EMISSION IN THE DOUBLE PULSAR SYSTEM J0737−3039

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ABSTRACT

The binary system J0737−3039AB includes two pulsars in a highly relativistic orbit. The pulsed radio flux from pulsar B brightens considerably during two portions of each orbit. This phenomenon cannot be naturally triggered by the illumination of γ-rays or X-rays from pulsar A or by the bow shock around pulsar B. Instead, we explain these periodic flares quantitatively as episodes during which pairs from pulsar A's wind flow into the open field line region of pulsar B and emit curvature radiation at radio frequencies within an altitude of ∼10^8 cm. The radio photons then travel through B's magnetosphere and eventually reach the observer on the other side of the pulsar. Our model requires that A's wind be anisotropic and that B's spin axis be somewhat misaligned relative to the orbital angular momentum. We estimate the expected γ-ray and X-ray emission from the system.

Subject headings: pulsars: individual (PSR J0737−3039A, PSR J0737−3039B) — stars: neutron — X-rays: stars

1. INTRODUCTION

In the double pulsar system PSR J0737−3039AB discovered recently (Burgay et al. 2004; Lyne et al. 2004), the pulsed radio emission from B brightens by orders of magnitude near the orbital longitudes 210° and 280°, while during most of the orbit, B's radio emission is faint or nondetectable (Lyne et al. 2004; Ramachandran et al. 2004). It has been heuristically suggested that B's radio flares might be induced by the illumination of A, either in the form of particles, γ-rays, or radio photons (Lyne et al. 2004; Jenet & Ransom 2004). Assuming a distance of ∼0.5 kpc (Lyne et al. 2004), the system was detected by *Chandra* to have an X-ray luminosity $L_X \sim 2 \times 10^{30}$ ergs s^{-1} (McLaughlin et al. 2004). It is also within the EGRET point-spread function of the unidentified γ-ray source 3EG J0747−3412 (Hartman et al. 1999), whose luminosity is $\sim 2 \times 10^{32}(\Delta\Omega_\gamma)$ ergs s^{-1} for the same distance and an unknown solid angle $\Delta\Omega_\gamma$.

2. BASIC EMISSION PROPERTIES

We first estimate the emission properties of both pulsars based on their measured period P and period derivative $\dot{P}$ by ignoring the interaction between them. Since the spin-down power of A is much larger than that of B, $\dot{E}_A \sim 5.9 \times 10^{33}$ ergs s$^{-1} \gg \dot{E}_B \sim 1.6 \times 10^{30}$ ergs s^{-1}, the interaction between the two pulsars is expected to have a negligible effect on A. The emission of B, however, is strongly influenced by the interaction, as we show in § 3.

Pulsar A.—The spin parameters $P_A = 22.7$ ms and $\dot{P}_A = 1.74 \times 10^{-18}$ (Burgay et al. 2004) yield a polar cap surface magnetic field $B_{p,A} \sim 1.3 \times 10^{10}$ G. The empirical relation between γ-ray luminosity L_γ and $\dot{E}$ for known γ-ray pulsars (i.e., $L_\gamma \propto \dot{E}^{1/2}$; Thompson 2003; Zhang & Harding 2000) yields $L_{\gamma,A} \sim 1.3 \times 10^{33}$ ergs s^{-1}. More adequate pulsar acceleration models suggest a γ-ray luminosity in the range of $(0.3\text{–}1) \times 10^{33}$ ergs s^{-1} (Zhang & Harding 2000; Harding et al. 2002). This estimate is consistent with the observed luminosity of the possibly related source 3EG J0747−3412, for $\Delta\Omega_\gamma \sim 1\text{–}3$. An associated X-ray luminosity $L_{X,A} \lesssim 10^{-3}\dot{E}_A \sim 5 \times 10^{30}$ ergs s^{-1} is expected from the full polar cap cascade (Zhang & Harding 2000), consistent with the empirical relation discovered in other spin-powered pulsars (Becker & Trümper 1997) and the *Chandra* data (McLaughlin et al. 2004). Like other millisecond pulsars, the radio emission of A has a wide double conal structure. Also the pulsar has a small inclination angle between the spin and magnetic axes (Demorest et al. 2004). The Goldreich-Julian (1969) pair flux from both magnetic poles is $\dot{N}_{GJ,A} = 2.8 \times 10^{32}$ s$^{-1}B_{p,10}P_{-2}^{-2} \sim 7 \times 10^{31}$ s^{-1}.

Pulsar B.—The spin parameters are $P_B = 2.77$ s and $\dot{P}_B = 0.88 \times 10^{-15}$ (Lyne et al. 2004), yielding a polar cap surface magnetic field of $B_{p,B} \sim 3.2 \times 10^{12}$ G. The pulsar polar gap is likely controlled by the inverse Compton (IC) process, and the γ-ray luminosity in this regime is $L_{\gamma,B} \sim 0.05\dot{E}_B \sim 8 \times 10^{28}$ ergs s^{-1} (Harding et al. 2002). The X-ray luminosity may be estimated as $\sim 10^{-3}\dot{E}_B \sim 10^{27}$ ergs s^{-1}. Both values are much smaller than the corresponding values for A. The Goldreich-Julian flux from both poles is $\dot{N}_{GJ,B} \sim 1.1 \times 10^{30}$ s^{-1}, and the expected pair multiplicity is $\kappa_B \sim 0.1\kappa_{B,-1}$ (Hibschman & Arons 2001). The intrinsic pair injection rate in the pulsar B magnetosphere is therefore

$$\dot{N}_\pm(\text{B}) \sim 10^{29} \text{ s}^{-1}. \tag{1}$$

3. PHYSICAL MECHANISMS FOR B's RADIO FLARES

Pulsar radio emission is broadly attributed to coherent emission by electron-positron pairs in the pulsar magnetosphere. Our working hypothesis is that during B's radio flares, there is a significant increase of the pair injection rate into the radio emission region.

3.1. *γ-Ray and X-Ray Precipitations*

We consider it unlikely that B brightens because it is illuminated by A's radio beam, since radio waves do not lead to the production of new e^+e^- pairs. Jenet & Ransom (2004) suggested that the γ-ray beam may coincide with the radio beam of A and that the energetic γ-ray photons would trigger a pair cascade in B's magnetosphere and lead to the radio flares. Putting aside the drawback that the γ-ray and radio beams are usually misaligned in known γ-ray pulsars (Thompson 2003), we demonstrate below that the physical parameters of this scenario are implausible.

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To maximize its effect, we assume that A's γ-ray luminosity is close to its highest expected value, $L_{\gamma,\rm A} \sim 10^{33}$ ergs s^{-1} beaming into a solid angle $\Delta\Omega_\gamma \sim 1$. We also assume that the γ-ray spectrum resembles that of known γ-ray pulsars; i.e., the energy flux νF_ν is flat between 1 MeV and ∼30 GeV (Thompson 2003). The range is bounded from above by the highest photon energy capable of escaping from the polar cap cascade of A (see eq. [29] in Zhang & Harding 2000). We may then express the injection spectrum as $E^2N(E) = 10^{33}/\log(3\times10^4) \sim 10^{32}$ ergs s^{-1}. In order to produce a pair in B's magnetosphere, the energy of a γ-ray photon, E_γ, needs to satisfy $(E_\gamma/2m_ec^2)\times(B_\perp/B_q) \geq \chi \sim 1/12$ (Ruderman & Sutherland 1975), where $B_\perp = B\sin\theta_{kB}$ and θ_{kB} is the angle between the γ-ray momentum and the magnetic field $\boldsymbol{B}$. Again, to maximize the effect, we adopt $\sin\theta_{kB} \sim 1$. For a pure dipole field, $B \sim B_p(R/r)^3$ (where R is the stellar radius and r is the radius at which pairs are produced), the threshold γ-ray energy is $E_{\gamma,\rm th} \sim 1.2\ {\rm MeV}(r/R)^3$. Given $E_{\gamma,\max}$, the maximum radius for pair production is then $r_{\max}/R = (3\times10^4/1.2)^{1/3} \sim 29$. The external pair cascade process is dominated by the synchrotron radiation of the higher generation pairs. Since the photon energy decreases by a factor of 16 in each generation, each primary γ-ray with energy E_γ can generate 2^ζ pairs, where $\zeta = [\log(E_\gamma/E_{\gamma,\rm th})/\log(16)] + 1$ (e.g., Zhang & Harding 2000). The radius-dependent solid angle (including both poles) of the open field line region is $\Delta\Omega_{\rm open}(r) = 4\pi^2 r/cP$, and so the pair injection rate into B's open field region due to γ-rays from A is $\dot{N}_\pm({\rm A}\rightarrow{\rm B}) = \int_R^{r_{\max}} [\int_{E_{\gamma,\rm th}(r)}^{E_{\gamma,\max}} 2^\zeta \dot{N}(E)dE]\,[\Delta\Omega_{\rm open}(r)/\Delta\Omega_\gamma]\,(r/d_{\rm AB}^2)dr$; i.e.,

$$\dot{N}_\pm({\rm A}\rightarrow{\rm B}) \sim 10^{26}\ {\rm s}^{-1}, \tag{2}$$

where the distance between the two pulsars is $d_{\rm AB} \sim 9\times10^{10}$ cm (Lyne et al. 2004). This rate is negligible compared with the intrinsic pair injection rate of B itself (eq. [1]). The total pair injection rate into B's magnetosphere (including the closed field line region) is 2×10^{29} s^{-1} [calculated by replacing $\Delta\Omega_{\rm open}(r)$ by 4π in eq. (2)], but it is believed that pairs in the closed field line region can not contribute to the observed coherent emission from pulsars.[3]

A's wind is terminated by the magnetic stress within B's magnetosphere through a bow shock. The distance of the bow shock from B is $d_{\rm sB} = (8\mu_{\rm B}^2 d_{\rm AB}^2 c/\dot{E}_{\rm A})^{1/6} \sim 5\times10^9$ cm (Arons et al. 2004), where $\mu_{\rm B} \sim 3.75\times10^{29}$ cgs is the magnetic moment of B. The bow shock produces a γ-ray luminosity of $\sim10^{30}$ ergs s^{-1} at ∼20 MeV (Granot & Mészáros 2004). The ratio between the γ-ray flux from A and this component is $\sim(10^{33}/10^{30})(d_{\rm sB}/d_{\rm AB})^2 \sim 3$, and so this component does not increase significantly the pair abundance in B's magnetosphere. The bow shock also produces X-rays, which may interact with the high-energy γ-rays from the polar cap to produce pairs (see, e.g., Zhang 2001 and Harding et al. 2002). However, for the estimated X-ray luminosity 10^{29} ergs s^{-1} (Granot & Mészáros 2004), the number density of X-ray photons in the open field line region is only $\sim10^9\ {\rm cm}^{-3}(\epsilon_{\rm X}/0.1\ {\rm keV})^{-1}$, leading to an optical depth $\tau_{\gamma\gamma} \sim 10^{-5}$ for a γ-ray traveling through the entire magnetosphere. The X-rays coming directly from A have an effect that is smaller by a factor $\sim(10^{30}/10^{29})(d_{\rm sB}/d_{\rm AB})^2 \sim 0.03$.

We therefore conclude that the radio flares from B are not due to γ-ray or X-ray precipitations from either pulsar A or the bow shock around pulsar B.

3.2. *Leakage of A's Wind into B's Magnetosphere*

The luminous A wind distorts B's magnetosphere into a shape analogous to the Earth magnetosphere as it is combed by the solar wind. According to the numerical simulation of Arons et al. (2004), the vertical radius of the magnetospheric sheath is $l \sim 7.5\times10^9$ cm. Interpreting A's eclipse as synchrotron self-absorption in the shocked A wind requires that the pair multiplicity of A be as high as $\kappa_{\rm A} \sim 10^6$ (Arons et al. 2004; Lyutikov 2004). This multiplicity value is much larger than in standard cascade theory, $\lesssim 100$ (Hibschman & Arons 2001). Hereafter, we normalize $\kappa_{\rm A}$ by 10^6, although our principal conclusions remain valid at lower values. The total number of the pairs deposited to the bow shock region from A's wind is $\dot{N}_\pm({\rm A}\rightarrow{\rm shock}) = \dot{N}_{\rm GJ,A}\kappa_{\rm A}\pi l^2/\Delta\Omega_{w,\rm A}(d_{\rm AB}-d_{\rm sB})^2$; i.e.,

$$\dot{N}_\pm({\rm A}\rightarrow{\rm shock}) \sim 1.2\times10^{35}\ {\rm s}^{-1}\kappa_{\rm A,6}(\Delta\Omega_{w,\rm A}/4\pi)^{-1}, \tag{3}$$

where $\Delta\Omega_{w,\rm A}$ is the unknown solid angle of A's wind.

It has been suggested that the B spin axis aligns in the direction almost perpendicular to the orbital plane because of the external torque exerted by A's wind (Demorest et al. 2004; Arons et al. 2004). Since the line of sight (which sweeps across B's radio beam) is offset by 3° from the orbital plane (Lyne et al. 2004; Kaspi et al. 2004), B's magnetic axis must be oriented at a small angle relative to the orbital plane. It is therefore likely that A's wind would directly stream into at least one of the open field regions of B. The "leakage" may be realized through resistive effects (see Lyutikov 2004 and references therein). The analogy to the solar wind interaction with the Earth's magnetosphere suggests that the pairs gain access near B's magnetic pole. When this happens, some fraction of the pairs in A's wind can directly slide into B's magnetosphere. At the same time, the open field region in the "day" side facing A is greatly broadened because of the ram pressure of the wind. In principle, the stream from A's wind may encounter B's pair stream ("wind") along its path. The distance from B where the pressures of the two streams balance, $d_{\rm bB}$, can be found by equating $\eta_{\rm B}\dot{E}_{\rm B}/(c\Delta\Omega_{w,\rm B}d_{\rm bB}^2) = \dot{E}_{\rm A}/[c\Delta\Omega_{w,}(d_{\rm AB}-d_{\rm dB})^2]$, where $\Delta\Omega_{w,\rm B} \propto d_{\rm bB}$ is the solid angle of B's wind, and B's wind luminosity is smaller than the spin-down power by a factor of $\eta_{\rm B} < 1$ because of pair screening. We get $d_{\rm bB} \sim 1.5\times10^9\ {\rm cm}\ \eta_{\rm B}^{1/2}(\Delta\Omega_{w,\rm A}/\Delta\Omega_{w,\rm B})^{1/2} < d_{\rm sB}$. Once pairs from A's bow shock leak into B's magnetosphere, they will stream all the way down to B's surface because of the external pressure gradient from above.

We parameterize the pair injection rate into B's open field line region as

$$\dot{N}_\pm({\rm shock}\rightarrow{\rm B}) \sim 1.2\times10^{34}\ {\rm s}^{-1}\eta_{-1}\kappa_{\rm A,6}(\Delta\Omega_{w,\rm A}/4\pi)^{-1}, \tag{4}$$

where $\eta = 0.1\eta_{-1}$ is the fraction of all pairs from A's bow shock that enter this region. The resulting injection rate is orders of magnitude larger than the intrinsic pair injection rate from B in equation (1), even if $\kappa_{\rm A,6}$ is smaller than unity. We therefore suggest that *these pairs are the catalyst for B's radio flares*. A natural coherent mechanism would be the two-stream instability between the downstream A wind and the upstream B wind. The radio photons emitted by these pairs travel downward, but owing to the curved dipole geometry of the magnetic field that is responsible for their production, they are not blocked by the neutron star. Rather, the radio waves pass

[3] When estimating the pair injection rates (eqs. [1] and [2]), a pure dipolar geometry was assumed for B. In reality, B's magnetosphere is severly distorted by A's wind (Arons et al. 2004; Lyutikov 2004), but our conclusion remains unchanged when the distortion effect is included.

through the inner magnetosphere and the gravitational field of B and eventually reach the observer on the other side of the neutron star.

The observed double conal emission of B is separated by about 0.03 s (Lyne et al. 2004). Since the open field region is nearly oriented toward the observer, the radio beam opening angle is $\theta_b \sim 2\pi(0.03/2.77) \sim 0.07$. Based on the dipole field geometry and the gravitational bending effect, this angle should be $\theta_b = 2(\theta_t - \theta_g)$, where $\theta_t = (3/2)\theta_r = (3/2)(r/r_L)^{1/2}$ is the angle between the tangent of the field line at the emission point and the magnetic polar direction, and $\theta_g = 2r_{\rm Sch}/b$ is the gravitational deflection angle. Here $r_{\rm Sch} = 2GM/c^2 \sim 3.7 \times 10^5$ cm is the Schwarzschild radius of the neutron star for a mass of 1.25 $M_\odot$ (Lyne et al. 2004), and $b \sim r(\theta_t - \theta_r)$ is the photon's impact parameter from the star. Due to A's wind pressure, the field lines on the "daytime" side are broadened. We still assume a dipolar geometry but take the light-cylinder radius r_L to be comparable to the vertical size of the magnetic sheath, $r_L \sim l \sim 7.5 \times 10^9$ cm. This gives $\theta_r \sim 0.12 r_8^{1/2}$, $\theta_t \sim 0.17 r_8^{1/2}$, and $\theta_g \sim 0.13 r_8^{-3/2}$, where $r_8 = r/10^8$ cm. We therefore obtain $\theta_b \sim 2(0.17 r_8^{1/2} - 0.13 r_8^{-3/2})$, or $\theta_b \sim 0.08$ for $r_8 \sim 1$. Thus $r_8 \sim 1$ is required from the data for such a geometry.

The average Lorentz factor of the pairs that enter B's magnetosphere could be estimated from the relation $\gamma_\pm m_e c^2 \times \dot{N}_{\rm GJ,A}\kappa_{\rm A} = \dot{E}_{\rm A}$. In pulsar magnetospheres, the synchrotron cooling timescale for pairs is very short, so that the perpendicular component of the pair energy is lost instantaneously. The parallel Lorentz factor of the pairs is $\gamma_{\pm,\parallel} = \xi_\parallel \gamma_\pm \sim 210\kappa_{\rm A,6}^{-1}\xi_\parallel$, where $\xi_\parallel \le 1$ is a geometric factor depending on the incidence angle of the pairs relative to the magnetic field (Zhang & Harding 2000). At a height $r \sim 10^8 r_8$ cm, the curvature radius of the field line for $r_L \sim l$ is $\rho \sim 1.2 \times 10^9 r_8^{1/2}$ cm, and the typical curvature radiation frequency of the pairs is

$$\omega_c = \frac{3}{2}\frac{\gamma_{\pm,\parallel}^3 c}{\rho} \sim 350\ {\rm MHz}(\kappa_{\rm A,6}^{-3}\xi_\parallel^3 r_8^{-1/2}). \quad (5)$$

The characteristic plasma frequency for the two-stream instability is $\omega_p = \gamma_{\pm,\parallel}(4\pi n' e^2/m_e)^{1/2}$ (Ruderman & Sutherland 1975; Medvedev & Loeb 1999), where $n' \sim \dot{N}_\pm({\rm shock} \rightarrow {\rm B})/\gamma_{\pm,\parallel}\pi r^2\theta_r^2 c$ is the comoving downstream plasma density. If $\omega_p < \omega_c$ (requiring $\kappa_{\rm A,6} < 0.25\xi_\parallel^{5/6} r_8^{1/3}$), then the two-stream instability greatly amplifies the curvature radiation (Ruderman & Sutherland 1975). Given the uncertainties in the value of $\kappa_{\rm A,6}$ and $\xi_\parallel$, the typical enhanced curvature radiation frequency is consistent with the 680–3030 MHz band at which B is detected (Lyne et al. 2004). We therefore conclude that the emission altitude is $\sim 10^8$ cm, a value consistent with the emission altitudes derived for other pulsars (Kijak & Gil 2003). We note that although some models of pulsar radio emission (e.g., Lyutikov et al. 1999) disfavor emission from regions near the magnetic pole, the observed narrow beam calls for this geometry, and we speculate that the two-stream instability discussed above plays an essential role in achieving the strong coherence of the emission.

3.3. *Consequences of the Model*

There are several direct consequences of our model. First, the pairs eventually deposit energy onto B's polar cap region, making B a strong X-ray emitter as well. The pairs lose energy via curvature radiation and the IC process as they stream toward B's surface, and both braking processes become more significant near the star surface. The curvature radiation power $\dot{\gamma}_{\rm CR} m_e c^2 = -(2c/3)(e^2/\rho)\gamma_\pm^4 \sim 10^{-7}$ ergs s$^{-1} r_6^{-1/2}$ is negligible. The IC braking is, however, important. With $\gamma_\pm \sim 210$, the IC process is not initially in the resonant regime; i.e., $\gamma_\pm \epsilon_{\rm X} > (B_p/B_q)m_e c^2 \sim 35$ keV$(B_p/3 \times 10^{12}$ G), where $\epsilon_{\rm X}$ is the typical X-ray photon energy (eq. [7]) and $B_q = 4.414 \times 10^{13}$ G is the critical magnetic field. However, even in the nonresonant regime, the IC power $\dot{\gamma}_{\rm CR} m_e c^2 = -(4/3)\gamma_\pm^2 c\sigma_{\rm T} U_{\rm ph}$ is large for typical parameter values, so that the pairs undergo significant deceleration at $r < 3R$. The IC process then enters the resonant regime, and the braking power becomes even larger. As the pairs hit B's surface, their typical Lorentz factor is of order a few. However, the IC γ-rays are beamed toward the surface, so that their energy is deposited on the near polar cap region as well. We therefore assume that all the initial pair energy is deposited on the polar cap region and later radiated as X-rays. The X-ray luminosity can then be estimated as $L_{\rm X,B} \sim \dot{N}_\pm({\rm shock} \rightarrow {\rm B})\gamma_{\pm,\parallel} m_e c^2$; i.e.,

$$L_{\rm X,B} \sim 2.1 \times 10^{30}\ {\rm ergs\ s^{-1}}\eta_{-1}\xi_\parallel(\Delta\Omega_{w,{\rm A}}/4\pi)^{-1}, \quad (6)$$

yielding a value that is consistent with the *Chandra* observations (McLaughlin et al. 2004) for $\eta \sim 0.1$ during the phases when B is illuminated by A's wind. The typical temperature of the polar cap is $T_{\rm pc} \sim (Ll/\sigma\pi R^3)^{1/4} \sim 3.1 \times 10^6$ K $\eta_{-1}^{1/4}\xi_\parallel^{1/4} \times (\Delta\Omega_{w,{\rm A}}/4\pi)^{-1/4}$, with a typical photon energy

$$\epsilon_{\rm X} \sim 2.8kT_{\rm pc} \sim 0.7\ {\rm keV}\eta_{-1}^{1/4}\xi_\parallel^{1/4}(\Delta\Omega_{w,{\rm A}}/4\pi)^{-1/4}. \quad (7)$$

This X-ray component should be modulated at B's spin period of 2.77 s but may not be modulated with orbital phase because of the long thermal inertial time of neutron stars (Eichler & Cheng 1989).

At the higher altitudes of $r \sim 10^7$cm, the IC photons produced by the pairs will not be blocked by the neutron star and can reach the observer. Their typical energy is $\epsilon_\gamma \sim \gamma_\pm^2\epsilon_{\rm X} \sim 30$ MeV. The number density of X-ray photons is $n_{\rm X} \sim L_{\rm X,pc}/(\epsilon_{\rm X} 2\pi r^2 c) \sim 2 \times 10^{11}$ cm$^{-3}\eta_{-1}^{3/4} r_7^{-2}$, giving a Thomson optical depth $\tau_{\rm IC} = n_{\rm X} r\sigma_{\rm T} \sim 1.3 \times 10^{-6}\eta_{-1}^{3/4} r_7^{-1}$. The γ-ray luminosity is $L_{\gamma,{\rm B'}} \sim 30$ MeV $[\dot{N}({\rm shock} \rightarrow {\rm B})]\ \tau_{\rm IC} \sim 7.5 \times 10^{23}$ ergs s^{-1}, much lower than the intrinsic γ-ray luminosity of B, which itself is much lower than the γ-ray luminosity of A.

Since we have attributed B's radio flares to the interaction between A's wind and the open field region of B, the geometric model of Jenet & Ransom (2004), which is based on A's radio beam illuminating B, has to be modified (keeping in mind that A's wind should be wider than its radio beam, allowing for a temporal mismatch between the two as reported [Ransom et al. 2004]). In order to obtain two specific orbital phases during which B flares, we require that A's wind be anisotropic and that B's spin axis be somewhat misaligned relative to the orbital angular momentum. The lack of a detection of interpulses supports the latter assumption. The suggestion of two additional orbital episodes of enhanced weak emission (Ramachandran et al. 2004) can be interpreted as the interaction of A's wind with B's second magnetic pole (which has the less favorable orientation). For the two bright phases, the roughly equal double-component radio profile near longitude 280° (Lyne et al. 2004) is interpreted as A's wind streaming directly into B's open field region, while the weak precursor followed by an intense main pulse at longitude 210° (Lyne et al. 2004) can be explained if A's wind only partially covers B's open field region. For the other two dim phases (Ramachandran et al. 2004), either the wind interaction region only covers a small fraction of the open field region or the line of sight only grazes the emission region.

A more refined geometric model could be developed from additional radio data, including the consequences of geodetic precession (Jenet & Ransom 2004).

In our model, the radio waves travel through near-surface closed field regions where the magnetic fields are stronger and the plasma is denser. At closest approach to the neutron star, the local magnetic field is $\sim 1.6 \times 10^{10}$ G. The local plasma frequency is $\omega_{p,c} = (4\pi n_{\pm,c} e^2/\gamma_{\pm,c} m_e)^{1/2} \sim 110$ MHz $(\kappa_{\mathrm{B},c}^{1/2} \gamma_{\pm,c,2}^{-1/2})$, where $n_{\pm,c}$, $\kappa_{\mathrm{B},c} = n_{\pm,c}/n_{\mathrm{GJ}}$, and $\gamma_{\pm,c}$ are the number density, multiplicity, and typical Lorentz factor of the pairs in the closed field region, respectively (with these pairs being seeded by the γ-rays emanating from A, the bow shock, and the radio emission region). The plasma cutoff frequency is much lower than the observed frequency but could introduce a large dispersion measure for B. The propagation through the plasma may also lead to novel polarization signatures.

4. SUMMARY

We have interpreted the periodical radio rebrightening of B as episodes during which pairs from A's wind flow into the open field line region of B and emit curvature radiation at an altitude of $\sim 10^8$ cm. The pair multiplicity required to explain A's eclipse as synchrotron absorption in the bow shock around B's magnetosphere yields the required radio frequency for the curvature radiation in B's magnetosphere (eq. [5]). The radio photons travel through B's magnetosphere and gravitational potential and eventually reach the observer on the other side of the pulsar. Our model requires that A's wind be anisotropic and that B's spin axis be somewhat misaligned with the orbital angular momentum.

The system has several components of high-energy emission. The dominant γ-ray source is A, whose luminosity $L_{\gamma,\mathrm{A}} \sim (0.3\text{–}1) \times 10^{33}$ ergs s^{-1} is consistent with that of the unidentified EGRET source 3EG J0747−3412. The source is expected to have a 22.7 ms period that could be detected by the future *GLAST* mission.[4] In the X-ray band, there are three sources that could account for the luminosity measured by the *Chandra* satellite, $L_{\mathrm{X}} \sim 2 \times 10^{30}$ ergs s^{-1}. They are (1) polar cap heating and cascade emission from A (Zhang & Harding 2000); (2) B's polar cap heating by A's wind (this work); and (3) emission by the interstellar medium shocked by A's wind (Granot & Mészáros 2004). The first two components should be pulsed with the corresponding pulsar periods (22.7 ms and 2.77 s, respectively) and should possess a thermal spectral component. Further observations with longer exposure times are needed to separate these components.

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[4] See http://glast.gsfc.nasa.gov.

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