On the relation between spin and orbital periods in Be/X-ray binaries

Li, X.D.; van den Heuvel, E.P.J.

Publication date
1996

Published in
Astronomy & Astrophysics

Astron. Astrophys. 314, L13–L16 (1996)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

On the relation between spin and orbital periods in Be/X-ray binaries

X.-D. Li[1,3] and E.P.J. van den Heuvel[1]

[1] Astronomical Institute, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[2] Department of Astronomy, Nanjing University, Nanjing 210093, P.R. China

Received 4 July 1996 / Accepted 30 August 1996

Abstract. The relation between the spin period P_s and the orbital period P_{orb} of neutron stars in Be/X-ray binaries is investigated. The spin periods of neutron stars in such systems can be appropriately explained in terms of the equilibrium spin, at which a small torque is exerted on the neutron stars. But the equilibrium is achieved in different ways. In short orbital period Be/X-ray binaries ($P_{orb} \lesssim 100$ days), the equilibrium spin is reached by angular momentum transfer via a disk, which is formed in the equatorial wind of the Be stars. In wider Be/X-ray binaries, the low angular momentum of the wind matter prevents the existence of an accretion disk, and the neutron star's spin remains close to its previous equilibrium value at an earlier evolutionary stage, similar as supergiant/X-ray binaries.

Key words: accretion, accretion disks – stars: Be – stars: neutron

1. Introduction

Most X-ray pulsars are in massive X-ray binaries (MXBs), which can be divided into two groups on the basis of the companion of the neutron star: supergiant/X-ray binaries (e.g., Cen X-3, Vela X-1), and Be/X-ray binaries (e.g., A 0535+26, X Per). The orbital periods of supergiant/X-ray binaries are between 1.4 and 10 days, and the supergiants generally lose mass in a roughly spherical stellar wind, a small fraction of which is captured by the neutron star. Some supergiants also lose mass by incipient Roche lobe overflow, and an accretion disk is formed in such systems. In Be/X-ray binaries, the Be stars are deeply within their Roche lobes due to their much longer orbital periods (15 – 200 days), and only stellar wind accretion occurs (see Bhattacharya & van den Heuvel 1991 for a review).

Send offprint requests to: X.-D. Li (email: li@astro.uva.nl)

The distribution of MXBs in the P_s vs. P_{orb} diagram was first studied by Corbet (1984), who noted a positive correlation between P_s and P_{orb} in Be/X-ray binaries, i.e., $P_s \propto {P_{orb}}^2$, while wind-fed and disk-fed supergiant/X-ray binaries occupy upper and lower parts of the diagram, respectively (see Fig. 1). The correlation between P_s and P_{orb} in X-ray binaries has been studied by many authors (Corbet 1984; Stella et al. 1986; van den Heuvel & Rappaport 1987; Waters & van Kerkwijk 1989), in terms of equilibrium spin period $P_s = P_{eq}$ of the neutron star in which the centrifugal force acting on the wind matter close to the magnetospheric boundary can prevent accretion onto the neutron star surface. For supergiant systems in which the stellar wind is usually assumed to be radially expanding with a constant velocity, the assumption of equilibrium spin requires a mass accretion rate two orders of magnitude lower than observed (Stellar et al. 1986; van den Heuvel & Rappaport 1987). It has been suggested that the present distribution of wind-fed supergiant/X-ray binaries may result from an earlier evolution phase when the companion was on the main sequence and its wind was much weaker (Waters & van Kerkwijk 1989).

Be stars are rapidly rotating and show different stellar wind structure from supergiants. Observations show evidence for the presence of high velocity ($\sim 10^3$ kms^{-1}), low density wind material in the polar regions as well as high density, low velocity wind material in the equatorial regions (cf. Waters et al. 1987). The observed X-ray luminosities are consistent with accretion from the equatorial, disk-like wind. Assuming that the density in the equatorial wind varies as $\rho(r) = \rho_0 (r/R)^{-n}$, where R and ρ_0 are the Be star radius and the wind density at the surface of the Be star respectively, and that angular momentum of the wind matter is sufficient to form an accretion disk, Waters & van Kerkwijk (1989) found that the spin period scales as $P_s \propto {P_{orb}}^{2(4n-6)/7}$ if the neutron star spins in equilibrium. The $P_s \propto {P_{orb}}^2$ relation can be accounted for given $n \simeq 3.25$, compatible with the value obtained from the infrared measurements.

The above arguments for Be/X-ray binaries was questioned by King (1991), who, according to analytical and numerical calculations of wind accretion, pointed out that the angular momentum transfer in the stellar winds of Be stars is inefficient to spin up a neutron star into equilibrium. In stead, he suggested that the P_s vs. P_{orb} relation in Be/X-ray binaries was established at an earlier evolutionary phase of Be stars.

The purpose of this paper is to examine the self-consistency of the assumption of equilibrium spin in disk accretion in Be/X-ray binaries. In section 2 we discuss the physical implications of the equilibrium spin period in disk and wind accretion cases, and extend the calculations of Waters & van Kerkwijk (1989) for the equilibrium spin period, by taking into account the rotation of the equatorial wind of Be stars. The angular momentum of the captured wind matter is then evaluated in section 3, and compared with the the Keplerian specific angular momentum at the magnetospheric boundary, to examine whether a disk can form. Our discussion and conclusions are in section 4.

2. Equilibrium spin period

That a neutron star rotates in equilibrium means that averaged over a long time scale it experiences zero or a small external torque (small short-term fluctuations of P_s do not imply it is not close to equilibrium). Equilibrium spin in disk accretion is reached when the spin up torque by the disk is counteracted by the coupling between the stellar field and the disk (Ghosh & Lamb 1979), at which the inner radius r_d of the disk becomes close to the corotation radius $r_{co} \equiv (GM_x P_s^2/4\pi^2)^{1/3}$, where G and M_x are the gravity constant and the neutron star mass, respectively. On the other hand, a neutron star in a stellar wind may first be slowed down by the "propeller mechanism" if its spin period is short initially (Illarionov & Sunyaev 1975). As P_s increases, the corotation radius r_{co} becomes close to the magnetospheric radius r_m, the spin down torque declines and accretion occurs. If we assume $r_d \simeq r_m$, which is commonly expressed by the Alfv́en radius at which magnetic pressure balances ram pressure of accreted matter, for both disk and wind accretion, the *instantaneous* equilibrium in spin can be described by the same normalization $r_m = r_{co}$. However, equilibrium spin in these two accretion cases has different characteristics. First, equilibrium spin of a neutron star accreting through a disk indicates, that the accreted matter at the inner boundary of the disk rotates at (nearly) Keplerian rate, which is close to the spin rate of the neutron star; in wind accretion, however, the rotation velocity of the accreted matter at the magnetospheric boundary can be much lower than that of the neutron star. Second, the equilibrium spin period evolves differently in disk and wind accretion. In the former case, P_{eq} changes with $\dot{M}$; while in wind accretion, once equilibrium has been reached, the value of P_{eq} varies little, since the transferred angular momentum by wind is insufficient to drive long-term spin up/down of the neutron star (see below). Hence, the equilibrium spin in wind accretion is not always equivalent with the condition $r_m = r_{co}$. The typical examples are wind-fed X-ray pulsars with supergiant companions. Their observed spin history, which does not show any long-term period variations, demonstrates that they are evidently near equilibrium (i.e., experience a small torque). But from their X-ray luminosities, one can easily derive $r_m < r_{co}$, implying they have deviated from the equilibrium spin established previously.

Using the parameters describing the equatorial wind of a Be star, we can deduce the equilibrium spin period from $r_m = r_{co}$, with preliminary assumption of disk accretion (cf. Waters & van Kerkwijk 1989):

$$P_{eq} = 2^{3/2}\pi \frac{\mu^{6/7}}{(2GM_x)^{11/7}} \delta^{-9/7} (\frac{\pi\rho_0}{v_{r0}^3})^{-3/7} [\frac{G(M_x+M)}{4\pi^2 R^2} P_{orb}^2]^{(4n-6)/7}, \quad (1)$$

where μ and M are the magnetic moment of the neutron star and the Be star mass, respectively. The radial velocity of the equatorial wind is supposed to change as $v_r(r) = v_{r0}(r/R)^{n-2}$, corresponding to density distribution $\rho(r) = \rho_0(r/R)^{-n}$ with mass continuity. The rotational law of the wind is adopted as $v_\phi(r) = v_{\phi 0}(r/R)^{-1}$, where $v_{\phi 0}$ is the rotation velocity of the Be star, and conservation of angular momentum is assumed. In Eq. (1) the factor $\delta = v_r/v_{rel}$, where v_{rel} is the wind velocity relative to the motion of the neutron star, $v_{rel} = [(v_x - v_\phi)^2 + v_r^2]^{1/2}$, $v_x = 2\pi a/P_{orb}$ the orbital velocity of the neutron star (a the binary separation). Here we assume the binary has a circular orbit (consideration of eccentricity does not change the results fundamentally).

The calculated equilibrium spin periods P_{eq} are shown in Fig. 1 versus the orbital periods P_{orb} in solid and dashed curves, corresponding to $v_{\phi 0} = 0$ (no rotation) and 500 $\mathrm{km\,s^{-1}}$ (close to break-up rotation), respectively. In Fig. 1 we also plot MXBs with known spin and orbital periods, whose data are taken from Nagase (1989) and White, Nagase & Parmar (1995). Be/X-ray binaries are indicated by circles, while rectangles and crosses represent wind-fed and disk-fed supergiant systems, respectively. In our calculation, the following parameters (similar as in Waters & van Kerkwijk 1989) are used: $n = 3.25$, $M_x = 1.4M_\odot$, $\mu = 10^{30}\ \mathrm{G\,cm^3}$, $M = 14M_\odot$, $R = 10\,R_\odot$, $\rho_0 = 10^{-12}$ $\mathrm{g\,cm^{-3}}$, and $v_{r0} = 5\ \mathrm{km\,s^{-1}}$.

The P_s vs. P_{orb} relation of Be/X-ray binaries can be well fitted by Eq. (1), as was found by Waters & van Kerkwijk (1989). Figure 1 shows that inclusion of v_ϕ changes the value of P_{eq} significantly only as $P_{orb} \leq 10$ days, and it seems that v_ϕ has little influence on the P_s vs. P_{orb} relation. But, as we shall see below, the rotation of the stellar wind can contribute significantly to the specific angular momentum, which plays a crucial role in determining whether disk formation is possible in the wind.

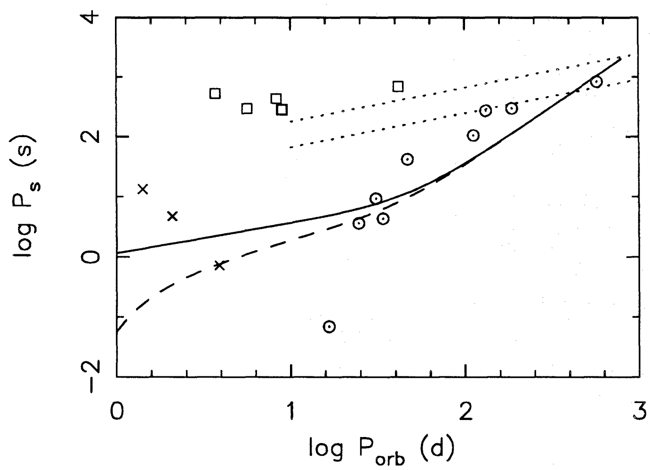

Fig. 1. Plot of the spin periods of neutron stars in MXBs versus the orbital periods. Circles, rectangles and crosses represent Be/X-ray binaries, wind-fed and disk-fed supergiant/X-ray binaries, respectively. The solid and dashed lines are calculated values of P_s from Eq. (1), with $v_{\phi 0} = 0$ and 500 km s^{-1}, respectively. Dotted lines are theoretical spin periods expected from spherical wind (Eq. [5]).

3. Angular momentum in the equatorial wind of Be stars

Though spin in equilibrium seems to account for Be/X-ray binaries in the P_s vs. $P_{\rm orb}$ diagram, it is not clear whether it is caused by spin up in disk accretion, or spin down in a wind. The answer lies in our knowledge of the specific angular momentum J of the accreted matter, which is difficult to assess. Early estimates showed that in spherically-symmetric wind the angular momentum transfer is due to density and velocity gradients in the wind (Shapiro & Lightman 1976; Wang 1981),

$$J = \eta \frac{{r_{\rm a}}^2}{2} \frac{2\pi}{P_{\rm orb}}, \qquad (2)$$

where $r_{\rm a}$ is the accretion radius, $r_{\rm a} = 2GM/{v_{\rm rel}}^2$, and η is a coefficient describing the efficiency of angular momentum capture, whose value was estimated to be close to unity. Davis & Pringle (1980) pointed out that the capture of angular momentum is extremely inefficient even if the wind is inhomogeneous. Recent multi-dimensional numerical simulations of wind accretion generally also gave a small value $\eta \sim 0.05$ (Livio et al. 1986; Blondin et al. 1986; Fryxell & Taam 1988; Taam & Fryxell 1989; Matsuda et al. 1991; Ruffert & Anzer 1994), which implies that disk formation is impossible in the wind of early type stars.

Most of the present calculations for wind accretion are restricted to the fast, radiation-driven, radially-expanding wind of supergiants. Their results may not be applied to the equatorial wind of Be stars, which is slowly expanding and rapidly rotating. No numerical calculation has been performed for it. It is noted, however, that transient Be/X-ray binaries showed rapid spin-up during an outburst (the typical example is EXO 2030+375, Parmar et al. 1989), which demonstrated that the angular momentum of the wind was sufficiently high, and that a disk was formed. For a rough estimate, we employ the analytical method of Wang (1981) to calculate the specific angular momentum of the equatorial wind, which is assumed to be axisymmetric and radially slow, and obtain

$$\begin{aligned} J &= \frac{3}{2}\frac{2\pi}{P_{\rm orb}}{r_{\rm a}}^2(\cos^2\beta - \frac{a}{v_{\rm x}}\frac{\partial v_{\rm x}}{\partial r}\cos^2\beta + \frac{a}{v_{\rm x}}\frac{\partial v_{\rm r}}{\partial r}\sin\beta\cos\beta \\ &\quad -\frac{a v_{\rm rel}}{6\rho v_{\rm x}}\frac{\partial\rho}{\partial r}\cos\beta)|_{r=a}, \\ &= 6\epsilon(\frac{M_{\rm x}}{M})^2(GM)^{2/3}(\frac{P_{\rm orb}}{2\pi})^{1/3}(\frac{v_{\rm x}}{v_{\rm rel}})^4, \qquad (3) \end{aligned}$$

where $\epsilon = [\cos^2\beta + \frac{v_\phi}{v_{\rm x}}\cos^2\beta + (n-2)\frac{v_{\rm r}}{v_{\rm x}}\sin\beta\cos\beta + \frac{v_{\rm rel}}{6v_{\rm x}}\cos\beta]|_{r=a}$, and $\sin\beta = v_{\rm r}(a)/v_{\rm rel}(a)$. As $v_{\rm r} \ll v_{\rm x}$ and $v_{\rm rel}$, J is mainly contributed by the orbital motion and the rotation of the Be star. Note that in this case $v_{\rm x} \sim v_{\rm rel}$, while in supergiant systems $v_{\rm x} \ll v_{\rm rel}$.

The condition for disk formation is that J in Eq. (3) is larger than the Keplerian specific angular momentum at the magnetospheric boundary, or the circulation radius $r_{\rm cir} = J^2/GM_{\rm x} \geq r_{\rm m} = r_{\rm co}$ in equilibrium assumption. Then the formation of a disk requires

$$\frac{r_{\rm cir}}{r_{\rm co}} = (6\epsilon)^2(\frac{M_{\rm x}}{M})^{8/3}(\frac{P_{\rm orb}}{P_{\rm s}})^{2/3}(\frac{v_{\rm x}}{v_{\rm rel}})^8 \geq 1. \qquad (4)$$

The calculated values of $r_{\rm cir}/r_{\rm co}$ are plotted in Fig. 2, versus $P_{\rm orb}$, with the same parameters adopted as in Fig. 1. We note two features in this figure: (1) there exists a critical value of the orbital period ($P_{\rm orb} \sim 100$ days) for Be/X-ray binaries, below which the specific angular momentum of the wind is sufficient to favor disk formation, while in wider systems, the circulation radius $r_{\rm cir}$ lies inside of $r_{\rm co}$, preventing the existence of a disk; (2) a rapidly rotating wind possesses much higher angular momentum than a slow one, especially as the orbit is narrow. This results from the fact that $v_{\rm x} > v_{\rm rel}$ if $v_{\rm x} \sim v_\phi$, and that J strongly depends on $v_{\rm x}/v_{\rm rel}$ (Eq. [3]). In a rapidly rotating wind, even if the coefficient ϵ is small (as in the wind of supergiants), J can still be sufficiently high to guarantee disk formation in narrower systems.

The actual value of the critical $P_{\rm orb}$ is somewhat uncertain, due to the uncertainties in the theoretical treatment and in the wind structure. Qualitatively, as we know, if $P_{\rm orb} \sim 100$ d, $v_{\rm r}(a) \sim v_{\rm rel}(a)$ and the slow wind assumption no longer holds, i.e., it is more like a fast, radially expanding wind from supergiants. The captured angular momentum in wider Be/X-ray binaries may be given by Eq. (2) instead and becomes even smaller. Disk accretion is impossible in such systems.

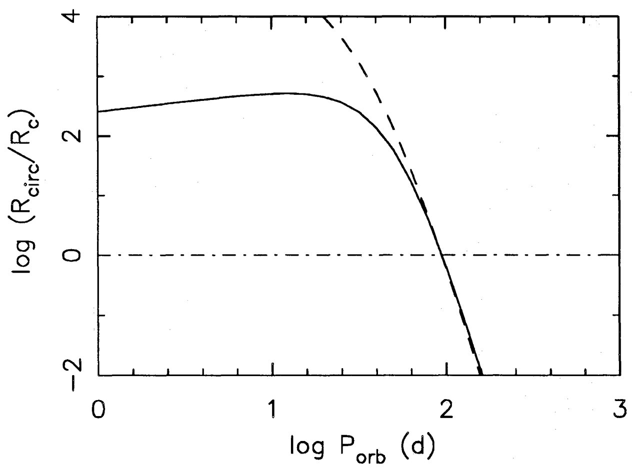

Fig. 2. Calculated values of r_{cir}/r_{co} as a function of the orbital periods, to determine the existence of an accretion disks. The solid and dashed lines are calculated from Eq. (3), with $v_{\phi 0} = 0$ and 500 $\mathrm{km\,s^{-1}}$, respectively. Other parameters are the same as in Fig. 1.

4. Discussion and conclusions

We have calculated the specific angular momentum of the equatorial wind of Be stars, to examine the self-consistency of the assumption of equilibrium spin period in disk accretion in Be/X-ray binaries. Our results demonstrate that the above assumption is self-consistent only in narrower Be/X-ray binaries, i.e. the present equilibrium spin is reached through angular momentum transfer in disk accretion. In wider systems, however, since disk formation seems impossible, there is no mechanism to change the neutron star's spin significantly, and it remains around its previous equilibrium value, determined by the condition at which the spin down due to the propeller mechanism ceased, and mass accretion started. If the Be star had formerly a spherical stellar wind, the corresponding equilibrium period is (Stella et al. 1986)

$$P_{\rm eq} \simeq 17.8(\frac{P_{\rm orb}}{1\ \rm d})^{4/7}(\frac{\dot{M}}{10^{-8}\,M_{\odot}\ \rm yr^{-1}})^{-3/7}\,\rm s, \qquad (5)$$

where we have assumed $M = 14\,M_{\odot}$, $\mu = 10^{30}$ G cm^3, and $v_{\rm r} = 10^3\ \mathrm{km\,s^{-1}}$. The calculated values of $P_{\rm eq}$ from Eq. (5) are shown in Fig. 1 in dotted lines with $\dot{M} = 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$ (lower) and $10^{-9}\,M_{\odot}\,\mathrm{yr}^{-1}$ (upper), respectively. It is seen that narrower Be/X-ra binaries deviate significantly from Eq. (5), demonstrating they have been spun up to short periods. The distribution of wider Be/X-ray binaries is consistent with the periods given by Eq. (5). The coincidence of both Eqs. (1) and (5) for long orbital period implies that the mass accretion rates of neutron stars in wider Be/X-ray binaries have not changed much.

Our results seem to be supported by observations of Be/X-ray binaries. Most transients are found in narrower systems ($P_{\rm orb} \lesssim 100$ d), which show strong spin-up during outbursts, indicating the presence of a disk. Some of wider Be/X-ray binaries (e.g., GX 304-1 and 4U 1145-619) also showed transient behavior, but they are still believed to be wind-accreted in general (White et al. 1983; Mereghetti et al. 1987). The pulse periods of neutron stars in wide Be/X-ray binaries occupy the same range as those in supergiant systems ($10^2 - 10^3$ sec), and they change in similar way (Nagase 1989 and references therein). In both types of systems, angular momentum transfer is expected to be inefficient.

So, based on above arguments, our conclusion is, between that of King (1991) and of Waters & van Kerkwijk (1989), that the $P_{\rm s}$ vs. $P_{\rm orb}$ relation for narrower Be/X-ray binaries can be well explained with the equilibrium spin period in disk accretion; while the distribution of wider Be/X-ray binaries in the $P_{\rm s}$ vs. $P_{\rm orb}$ diagram results from an earlier evolutionary stage, similar to the case of supergiant systems.

Acknowledgements. The authors thank Dr. H. Tjin A Djie for carefully reading the manuscript and help suggestions.

References

Bhattacharya, D., van den Heuvel, E. P. J., 1991, Phys. Rep., 203, 1
Blondin, J. M., Kallman, T. R., Fryxell, B. A., Taam, R. E., 1990, ApJ, 335, 862
Corbet, R. H. D., 1984, A&A, 141, 91
Davis, R. E., Pringle, J. E., 1981, MNRAS, 191, 599
Fryxell, R. A., Taam, R. E., 1988, ApJ, 335, 862
Ghosh, P., Lamb, F. K., 1979, ApJ, 234, 296
King, A. R., 1991, MNRAS, 250, 3P
Illarionov, A. F., Sunyaev, R. A., 1975, A&A, 39, 185
Livio, M., Soker, N., de Kool, M., Savonije, G. J., 1986, MNRAS, 218, 593
Matsuda, T., Sekino, N., Sawada, K. et al.,1991, A&A, 248, 301
Mereghetti, S. et al., 1987, ApJ, 312, 755
Nagase, F., 1989, PASJ, 41, 1
Ruffert, M., Arnett, D., 1994, ApJ, 427, 351
Shapiro, S. L., Lightman, A. P., 1976, ApJ, 204, 555
Stella, L., White, N. E., Rosner, R., 1986, ApJ, 308, 669
Taam, R. E., Fryxell, R. A., 1989, ApJ, 339, 297
van den Heuvel, E. P. J., Rappaport, S., 1987, in Proc. IAU Symposium 98, Physics of Be stars, Eds. A. Slettebak and T. P. Snow, p. 291
Wang, Y.-M., 1981, A&A, 102, 36
Waters, L. B. F. M., Cote, J., Lamers, H. J. G. L. M., 1987, A&A, 185, 206
Waters, L. B. F. M., van Kerkwijk, M. H., 1989, A&A, 223, 196
White, N. E., Swank, J. H., Holt, S. S., 1983, ApJ, 270, 711

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.