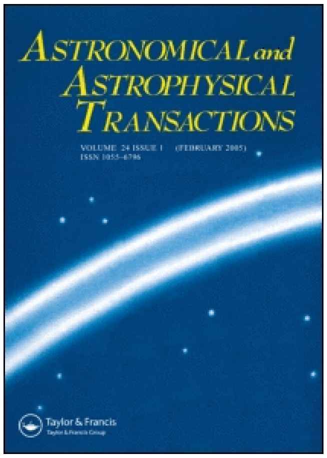

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High-eccentric X-ray binary A0538-66: Evolution status, wind rose effect, and accretor-propeller luminosity GAP

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HIGH-ECCENTRIC X-RAY BINARY A0538–66: EVOLUTION STATUS, WIND ROSE EFFECT, AND ACCRETOR–PROPELLER LUMINOSITY GAP

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Using the parameters appropriate for the binary X-ray transient A0538–66, the wind rose effect on the X-ray light curve is examined using the properties of circumstellar disks derived from IR observations (Waters *et al.*, 1988). The effects of the wind geometry, velocities and densities in the stellar wind of the Be star, and the orbital motion of the neutron star on the expected X-ray luminosity are investigated. It is shown that the shapes of the X-ray light curves depend strongly on the velocity of the gas outflow of the Be star. It is proposed that in some cases an accretion disk may be temporarily formed around the neutron star. The observed X-ray light curves of A0538–66 are analysed using the developed model. We show that the X-ray transient A0538–66 is likely to undergo transitions from the accreting neutron star regime to the propelling stage. The evolutionary scenario that can lead to the formation of the binary system A0538–66 is presented. For the first time, the evolutionary track includes both the orbital period changes and the neutron star spin period history.

KEY WORDS Binary evolution, X-ray sources, accretion processes

In recent years, a number of authors have discussed several non-classical effects in high eccentric X-ray transients such as A0538–66. King and Cominsky (1994), Campana *et al.* (1995), Corbet (1996) and Campana (1997) considered the possibility of X-ray production by magnetospheric accretion in the case of a neutron star rotating rapidly enough. Campana *et al.* (1995) suggested that the X-ray emission observed by *ROSAT* could be a result of energy release occurring when accreting material is halted at the magnetosphere. Recently Corbet (1996) pointed out that the luminosity gap (a sharp increase in the X-ray luminosity given by the ratio of the minimal neutron star accretion luminosity to the maximal 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 a paper by Gnusareva and Lipunov (1985).

Another important effect discussed in the literature (Waters *et al.*, 1989) is the wind rose effect on the X-ray light curve. In this paper we consider in more detail all these effects and make an attempt to fit the single X-ray flares observed for A0538–66 by the model, including all of these effects.

1 BE DISK-FED OUTFLOW

Here we consider the effect of the Be star wind on the compact magnetized component. The velocity structure of the polar and the equatorial regions of the stellar wind of the Be star are essentially different. We will assume that the neutron star orbit is in the equatorial plane of the Be star. The velocity law in the equatorial regions was derived from the IR excess (Waters *et al.*, 1988). Assuming a power-law wind density distribution

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

and using the equation of continuity in the disk, we obtain the velocity distribution as

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

where the density parameter $n = 2.1$ for A0538–66 (Waters *et al.*, 1988).

We adopted an opening angle for the disk of $\theta = 10^\circ$ and assumed that the radius of the disk is much larger than the dimension of the orbit of the binary.

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 radial outflow velocity. Assuming the value of $\dot{M}_w$ is constant and using equation (2), we obtain ρ.

The exact value of v_0 in equatorial regions is uncertain, but most probably lies between 2 and 20 km s^{-1} (Lamers and Waters, 1987). We shall use $v_0 = 10$ km s^{-1}.

The wind velocity consists of a radial component v_r and a rotational component v_φ. We will assume the Keplerian rotational velocity law

$$v_\varphi = \sqrt{\frac{GM}{r}}. \tag{4}$$

The relative velocity $v_{\rm rel}$ of the wind with respect to the neutron star can then be written as

$$v_{\rm rel}^2 = v_r^2 + v_\varphi^2 + v_{\rm orb}^2 + 2v_{\rm orb}(v_r \cos\alpha - v_\varphi \sin\alpha). \tag{5}$$

The different velocity components are illustrated in Figure 1. The accretion rate can be estimated by the Bondi–Hole–Lyttleton formula in the form

$$\dot{M} = \pi \frac{(2GM_{\rm ns})^2}{v_{\rm rel}^3} \rho. \tag{6}$$

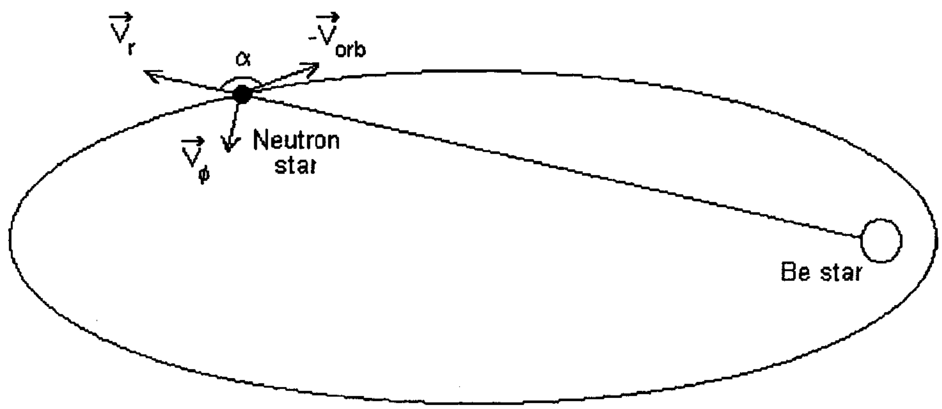

Figure 1 The different velocity components that constitute the relative wind velocity with respect to the neutron star. The wind velocity consists of a radial component v_r and rotational component v_φ.

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

$$L_x = \dot{M}_a \frac{GM_{\rm ns}}{r_{\rm ns}} = \pi \frac{4G^3 M_{\rm ns}^3}{r_{\rm ns} v_{\rm rel}^3} \rho. \tag{7}$$

In Figure 2 we have plotted the logarithm of the ratio $(L_x/L_x^{\max})$ as a function of orbital phase for different values of eccentricity. We use $M_{\rm opt} = 12 M_\odot$, $R_{\rm opt} = 8 R_\odot$, and orbital separation $a = 65 R_\odot$ (i.e. typical values for the system A0538–66). We show the expected X-ray light curves for a neutron star embedded in a stellar wind expanding with nearly constant velocity ($n = 2.1$). Notice that due to the complex velocity field of the Be star the expected X-ray light curves have several shapes. All curves are normalized to the maximum X-ray luminosity.

The observed light curves of some sources show a much stronger variability related to the orbital motion than that expected from our previous wind rose model. This can be explained in terms of centrifugal inhibition of accretion. Accretion onto a rotating neutron star occurs only if the centrifugal drag exerted by the magnetosphere on the accreting matter is weaker than gravity, i.e. the centrifugal barrier is open. If the magnetosphere rotates at a super-Keplerian rate, matter cannot penetrate the magnetospheric boundary. In this case the luminosity produced by magnetospheric impact is

$$L(r_m) = \frac{GM_{\rm ns}}{r_m} \dot{M}_a. \tag{8}$$

In order for accretion onto a rotating magnetized neutron star to occur, it is necessary for the centrifugal barrier to be overcome. In this case accretion onto the neutron star surface releases gravitational energy with a much higher efficiency:

$$L(r_{\rm ns}) = \frac{GM_{\rm ns}}{r_{ns}} \dot{M}_a. \tag{9}$$

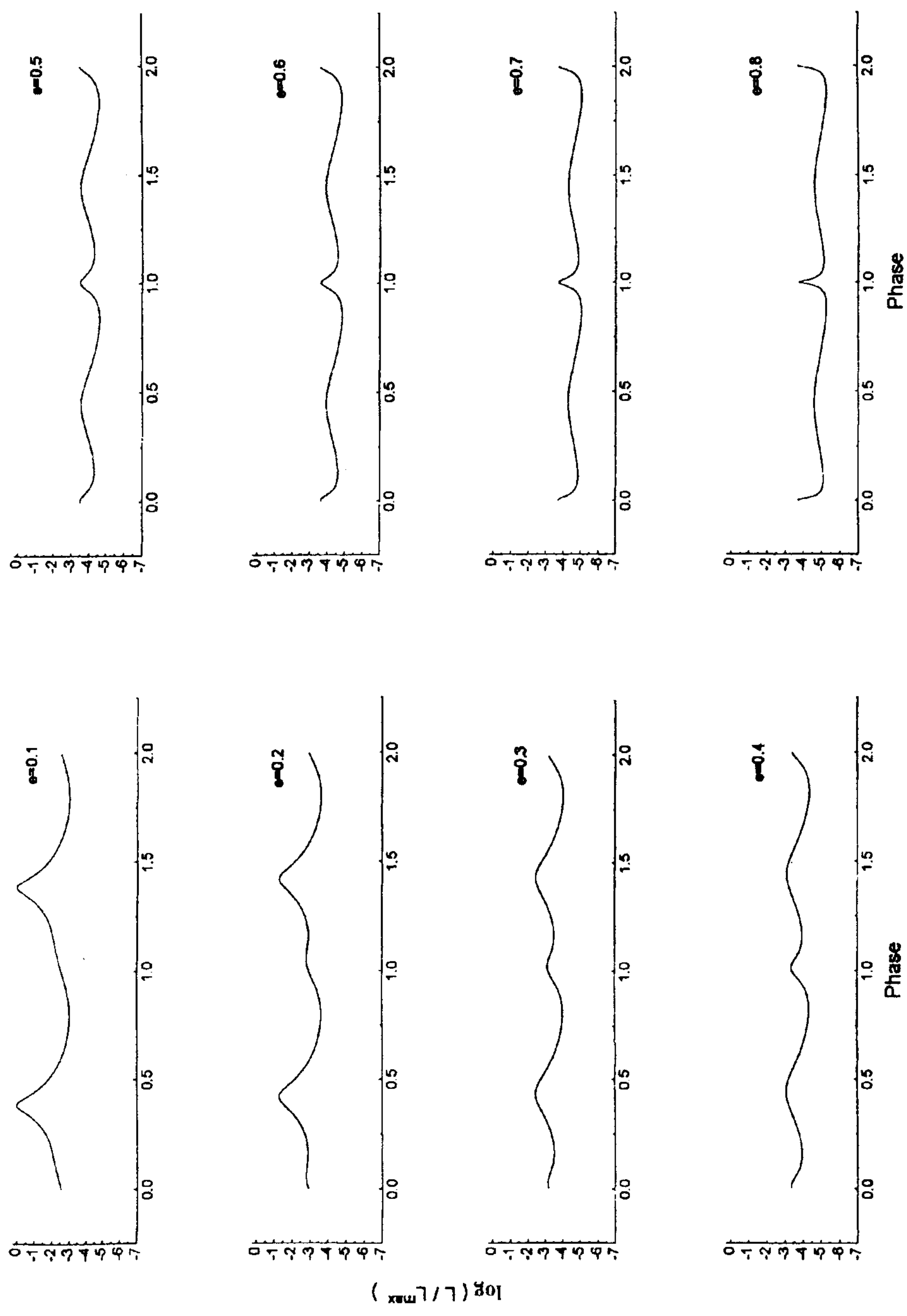

Figure 2 The influence of the wind rose effect on the X-ray light curve for different eccentricity values. We use the parameters of A0538–66.

When computing X-ray light curves one should take account of the occurrence of such a centrifugal barrier. The origin of the barrier is discussed in the next section.

2 GAP, MIXED NEUTRON STAR STAGES

In recent years, a number of authors (Campana *et al.*, 1995; Campana, 1997; Corbet, 1996; King and Cominsky, 1994) have considered the possibility that if the neutron star is rotating rapidly enough then X-rays can be produced by magnetospheric accretion.

The most important consequence of the orbital eccentricity for the evolution of neutron stars is the existence of two different types of binary systems separated by the critical eccentricity (Gnusareva and Lipunov, 1985), $e_{\rm cr}$.

Consider a neutron star in a binary system with some eccentricity. The normal star supplies matter to the compact object. We assume that all the parameters of the binary system (binary separation, eccentricity, masses, accretion rate, etc.) are stationary and unchanged. Then there is some critical value of eccentricity, $e_{\rm cr}$ such that if $e > e_{\rm cr}$ accretion onto the neutron star is never established. Let the neutron star spin initially rapidly enough to be in the ejector (E) state (Lipunov, 1992). The evolution of such a star is determined only by its spindown (because other parameters do not change). The star will gradually spin down until it switches to the propeller state in the periastron, where the wind density is the highest. For some small part of its life the neutron star will be in a mixed EP-state, being in the propeller state at the periastron and in the ejector state when close to the apastron. The subsequent spindown of the magnetized neutron star leads most probably to the propeller state along the entire orbit. This is due to the fact that the pressure of matter penetrating the light cylinder increases faster than that caused by relativistic wind and radiation, as first noted by Schwartzman (1971). So it proves to be much harder for the neutron star to pass from the P state to the E state than back from the E to P state. Finally the neutron star will spin down to some period, p_a, at which accretion will be possible during the periastron passage. Accretion will lead to a spin-up of the neutron star, so that it reaches some average equilibrium state characterized by an equilibrium period $p_{\rm eq}$ defined by the balance of accelerating and decelerating torques averaged over the orbital period. If the eccentricity were zero, the neutron star would be in the accretion state all the time. By increasing the eccentricity and keeping the periastron separation between the stars unchanged, we increase the contribution of the decelerating torque over the orbital period and thus decrease $p_{\rm eq}$. At some ultimate large enough eccentricity $e_{\rm cr}$ the equilibrium period will be less than the critical period p_a permitting the transition from the propeller state to accretor state at apastron to occur. The rotational torque averaged over the orbital period vanishes, and in this sense the equilibrium state is achieved, but the neutron star periodically passes from the propeller state to the accretion state. Thus, X-ray pulsars with an unreachable full-orbit accretion state must exist. Such binaries would be observed as transient X-ray sources with stationary parameters for the normal component.

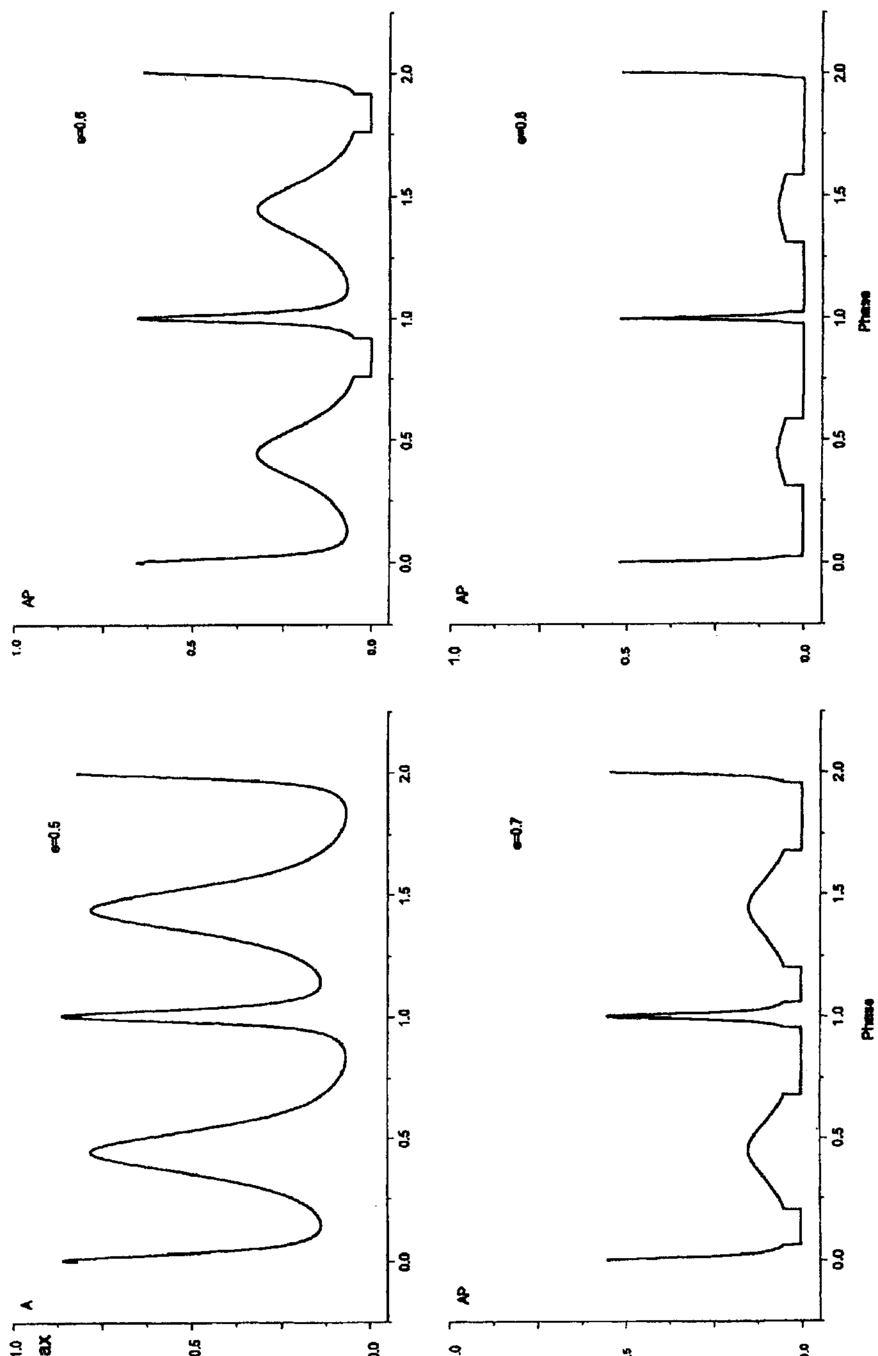

Figure 3 The influence of the neutron star transition from the accretor to the propeller state on the X-ray light curve.

The evolutionary track of a neutron star in an eccentric binary ($e > e_{\rm cr}$) is

$$E \rightarrow PE \rightarrow P \rightarrow AP,$$

which must be the main way of formation of such X-ray transients as A0538–66. In Figure 3 we show the influence of the transition from the accretor to the propeller state on the X-ray light curve. 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. Note that a luminosity gap takes place before transition to the accretion stage. It is obvious that the ratio L_x (before)/L_x (after) is independent of the magnetic field strength for the PA-transition model. The gap value is given by (Gnusareva and Lipunov, 1985)

$$\frac{L_x\ (\text{before})}{L_x\ (\text{after})} = \frac{r_c}{r_{\rm ns}} = (GM_{\rm ns})^{1/3}(P_s/2\pi)^{2/3} r_{\rm ns}^{-1} \qquad (10)$$

when $r_{\rm ns} = 10$ km is the neutron star radius and r_c is the corotation radius:

$$r_c = (GM_{\rm ns}/\omega^2)^{1/3} = (GM_{\rm ns})^{1/3}(P_s/2\pi)^{2/3}. \qquad (11)$$

The detection of X-ray luminosity L_x (before) from equation (10) would be great evidence that the luminosity gap occurs due to overcoming the centrifugal barrier.

3 A0538–66

3.1 X-ray Light Curve

So far two mechanisms have been proposed for explaining the X-ray temporal behaviour of A0538-66: (i) during periastron passage the mass loss rate of the Be star can be enhanced due to dynamical tidal interaction of the primary component and the neutron star; (ii) the neutron star moves through the unchanged stellar wind. However a sharp increase in the X-ray luminosity cannot be treated by purely embedding the neutron star in a high-density wind of the Be primary. It should be taken into account that the neutron star passes from the propeller state to the accretor state. For our modelling besides the wind rose effect we take into consideration the AP-transition effect on the X-ray luminosity behaviour.

The source A0538-66 was discovered with the *Ariel 5* satellite when two outbursts were observed in June and July 1977 (White and Carpenter, 1978). The source was shown to be a recurrent transient with a period of about 16.6 days (Johnston *et al.*, 1979; Skinner *et al.*, 1980). The optical counterpart has spectral type B2IIIe (Charles *et al.*, 1983) and shows flares of ~ 2 mag brightness in phase with the X-ray outbursts, as discovered by Skinner (1980). Observations with the *Einstein* satellite during an outburst (Skinner *et al.*, 1982) led to the discovery of rapid X-ray pulsations with a period $P = 69$ ms. Johnston *et al.* (1979) reported two further outbursts observed with the *HEAO 1* scanning modulation collimator in

Table 1. Observed outbursts from A0538–66

Outburst number	*Observation time (JD 2440000.0+)*	*Peak phase*	*Peak intensity* (erg/s)
0	3323.91	0.04	$> 7.3 \times 10^{38}$
1	3340.73	0.03	1.3×10^{39}
3	3375.6	0.9	3.9×10^{38}
4	3391.8	0.0	2.8×10^{38}
6	3423.98	0.03	7.9×10^{38}
8	3457.30	0.03	4.0×10^{38}
11	3507.14	0.04	3.0×10^{38}
	...		
150 (*ROSAT*)	8220.06	0.01	7.8×10^{37}
151 (*ROSAT*)	8240 ± 1	0.2 ± 0.1	4.6×10^{37}

October and November 1977 and pointed out that the onsets of the outbursts were consistent with a period of 16.65 days. Further X-ray observations of outbursts were made by Skinner *et al.* (1980) using the *HEAO 1* satellite. The X-ray outbursts were found to last up to at least 14 days or to be as short as a few hours. A0538–66 in its largest outbursts (Skinner *et al.*, 1980) has luminosity around 10^{39} erg s^{-1}.

ROSAT (Mavromatakis and Haberl, 1993) and *ASCA* observations (Corbet *et al.*, 1995) have revealed low-level outbursts with luminosities of 4×10^{37} erg s^{-1} and 2×10^{37} erg s^{-1} in the two *ROSAT* observations and $\sim 5.5 \times 10^{36}$ erg s^{-1} in the *ASCA* observation. Due to the low count rate and sampling frequency it was not possible to determine whether the 69 ms pulsations were present in the data. An upper limit of $\sim 5 \times 10^{34}$ erg s^{-1} on the X-ray luminosity in quiescence between outbursts has been obtained with *ROSAT*. As a result the ratio of $L_{\rm max}$ to $L_{\rm min}$ in soft X-rays is > 1000.

Table 1 shows a summary of the X-ray outbursts of A0538–66, detected since 1977. The original *Ariel 5* observations of this source are included in this compilation. Although the outbursts conform to the general pattern of the 16.65 day periodicity, they usually occur late by 0.2–0.7 days (except for the second ROSAT outburst). The peak phases were calculated from the ephemeris of Hutchings *et al.* (1985).

We have attempted to fit the light curves for single X-ray flares observed for A0538–66. The upper limit on the emission between the two *ROSAT* outbursts is at least 1000 times lower than the maximum luminosity (8×10^{37} erg s^{-1} in the first short outburst). None of the known mechanisms of mass transfer via wind accretion can explain these large differences. The high ratio of $L_{\rm max}$ to $L_{\rm min}$ in soft X-rays led us to conclude that switching an accretor on occurred as a result of a PA-transition during the first short outburst. This transition probably takes place due to the very large eccentricity which should be greater than $e_{\rm cr}$ for this system. In Figure 4 the observed X-ray light curve of A0538–66 in 1990 (Mavromatakis and Haberl, 1993) is plotted. The solid line is the theoretical X-ray light curve account

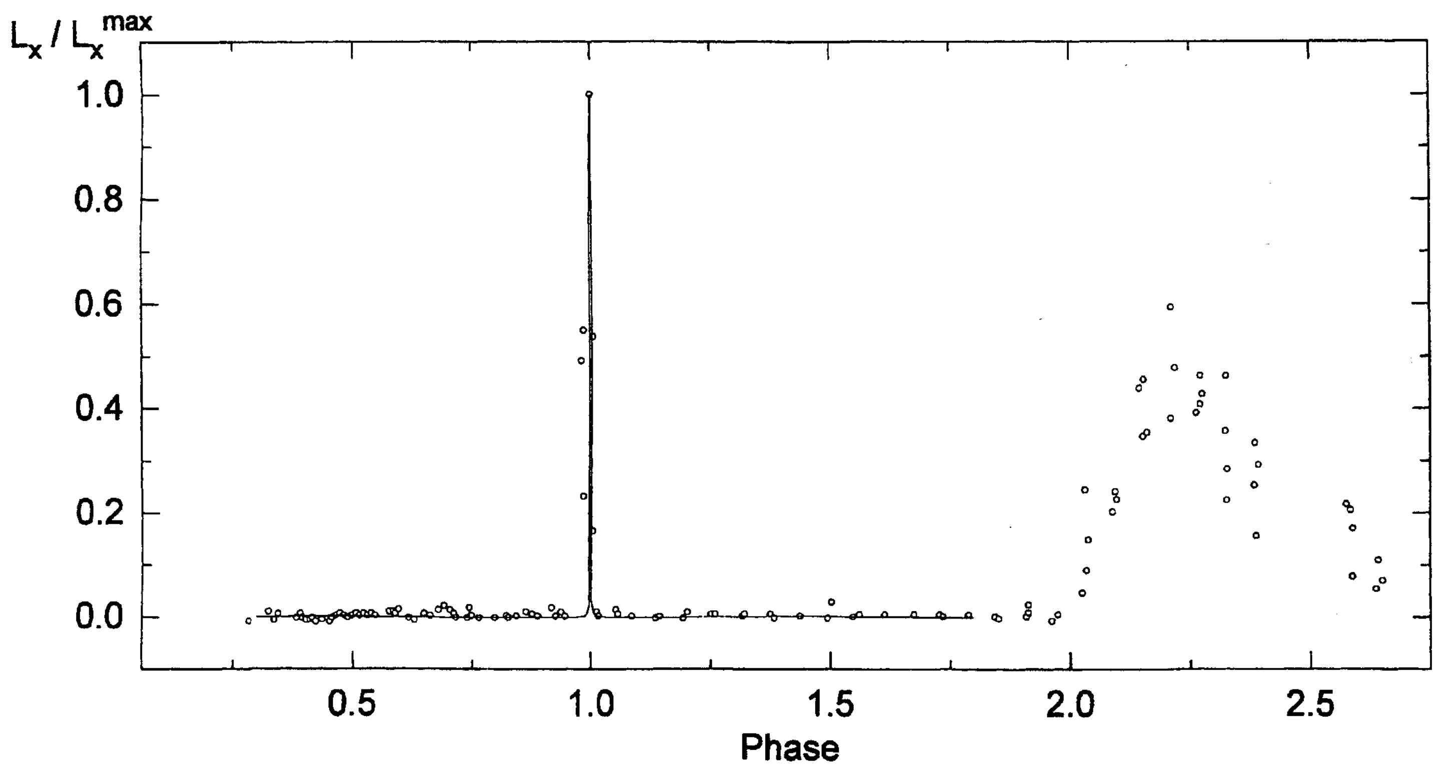

Figure 4 The light curve fitted to the observations of the flare in the sequence of flares given by Mavromatakis and Haberl (1993) for A0538–66. Open circles indicate the observed data.

of the PA-transition for a model with $R = 8R_\odot$, $M = 10M_\odot$, $P_{\rm orb} = 16.65$ days, $e = 0.85$ and $n = 2.1$. We could not fit the theoretical light curves for other X-ray flares observed for A0538–66. The different shapes and intensities of the sequence of flares indicate that the density structure of the Be disk of matter is not constant. Optical spectroscopic observations show (Doazan, 1982) that at least in the case of some Be stars the disks move radially away from the Be star. The theoretical considerations also imply that the structure of a gas ring around a Be star should change with time (Pringle, 1981). From the duration of the longest X-ray flares we can conclude that an accretion disk exists in the A0538–66 system around the neutron star (at least during the longest X-ray outbursts). In this case the shape of the X-ray light curve is determined by non-stationary flow in the accretion disk rather than by the wind rose effect. The presence of an accretion disk should affect the shape of the X-ray light curve. The formation of such a disk should result in additional flattening of the X-ray light curve. The shape of the outburst in this case cannot be predicted and our model is inapplicable for such X-ray behaviour.

3.2 The Evolution Stage of A0538–66

Here we present the results of the Scenario Machine (Lipunov *et al.*, 1996) computations for A0538–66. The continuous evolution of a binary component here is treated as a sequence of a finite number of distinct evolutionary stages. The evolutionary track that can lead to the formation of a Be+ "AP" NS binary with the parameters similar to those of the A0538–66 is presented in Table 2. Here we use the notation of the evolutionary stages of the components: MS = a main sequence star inside its Roche lobe (RL); an MS-star that accretes matter during the first mass transfer is considered to be a rapidly rotating Be-star; WR = a helium star

Table 2. Possible evolutionary track leading to A0538–66 formation

Stage	Δt (10^6 *yr*)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	a ($R_\odot$)	P_{orb} (*days*)	e	P_{ns} (*ms*)
Two ZAMS stars	4.2	29	10	55	7.6	0.70	...
		28	10	29	3.0	0.00	...
Fast RL overflow + MS	4.4×10^{-3}	28	10	29	1.4	0.00	...
		12	12	15	1.4	0.00	...
Slow RL overflow +Be	1	12	12	15	1.4	0.00	...
		11	12	15	1.4	0.00	...
WR + Be	0.18	11	12	15	1.4	0.00	...
		10	12	16	1.6	0.00	...
Supernova explosion (type Ib) of WR star to NS; $v_{\rm kick} = 200$ km s^{-1}							
PSR + Be	1.7	1.4	12	240	120.8	0.94	1
		1.4	12	180	75.0	0.92	66
NS "AP" + Be; A0538–66	7.4	1.4	12	180	75.0	0.92	66
		1.4	11	65	16.7	0.85	68

remaining after the mass transfer; RLO(fast) = Roche lobe overflow in the dynamical timescale; RLO(slow) = Roche lobe overflow in the thermal timescale; PSR = radiopulsar; E, P, A correspond to ejecting, propelling, and accreting stages of a compact magnetized star.

Immediately before the supernova explosion the orbit is circular as the result of strong tidal interaction in the mass-transfer phase. An asymmetric supernova explosion gives a kick to the collapsing star which leads to very large eccentricities. In the presented track the kick velocity was taken to be as high as 200 km s^{-1} which is necessary to provide the observed high eccentricity of the system orbit. According to the present evolutionary scenario the age of A0538–66 is estimated as 1.4×10^7 yr.

4 DISCUSSION

The nature of the physical variability of a Be star is not yet clearly understood. However, the observed X-ray fluxes during the outbursts of A0538–66 can be explained in terms of accretion from a low-velocity, high-density equatorial wind of the Be star. It seems that due to strong variability of the Be envelope on relatively short time scales (comparable to the orbital period of 16.61 d) the outbursts from A0538–66 in many binary cycles are absent (for example, the outburst with $n = 5$ was absent (Skinner *et al.*, 1980) but outbursts with $n = 4$ and $n = 6$ have been observed). In addition the shapes of the X-ray outbursts are different during two consecutive cycles. Usually, the matter accreted directly from the stellar wind should possess very small specific angular momentum with respect to the neutron star; thus the formation of a disk is not possible. However, the observations of spin-up time scales of the X-ray pulsars in binary systems associated with Be stars show that the accreting matter can have very large specific angular momentum, enough to produce a Keplerian disk (Rappaport and Joss, 1977). From the duration of the longest X-ray flares we can conclude that an accretion disk exists in the A0538–66 system (possibly at least during X-ray outbursts, which are triggered when the neutron star passes periastron) around the neutron star. In this case the shape of the X-ray light curve is determined by the non-stationary flow in the accretion disk rather than by the wind rose effect. If such a disk, is formed, this will result in an additional flattening of the X-ray light curve. For these reasons the wind rose model can explain the X-ray outburst in general but cannot explain every particular outburst from A0538–66.

The A0538–66 system originated from a supernova event forming the neutron star. Depending on the asymmetry of the supernova explosion, the newly formed neutron star can be substationally kicked out of the original orbit plane. In the A0538–66 case there is no strong evidence supporting a large inclination angle between the orbital plane of the neutron star and the equatorial plane of the Be star, as X-ray flares occur only near the expected zero phase (the neutron star passes at the periastron) of the 16.6 d cycle. This inclination angle can be quite large and we shall study such systems in a forthcoming paper (Raguzova and Lipunov, in preparation).

5 CONCLUSIONS

We conclude that the different shapes of outbursts are associated with the changing nature of circumstellar matter that envelopes the primary star. An extended envelope around the primary evolves rapidly from cycle to cycle and the variability in the outbursts is governed by the varying size and density of this envelope. For the longest X-ray flares the formation of an accretion disk is possible. All these arguments led us to conclude that due to these non-stationary effects our model can explain X-ray outbursts only in general.

The modelling of the previous evolution of A0538–66 showed that its high eccentricity could be a results of the asymmetric supernova explosion which provided the neutron star with a kick ~ 200 km s^{-1}. Also this modelling gave an estimate of the age of the system as 1.4×10^7 yr.

The predicted luminosity gap (Gnusareva and Lipunov,1985; Corbet, 1996) has not yet been detected. The primary candidate for detecting this gap is A0538–66. Unfortunately, the low-luminosity flares of A0538–66 are rather faint, even though the source itself is still rather luminosity due to its location in the LMC. The detection of the luminosity gap could be much easier if a similar source was located closer to the Earth.

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