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X-ray orbital modulations in low-mass x-ray binaries

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Abstract. It is suggested that the absorption dips observed in many low-mass x-ray binaries at various phases may be due to obscuration of the central x-ray source by the matter pulled out of the orbital plane presumably in the outer disc rim as a result of tidal forces due to the companion star.

Key words : x-ray sources—binaries

1. Introduction

There are observed two types of x-ray sources in binary systems. Type I sources exhibit hard x-ray spectra in most cases with $kT > 10$ keV, and often show x-ray pulsations. The optical counterparts are generally massive stars with masses $\gtrsim 15\ M_\odot$, early type, main sequence stars. Many of these systems are massive x-ray binaries, in which the neutron star is accreting material through stellar wind from the companion (Parmar & White 1988). The type II sources show softer spectra with $kT < 10$ keV and consist of a neutron star as the compact object with a low-mass ($M \lesssim 1\ M_\odot$) companion which transfers matter via Roche lobe overflow.

These low-mass x-ray binaries (LMXRB) have further been classified into two groups; the low luminosity group ($L_X \leqslant 10^{36}$ erg s^{-1}) in which the companion is a main sequence star and the high luminosity group ($L_X \sim 10^{37}$ erg s^{-1}) in which the companion is a hydrogen-shell burning sub-giant. It is interesting to note that the modulation in the x-ray flux with period 0.19 h from the source in the globular cluster NGC 6624 (X 1820-303); using EXOSAT (Stella, Priedhorsky & White 1987) and also a 8.5 h modulation in both the optical and x-ray flux from the source in M15 (X 21.17 + 19) (see *e.g.* Ilovaisky *et al.* 1986; Naylor *et al.* 1986; Hertz 1986; Callanan *et al.* 1987) have been discovered.

An analysis of x-ray light curves of low-mass x-ray binaries indicates three types of orbital modulations provided of course the orbits are properly inclined to the observer. These are (i) eclipses of the x-ray source by the companion star; (ii) quasi-sinusoidal modulations of the x-ray flux; and (iii) absorption dips being variable in width, depth and morphology but recurring periodically. Rather than discussing different types of modulations and their probable origin, we shall confine our attention here to the modulation of the third type.

EXOSAT medium energy 1 to 10 keV light curves (Parmar & White 1988) showed regularly occurring intensity dips having orbital periodicity in the 20 μ Jy x-ray source X 1916 − 053 (*cf.* White & Swank 1982; Walter *et al.* 1982 for obscuration of the x-ray source by the material located at the point where gas stream meets the source). In accordance with the proposed model, there are thickened regions or bulges (White & Holt 1982; Mason & Cordova 1982; Parmar & White 1988) located at the outer rim of the accretion disc. Thus, one comes across two bulges (origin unclear); one located between orbital phases 0.6-0.0 and the other though smaller located at $\sim 150°$ from the first. The disc bulge at two different sites and of different sizes does not appear to be the correct explanation of the dips in the x-ray spectra. The disc's other rim bulge must rotate rigidly with orbital periodicity to make probable the recurrence of absorption dips. It is found that the Keplerian period of the outer part of the disc is very small as compared to the orbital period of the binary system. It is inferred that the flow of matter there is non-Keplerian. For example, the circularization radius $R_{circ} = 0.238 R_{\odot}$ for X 0748 − 676 whereas the disc is supposed to extend to a radius larger than this. Modelling of the X 1822 − 371 light curve requires the obscuring material to be situated at a radius of 0.6 $R_{\odot}$.

We suggest (Pandey 1989) that structures in the outer parts of the accretion disc may be due to tidal action of the secondary (the companion star) which is overflowing its Roche lobe. These structures at various phases (with mid-eclipse as the zero phase $\Phi = 0.0$) may result from inhomogeneous tidal forces to which the matter in the outer parts of the disc is subjected. Let us examine this in detail.

2. Tidal interaction due to companion

Let the line joining the centres of the two stars be along X^1-axis in cartesian coordinates and the distance between their centres be a. The axis of rotation and hence the axis perpendicular to the orbital plane is X^3. Let the centre of the compact object be taken to be the origin of the coordinate system. It is also assumed that the compact object does not produce any distortion in the companion. If a is sufficiently large compared to the radius of the disc, and mass m of the outer bulge is negligibly small compared to the mass M_c of the companion, then the tidal force F due to the companion expressed in cylindrical geometry is given by

$$F = \frac{GM_c}{a^3}\,[45\,\rho^2 \cos^2\varphi + 4\,\rho^2 + 25\,z^2]^{1/2} \qquad \ldots(1)$$

The tidal force is effective at all phases and is probably most predominant at the outer rim. Table 1 gives the F_z/F values for various phases and also at a number of z-values for the x-ray source XBT 0748-676 for a typical binary separation $a = 10.462 \times 10^{10}$ cm, $M_1 = 1.4\ M_{\odot}$, $M_2 = 0.45\ M_{\odot}$ and $q = 0.32$. We find that the ratio F_z/F_ρ increases with the tidal force F. The bulge angle θ measured by the ratio F_z/F_ρ is therefore increased. The variation of angle θ that the bulge subtends at the centre of disc against various phases for this system is given in table 2. Here the angle θ is measured by

$$\theta = \tan^{-1}\left(\frac{F_z}{F_\rho}\right) = \tan^{-1}\left[\frac{5z}{\rho(9\cos^2\varphi - 2)}\right], \qquad \ldots(2)$$

where $\varphi = 0$ corresponds to phase $\Phi = 0.0$. The typical values of z and ρ are 0.3 $R_{\odot}$ and 0.6 $R_{\odot}$ respectively. Smaller values of the bulge angle θ are expected to occur if one

Table 1. F_z/F at various phases Φ and z for the system XBT 0748-676

$z(R_O)$	F_z/F at various phases						
	$\Phi = 0\ 0$	$\Phi = 0.1$	$\Phi = 0\ 2$	$\Phi = 0\ 25$	$\Phi = 0\ 3$	$\Phi = 0\ 4$	$\Phi = 0\ 5$
0 0001	0 000119	0 000125	0 000189	0 000214	0 000189	0 0001254	0 000119
0.001	0 001190	0.001250	0 001890	0 002140	0 001890	0 001250	0 001190
0 01	0 011903	0 012500	0 018910	0 021437	0 018904	0 012483	0 011903
0 15	0 176	0.211	0 398	0 530	0 398	0 211	0 176
0.30	0.336	0.397	0.655	0.781	0 655	0.397	0 336
0 40	0.430	0 499	0 756	0.858	0 756	0.499	0 430
1 00	0.765	0 821	0.945	0 972	0.945	0.821	0 765

F_z/F valuesat phases $\Phi = 0.6$-0 9 are the repetitions of values listed in the table

Table 2. Bulge angle θ at various phases

Phases	F_z/F_p	θ (degrees)
0.0	0 357	19.7
0.1	0.643	32.7
0.2	2 191	65.5
0.25	−1.250	141.3
0 3	2.191	65 5
0.4	0 643	32.7
0 5	0.357	19 7

considers the tidal effect on matter close to the orbital plane. Thus, disc bulging emerges as a natural phenomenon in x-ray emitting binaries.

3. Origin of dips

The F_z/F values from table 1 indicate that at phase $\Phi = 0.2$ and $\Phi = 0.8$ the same values occur with a maximum between phases $\Phi = 0.2$, $\Phi = 0.3$ and between $\Phi = 0.7$, $\Phi = 0.8$ for all z. We therefore suggest that the tidal accelerations of the matter on the disc rim presumably at some selected phases cause the matter to be pulled out of the orbital plane. This however obscures the x-rays from the central source. Since the outer disc rim is affected tidally at all the phases wheresoever the companion star may be, the extent of obscuration therefore may depend upon the instantaneous pulling out of the material in that phase. This may be the cause of different durations and irregular variability of the dips of the x-ray source X 1755 − 338.

The tidal forces produce azimuthal structures predominantly at two selected phases in the rim. It is suggested that these structures at phases ($\approx 180°$ apart) partially occult the x-ray sources and may be responsible for anomalous dips observed in LMXRB. The theoretical values of θ from table 2 are in fairly good agreement with the occurrence of absorption dips at particular phases (θ being larger there). However, every binary system has different separation a, mass ratio q, as well as orbital period P which therefore indicate different dip morphology.

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