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Letter to the Editor

A model for the binary pulsar radio eclipse

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Abstract. A problem of the binary pulsar radio eclipses is considered. Recent theoretical work concerning this problem is discussed and a plasma mechanism of radio eclipses in the PSR B1957+20 binary system is presented. The companion star is assumed to be a degenerate white dwarf with nearly dipolar magnetosphere filled with relativistic particles of the pulsar wind. It is argued that radio waves are strongly damped in the companion's magnetosphere due to the cyclotron resonance with particles of the electron-positron plasma. The large, stable, continuous and frequency-dependent eclipses should occur as a result of this process, which agrees well with observations. Possible mechanisms of generation of the optical and high-energy emission are also suggested in the framework of the presented model.

Key words: pulsars: PSR B1957+20 - binaries: eclipsing

1. Introduction

It is widely believed that millisecond pulsars are the end products of the evolution of low-mass X-ray binaries (LMXBs). In most scenarios a neutron star with a weak magnetic field is spun up to its rapid rotation rate by mass transfer from a secondary star during an accretion phase. The existence of eclipsing millisecond pulsars was expected on theoretical grounds based on the evolutionary connection between millisecond pulsars and LMXBs (Brookshaw & Tavani 1995, hereafter BT95). It was thought that such systems might provide the missing link between LMXBs and solitary millisecond pulsars; millisecond pulsars might evaporate their companions. Observations of at least five low-mass binary systems, containing eclipsing millisecond pulsars, have been reported in the literature for today: PSR B1957+20, B1744-24A, B0021-72J, B0021-72I and J2051-0827. One more eclipsing binary system contains slow pulsar PSR B1718-19. These systems provide substantial insight into the physics of pulsar-companion interactions. Moreover, they can provide a probe of the physical parameters of the pulsar MHD wind, and perhaps even shed some light on the general problem of pulsar emission mechanisms.

The firstly discovered and by far the best studied among these eclipsing systems is PSR B1957+20. As we are going later on to restrict ourselves mainly to this particular object, which is extraordinarily rich astrophysical system, let us shortly summarize its main observational features. This galactic disk pulsar (the other four eclipsing systems belong to globular clusters) was discovered in 1988 at Arecibo Observatory, and now has been detected in radio, X-ray and optical band of spectrum. One of the two fastest known pulsars (with period of $P \approx 1.6ms$), the 'black-widow-pulsar' PSR B1957+20 shows regular and entirely periodic eclipses at meter wavelengths, which occupy about 10% of the 9.2 hr orbital period. They are quite stable in length at any given observing frequency, though eclipse length depends strongly on the frequency: at 318 MHz eclipse length averages about 55 minutes, but decreases to about 33 minutes at 1400 MHz. This frequency dependence appears to fit a $f^{-0.4}$ power law well.

Probing the eclipse material at different frequencies with the pulsed signal shows quite rapid eclipse ingress and slower as wellas somewhat turbulent eclipse egress. The excess electron density on either side of eclipse is found to vary by a factor of two from eclipse to eclipse. The delay between the left and right circularly polarized pulse arrival times have also been detected (Thorsett et al. 1989; Fruchter et al. 1990; Ryba & Taylor 1991).

Broad band optical observations (see HST images of the PSR B1957+20 system taken at different orbital phases in Fruchter 1995, also the references therein) display a dramatically variable system which is brightest when the side of the companion heated by the pulsar wind faces the Earth, and which darkens by several magnitudes when the cool backside comes into view. Soft X-rays from this system have been detected by

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two groups using the ROSAT observatory (Fruchter et al. 1992; Kulkarni et al. 1992). Both groups have found an X-ray luminosity of about $\sim 10^{31} erg/s$ (i.e. $\sim 1.3 \cdot 10^{-4}$ part of the pulsar spin-down energy) and neither have found any variability. We will shortly discuss some possible sources of this high-energy and optical radiation below.

2. Plasma mechanism for the PSR B1957+20 eclipse

Let us begin the discussion with some comments on the companion star. Fruchter (1995) argues that the companion is obviously well below the hydrogen burning limit, and one would expect a $0.022 M_\odot$ star to be a degenerate dwarf. The radius of the companion was calculated from the optical images which provide its color temperature and apparent magnitude. Taking into account the estimated distance of 0.8 kpc, it is about $0.12 R_\odot$– somewhat less than one-half the Roche lobe radius (Djorgovski & Evans 1988). The recent reevaluation of dispersion measure (Taylor & Cordes 1993) doubles the estimated distance to the pulsar and hence the estimated radius of the companion (Fruchter & Goss 1992). On the other hand, the pulsar eclipse length ($\sim$ 10% of the orbital period) means that the eclipsing matter occupies at least $1.5 R_\odot$ across, much larger than the companion of any conceivable composition (Fruchter 1995). Indeed, the size of companion's Roche lobe $R_L \sim 0.5 R_\odot$ indicates that most of the volume occupied by the eclipsing medium lies well outside the Roche lobe. Brookshaw & Tavani (1995) considered different scenarios of the mass outflow in binaries, such as mass outflow intrinsic to the companion star and pulsar irradiation-driven outflows or Roche lobe overflow, and discarded the latter. Hence the companion of PSR B1957+20 does not even fill its Roche lobe.

There is a set of physical mechanisms which can cause pulsar eclipses. Thompson (1995) reviewed a variety of them, such as free-free absorption (this mechanism was suggested by a number of groups soon after the discovery of PSR B1957+20), cyclo-synchrotron absorption, scattering by plasma turbulence, induced Compton scattering and stimulated Raman scattering parametric instability. He is inclined to the opinion (Thompson et al. 1994) that the eclipse is due to cyclo-synchrotron absorption by plasma of temperature $T_e \sim (1 \div 4) \cdot 10^8 K$ in a field of strength $\sim 15 \div 20G$. The detailed discussion of eclipse mechanisms have been performed by Eichler & Gedalin (1995). They focus on three wave processes, in particular Raman scattering (the decay $photon \rightarrow photon + plasmon$ stimulated by an ambient plasmon field) and induced plasmon emission (i.e. the same process stimulated by photons already in the final state). They conclude that both mechanisms are able to produce pulsar eclipse via large angle scattering on the initially beamed pulsar radiation, and neither of them requires high plasma densities.

Thompson (1995) points out that the large size of the eclipses (compared to the companion's Roche lobe) could be explained either by diffusion of plasma into the pulsar wind, or by a large companion magnetosphere. Further indirect evidence for a magnetosphere is provided by the orbital period variations (Arzoumanian et al. 1994).

We assume the companion to be a degenerate white dwarf with radius of about $R_* \sim 0.01 \div 0.02 R_\odot$ and with a magnetic field at the stellar surface of $B_* \simeq 10^7 G$. It can be noticed here that about 5% of the observing white dwarfs possess surface magnetic fields in the range of $10^6 \div 10^8 G$, hence this value is quite realistic.

It is assumed that the pulsar magnetosphere is filled by dense relativistic electron-positron plasma flowing along the open magnetic field lines, which is generated by the consequence of the avalanche process, first described by Goldreich & Julian (1969) and developed by Sturrock (1971). This plasma is multicomponent, with one-dimensional distribution function (see Fig.1 in Arons 1981) containing: i) electrons and positrons of the bulk of plasma with the mean Lorentz factor of γ_p and density n_p; ii) particles of the high-energy 'tail' of the distribution function with γ_t and n_t, stretched in the direction of positive momenta; iii) the ultrarelativistic ($\gamma_b \simeq 10^6$) primary beam with so called 'Goldreich-Julian' density $n_b \approx 7 \cdot 10^{-2} B_0 P^{-1} [cm^{-3}]$ (where P is pulsar period and B_0 is magnetic field at the neutron star surface).

It was shown (Lominadze et al. 1986) that two types of waves can propagate in the relativistic electron-positron plasma: a purely transverse electromagnetic t-wave and an electrostatic-electromagnetic lt-wave. Both have high and low frequency branches. The spectra of the high-frequency waves are in the superluminous region (their phase velocity exceeds the speed of light) and they cannot be excited. The spectra of the low-frequency modes are as follows ($\omega_0 \equiv$Reω):

$$\omega_0^t = kc(1 - \delta), \quad \omega_0^{lt} = k_\phi c \left(1 - \frac{k_\perp^2 c^2}{8 \omega_p^2 \gamma_p} \right). \tag{1}$$

Here the cylindrical coordinate system $x,\ r,\ \phi$ has been chosen, with the x-axis directed transversely to the plane of the magnetic field curvature, r and ϕ are the radial and azimuthal coordinates; k_ϕ is the component of the wavevector along the magnetic field, $k_\perp = (k_r^2 + k_x^2)^{1/2}$, $\delta = \omega_p^2 / 4 \omega_B^2 \gamma_p^3$, $\omega_p^2 = 4 \pi n_p e^2 / m$, $\omega_B = eB/mc$.

The loss of the pulsar rotational kinetic energy $\dot{W}_k = 4\pi^2 I \dot{P} / P^3$ is distributed between the acceleration of particles to ultrarelativistic velocities on the one hand, and generation of large-amplitude magnetic dipol radiation on the other (the losses on radio- and high-energy emission are negligibly small in comparison with these two).

We take as a basis an assumption that in the case of PSR B1957+20 the magnetosphere of the companion star is filled by relativistic particles from the pulsar wind. Its density at the pulsar's surface can be estimated as (Melikidze & Khechinashvili 1995)

$$n_p^0 = \frac{I \varepsilon}{2 m c^2 R_0^3 \gamma_p} \dot{P} P^{-2} \approx 8.6 \cdot 10^{32} \frac{\varepsilon}{\gamma_p} \dot{P} P^{-2}, \tag{2}$$

which is about $n_p^0 \simeq 10^{18} cm^{-3}$ for $\gamma_p \approx 3$ (here $R_0 \simeq 10^6 cm$ is the neutron star radius, $I \approx 1.4 \cdot 10^{45}$– is its moment of inertia, m is the electron mass and $\varepsilon \simeq 0.5$ is the part of particles energy in the whole spin-down loss). Given that the concentration is changing according to $n_p = n_p^0(R/R_0)^3$ law inside the pulsar's light cylinder ($R_c = Pc/(2\pi)$), and $n_p = n_c(R_c/R)^2$ beyond it, one obtains the value of $n_p^d \simeq 10^7 cm^{-3}$ for the plasma density in the eclipse region (here we take the binary separation of $a \approx 1.71 \cdot 10^{11} cm$ from BT95).

Radio waves emitted by the pulsar (with the vacuum spectrum $\omega = kc$), reaching this region, transform into the plasma t-waves (lt-waves cannot be excited because of their spectral behavior) and must be strongly damped due to the cyclotron resonance with particles of the bulk of plasma with mean Lorentz factor of $\gamma_p \simeq 3$. The resonant condition for this instability is as follows:

$$\omega - k_\phi v_\phi - k_x u_x - \omega_B/\gamma_p = 0. \tag{3}$$

Here $u_x = cv_\phi p_\phi / R_B \omega_B$ is the particle drift velocity caused by the curvature of magnetic field lines and R_B is the curvature radius. Given that $k = k_\phi(1 + k_\perp^2/2k_\phi^2)$ and $v_\phi = c(1 - 1/2\gamma_p^2 - u^2/2c^2)$, the frequency of damped waves can be obtained from the condition (3):

$$f_d \approx \frac{1}{\pi}\gamma_p \omega_B, \tag{4}$$

hence it is proportional to the magnetic field in the region. This magnetic field is supposed to be nearly dipolar ($B \sim B_*(R_*/R)^3$) in the eclipse region. The character of dependence of the damped frequency on the eclipse length $\Delta t \sim f^{-0.4}$ might be an indication of this fact. Slight deviation from the dipolar law reflected in the latter function can mean that the companion's field is affected by the pulsar wind. It appears that the whole range of radio frequencies is damped in the white dwarf's magnetosphere. What is more, definite frequencies are damped at definite heights from the surface, corresponding to the appropriate values of the magnetic field. The waves with frequencies much higher and much less than ω_B propagate almost freely in this plasma. It is clear that the higher frequencies are damped closer to the star. Therefore, the size of 'eclipsing spot' is strongly frequency-dependent, being larger for the lower frequencies. For example, the radio waves with frequency of 318 MHz are damped at larger distance from the white dwarf surface and in the region, where the appropriate value of magnetic field is $\simeq 20G$. The waves with $f \approx$1.4 GHz propagate almost freely throughout this outer region, although they are damped within the radius where the value of magnetic field is higher ($\simeq 80G$).

A corresponding decrement is given by the following expression:

$$\Gamma_d = -\frac{\omega_p^2}{2 f_d \gamma_p}, \tag{5}$$

from which the characteristic damping timescale of the radio waves can be estimated as $\tau_d = 1/|\Gamma_d| \simeq 10^{-8}s$. This value is incomparably smaller than the time of wave escape from the eclipse region $\tau \simeq 2R_d/c \approx 3s$ (where R_d is the distance from the white dwarf at which 318 MHz radio waves are damped), which means that damping is very strong. It can be even said that the damping occurs almost in the skin-layer of the companion's magnetospheric plasma and the radio waves certainly cannot reach an observer. This leads to a stable and continuous eclipse.

As it was mentioned above, the dipolar magnetosphere of the white dwarf is modified at sufficiently large heights from the star due to influence from the pulsar MHD wind (this distance can be determined by setting the pressure of the pulsar wind F_{sd}/c equal to magnetic pressure $B^2/8\pi$ of the companion's magnetosphere). An extended magnetotail should form as a result of this pressure, stretched on several thousands of stellar radii away, in the direction opposite to the pulsar. Though the tangential orbital velocity is not very high ($v_{orb}/c \simeq 10^{-3}s$), the sufficiently long magnetotail (slightly deviated in the direction opposite to the rotation) is able to cause the observed slow and somewhat turbulent eclipse egress.

We are going to finish discussion by a few remarks concerning the optical and X-ray emission from this binary system. It is out of the question that the only source for such an 'insolation' is the pulsar, but there are still a lot of uncertainties in the explanation of the actual physical mechanisms. There is no data so far on the X-ray spectrum, and it is still not clear whether these X-rays are emitted by the millisecond pulsar itself, or they originate due to some other processes taking place somewhere between the pulsar and the component star. Thompson (1995) points to the fact that the large spin-down luminosity of PSR B1957+20, taking into account the radius of the companion's orbit ($2.5R_\odot$), gives the energy flux at the companion's orbit which is seven times more than the one existing at the surface of our sun. In the model of Arons & Tavani (1993) the pulsar wind, shocked by its interaction with the wind off the companion, emits X-rays and γ-rays with a soft X-ray luminosity comparable to that observed. A large fraction of this radiation is then absorbed by the companion's surface facing the pulsar, due to the combination of relativistic beaming and the proximity of the companion to the shock. They show that the observed luminosity of X-rays can easily power the companion's optical emission.

We suppose that the optical (and perhaps also the X-ray) emission can be nonthermal. The particles from the 'tail' of distribution function of the pulsar wind reach the magnetic field lines of the white dwarf with ultrarelativistic energies. Estimations show that the gyrating particles with mean Lorentz factor of $\gamma \sim 10^2 \div 10^3$ (from 'tail' of the distribution function) should emit a synchrotron optical emission. This occurs at distances from the companion's center that compare with the companion's optical sizes calculated from the observations (see Introduction).

Another mechanism can be suggested to explain the companion's high-energy radiation if the latter proves to be of thermal nature. Relativistic electrons and positrons trapped by the magnetic field of the white dwarf 'bounce' between higher-field points near the North and South poles (in the same manner as in the magnetic mirror or in the Earth's magnetosphere) and slowly precesses around the star due to ∇B and curvature drift. The most energetic particles (e.g., from the 'beam' of the distribution function) with ratio $v_\parallel/v_\perp$ at the equatorial plane

$$v_\parallel/v_\perp > (B_{max}/B_{min} - 1)^{1/2}, \quad (6)$$

are in a 'loss cone', and should be 'poured out' on the poles. It can be shown that in consequence of this process the companion's polar caps are heated up to temperatures high enough to power the optical, as well as the thermal X-ray emission.

We understand that there are still a lot of 'white spots' in our model, and the real picture might be rather complicated by different physical processes taking place in such a medium. We are going to consider these questions in detail in the forthcoming work.

3. Conclusion

We studied the problem of the radio eclipses in the millisecond PSR B1957+20 binary system. The consideration is based on assumption that the companion star is a degenerate white dwarf with radius of about $R_* \sim 0.01 \div 0.02 R_\odot$, and a magnetic field at the stellar surface of $B_* \simeq 10^7 G$. The magnetosphere of the companion star is supplied permanently by the relativistic plasma from the pulsar MHD wind. We estimate that its density $n_p^d \simeq 10^7 cm^{-3}$ and the value of the magnetic field $B_d \simeq 10 \div 100\ G$ are large enough to cause the strong development of cyclotron instability on the distances of about $1.5 R_\odot$. Radio waves emitted by the pulsar reach this region and are damped due to resonance with the particles of plasma (with mean Lorentz factor of $\gamma_p \simeq 3$). The waves with different frequencies should be damped at the different heights from the stellar surface with the appropriate values of dipolar magnetic field strength. This will result in the frequency-dependent eclipses, which are though stable and continuous at any given frequency. The problem of anomalously long eclipses (hence inconceivable sizes of the companion star) is resolved in a quite natural way.

Some other observational features of the radio eclipses were also discussed, and the possible explanation of optical/X-ray emission was suggested in the frame of this model. We plan to develop the presented model in the near future.

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References

Arons J., 1981, in: Proc. Varenna Summer School & Workshop on Plasma Astrophysics, ESA, 273
Arons J. & Tavani M., 1993, ApJ 403, 249
Arzoumanian Z., Fruchter A.S. & Taylor J.H., 1994, ApJ 426, L85
Brookshaw L. & Tavani M., in: Fruchter A.S., Tavani M. & Backer D.C. (eds.) Millisecond Pulsars: A Decade of Surprise, ASP Conference Series, 1995, Vol.72, p.244
Djorgovski S. & Evans C.R., 1988, ApJ 335, L61
Eichler D. & Gedalin M., in: Fruchter A.S., Tavani M. & Backer D.C. (eds.) Millisecond Pulsars: A Decade of Surprise, ASP Conference Series, 1995, Vol.72, p.235
Fruchter A.S., Bergman G., Bower G. et al., 1990, ApJ 351, 642
Fruchter A.S. & Goss W.M., 1992, ApJ 384, L47
Fruchter A.S., in: Fruchter A.S., Tavani M. & Backer D.C. (eds.) Millisecond Pulsars: A Decade of Surprise, ASP Conference Series, 1995, Vol.72, p.213
Goldreich P. & Julian W., 1969, ApJ 157, 869
Kulkarni S., Phinney E., Evans C., Hasinger G., 1992, Nature 359, 300
Lominadze J.G., Machabeli G.Z., Melikidze G.I. & Pataraya A.D., 1986. Sov. J. Plasma Phys. 12, 712
Melikidze G.I. & Khechinashvili D.G., 1996, Izv. Vuz. Radiofizika, v.39, N3, p.346
Ryba M.F. & Taylor J.H., 1991, ApJ 380, 557
Sturrock P.A., 1971, ApJ 164, 529
Tavani M. & Brookshaw L., 1993, A&A 267, L1
Taylor J.H. & Cordes J.M., 1993, ApJ 411, 674.
Thompson C., Blandford R.D., Evans C.R. & Phinney E.S., 1994, ApJ 422, 304
Thompson C., in: Fruchter A.S., Tavani M. & Backer D.C. (eds.) Millisecond Pulsars: A Decade of Surprise, ASP Conference Series, 1995, Vol.72, p.225
Thorsett S.E., Fruchter A.S., Stinebring D.R. & Taylor J.H., 1989, in: Proceedings, 14th Texas Symposium on Relativistic Astrophysics, ed. E.J. Fenyves (N.Y. Acad. Sci.)

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