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Radio pulsar and accretion regimes of rapidly rotating magnetic neutron stars in early-type eccentric binaries

S. Campana[1,2], **L. Stella**[1,2], **S. Mereghetti**[3], **and M. Colpi**[4]

[1] Osservatorio Astronomico di Brera, Via Brera 28, I-20121 Milano, Italy;
e-mail: (campana, stella)@astmim.mi.astro.it
[2] Affiliated to I.C.R.A.
[3] Istituto di Fisica Cosmica del C.N.R., Via Bassini 15, I-20133 Milano, Italy;
e-mail: sandro@ifctr.mi.cnr.it
[4] Università degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy;
e-mail: colpi@astmiu.mi.astro.it

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Abstract. Rapidly rotating magnetic neutron stars in eccentric binary systems containing an early type star provide a unique opportunity to investigate the interplay between radio pulsar, stellar wind and accretion phenomena. We summarise the radio pulsar-dominated and the accretion-dominated regimes, discussing how the transition from one regime to another can take place as a result of the varying orbital distance and relative velocity along the orbit, as well as changes of the wind characteristics. We derive the conditions under which the two known B star/radio pulsar binaries (PSR 1259–63 and PSR J0045–7319) can undergo a transition to the accreting regime. A strong increase of the mass loss ouflow from the companion is required, just to cause the onset of accretion onto the magnetospheric boundary. We also show that the X–ray transient A0538–66 is likely to undergo transitions from the accreting neutron star regime, to the regime of accretion onto the magnetosphere. These two regimes might correspond to the high ($\gtrsim 10^{38}$ erg s^{-1}) and the low-luminosity ($< 10^{38}$ erg s^{-1}) outbursts observed from this source. A radio pulsar might become detectable in the long quiescent states of A0538–66. A new model of the enigmatic high-energy binary LS I $+61^\circ$ 303 involving accretion onto the magnetosphere is also presented.

Key words: Pulsars – X–ray: binaries – stars: individual: PSR 1259–63 - PSR J0045–7319 - A0538–66 - LS I $+61^\circ$ 303

1. Introduction

Two radio pulsars with massive B-star companions have been discovered in the last few years: PSR 1259–63 and PSR J0045–7319 (Johnston et al. 1992; Kaspi et al. 1994). Both are in highly eccentric orbits ($e > 0.8$) and likely represent the progenitors of high mass X–ray binaries (Bhattacharya & van den Heuvel 1991). These systems are of great importance for the investigation of the interplay between pulsar activity and stellar wind, including possible transitions to the accretion regime (e.g. Lipunov 1992; Kochanek 1993). On the other hand, during the quiescence intervals of X–ray transient binaries, accretion onto the fast rotating neutron stars can stop completely and radio pulsar activity may set in (e.g. Stella et al. 1994).

In Section 2 we briefly outline the different regimes of a radio pulsar moving in the companion star's wind in an eccentric orbit. Depending on the neutron star spin and magnetic field, on the orbital parameters and on the stellar wind characteristics, the neutron star can alternate the behaviour of a radio pulsar to that of an accreting X–ray source (Illarionov & Sunyaev 1975; Lipunov 1992). These considerations are applied to the two radio pulsars with B companions (Sections 3 and 4) and to two peculiar X–ray binaries (A0538–66 and LS I $+61^\circ$ 303; Sections 5 and 6). Our results are summarised in Section 7.

2. Radio pulsar activity versus accretion

Different regimes are possible for a radio pulsar immersed in the wind of its companion star. If the radio pulsar is strong enough, a shock forms in the interaction of the relativistic pulsar wind with the companion star wind, well outside the accretion radius $r_{acc} = 2\,G\,M/v_{rel}^2$ (M is the neutron star mass and v_{rel} the relative velocity between the neutron star and the stellar wind matter). The condition for this "pulsar radiation barrier" to work is obtained by equating the stellar wind ram pressure and the pulsar radiation pressure at the accretion radius:

$$\dot M < \frac{f\,L^{sd}}{c\,v_{rel}} \simeq 3.3\times10^{17}\,f\,L^{sd}_{35}\,v_7^{-1}\ \mathrm{g\,s^{-1}}$$

$$\simeq 1.3\times10^{16}\,f\,\mu_{29}^2\,P_{-1}^{-4}\,v_7^{-1}\ \mathrm{g\,s^{-1}}\ , \qquad (1)$$

Send offprint requests to: S. Campana

Table 1. Parameters of the neutron star binaries discussed in the text.

Name	P	μ	L^{sd}	e	P_{orb}	r_{per}	M_*	d
	(ms)	(10^{29} G cm^3)	(10^{35} erg s^{-1})		(d)	(cm)	($M_\odot$)	(kpc)
PSR 1259–63	47.8	3.3	8.3	0.87	1237	2.1×10^{13}	~ 11	1.5
PSR J0045–7319	926	20.6	2.2×10^{-3}	0.81	51.2	3.0×10^{12}	~ 10	60
A0538–66	69.2	$3 \times 10^{-3} - 1$	< 0.17	> 0.4 ?	16.7	$< 3.0 \times 10^{12}$?	~ 12	55
LS I +61°303				> 0.3 ?	26.5	$< 4.3 \times 10^{12}$?	~ 10	2.3

where $\dot{M}$ is the mass capture rate, L^{sd}_{35} the spin down luminosity in units of 10^{35} erg s^{-1}, μ_{29} the magnetic dipole moment of the neutron star in units of 10^{29} G cm^3 and P_{-1} the spin period in units of 0.1 s; f represents the fraction of the pulsar pressure interacting with the stellar wind (we assume $f = 1$) and $v_7 = v_{rel}/10^7$ cm s^{-1}. The mass capture rate is related to the mass outflow from the companion star, $\dot{M}_W$, by $\Omega\, r^2\, \dot{M}_W = \pi\, r^2_{acc}\, \dot{M}$ (Ω is the angle subtended by the wind at the companion star and r the distance between the two stars).

The "pulsar radiation barrier" can be overcome by the stellar wind material if the mass capture rate $\dot{M}$ increases above the value in Eq.(1), either as a consequence of the different orbital distance and relative velocity, or as a result of substantial variations in the stellar wind parameters. Inside the accretion radius the radial dependence of the radio pulsar pressure ($\propto r^{-2}$) is less steep than that of the pressure exerted by the stellar wind matter flowing towards the neutron star ($\propto r^{-5/2}$ in the case of spherical free fall or $\propto r^{-\alpha}$ with $51/20 < \alpha < 7/2$ in the case of a standard accretion disk; Illarionov and Sunyaev 1975; Campana et al. 1995). Therefore, if the "pulsar radiation barrier" is won, the matter inflow can proceed inside the light cylinder radius ($r_{\rm lc} = \frac{cP}{2\pi}$, with P the spin period), quenching the radio pulsar emission (e.g. Illarionov & Sunyaev 1975; Lipunov 1992). The motion of the infalling matter becomes dominated by the rapidly increasing magnetic field pressure ($\propto r^{-6}$) at the magnetospheric boundary

$$r_{\rm m} \simeq 8.3 \times 10^7\, \mu_{29}^{4/7}\, M_{1.4}^{-1/7}\, \dot{M}_{17}^{-2/7} \text{ cm} , \qquad (2)$$

where $M_{1.4}$ the neutron star mass in units of 1.4 $M_\odot$ and $\dot{M}_{17}$ the accretion rate in units of 10^{17} g s^{-1}.

In general, 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 and an accretion-luminosity of only

$$L(r_{\rm m}) = GM\dot{M}/r_{\rm m} \simeq 2.2\times10^{35}\, \mu_{29}^{-4/7}\, M_{1.4}^{8/7}\, \dot{M}_{17}^{9/7} \text{ erg s}^{-1} \quad (3)$$

is released (Stella et al. 1994; King & Cominsky 1994). In this regime the fate of matter is uncertain: it can either accumulate outside the magnetospheric boundary (possibly giving rise to a quasi-steady atmosphere; Davies & Pringle 1981) or be swang away by the magnetospheric drag (as a result of either a supersonic or a subsonic propeller; Davies & Pringle 1981) at the expenses of the rotational energy of the neutron star. X–ray pulsations might be produced in this regime as a result of the azimuthal asymmetry of the rotating magnetospheric boundary. The "centrifugal barrier" can be won only if the accretion rate increases above

$$\dot{M} \gtrsim 1.8 \times 10^{18}\, \mu_{29}^2\, M_{1.4}^{-5/3}\, P_{-1}^{-7/3} \text{ g s}^{-1} . \qquad (4)$$

In this case accretion onto the neutron star surface takes place releasing gravitational energy with a much higher efficiency of $L(R) = GM\dot{M}/R$, with R the neutron star radius (we assume $R = 10^6$ cm). X–ray pulsations are likely to occur due to the channeling of the accreting matter onto the neutron star magnetic poles.

When the "centrifugal barrier" is closed, the magnetospheric boundary expands for decreasing accretion rates. Eventually, $r_{\rm m}$ becomes larger than the light cylinder radius and the radio pulsar mechanism can resume. In the absence of accumulation of matter outside the magnetosphere, this is expected to take place for

$$L(r_{\rm lc}) \simeq 8.5 \times 10^{31}\, f\, \mu_{29}^2\, M_{1.4}^{1/2}\, P_{-1}^{-9/2} \text{ erg s}^{-1} . \qquad (5)$$

Due to its flatter radial dependence, the radio pulsar pressure sweeps the material outside the accretion radius and the "pulsar radiation barrier" gives rise again to a shock front with the stellar wind. Note that the luminosity in Eq.(3) is substantially higher than that in Eq.(5), implying a higher luminosity threshold at the onset of accretion and, therefore, a limit cycle behaviour.

When the radio pulsar mechanism resumes the rotational energy of the neutron star must have decreased at least by the amount needed to eject to infinity the matter accreted onto the magnetospheric boundary when the "centrifugal barrier" was closed. This is equal to the total gravitational energy released during the interval Δt in which accretion onto the magnetosphere takes place

$$\Delta E = 4\,\pi^2\, I\, \frac{\Delta P}{P^3} \gtrsim \int_{\Delta t} L(t)\, dt , \qquad (6)$$

where I is the moment of inertia of the neutron star and $L(t)$ can vary between $L(r_{\rm m})$ and $L(r_{\rm lc})$. This rotational energy loss can exceed the radio pulsar spin-down rate.

3. PSR 1259–63

PSR 1259–63 was the first radio pulsar to be found in a binary system with an early type companion, the Be star SS2883 (Johnston et al. 1992, 1994; see Table 1). A campaign of multiwavelength observations was carried out around the January 1994 periastron passage (the results for the most part are still to be published). The radio pulsar emission disappeared during the two observed periastron passages (Johnston et al. 1992;

Manchester et al. 1994), while it was clearly detected during the rest of the orbit. These eclipses are due to an increase of the free-free optical depth (Kochanek 1993; Lipunov et al. 1994) as testified by the frequency dependence of the eclipse ingress (Manchester et al. 1994). X–ray observations were carried out around apoastron (Cominsky, Roberts & Johnston 1994). X–rays were detected by ROSAT at orbital phases 0.6 and 0.73. The average flux was about 40% higher during the second observation, which also showed a harder spectrum and evidence for variability on timescales of days. The conversion from observed count rate to the unabsorbed X–ray luminosity is quite sensitive to the model spectrum used to fit the data. A 0.1–2.4 keV luminosity of $\sim 5 \times 10^{32}\, d_{1.5}^2$ erg s^{-1} is obtained in both observations for the thermal bremsstrahlung and Raymond–Smith best fit models. On the other hand, if the same data are fit with a power law spectrum, substantially higher luminosities can be obtained (up to $\sim 8 \times 10^{33}\, d_{1.5}^2$ erg s^{-1}, in the case of the very soft spectrum of the first observation). No pulsations at the radio period were detected. GINGA obtained an upper limit corresponding to a 2–10 keV luminosity of $6 \times 10^{32}\, d_{1.5}^2$ erg s^{-1} (for a Crab-like spectrum) at phase 0.31. The ROSAT observation at phase 0.45 gave a flux comparable to those measured after periastron, at variance with earlier results reported by Cominsky et al. (Belloni 1994, private communication).

In the case of PSR 1259–63, the "pulsar radiation barrier" can be overcome only for $\dot{M} > 2.8 \times 10^{18}\, v_7^{-1}$ g s^{-1} [see Eq.(1)], corresponding to an accretion-induced luminosity of $L(r_{\rm m}) \simeq 8.0 \times 10^{36}\, v_7^{-9/7}$ erg s^{-1} [see Eq.(3)]. The condition for the radio pulsar activity to resume and the inflowing matter to be swept beyond the accretion radius (in the absence of accumulation outside the magnetospheric boundary), corresponds to a luminosity of 2.6×10^{34} erg s^{-1} [see Eq.(5)].

King & Cominsky (1994) proposed that the X–ray luminosity observed near apoastron is produced by the release of gravitational energy down to the magnetospheric boundary. This possibility, however, presents serious problems. Firstly, due to the radial dependence of the radio pulsar and the matter pressure, the inflowing material cannot be stopped in a stable fashion just outside the light cylinder radius. If it is stopped inside the light cylinder, then the radio pulsar mechanism is expected to be suppressed (e.g. Illarionov & Sunyaev 1975; Lipunov 1992). Secondly, the measured X–ray luminosities are ~ 50 times lower than the luminosity below which sweeping by the radio pulsar pressure sets in (only for the X–ray observation around phase 0.6 this factor might reduce to a value as low as ~ 3). Only if most of the energy is released outside of the ROSAT and GINGA energy bands the observed luminosities could be compatible with magnetospheric accretion.

The luminosities derived from the thermal model fits to the ROSAT data are not incompatible with emission from the Be star. The corresponding value of the X–ray to bolometric luminosity ratio, $L_X/L_{bol} \sim 3 \times 10^{-6}$, though higher than average, is well within the range of values measured for B-type stars with or without emission lines (Meurs et al. 1992). Alternatively, the observed X–ray emission might originate in a discontinuity shock between the relativistic pulsar wind and the matter outflowing from the Be companion. As shown by Tavani, Arons & Kaspi (1994), for PSR 1259–63 an X–ray luminosity of $\sim 10^{33}\, n_8^{1/2}\, v_7$ erg s^{-1} can be obtained (n_8 is the density at the shock in units of 10^8 cm^{-3}), with a power-law spectrum extending from keV to MeV energies.

Accretion onto the magnetospheric boundary would take place if the "pulsar radiation barrier" were overcome around periastron[1]. This requires an accretion-induced luminosity, at least temporarily, higher than $\sim 10^{37}$ erg s^{-1}, probably yielding a highly absorbed X–ray spectrum ($N_H \gtrsim 4 \times 10^{23}\, v_7^{-9/7}$ cm^{-2}). This value implies also a very large free-free optical depth at radio wavelengths and the transition to the accretion regime would occur when the radio pulsar is already undetectable. The mass outflow from the Be star can be derived from the required mass capture rate within the accretion radius at periastron. For the equatorial disk mass loss, Waters et al. (1988) estimate an outflow velocity law $v(r) \sim v_0 \left(\frac{r}{R_*}\right)$, with $v_0 \simeq 5 \times 10^5$ cm s^{-1} and $R_* \simeq 7.6 \times 10^{11}$ cm the stellar radius (taking a companion mass of $M_* \simeq 11\, M_\odot$ and $R_* \propto M_*$). At large distances from the Be star ($\sim 100\, R_*$) the equatorial wind achieves its terminal velocity, v_∞, of about three times the escape velocity. Since at periastron $r = r_{per} \simeq 2.1 \times 10^{13}$ cm, the pulsar velocity is comparable to the outflow wind velocity giving $v_{rel} \simeq 2 \times 10^7$ cm s^{-1}. Waters et al. (1987) estimate that the characteristic solid angle of the Be equatorial wind is $\Omega \sim \pi$. Therefore, we evaluate that a wind mass-loss rate of $\dot{M}_W = 1.3 \times 10^{-5}\, M_\odot$ yr^{-1} is required to overcome the "pulsar radiation barrier". This value is higher than the upper limit of $\dot{M}_W < 10^{-7}\, M_\odot$ yr^{-1} on the mass outflow rate obtained by Waters et al. (1987) for $L_{bol} = 2 \times 10^{38}$ erg s^{-1}. However, a substantially higher mass loss can occur during equatorial shell-ejection episodes, such as those that cause the outbursts of accreting X–ray pulsars with Be companions (e.g. A0535+26; Nagase et al. 1982). Further information can be derived from the reappearance of the radio pulsar after periastron. This occurred about one month after the 1990 periastron passage (Johnston et al. 1992). On the contrary if accretion onto the magnetosphere sets in around periastron and $\dot{M}_W$ remains near or above the critical value, then the radio pulsar will resume and start sweeping away the inflowing material not earlier than 8 months after periastron; moreover the free-free optical depth would be > 1 even at apoastron both for an isothermal and an adiabatic wind model (Kochanek 1993 and references therein). Therefore the mass loss rate from the Be star must decrease before the radio pulsar signal can be detected again.

If shock emission is responsible for the X–ray emission at periastron a luminosity of $\sim 10^{35}$ erg s^{-1} is expected (for details see Tavani et al. 1994). In any case the peak emission should not exceed the spin down luminosity.

4. PSR J0045–7319

This radio pulsar is the only known in the Small Magellanic Cloud. Timing measurements show that it is in an eccentric orbit around a massive B-type star showing, thus far, no evidence for emission lines (Kaspi et al. 1994). The lower spin-down luminosity and the smaller distance to the companion (see Table 1) allow the transition from the radio pulsar regime to the magnetospheric accretion regime to occur for a less intense stellar wind than in PSR 1259–63. We consider the standard spherical wind model for O and B stars, with a radial velocity law $v(r) = v_\infty (1 - R_*/r)^{1/2}$ (e.g. Castor & Lamers 1979). At pe-

[1] For accretion onto the neutron star surface to occur, a highly super-Eddington accretion luminosity of $> 10^{40}$ erg s^{-1} is needed.

riastron $v_{rel} \simeq 2 \times 10^8$ cm s^{-1} and, as long as the mass loss rate from the B star is $\dot{M}_W \leq 1.4 \times 10^{-7}$ $M_\odot$ yr^{-1}, the "radiation pulsar barrier" cannot be overcome. No regular eclipses of the radio pulses nor changes in the dispersion measure were observed, implying that the wind from the B companion does not exceed 10^{-11} $M_\odot$ yr^{-1} (note, however, that the radio pulses were not detected on a few occasions; Kaspi et al. 1994). This limit is somewhat lower than the mass loss expected for an isolated B star (de Jager et al. 1988) and is strong enough to conclude that no radio pulsar quenching can occur unless a very large variation of the wind parameters, possibly a shell ejection, takes place.

5. A0538–66

The X–ray transient A0538–66 in the Large Magellanic Cloud contains the accreting neutron star with the shortest known spin period (69 ms). The periodic recurrence of most of its X–ray outbursts is highly suggestive of a 16.7 d eccentric orbit around the Be star companion (White & Carpenter 1978; Skinner et al. 1982). The high X–ray luminosity ($\sim 10^{39}$ erg s^{-1}; Skinner et al. 1980) and the presence of pulsations testify that during the bright outbursts the "centrifugal barrier" is open and accretion onto the neutron star surface takes place. As noted by Skinner et al. (1982), the lower range of X–ray luminosities observed during the bright outbursts implies an upper limit of $\mu_{29} \lesssim 1$ [from Eq.(4)] (see also Maraschi, Traversini & Treves 1983; Stella, White & Rosner 1986). On the other hand, if X–ray pulsations are present also for the highest luminosities observed, then a small magnetosphere is still present (i.e. $r_{\rm m} > R$); this implies $\mu_{29} \gtrsim 3 \times 10^{-3}$. For A0538–66 the X–ray luminosity resulting from accretion onto the magnetosphere when the "centrifugal barrier" closes is $\sim 3 \times 10^{37}\,\mu_{29}^2$ erg s^{-1}.

During the ROSAT all-sky survey two weak outbursts from A0538–66 were detected, with average luminosities of ~ 4 and $\sim 2 \times 10^{37}$ erg s^{-1} in the 0.1–2.4 keV range (Mavromatakis & Haberl 1993). The emission was well fit by a black body spectrum with a temperature ~ 0.2 keV, a characteristic radius $\lesssim 5 \times 10^7$ cm and a column density of $N_H \sim 10^{20}$ cm^{-2}. This is unlike the factor of ~ 10 more intense outbursts observed with Einstein, that were characterised by harder and more absorbed spectra. If $\mu_{29} \sim 1$, the characteristic radius and X–ray luminosity derived from the ROSAT data are close to the magnetospheric radius and the maximum luminosity released by accretion onto the magnetosphere, when the "centrifugal barrier" is about to open. In this case, values of N_H as low as those measured can be obtained for an accretion-disk flow outside the magnetosphere. Therefore, we suggest that the low-luminosity and soft outbursts of A0538–66 could be powered by accretion onto the neutron star magnetosphere, whereas during the outbursts with harder spectra and $L \gtrsim 10^{38}$ erg s^{-1} the "centrifugal barrier" is open and accretion can proceed down to the neutron star surface, generating radiative energy and pulsations more efficiently. An upper limit of $\sim 5 \times 10^{34}$ erg s^{-1} on the X–ray luminosity in quiescence has been obtained with ROSAT. For this luminosity level, accretion onto the neutron star surface is almost ruled out (it would require $\mu_{29} \lesssim 7 \times 10^{-3}$), whereas accretion onto the magnetosphere can take place over a wide range of allowed magnetic dipole moments. If the accretion-induced luminosity decreases below $4 \times 10^{32}\,\mu_{29}^2$ erg s^{-1}, then the radio pulsar activity sets in and sweeps away the inflowing matter beyond the accretion radius.

If in the extended quiescent state the Be equatorial disk does not contribute significantly, the mass inflow towards the neutron star can be calculated based only on the properties of the spherical wind, yielding a rate of $\sim 3 \times 10^{-9}$ $M_\odot$ yr^{-1} (Waters et al. 1988). With $e \gtrsim 0.4$ a value of $\mu_{29} \gtrsim 10^{-2}$ would be sufficient for the radio pulsar to sweep away the incoming matter around apoastron. We note that for $e = 0.4$ this limit on the magnetic dipole is also sufficient to ensure that the "pulsar radiation barrier" remains closed even at periastron [see Eq.(1)] (a magnetic dipole 3 times larger would be required for $e = 0.7$). The free-free optical depth at 1 GHz is expected to be $\ll 1$. Therefore a 69 ms radio pulsar might be active and detectable in the quiescent state of A0538–66.

6. LS I +61° 303

The Be star LS I +61° 303 shows strong radio outbursts with a periodicity of 26.5 d, which are strongly suggestive of the presence of a compact companion (Gregory & Taylor 1978). Infrared observations indicate a high mass loss in the stellar wind of the Be star ($1-4 \times 10^{-7}$ $M_\odot$ yr^{-1}; Waters et al. 1988). VLBI observations show that the radio outbursts are produced by synchrotron emission from a 2 milliarcsecond double source expanding at $\sim 5 \times 10^7$ cm s^{-1} (Massi et al. 1994). No periodic pulsations have been detected in the radio emission, nor in its weak X–ray emission ($\sim 10^{33}\,d_{2.3}^2$ erg s^{-1} in the 0.2–4 keV range with $d = 2.3\,d_{2.3}$ kpc the distance; Bignami et al. 1981). It has also been suggested that this source is responsible for the γ–ray emission observed with COS–B and EGRET from this region in the sky ($\sim 2.6 \times 10^{35}\,d_{2.3}^2$ erg s^{-1} in the > 100 MeV range; Fichtel et al. 1994).

Two models have been proposed: (a) shock emission from the relativistic wind of a young neutron star colliding with the Be star wind (Maraschi & Treves 1981), similar to the model discussed in Section 3 for PSR 1259–63; (b) super-Eddington accretion onto a neutron star close to the periastron of an eccentric orbit (for the mass loss rate quoted above this requires $e > 0.3$; Taylor & Gregory 1984; Taylor et al. 1992).

A problem with the latter model is that the measured X–ray and γ–ray luminosities are orders of magnitude below the Eddington limit. A possibility is that the accreting matter is stopped at the magnetospheric radius, by the "centrifugal barrier" and that a much lower accretion luminosity is released. In this case the matter ejected through the centrifugal mechanism could explain the expansion of the radio source. By imposing that the measured X–ray luminosity is lower than the luminosity for which the "centrifugal barrier" opens [see Eq.(3) and (4)], we obtain the condition $\mu_{29}^2\,P_{-1}^{-3} \gtrsim 10^{-4}$ (or $\gtrsim 3 \times 10^{-2}$ if the γ–ray luminosity is used). The condition that the accreting material is not swept away by the pulsar pressure [see Eq.(5)] gives instead $\mu_{29}^2\,P_{-1}^{-9/2} \lesssim 10$ (or $\lesssim 3 \times 10^3$, see above). We note that the high mass inflow rate estimated by Taylor et al. (1992) for the periastron of an $e = 0.6$ orbit ($\dot{M} \simeq 2 \times 10^{18}$ g s^{-1}) is incompatible with the magnetospheric accretion model, if the accretion-induced luminosity is of the order of the observed X–ray luminosity. On the contrary the observed γ–ray luminosity could be generated through this mechanism in the case of a highly magnetic slowly rotating neutron star ($\mu_{29} \simeq 600$, $3 \lesssim P_{-1} \lesssim 250$).

7. Summary

Due to the mass inflow variations resulting from the orbital motion and/or the changing properties in the companion's wind, radio and X–ray pulsars in eccentric early-type binaries offer the possibility of studying the different regimes of a rapidly spinning neutron star immersed in a stellar wind. Three different regimes are expected for increasing mass inflow rates towards the neutron star: (i) radio pulsar; (ii) accretion onto the neutron star magnetosphere; (iii) accretion onto the neutron star surface. The transition *from* the radio pulsar regime is expected to take place for mass inflow rates substantially higher (a few orders of magnitude) than the transition *to* the radio pulsar regime, therefore generating a characteristic limit cycle behaviour. The transitions between the two accretion regimes do not involve instead any limit cycle, such that, in principle, small variations of the mass inflow rate can cause them to occur in both directions.

The regime of magnetospheric accretion (i.e. down to $r_{\rm m}$) should be characterised, in the optically thick regime, by temperatures in the $10^5 - 10^6$ K range and radii comparable to the magnetospheric radius. This regime might be relevant to the quiescent emission of a number of transient X–ray binaries containing a magnetic neutron star (Stella et al. 1994; Campana et al. 1995). We suggest that the low-luminosity ($< 10^{38}$ erg s^{-1}) soft outbursts from the Be star/X–ray pulsar transient A0538–66 are the result of magnetospheric accretion, whereas the high-luminosity hard outbursts (during which 69 ms pulsation are detected) are powered by accretion onto the neutron star surface. This interpretation implies $\mu_{29} \sim 1$. The occurence of transitions between the two accretion regimes can be tested through the monitoring of the temperature and radius variations during the rise or the decay of very large outbursts.

The high energy emission from LS I +61° 303 might also arise from accretion onto the magnetosphere of a neutron star.

Contrary to previous suggestions (King & Cominsky 1994), we conclude that the X–ray flux detected away from periastron in the eccentric radio pulsar/Be star binary PSR 1259–63 is not powered by magnetospheric accretion. More likely models include shock emission at the interface between the pulsar and the Be star winds (Tavani et al. 1994) or emission by an active Be companion.

No direct observational evidence has yet been found for a transition from the radio pulsar regime to an accretion regime or viceversa. We have shown that for the radio pulsars in PSR 1259–63 and PSR J0045–7329 to undergo a transition to the magnetospheric accretion regime a drastic increase of the mass inflow rate must occur. The radio pulsed emission would resume only for much lower mass inflow rates, requiring in turn a decrease of mass loss rate from the companion star (the variation caused by the orbital motion alone would not be sufficient). The ejection of the accreted material by the rotating magnetospheric boundary at the expenses of the rotational energy of the neutron star is expected to cause a pronounced spin-down during the magnetospheric accretion regime, which can exceed the radio pulsar spin-down rate. In the absence of X–ray pulsations in the magnetospheric accretion regime, this prediction can be tested through radio pulse period measurements before and after a magnetospheric accretion episode.

Concerning accreting neutron stars in X–ray binaries, a transition to the radio pulsar regime is most likely to occur during the extended quiescent states of X–ray transients (Stella et al. 1994; Campana et al. 1995). Among early-type systems, especially promising is the case of A0538–66. In quiescence the inflow rate from the radial wind of the Be star cannot prevent the transition to the radio pulsar regime to occur around apoastron. The resulting "radio pulsar barrier" would then inhibit accretion until substantially higher mass inflow rates are achieved again. In particular if $\mu_{29} \sim 1$, the radio pulsar signal should be detectable with current instrumentation.

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