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Highly-Eccentric Be/X-ray Binaries: Evolution, Wind Rose Effect, Accretor-Propeller Luminosity Gap

Natalya V. Raguzova and Vladimir M. Lipunov

Sternberg Astronomical Institute, Moscow, 119899 Russia

Faculty of Physics, Moscow University, Moscow, 117234 Russia

Abstract. The influence of the spatial distribution of stellar wind velocities (Wind Rose effect) on the X-ray light curve of highly eccentric binaries is examined using the properties of Be disk-fed outflow. It is shown that a phase shift of the maximum X-ray luminosity is always present in the X-ray light curves. The observed X-ray light curves of some transient binaries are analysed using the developed model. We show that the Be/X-ray transients A0538−66, X0331+53 are likely to undergo transitions from the accreting neutron star regime to the propelling one. The example of evolutionary track which can lead to a formation of the Be/X-ray binary is presented. We conclude that synchronization is a very important process for Be star evolution in binary systems and calculate the critical orbital period for existence of a Be/X-ray binary.

1. Be disk-fed outflow

Let us assume that the neutron star orbit is in the equatorial plane of the Be star. The velocity and density law in the equatorial regions was derived from the IR excess (Waters et al. 1988)

$$\rho = \rho_0 (r/R)^{-n} \tag{1}$$

$$v_r = v_0 (r/R)^{n-2} \tag{2}$$

From the equation of mass continuity the mass loss rate can be derived as

$$\dot{M}_w = 4\pi r^2 \sin\theta v_r \rho \tag{3}$$

where v_r is the radial outflow velocity. The exact value of v_0 in the equatorial regions is uncertain. We used $v_0 = 10$ km s^{-1}. The wind velocity consists of a radial component v_r and a rotational component v_φ. We assumed a Keplerian rotational velocity law for v_φ. The relative velocity v_{rel} of the wind with respect to the neutron star can then be written as

$$v_{rel}^2 = v_r^2 + v_\varphi^2 + v_{orb}^2 + 2v_{orb}(v_r \cos\alpha - v_\varphi \sin\alpha) \tag{4}$$

The different velocity components are illustrated in Fig. 1. The accretion rate can be estimated by the Bondi-Hoyle-Lyttleton formulae in the form

$$\dot{M}_a = \pi \frac{(2GM_{ns})^2}{v_{rel}^3} \rho \tag{5}$$

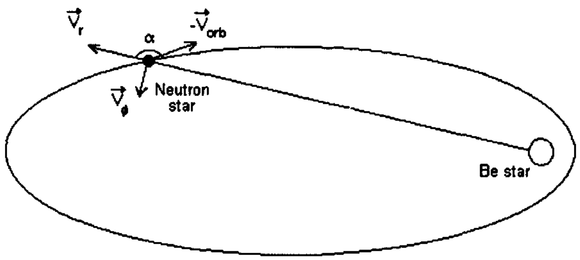

Figure 1. The different velocity components that constitute the relative wind velocity with respect to the neutron star.

If all gravitational energy is converted into X-rays, the luminosity is given by

$$L_x = \dot{M}_a \frac{GM_{ns}}{r_{ns}} = \pi \frac{4G^3M_{ns}^3}{r_{ns}v_{rel}^3}\rho \tag{6}$$

Due to the complex velocity field of the Be star (Wind Rose effect) the maximum of the X-ray light curve does not necessarily occur at periastron. The X-ray light curves of Be/X-ray binaries always show a phase shift in the maximum X-ray luminosity and vary in shape and amplitude with eccentricity.

2. Gap, mixed neutron star stages

The observed light curves of some sources show a much stronger variability related to the orbital motion than expected from our previous Wind Rose model. This can be explained by a centrifugal inhibition of accretion. If the magnetosphere rotates at a super-Keplerian rate, matter cannot penetrate the magnetospheric boundary. Recently Corbet (1996) pointed out that a luminosity gap (a sharp jump in the X-ray luminosity given by the ratio of the minimum neutron star accretion luminosity and maximum magnetospheric accretion luminosity) should be observed for transient X-ray binary systems. The idea that such a luminosity gap takes place during a transition from magnetospheric accretion to neutron star accretion was put forward, for the first time, in paper by Gnusareva & Lipunov (1985). For the neutron star mixed stages the transition from the propeller state to the accretor state causes a sharp increase in the X-ray luminosity

$$\frac{L_x(\mathrm{after})}{L_x(\mathrm{before})} = \frac{r_c}{r_{ns}} = (GM_{ns})^{1/3}(P_s/2\pi)^{2/3}r_{ns}^{-1} \tag{7}$$

when $r_{ns} = 10$ km is the neutron star radius and r_c is the corotation radius. Detection of X-ray luminosity L_x(before) from Eq. 7 would be good evidence that a luminosity gap occurs due to overcoming the centrifugal barrier.

In Figure 2 we show theoretical light curves fitted to the observations of X-ray outbursts for A0538−66 and X0331+53 with account of the Wind Rose

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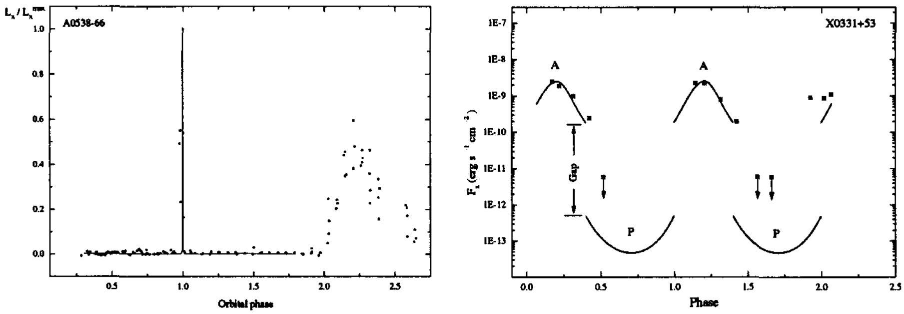

Figure 2. The X-ray light curves for A0538−66 and X0331+53

and luminosity gap effects. Using the "Scenario Machine" (Lipunov et al. 1996) we calculated an evolutionary track that can lead to the formation of such X-ray transients as A0538−66, X0331+53 (see Fig. 3).

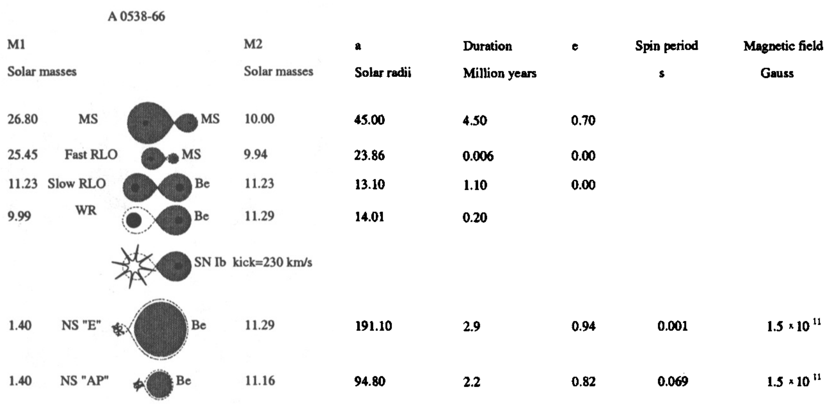

Figure 3. Possible evolutionary track leading to Be/X-ray transients formation

3. About the inclusion of the influence of synchronization on the evolution of close binaries

As was originally pointed out by Kreiken (1935), the components of close binaries have their rotational velocities significantly diminished with respect to single, main-sequence stars of the same spectral type. Tassoul (1987) has presented a purely hydrodynamical mechanism which tends to synchronize the axial and orbital motions of components of binary. This process involves a large-scale meridional flow, superposed on the motion around the rotation axis of the tidally distorted component. According to Tassoul (1987) the synchronization time

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scale is

$$\tau_{syn} = 5.35 \times 10^{3-N/4} \frac{1+q}{q} L^{-1/4} M^{5/4} R^{-3} P^{11/4} \quad (8)$$

where M, L and R are in solar units and P and τ_{syn} are in days, q is the mass ratio. The parameter N is connected with the different ways to transport energy into the outer layers of the stars. For stars with envelopes in radiative equilibrium, $N = N_r$ assumed to be 0.

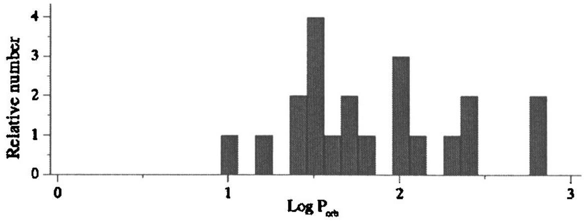

Figure 4. The distribution of the number of observational Be/X-ray binaries over orbital periods.

The synchronization time scale may be less than the life-time scale of the Be star at the main sequence after the first mass transfer. The observational distribution of the number of Be/X-ray systems over orbital periods are plotted in Figure 4. Note the lack of Be stars paired with neutron stars "accretors" with orbital period $P_{orb} < 10 - 15$ days. Let us estimate the minimal orbital period for the production of a Be/X-ray pulsar binary at the end of the evolutionary track. For this purpose, we equate τ_{ev} (Iben & Tutukov 1987) and τ_{syn}

$$\tau_{ev} = 10^{3.9-3.8\log M+\log^2 M} = \tau_{syn} \quad (9)$$

where M is in solar units and τ_{ev} is in days. As a result, we get $P_{orb}^{crit} = 15 - 20$ days for Be stars with M=10 – 20 $M_\odot$. Thus, we explain the lack of Be stars paired with neutron stars "accretors" with orbital period $P_{orb} < 15$ days by synchronization in a binary system.

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