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An ejector–propeller model for LSI + 61°303

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ABSTRACT
We suppose two different types of interaction between the neutron star and the wind of the primary in LSI + 61°303: a propeller regime at the periastron and an ejector regime close to the apastron. The radio eruptions are a result of the transition from propeller to ejector and the subsequent expansion of the region dominated by the relativistic wind. Under these circumstances, the spin period is evaluated to be of the order of 0.15–0.20 s. The estimated values of the expansion velocity (250 km s^{-1}), the maximum size of the region dominated by the relativistic wind (1.9 au), the X-ray luminosity and the suspected phases of the outbursts are in agreement with the observations.

Key words: binaries: close – stars: individual: LSI + 61°303 – stars: neutron – radio continuum: stars – X-rays: stars.

1 INTRODUCTION

LSI + 61°303 (V615 Cas) is a radio-emitting X-ray binary, with a primary which is a rapidly rotating B0V star with an equatorial disc and mass loss. The secondary is a compact object, most probably a neutron star, orbiting in an eccentric orbit (Hutchings & Crampton 1981). The most spectacular phenomena associated with this binary are periodic non-thermal radio outbursts with a period of 26.496 d (Taylor & Gregory 1982, 1984).

Two models of the system have been proposed so far. Maraschi & Treves (1981, hereafter MT81) supposed that the secondary is a relatively young pulsar, and that the relativistic electrons responsible for the radio emission are produced by the interaction between the normal wind from the primary and the relativistic wind of the neutron star. Later, Taylor & Gregory (1982, 1984), considering this possibility, supposed that as a result of the eccentric orbit the position of the shock front is variable and causes periodic variations of the radio-synchronous luminosity. The second model was proposed by Taylor & Gregory (1982, 1984), who suggested ejections of high-energy particles produced by supercritical accretion events on to the neutron star. Neither model is able to explain the observed expansion of the radio-emitting region with a velocity of order a few × 100 km s^{-1} (see Taylor et al. 1992). In the model of MT81, considerable changes in the size of the emitting region cannot be expected. In the case of supercritical accretion, the velocity of the ejections would be of the order of 10^4 km s^{-1}.

The theory of the gravimagnetic rotator (Lipunov 1987, 1992) predicts different types of interaction between a neutron star and the surrounding matter: accretor, propeller, ejector, georotator and magnetor. In terms of this theory, the model of MT81 corresponds to an ejector regime, and that of Taylor & Gregory (1984) to a superaccretor.

We suppose that the variations in the mass-capture rate, due to the eccentric orbit, may change the type of interaction between the neutron star and the wind of the primary. The basic assumption is that the neutron star is in the propeller regime (‘P’) around the periastron passage, but that close to the apastron it is in the ejector (‘E’) regime. We also suppose that the radio outbursts are a result of the transition from propeller to ejector.

2 EJECTOR–PROPELLER TRANSITION

The type of interaction between a neutron star and the ambient plasma is defined by the pressure of the surrounding matter ($P_{\rm out}$) and the pressure of the magneto-dipole radiation of the neutron star ($P_{\rm L}$). The change of the regime from ‘E’ to ‘P’ requires (Lipunov 1987)

$$P_{\rm out}(R_{\rm a}) > P_{\rm L}(R_{\rm a}), \qquad (1)$$

where $R_{\rm a} = 2GMv_{\rm rel}^{-2}$ is the accretion radius. Here, M is the mass of the neutron star and $v_{\rm rel}$ is the velocity relative to the surrounding matter.

For the inverse transition (‘P’–‘E’) it is necessary to have (Prokhorov 1988)

$$P_{\rm out}(R_{\rm L}) < P_{\rm L}(R_{\rm L}), \qquad (2)$$

where $R_L = (2\pi)^{-1}cT$ is the light-cylinder radius, and T is the spin period. P_L can be expressed by

$$P_L = \frac{L}{4\pi c R^2}, \tag{3}$$

where $L = k\mu^2 T^{-4}$ is the magneto-dipole luminosity of the neutron star, μ is its magnetic dipole moment and k is a constant.

Bearing in mind that the compact star moves supersonically and that, in the realistic cases, $R_L \ll R_a$, we adopt the following expressions for P_{out}:

$$P_{out}(R_a) = \frac{\dot{M}_c v_{rel}}{2\pi R_a^2} \tag{4}$$

and

$$P_{out}(R_L) = \frac{\dot{M}_c \sqrt{2GM}}{8\pi R_L^{5/2}}, \tag{5}$$

where $\dot{M}_c$ is the mass-capture rate.

Using the expressions given by (1) and (2), and the other equations, we obtain the result that a neutron star orbiting in an eccentric orbit would be in the propeller regime at the periastron and in the ejector regime close to the apastron, if the following conditions were fulfilled:

$$T > \left(\frac{k\mu^2}{2cv_{rel}\dot{M}_c}\right)^{1/4} \quad \text{at the maximum } \dot{M}_c \tag{6}$$

and

$$T < \left(\frac{k\mu^2}{\dot{M}_c\sqrt{\pi c G M}}\right)^{2/7} \quad \text{at the minimum } \dot{M}_c. \tag{7}$$

3 APPLICATION TO LSI + 61°303

To apply the above considerations to LSI + 61°303, we use the orbital solution given by Hutchings & Crampton (1981): $e = 0.6$, $M_1 = 10\ \mathrm{M}_\odot$, $M = 1.4\ \mathrm{M}_\odot$, periastron passage at radio phase ~0.2; and an orbital period of 26.496 d.

Let us accept that the B star loses mass via a disc at a rate of $10^{-8}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$. Following Waters et al. (1988), we adopt a disc opening angle of $\theta = 15°$, an outflow velocity of 5 km s^{-1} at R_*, and a power-law density structure of the form $\rho(d) = \rho_0(d/R_*)^{-3.25}$, where d is the distance from the B star, and $R_* = 10\ \mathrm{R}_\odot$ (Howarth 1983). We also accept that the disc rotates with a velocity equal to $0.5v_k(d)$, where v_k is the Keplerian velocity at a distance d from the primary. The neutron star is assumed to orbit in the equatorial plane of the primary. In this way, it will lie within the equatorial wind region all of the time.

Following Bondi (1952) and including a new factor β, for the mass-capture rate we have

$$\dot{M}_c = 4\pi\beta\rho(GM)^2 v_{rel}^{-3}. \tag{8}$$

The underlying assumption in equation (8) is that all the material entering a cylinder with a radius equal to the accretion radius will be captured. β is included because at phases of ~0.4 the accretion radius exceeds the vertical size of the Be-star disc. β is a dimensionless factor ($\beta \le 1$), which represents that part of the accretion cylinder that is filled by the matter of the outflowing disc of the primary. Simple geometrical considerations give us

$$\beta = \begin{cases} 1 & \text{for } R_a < y, \\ 2\pi^{-1}R_a^{-2}[y\sqrt{R_a^2 - y^2} + R_a^2 \sin^{-1}(y/R_a)] & \text{for } R_a > y, \end{cases} \tag{9}$$

where $y = d\tan\theta$ is the vertical size of the outflowing disc at a distance d from the primary. The mass-capture rate calculated in this way is shown in Fig. 1.

We suppose that the radio eruptions observed in LSI + 61°303 are due to a change of the regime from 'P' to 'E'. The spin period needed for an alteration of the regime from 'P' to 'E' and back to 'P', during an orbital cycle, can be estimated using (6) and (7). Adopting $\mu = 2\times10^{30}$ G cm^3, we obtain the value of 0.15–0.20 s for the spin period of the neutron star in LSI + 61°303. The magneto-dipole luminosity corresponding to this spin period during the 'E' regime would be $(1\text{–}5)\times10^{35}$ erg s^{-1}. The estimated period is shorter than all but one of the observed periods of the X-ray pulsars, listed by Nagase (1989), and is in accordance with the supposition of MT81 that the neutron star in LSI + 61°303 is relatively young. The exception to the above is A0538 − 66, for which a transition between different regimes has also been suggested, by several authors: propeller–accretor (Lipunov & Shakura 1976); ejector–accretor (Maraschi, Traversini & Treves 1983).

When the regime changes from 'P' to 'E', a relativistic wind from the neutron star will appear and the region dominated by this wind will start to expand outward. During the ejector phase, the radiation will be generated in the manner supposed by MT81 (see also Taylor & Gregory 1982, 1984). In our opinion, this may cause the observed radio outbursts. This picture does not contradict the assumptions of the adiabatic expansion models of the radio light curves (Taylor & Gregory 1984; Paredes et al. 1991; Marti 1993). Moreover, it can be used as a basis of these models.

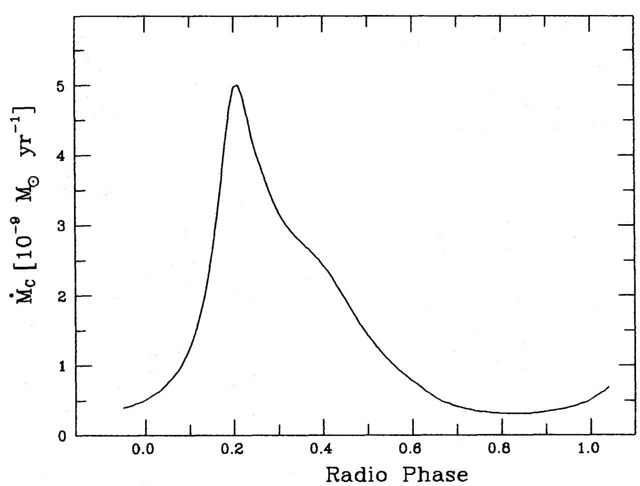

Figure 1. Mass-capture rate for a 1.4-M$_\odot$ companion star in LSI + 61°303. The periastron corresponds to phase ~0.2.

Various set-ups are possible for the propeller stage (see Lipunov 1992, and references therein). The situation proposed by Illarionov & Sunyaev (1975) – in which the magnetosphere corotating with the neutron star does not permit accretion on to the surface, so throwing away the captured matter – seems to be the most plausible for the realization of the transition 'P'–'E'. In the case of LSI + 61°303, the most suitable conditions for such a transition appear to be those at phases 0.6–1.0, i.e. at lower values of the mass-capture rate (see Fig. 1). This is in good agreement with the fact that, typically, the radio outbursts peak around phases 0.6–0.8 (Paredes, Estalella & Rius 1990).

As mentioned above, the region dominated by the relativistic wind will expand outward. The configuration that appears will be similar to that of colliding winds in symbiotic nova stars (Girard & Willson 1987). To obtain a rough estimation of the expansion velocity we can use the formula of Kwok, Purton & FitzGerald (1978), in which appropriate terms for the relativistic wind are set out:

$$V_{\rm exp} = v + \sqrt{\frac{Lv}{c\dot{M}}}, \tag{10}$$

where $\dot{M}$ is the mass-loss rate of the primary, and v is its wind velocity. Adopting $L = 2 \times 10^{35}$ erg s^{-1}, and a wind velocity of the primary at the apastron of $v = 130$ km s^{-1}, we obtain $V_{\rm exp} = 250$ km s^{-1}. Assuming that the neutron star in LSI + 61°303 is in an ejector regime for about half of the period, we estimate a maximum size of the region dominated by the relativistic wind of 1.9 au. This value is in reasonable agreement with the upper limit for the linear size of the radio-emitting region, 3.7 au, given by Taylor et al. (1992).

Paredes et al. (1991), via a fit of an adiabatic expansion model to the two-frequency radio curves, have derived an expansion velocity of 250 km s^{-1}. From high-resolution radio maps, Massi et al. (1993) have obtained a value of 440 km s^{-1}. Taylor et al. (1992) have derived an expansion velocity of 205 km s^{-1} and an upper limit of 640 km s^{-1}. The value of 250 km s^{-1} estimated by us is therefore in agreement with the values derived in other ways.

X-ray emission will be generated during both regimes. To obtain a rough estimate of the X-ray luminosity during the propeller stage, we use

$$L_{\rm x} = GM\dot{M}_{\rm c}R_{\rm m}^{-1}, \tag{11}$$

where $R_{\rm m}$ is the Alfvén radius given by Lipunov (1987):

$$R_{\rm m} = \left(\frac{\mu^2}{\dot{M}_{\rm c}\sqrt{2GM}}\right)^{2/7}. \tag{12}$$

The expected X-ray luminosity has to be variable, since the mass-capture rate depends on the orbital phase. Another reason for variability may be the absorption from the stellar wind of the primary, as was supposed by Murdin et al. (1980) for Cir X-1. Using (11) and (12), and ignoring stellar wind absorption, we estimate $L_{\rm x} = 10^{33}$–10^{35} erg s^{-1}. This agrees with the results of Bignami et al. (1981), who have observed $L_{\rm x} = 1.3 \times 10^{33}$ erg s^{-1}.

The emission of γ-rays can be expected during the ejector regime only. The most plausible mechanism for γ-ray production is Compton scattering of relativistic electrons, generated by the pulsar, off the optical photons of the primary (MT81). Our model does not discount the possible identification of LSI + 61°303 with the *COSB* γ-ray source CG135 + 01 (Perotti et al 1980).

Taylor & Gregory (1984) have noted that a pulsar can readily explain γ-rays and the energetic particles necessary to produce the radio flux, if the pulsar can turn off. The transition 'P'–'E'–'P' supposed in the present paper does switch on and switch off the relativistic wind. The expected behaviour at the change of the regime from propeller to ejector is in good agreement with the observations of LSI + 61°303.

A radio pulsar probably will not be observable because of the free–free absorption in the stellar wind of the primary. In our opinion, however, it is worthwhile to search for low-amplitude light modulations on a time-scale of 0.1 s in various wavelength bands, which may be consistent with the spin period. X-ray and γ-ray observations over the whole period will be useful too. We hope that the present model will be applicable to the case of Circinus X-1, which exhibits similar periodic radio outbursts (Haynes et al. 1978).

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