GAMMA-RAY BURSTS FROM A CLOSE PULSAR BINARY SYSTEM

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Abstract

The double system of neutron stars observed as radio pulsars PSR J0737-3039 A,B is discussed. Based on the observations it is shown that the wind from the pulsar 'A' distorts strongly the magnetosphere of pulsar 'B'. The shock, dividing the relativistic wind of pulsar 'A' and the corotating magnetosphere of pulsar 'B', is formed inside the light cylinder of 'B'. The slowly diverged tail of magnetic field of pulsar 'B' is also formed by the wind from 'A'. The magnetic field energy stored in this tail is 10^{30} erg. Due to the magnetic field reconnection the energy of magnetic field in the tail can release duiring the short time of 0.1 sec. It will be observed on Earth as the bursts of electromagnetic radiation in the band of 100 KeV and of the flux of $4 \cdot 10^{-11} erg/cm^2 sec$. Such bursts will originate irregular similar to the magnetospheric substorms on Earth.

1 Introduction

Lyne et al.[1] report the discovery of a unique binary system: two neutron stars, both observed as radio pulsars (PSR J0737-3039 A and B) and with the system having asmall orbital period of 0.1 day. Component A is a millisecond pulsar with period $P_A = 22.7ms$, while component B is an ordinary pulsar with period $P_B = 2.773s$. The uniqueness of this system is that, in addition to being a natural laboratory for the measurement of general-relativistic effects, it also provides the opportunity to study the structure of the pulsar's magnetospheres. The reason is that the plane of the orbital motion is inclined only $3°$ to the line of sight, so that we can observe the propagation of the radio waves from one pulsar through the magnetosphere of the other. Periodic eclipses of both pulsars are observed in the radio [1,2]. It is important that the eclipses of the more powerful millisecond pulsar A are brief (about 27s), which corresponds to an eclipsing region near pulsar B of about $1.9 \cdot 10^9 cm$, appreciably smaller than B's magnetosphere, $R_{LB} = cP_B/2\pi = 1.3 \cdot 10^{10} cm$. The quantity R_L (in this case, R_{LB}) is the radius of the light surface where the co-rotation speed of the plasma is comparable to the speed of light c. This is due to the fact that the neutron-star binary system is so close that the plasma wind coming from the millisecond pulsar A penetrates and strongly distorts the magnetosphere of pulsar B. The total rate of rotational energy loss by pulsar A is

$$\dot{E}_A = 5.8 \cdot 10^{33} \left(\frac{J}{10^{45} gcm^2} \right) erg/s,$$

since $\dot{E} = 4\pi^2 J\dot{P}/P^3$, $\dot{P}_A = 1.7 \cdot 10^{-18}$, and $J \simeq 10^{45} gcm^2$ is the standard value for the moment of inertia of a neutron star. The distance between the stars is $d = 8.5 \cdot 10^{10} cm$. With this separation, the flux of stellar-wind energy from pulsar A in the vicinity of pulsar B is $F_A = \dot{E}_A/4\pi d^2 = 6.4 \cdot 10^{10} ergcm^{-2}s^{-1}$. Assuming the wind is relativistic, we can find the energy density in the stellar wind from pulsar A acting on the magnetosphere of pulsar B: $W_A = F_A/c = 2.1 erg/cm^3$. The magnetic field for which the stellar-wind energy would be comparable to the magnetic-field energy ($B^2/8\pi = W_A$) is $B_a = 7.3G$. This value corresponds to the magnetic field inside the magnetosphere of pulsar B. Even if this is the value at the magnetosphere boundary, $r = R_{LB}$, the magnetic field at the surface of the neutron star should be $1.6 \cdot 10^{13} G$, in strong contradiction to its rotational energy losses. The flux of charged particles in A's wind compresses the magnetic fieldin the magnetosphere of pulsar B where the wind encounters and flows past B, stretching out the field on the opposite side of B (forming a so-called magnetospheric 'tail'). Thus, the structure of B's magnetosphere is strongly distorted by the wind from A, and resembles the shape acquired bythe magnetosphere of the Earth due to the action of the solar wind flowing past its dipolar magnetic field. In this case, the rotational energy losses of pulsar B should differ markedly from those for a 'classical' ordinary radio pulsar. The figure shows a schematic of the interaction between radio pulsars A and B. It is usually assumed that a rotating dipolar magnetic field leads to the radiation of electromagnetic radiation at a freqeuncy equal to the rate of rotation of the neutron star, $\omega = \Omega = 2\pi/P$. This is called magnetic-dipole radiation, and is the mechanism via which a neutron star loses rotational energy. To order of magnitude, these magnetic-dipole losses are equal to

$$\dot{E}_{MD} \simeq B^2 \Omega^4 R^6 c^{-3},$$

where B is the dipolar magnetic field at the surface of the star and R is the star's radius. These losses are also proportional to the square of the sine of the inclination of the dipole axis to the rotational axis; since we do not know this quantity for pulsar B, we will take it to be of order unity. On this basis, we estimate the magnetic field at the surface of the radio pulsar using the relation $\dot{E}_{MD} = J\Omega\dot{\Omega} : B \simeq (P\dot{P}_{-15})^{1/2} \cdot 10^{12} G$, where $\dot{P}_{-15}$ is the deceleration of the rotation in units of $10^{-15} s/s$. We find for pulsar B $\dot{P}_B = 0.8 \cdot 10^{-15}$ and the corresponding magnetic field $B_B \simeq 1.6 \cdot 10^{12} G$ [1].

Magnetic-dipole radiation arises during the rotation of a dipolar field in a vacuum, but in reality, the pulsar magnetosphere is filled with relativistic plasma. In this case, the magnetic-dipole radiation is screened [3], and the rotational energy losses are associated with electric currents flowing in the magnetosphere in the vicinity of open field lines, which close at the surface of the neutron star in a region with size $r_0 \simeq R(R\Omega/c)^{1/2}$ near the poles. The rotational energylosses are associated with radiation by the relativistic wind generated in the magnetosphere. To order of magnitude, the radiated energy is

$$\dot{E}_c \simeq B^2\Omega^4R^6c^{-3}i,$$

where $i = j/j_{GJ}$ is the dimensionless electrical current flowing in the magnetosphere in units of the so-called Goldreich-Julian current $j_{GJ} = B\Omega/2\pi$. The current flowing along the neutron-star surface at the polar cap creates a braking torque $K \simeq \pi jB{r_0}^4/c$, which leads to the energy losses $\dot{E}_c = K\Omega$. We can see that, when the current is $j \simeq j_{GJ}$, the magnetic-dipole energy losses and energy losses associated with currents are comparable.

2 The magnetosphere of pulsar B

The distorted structure of the magnetic field in the magnetosphere of pulsar B should strongly influence its energy losses. We denote the distance from the center of pulsar B where a shock dividing the wind from pulsar A and the magnetosphere of B forms r_a (the Alfven radius). Within $r < r_a$, the magnetic field of B is close to dipolar and the magnetosphere co-rotates with the pulsar at the angular speed Ω_B.

Schematic of the interaction between pulsars A and B. The wind from the stronger pulsar A penetrates the light surface of pulsar B, leading to the formation of an elongated tail in the magnetosphere of B.

Thus, $B_B(R/r_a)^3 = B_a = (8\pi W_A)^{1/2} = 7.3G$. The projection of the region with $r \simeq r_a$ onto the stellar surface along the magnetic field in the vicinity of the magnetic poles is $r_0 \simeq R(R/r_a)^{1/2}$. We can see that the size of the polar cap is appreciably larger than in the case of an ordinary pulsar ($r_a << c/\Omega_B = R_{LB}$) due to the flow of the companions wind past the pulsar. Furthermore, the electric current j flowing in the polar region is also increased. The maintenance of a magnetic field in the magnetosphere tail $B \simeq B_a$ requires a current $j = B_ac/2\pi r_a \simeq j_{GJ}(c/\Omega_B r_a) >> j_{GJ}$. The electrical current j closing in the polar region at the stellar surface creates a braking torque that leads to the rotational energy losses

$$\dot{E}_B = B_B^2\Omega_B r_a^3\left(\frac{R}{r_a}\right)^6,$$

which exceed the magnetic-dipole losses by a factor of $(c/\Omega_B r_a)^3$. This increase in the loss rate is associated with the more efficient action of the rotating magnetic field of the star as a unipolar inductor [4]. The potential difference arising at the contacts of the inductor is $U = \Omega\Delta f/c$, where Δf is the difference of the magnetic fluxes at the two contacts. For an ordinarypulsar, $\Delta f = Br_0^2 \simeq BR^2(R\Omega/c)$, while, in our case, the magnetosphere tail closes a region $r \simeq r_a$ with the light surface $r = R_L$, $\Delta f = BR^2(R/r_a) >> BR^2(R\Omega/c)$. The magnitude of the electric current flowing in the magnetosphere, $I = \pi jr_a^2$, likewise increases. This leads to an increase in the rotational losses of the star:

$$\dot{E}_B = U \cdot I = B_B^2 R^6 \Omega_B r_a^{-3}.$$

The electrical potential U acts on the charged particlesin the magnetosphere, giving rise to a relativistic wind from pulsar B.

Using the two relations

$$\dot{E}_B = B_B^2 R^6 \Omega_B r_a^{-3}; \qquad 2\dot{E}_A = cB_B^2 \left(\frac{R}{r_a}\right)^6 d^2,$$

we can independently determine the values of r_a and B_B:

$$r_a = \left(\frac{cd^2}{2\Omega_B}\frac{\dot{E}_B}{\dot{E}_A}\right)^{1/3}; \qquad B_B = \dot{E}_B \left(\frac{cd}{\Omega_B R^3}\right)\left(\frac{1}{2c\dot{E}_A}\right)^{1/2}.$$

Substituting the observed values for $d, \Omega B, \dot{E}_A$, and $\dot{E}_B = 1.6 \cdot 10^{30} erg/s$, we obtain

$$r_a = 2.4 \cdot 10^9, \qquad B_B = 10^{11}\left(\frac{R}{10^6 cm}\right)^{-3} G.$$

Note that this value for r_a - the size of pulsar B's magnetosphere - coincides with the size of the region that eclipses the radio emission from pulsar A, $1.9 \cdot 10^9 cm$. This indicates that there is, indeed, an interface separating the wind from pulsar A and the magnetosphere of pulsar B. This interface lies in the region where the pressures of the wind and of the magnetosphere magnetic field are equal, and has the form of a shock and contact discontinuity at the front and lateral surfaces. This raises the question of the nature of the radio eclipse at $r \simeq r_a$. Various opinions about this have been expressed in the literature.

1. Kaspi et al. [2] and Lyutikov [5] have proposed that the eclipses are due to cyclotron absorption of the radio waves from pulsar A by relativistic particles in the wind from pulsar B near the shock interface. However, the magnetic field near the magnetosphere boundary of pulsar $B, B \simeq B_a = 7.3G$, implies a modest electron-cyclotron frequency in this region, $\nu_{ca} \simeq 10^7 s^{-1}$, which is appreciably lower than the radio frequencies at which the eclipses are observed, $\nu_{ca} << \nu \simeq 10^9 s^{-1}$. This hinders the realization of an electron-cyclotron resonance thatis capable of strongly absorbing the radio emissionof pulsar A. 2. Another mechanism that can explain the eclipses is the linear transformation of electromagnetic waves frozen in the pulsar wind into longitudinal waves in the strong gradient of the electron density in the vicinity of the shock [6]. The transformation coefficient has an exponential dependence on the frequency of the waves, $\exp\{-\nu/\nu_{cr}\}$, which can explainthe absence of a frequency dependence for the eclipse characteristics at frequencies $\nu < \nu_{cr}$, as is observed for J0737-3039, if $\nu_{cr} > 10^9 s^{-1}$.

Our estimate of the magnetic field at the surface of pulsar B ($B_B = 10^{11} G$) is an order of magnitude lower than estimates based on magnetic-dipole losses ($1.6 \cdot 10^{12} G$ [1]). Essentially, a neutron star with $B_B = 10^{11} G$ and $P_B = 2.77s$

should not be a radio pulsar, and pulsar B would not be a radio pulsar without a second neutron star as a close companion. Pulsar B lies below the 'death line' for ordinary neutron stars on the B-P diagram. The relativistic wind from pulsar A flowing past its magnetosphere creates the conditions required for the generation of an electron-positron plasma in the polar regions, thereby leading also to the generation of radio emission. It follows that the radio emission should arise in inner regions of the pulsar magnetosphere ($r < r_a$), where the magnetosphere co-rotates with the star. This inner region of the magnetosphere with size r_a is at least an order of magnitude smaller than the light surface, $R_L = 1.3 \cdot 10^{10} cm$.

It is important that the size of the surface from which the relativistic wind flows from pulsar B can be estimated by equating the energy fluxes from the two pulsars:

$$S = 4\pi d^2 \left(\frac{\dot{E}_B}{\dot{E}_A} \right).$$

This area corresponds to a radius of $r = 2d(\dot{E}_B/\dot{E}_A)^{1/2} = 2.8 \cdot 10^9 cm$. The closeness of this radius to $r_a = 2.4 \cdot 10^9 cm$ indicates that all the wind from pulsar B flows out through its magnetosphere tail. The divergence angle of the tail 2θ is determined by the divergence angle of the wind from pulsar A at a distance r_a from the center of pulsar B: $2\theta = 2r_a/d = 5.6 \cdot 10^{-2} rad = 3.2°$. This is close to the angle between the line of sight and the orbital plane for the binary system. This indicates that we can observe the magnetospheric tail, and therefore observe radio eclipses of pulsar A. The tail will extend to large distances l, until its magnetic field $B = B_a(1 + l/d)^{-2}$ becomes comparable to the interstellar field. It isclear, however, that the effective size of the taiis equalto the distance between the pulsars, $d = 8.5 \cdot 10^{10} cm$. Indeed, the energy stored in the tail's magnetic field is

$$\epsilon_m = \int \frac{B^2}{8\pi} \pi r_a^2 \left(1 + \frac{l}{d} \right)^{-2} dl = \frac{B_a^2}{8\pi} \pi r_a^2 d.$$

In our case, the stored magnetic energy is $\epsilon_m = 3.3 \cdot 10^{30} erg$.

3 Flares

The magnetic field in the tail is directed in different directions on opposite ends of the tail - a configuration that is unstable to magnetic reconnection. The characteristic time for reconnection is given by the ratio of the transverse size of the tail r_a to the Alfven speed v_a. Inside the magnetosphere, the energy density of the particles is lower than the energy density of the magnetic field, so that $v_a \simeq c$.Thus, the decay time for current sheets in the magnetosphere tail is roughly $\tau \simeq 0.1s$. The magnetic energy stored in the tail should be transformed into the energy of accelerated particles on this time scale, with the subsequent radiation of electromagnetic radiation. Electrons and positrons in the magnetosphere will be accelerated by the electric field arising due to the annihilation of the magnetic field, $E \simeq B(r_a/c\tau) = 7.3cgs = 2.2 \cdot 10^3 V/cm$. The maximum energy that can be acquired by these electrons and positrons is $\mathcal{E}_{max} = Er_a = 5 \cdot 10^{11} eV$. On the other hand, the particles cannot achieve very high energies due to synchrotron losses. The energy balance for the particles is determined by the equation

$$\frac{d\mathcal{E}}{dt} = ecE - \frac{2}{3}\frac{e^4 B^2}{m_e^2 c^3}\gamma^2, \tag{1}$$

where $\gamma = \mathcal{E}/m_e c^2$ is the Lorentz factor of the particles. In our case, when $E \simeq B$, the characteristic limiting Lorentz factor determined by the synchrotron losses is

$$\gamma_c = (3c/2r_e\omega_c)^{1/2} \simeq 3.5 \cdot 10^7.$$

Here, r_e is the classical radius of the electron and ω_c is the electron-cyclotron frequency, $\omega_c = eB/m_e c \simeq 1.3 \cdot 10^8 s^{-1}$. Thus, we can see that during the reconnection, particles can be accelerated to maximum Lorentz factors of the order of

$$\gamma_{max} = \mathcal{E}_{max}/m_e c^2 \simeq 10^6.$$

The characteristic frequency for synchrotron radiation by accelerated particles with $\gamma \simeq \gamma_{max}$ is $\omega \simeq \omega_c \gamma_{max}^2 \simeq 1.3 \cdot 10^{20} s^{-1}$. The energy of the corresponding synchrotron photons is $\mathcal{E}_{ph} = \hbar\omega \simeq 10^{-7} erg \simeq 10^5 eV = 100 keV$. The synchrotron-loss time is $\tau_r = \gamma_c^2 \gamma_{max} \omega^{-1} \simeq 10s$. All the energy stored in the magnetic tail, $\epsilon \simeq \epsilon_m = 3.3 \cdot 10^{30} erg$, will go into gamma-ray radiation over this time scale. Since the accelerated particles will move along the magnetic field in the tail at relativistic speeds ($\gamma \simeq \gamma_{max} \simeq 10^6$), the directivity of the synchrotron radiation will be determimed by the divergence angle of the magnetic field in the tail, $2\theta = 3.2^\circ >> \gamma_{max}^{-1}$. With this divergence angle, the flux of gamma-ray energy in the direction of the Earth, which is at a distance $D \simeq 0.6 kpc$ from the binary system, will be equal to

$$F_{ph} = \frac{\epsilon_m}{\pi\theta^2 D^2 \tau_r} \simeq 4 \cdot 10^{-11} erg cm^{-2} s^{-1}.$$

Thus, flares of gamma-ray radiation with energies near $100keV$, durations of about $10s$, and fluxes of $4 \cdot 10^{-11} erg cm^{-2} s^{-1}$ may be observed during the radio eclipses of pulsar A. These flares should be irregular, as is the case for magnetic substorms in the Earth's magnetosphere, due to the release of energy during the reconnection of magnetic field lines in the 'tail' that forms due to the action of the solar wind.

In conclusion, we note that Istomin and Komberg [7,8] have considered a model for the origin of cosmological gamma-ray bursts in which the energetics of the process is provided by the reconnection of magnetic-field lines in the narrow magnetospheric tail of a neutron star or white dwarf, as in the case of the binary pulsar considered here. However, in this model, the tail arises due to the action of the shock from a supernova that occurs in a closebinary containing a compact magnetized stellar object. In this context, gamma-ray observations of PSR J0737-3039 could shed light on this possible mechanism for the radiation of 'classical' gamma-ray bursts.

4 References

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