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On the origin of quiescent X-ray emission from A0535+26

N. R. Ikhsanov[1,2]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Central Astronomical Observatory of the Russian Academy of Science at Pulkovo, Pulkovo 65–1, 196140 Saint-Petersburg, Russia

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Abstract. The quiescent X-ray emission from A0535+26 ($L_{\rm x} \sim 2\ 10^{35}$ erg s^{-1}) is explored in terms of the spherically symmetrical accretion onto a magnetized neutron star. I find the magnetospheric boundary of the neutron star in A0535+26 to be stable with respect to interchange instabilities. The fastest mode by which the accreting plasma can enter the magnetosphere is the magnetic lines reconnection. Under this condition the quiescent X-ray luminosity of the system can be explained provided the mass capture rate by the neutron star from the wind of the Be companion of $\sim 10^{-9}\ M_{\odot}$ yr^{-1}. I show this value to be in a good agreement with the mass capture rate independently evaluated from the established parameters of the Be star circumstellar environment. The suggested approach allows to interpret the low luminous state of the system ($L_{\rm x} \sim 4\ 10^{33}$ erg s^{-1}) in August – November 1998 in terms of the accretion powered pulsar model. I find the mass capture rate by the neutron star during this time of $3\ 10^{-11}\ M_{\odot}$ yr^{-1}. This can be realized provided the plasma density in the circumstellar disk of the Be companion is by two orders of magnitude smaller than its average value. Under this condition the disk is expected to be invisible in the optical/IR.

Key words. accretion – magnetic fields – stars: close binaries – stars: Be – stars: neutron star

1. Introduction

Be/X-ray transient A0535+26 is the binary system which contains the Be star HDE 245770 and a rotating, strongly magnetized neutron star (see Table 1). On the time scale of orbital period the system exhibits either no outburst, a moderate or a giant X-ray outburst. The moderate outbursts have typical duration of 10–15 days, the X-ray luminosity of about[1] a few $\times 10^{36}$ erg s^{-1} and occur around a certain orbital phase $\phi = 0$. Giant X-ray outbursts have longer duration (up to 40 days), their luminosity exceeds that of moderate outbursts by almost an order of magnitude and some of them[2] were observed to be delayed in phase with respect to the moderate flares by $(0.08 \div 0.14) P_{\rm orb}$ (Priedhorsky & Terrell 1983). Apart from these events the mean X-ray luminosity of the system is about $2.5\ 10^{35}$ erg s^{-1}. The X-ray radiation during this *quiescent state* is modulated with the spin period of the neutron star and is observed at any orbital phases (Motch et al. 1991).

Table 1. Parameters of A0535+26

System parameters	Value	References*
Distance	2 kpc	(1), (2)
Orbital period	111 days	(3)
Inclination	$40° < i < 60°$	(1), (4)
Eccentricity	0.47 ± 0.02	(5)
Mass ratio	~ 10	(1)
Stellar parameters	Secondary	Primary
Type	O9.7IIIe–B0Ve	Neutron star
Stellar mass ($M_{\odot}$)	$13 \div 15$	~ 1.5
Radius	$14\ R_{\odot}$	10^6 cm
Spin period	2.2 days	$103 \div 104$ s
Spin up ** (Hz s^{-1})	–	$2\ 10^{-9}$
Magnetic field (G)	???	10^{13}

* (1) Giovannelli & Graziati (1992).
(2) Steele et al. (1998).
(3) Priedhorsky & Terrell (1983).
(4) Clark et al. (1998a).
(5) Finger et al. (1996).
** During giant X-ray flares.

The observed properties of X-ray emission can be well interpreted within the accretion powered pulsar model and

Send offprint requests to: N. R. Ikhsanov,
e-mail: ikhsanov@mpifr-bonn.mpg.de

[1] Hereafter the distance to the system is adopted to be 2 kpc.
[2] Since 1975 five giant flares have been observed in the system.

the transient behaviour is currently explained in terms of the so called eccentric orbit model (see Giovannelli & Graziati 1992). In the frame of this approach the orbital phase at which the moderate outbursts occur is associated with the periastron passage of the neutron star when it moves through the circumstellar dense disk of the Be companion. The presence of the disk surrounding the Be star at the equatorial plane has been established from the spectroscopical and IR observations of A0535+26 (see Clark 1998a, 1999 and references therein). Motch et al. (1991) have shown that for the typical densities in the circumstellar disks of Be stars ($N \sim 10^8$–10^{11} cm^{-3}) the rate of mass capture by the neutron star at the periastron is high enough for the neutron star to be in the state of *accretor*, i.e. $R_{\rm m} \lesssim R_{\rm cor}$, and to power the observed luminosity of X-ray source. Hereafter, $R_{\rm m}$ denotes the magnetospheric (Alfvén) radius,

$$R_{\rm m} = (\mu^2/\dot{M}_{\rm c}\ \sqrt{2GM_{\rm ns}})^{2/7}, \quad (1)$$

and $R_{\rm cor}$ – the corotational radius,

$$R_{\rm cor} = 3.8\ 10^9\ {\rm cm}\ M_{1.5}^{1/3}\ P_{103}^{2/3}. \quad (2)$$

μ, $M_{\rm ns}$ are the magnetic moment and mass of the neutron star, respectively, $M_{1.5} = M_{\rm ns}/1.5\ M_{\odot}$, P_{103} is the spin period of the neutron star expressed in units of 103 s, and $\dot{M}_{\rm c}$ is the rate of mass capture by the neutron star from the wind of Be companion.

A problem arose after Negueruela et al. (2000) had reported the detection of the 103.5 s pulsing X-ray emission from A0535+26 in August – November 1998 when the system luminosity was $L_{\rm x} \simeq 4\ 10^{33}$ erg s^{-1} (hereafter I call this as low luminous state). Optical/IR observations of the system performed during this time revealed the essential changes in the circumstellar environment of the Be companion: the loss of the JHK infrared excess and optical/IR line emission (Haigh et al. 1999; Negueruela et al. 2000). This indicates that the circumstellar disk surrounding the Be star was lost or became temporally invisible.

Interpretation of the low luminous pulsing X-ray emission from A0535+26 within the currently accepted steady state accretion model faces the following problems. Assuming the steady state accretion process to be realized in the system (i.e. almost all material captured by the neutron star from the wind of the normal companion is accreted onto its surface) one finds the mass exchange rate of $\lesssim 3\ 10^{13}$ g s^{-1}. In this case however the magnetospheric radius of the neutron star ($\sim$1.2 10^{10} cm) exceeds the corotational radius by a factor of three. This means that the neutron star during this time is in the state of *propeller* (i.e. in the centrifugal inhibition regime) and hence no steady state accretion onto its surface can occur.

On the other hand, the assumption that the observed X-ray emission has another energy source also leads to serious problems. The neutron star in A0535+26 cannot be considered as a spin powered pulsar since the magnetodipole losses of the star is $L_{\rm md} \lesssim 4\ 10^{25}$ erg s^{-1}. This also indicates that the polar cap regions at the magnetic poles of the neutron star cannot be heated by particles accelerated in the magnetosphere as it occurs in spin powered pulsars (Arons 1981). If the hot polar caps are due to the heated core of the neutron star it remains to be explained why their radius, $R_{\rm cp} \sim 0.1$ km, and temperature, $T_{\rm cp} \simeq 1.6\ 10^7$ K, derived by Negueruela et al. (2000) are essentially different from the parameters of polar caps predicted by the theoretical models (e.g. Shibanov & Yakovlev 1996; Zavlin et al. 1995). Furthermore the attempt to interpret the observed spectrum within the Hydrogen atmosphere spectral model (Rutledge et al. 1999) leads to rather unrealistic assumptions about the neutron star luminosity (Negueruela et al. 2000) and the physical parameters in its atmosphere (Zavlin 2000).

In this Paper I explore a possibility to interpret the low luminous state of A0535+26 in terms of the accretion powered pulsar. I start with the investigation of accretion picture during quiescent state of the system (which has not been studied in detail so far). I find that under conditions of interest the magnetospheric boundary of the neutron star is stable with respect to interchange instabilities and that the fastest mode by which the accreting plasma can enter the magnetic field of the neutron star during quiescence is the reconnection of the magnetic field lines (Sect. 2). In this situation the observed quiescent X-ray luminosity can be interpreted only if the average mass capture rate by the neutron star from the wind of the Be companion is $\sim 10^{17}$ g s^{-1}. The realization of this condition in A0535+26 is discussed in Sect. 3.1. Following the reconnection driven accretion model I find the mass capture rate by the neutron star during the low luminous state to be 2 10^{15} g s^{-1}. This means that the neutron star during this time is in the state of *accretor* and thus, the observed radiation can be interpreted within the canonical accretion powered model. The accretion picture and the parameters of the circumstellar disk during the low luminous state are the subject of Sect. 3.2. The results are summarized in Sect. 4.

2. Plasma entry the neutron star magnetosphere

Motch et al. (1991) and Negueruela et al. (2000) have argued that the accretion flow onto the neutron star magnetosphere in A0535+26 during the quiescent state has spherical geometry. This means that the plasma captured by the neutron star flows toward the star in almost radial direction with the free-fall velocity,

$$V_{\rm ff}(R) = \sqrt{2GM_{\rm ns}/R}.$$

Interaction of the accreting plasma with the magnetic field of the neutron star leads to the formation of a magnetosphere. The equilibrium magnetospheric shape of a neutron star undergoing spherical accretion has been calculated by Arons & Lea (1976a). They have shown that the magnetosphere in this case tends to be closed and its boundary is convex towards the accreting plasma, with two cusp points situated on the magnetic axis of the neutron star.

The formation of the magnetosphere, in the first approximation, prevent the plasma from reaching the neutron star itself. That is why, the rate of mass accretion onto the neutron star surface strongly depends on the rate of plasma penetration into the magnetosphere at its boundary. The following mechanisms of plasma penetration into the magnetosphere have been suggested: (i) the interchange instability of the magnetospheric boundary, (ii) the turbulent diffusion and (iii) the reconnection of the magnetic field lines.

2.1. Interchange instability

Arons & Lea (1976a) and Elsner & Lamb (1976) have shown that the magnetospheric boundary of a spherically accreting neutron star is interchange unstable if the effective gravitational acceleration at the magnetospheric boundary has a positive sign:

$$g_{\rm eff} = \frac{GM_{\rm ns}}{R_{\rm m}^2}\cos\kappa - \frac{V_{T_{\rm i}}^2(R_{\rm m})}{R_{\rm c}(\kappa)} > 0, \quad (3)$$

where $R_{\rm c}$ is the curvature radius of the field lines, κ is the angle between the radius vector and the outward normal to the magnetospheric boundary and $V_{T_{\rm i}}(R_{\rm m})$ is the ion thermal velocity of the accreting plasma at the boundary. For the case of the equilibrium magnetospheric shape derived by Arons & Lea (1976a) the condition (3) can be expressed in terms of the plasma temperature at the magnetospheric boundary as

$$T(R_{\rm m}) < T_{\rm cr} \approx 0.3 T_{\rm ff}(R_{\rm m}) = 0.3\frac{GM_{\rm ns}m_{\rm p}}{kR_{\rm m}}, \quad (4)$$

where $T_{\rm ff}$ is the free-fall temperature, $m_{\rm p}$ is the proton mass and k is the Boltzmann constant.

For this condition to be satisfied the cooling time of plasma at the boundary should be smaller than the free-fall time, $t_{\rm ff} = \sqrt{R_{\rm m}^3/2GM_{\rm ns}}$, i.e. a typical time of plasma heating due to the steady accretion process. Arons & Lea and Elsner & Lamb have shown that for the conditions of interest the characteristic cooling time due to the free-free and cyclotron radiation of plasma at the boundary essentially exceeds the free-fall time and thus, the magnetospheric boundary can be interchange unstable only if the Compton cooling is effective. This allows to express the condition for the magnetospheric boundary to be interchange unstable in the following form:

$$L_{\rm x} \gtrsim L_{\rm cr} = 6.5\ 10^{36}\ {\rm erg\,s^{-1}}\ \mu_{31}^{1/4}\ M_{1.5}^{1/2}\ R_6^{-1/8}, \quad (5)$$

where μ_{31}, $M_{1.5}$ and R_6 are the magnetic moment, mass and the radius of the neutron star expressed in units of 10^{31} G cm^3, 1.5 $M_\odot$ and 10^6 cm, respectively.

However the mean X-ray luminosity of the neutron star in A0535+26 during quiescence ($\sim$2 10^{35} erg s^{-1}) is essentially smaller than $L_{\rm cr}$. This means that interchange instabilities of the boundary during this state are suppressed by the "favorable curvature" of the magnetospheric lines and hence, the accreting plasma enters the magnetic field of the neutron star due to a different process.

2.2. Diffusion

If the plasma penetrates the magnetosphere due to diffusion process the maximum inflow rate is limited as

$$\dot{M}_{\rm diff} \lesssim 4\pi R_{\rm m}^2 \rho(R_{\rm m}) V_{\rm diff} = \frac{\mu^2}{GM_{\rm ns}R_{\rm m}^3} V_{\rm diff}, \quad (6)$$

where $V_{\rm diff}$ is the diffusion velocity.

The diffusion velocity can be expressed in the following form (see Ikhsanov & Pustil'nik 1996)

$$V_{\rm diff} = \sqrt{D_{\rm eff}/t_{\rm ff}}. \quad (7)$$

The maximum inflow rate is realized if the diffusion process is governed by drift-dissipative instabilities (i.e. Bohm diffusion)

$$D_{\rm eff} = D_{\rm B} = \zeta ckT_{\rm i}(R_{\rm m})/16eB(R_{\rm m}), \quad (8)$$

where $T_{\rm i}$ is the ion plasma temperature at the base of the envelope and ζ is the diffusion efficiency ($\zeta < 1$).

Combining Eqs. (6–8) yields

$$\dot{M}_{\rm diff} \lesssim 4\ 10^{12}\ {\rm g\,s^{-1}}\ \zeta^{1/2}\ \mu_{31}^{-1/14}\ M_{1.5}^{1/7}\ \dot{M}_{17}^{11/14}, \quad (9)$$

where $\dot{M}_{17}$ is the rate of mass captured by the neutron star expressed in units of 10^{17} g s^{-1}. The obtained value of $\dot{M}_{\rm diff}$ is however too small to explain the observed luminosity of the X-ray source in A0535+26.

2.3. Reconnections

According to Elsner & Lamb (1984) the rate of plasma entry into the magnetosphere due to reconnection of the magnetic field lines is

$$\dot{M}_{\rm rec} \simeq \alpha_{\rm R} \frac{\mu^2}{GM_{\rm ns}R_{\rm m}^3}\ \frac{A_{\rm R}}{4\pi R_{\rm m}^2} V_{\rm a}, \quad (10)$$

where $\alpha_{\rm R}$ is the efficiency of the reconnection process, $A_{\rm R} = 4\pi R_{\rm m}\lambda_{\rm m}$ is the effective area of the reconnection region and $V_{\rm a} = B/\sqrt{4\pi\rho}$ is the Alfvén velocity, which in the boundary layer at the base of the hot envelope is of the order of $V_{\rm ff}(R_{\rm m})$.

The values of $\alpha_{\rm R}$ and $A_{\rm R}$ depend on the current sheet parameters and the magnetic field configuration in the accretion flow. Detailed investigation of these items however is beyond the scope of the present paper. Here I use the most probable values of $\alpha_{\rm R}$ and $A_{\rm R}$ which are currently accepted.

Investigations of reconnection processes in solar flares and in the Earth's magnetopause suggest the average value $\alpha_{\rm R} \approx 0.1$ (see Priest & Forbes 2000 and references therein).

The effective area of the reconnection region depends of the scale of the magnetic field in the accreting plasma over the magnetospheric boundary. It is limited by the initial inhomogeneity of the accretion flow and/or by the fragmentation of plasma over the rotation magnetospheric boundary due to the Kelvin-Helmholtz instability. In the last case the scale of plasma vortexes of embedded field lies within the interval $\lambda_{\rm m} \sim 0.1{-}0.01 R_{\rm m}$ (Arons & Lea 1976b; Wang & Robertson 1985).

Under these conditions the rate of plasma penetration into the neutron star magnetic field due to the magnetic lines reconnection reads

$$\dot{M}_{\rm rec} \simeq 10^{15}\ {\rm g\,s^{-1}}\ \left[\frac{\alpha_{\rm R}}{0.1}\right] \left[\frac{\lambda_{\rm m}}{0.1 R_{\rm m}}\right] \left(\frac{\dot{M}_{\rm c}}{10^{17}\ {\rm g\,s^{-1}}}\right). \quad (11)$$

The obtained value of $\dot{M}_{\rm rec}$ essentially exceeds the rate of plasma diffusion into the magnetosphere. It is comparable with the value of the mass accretion rate required to power the observed X-ray luminosity of A0535+26 during quiescent state if the mass capture rate by the neutron star is $\dot{M}_{\rm c} \sim 10^{17}\ {\rm g\,s^{-1}}$. But is this estimate of $\dot{M}_{\rm c}$ reasonable in the case of A0535+26? The answer to this question is the subject of the next section.

3. Accretion picture during quiescent state

Properties of the X-ray emission observed from A0535+26 during quiescence can be well explained in terms of plasma accretion via the accretion column onto the neutron star surface. The observed average X-ray luminosity calculated under the assumption that the source is situated at the distance of 2.6 kpc is $L_{\rm x}(1{-}20\ {\rm keV}) = 2.5\ 10^{35}\ {\rm erg\,s^{-1}}$ (Motch et al. 1991). If the source is situated closer to the Earth: 1.5–2 kpc (Giangrande et al. 1980; Steele et al. 1998), its quiescent X-ray luminosity is $(8{-}15)\ 10^{34}\ {\rm erg\,s^{-1}}$. This corresponds to the average mass accretion rate onto the star surface:

$$\dot{M}_{\rm a,q} = 5\ 10^{14}\ {\rm g\,s^{-1}}\ R_6\ M_{1.5}^{-1} \left[\frac{L_{\rm x}}{10^{35}\ {\rm erg\,s^{-1}}}\right]. \quad (12)$$

An attempt to explain the quiescent X-ray emission in the frame of the steady accretion model reveals some controversial points. If the mass accretion rate onto the star surface is equal to the rate of mass capture by the neutron star it remains to be explained in which mode the accreting plasma penetrates the magnetosphere. Since the interchange instabilities of the magnetospheric boundary are suppressed (see Sect. 2) another mechanism of plasma penetration into the magnetosphere should be invoked.

Another controversial point of the steady accretion approach is the state of the neutron star. For the neutron star in A0535+26 to be in the state of *accretor* the following condition should be satisfied:

$$\dot{M}_{\rm c} \gtrsim \dot{M}_{\rm cr} = 1.5\ 10^{15} {\rm g\,s^{-1}} \mu_{31}^2 P_{103}^{-7/3} \left[\frac{M_{\rm ns}}{1.5\ M_{\odot}}\right]^{-5/3}, \quad (13)$$

where P_{103} is the spin period of the neutron star expressed in units of 103 s. Comparison of Eqs. (12) and (13) indicates that for the neutron star during quiescence to be in the state of *accretor* its magnetic moment should be $\lesssim 6\ 10^{30}\ {\rm G\,cm^3}$. Since this value is close to the lower limit to μ the *accretor* state of the neutron star cannot be completely excluded. But during the periods when the X-ray luminosity decreases below the average value (Ricketts et al. 1975; Polcaro et al. 1983) and especially during the low luminous event in August – November 1998 ($\dot{M}_{\rm a} \lesssim 3\ 10^{13}\ {\rm g\,s^{-1}}$) the neutron star *definitely* cannot be in the state of accretor. If however the neutron star during these periods is in the state of *propeller*, it remains to be explained why the X-ray spectrum of the source during these low luminous events is similar to the spectrum of an accreting neutron star rather than to the soft X-ray spectrum predicted by Davies & Pringle (1981) and Wang & Robertson (1985) for a neutron star in the state of *propeller*.

In principal, both problems mentioned above could be avoided assuming the disk accretion geometry. But extensive investigations of A0535+26 in almost all spectral regions (e.g. Motch et al. 1991; Clark et al. 1999; Negueruela et al. 2000) have not revealed any signs of an accretion disk in the system during quiescent state. That is why the investigation of alternative possibilities to explain the quiescent X-ray luminosity of the system in the frame of the spherically symmetrical accretion approach seems to be more fruitful. One of these possibilities – a spherical accretion onto the interchange stable neutron star magnetosphere – is discussed in this section.

As it has been shown in Sect. 2 the interchange instabilities of the magnetospheric boundary of the neutron star in A0535+26 during quiescent state are suppressed by the "favorable curvature" of the magnetospheric lines. In this case the accreting plasma can enter the neutron star magnetic field due to the diffusion and magnetic lines reconnection processes. The efficiency of these processes however is too small for all the plasma captured by the neutron star to be accreted onto the star surface (see Eq. (11)). What kind of accretion picture is expected in this case?

If the magnetospheric radius is smaller than the corotational radius the inflowing plasma cannot be expelled from the vicinity of the magnetosphere. This means that the material captured by the neutron star, in the first approximation, stagnates over the boundary forming a plasma envelope around the magnetosphere. The inner radius of the envelope is equal to $R_{\rm m}$ which is determined by Eq. (1). The outer radius of the envelope depends on the value of the ratio $t_{\rm c}/t_{\rm h}$, where $t_{\rm c}$ is the time of plasma cooling in the envelope due to radiative losses and $t_{\rm h}$ is the time of plasma heating due to the release of accretion energy in the envelope.

If the radiative losses dominate the energy input, i.e. $t_{\rm c}/t_{\rm h} < 1$, the outer radius of the envelope is limited by the height of homogeneous atmosphere, $h = c_{\rm s}^2/g$, where $c_{\rm s}$ is the sound speed in the envelope and g is the gravitational acceleration. In this case however the plasma in the envelope cools rapidly and since its temperature decreases below $0.3 T_{\rm ff}$ the magnetosphere proves to be unstable with respect to interchange instabilities (Arons & Lea 1976a; Elsner & Lamb 1976). This means that the accretion process in the case of $t_{\rm c}/t_{\rm h} < 1$ quickly reduces to the steady accretion.

A situation is completely different if the energy input dominates the radiative losses, i.e. $t_c/t_h \geq 1$. In this case the plasma temperature in the envelope is $T(R) \approx T_{\rm ff}(R)$, and, correspondingly, the sound speed is of the order of the free-fall velocity, $c_s(R) \approx V_{\rm ff}(R)$. As it has been shown by Davies & Pringle (1981) under this condition the envelope can be described as a quasi-static adiabatic atmosphere ($p \propto \rho^{5/3}$) in which the sound speed is $c_s \propto R^{-1/2}$ independently on the plasma density. This means that all length-scales in each point of the envelope (in particular, the height of homogeneous atmosphere) is comparable to the radius ($h(R) \approx R$) and hence, the envelope turns out to extend up to the accretion radius of the neutron star. The plasma pressure at the inner edge of the envelope is determined by the magnetic contra-pressure $p(R_{\rm m}) = B^2(R_{\rm m})/8\pi$. At the outer edge of the envelope the gas pressure is determined by the interaction between the envelope, which moves together with the neutron star through the wind of the normal companion, and the surrounding material, which overflows the outer edge compressing and heating the envelope plasma.

If no accretion onto the neutron star surface occurs the formation of the hot envelope prevents the surrounding material from penetration into the accretion lobe of the neutron star. This is just the case discussed by Davies & Pringle (1981) for a neutron star in the supersonic propeller state. However, if the rate of plasma inflow into the magnetic field of the neutron star from the base of the envelope is $\dot{M}_{\rm a} \neq 0$ the drift of the material through the envelope with the velocity $V_{\rm dr} = (\dot{M}_{\rm a}/\dot{M}_{\rm c})V_{\rm ff}$ is expected. The rate of the accretion energy release due to the plasma drift through the envelope in this case is $\dot{M}_{\rm a}GM_{\rm ns}/R$ and, correspondingly, the heating time of the envelope is

$$t_{\rm h} = \frac{R}{V_{\rm dr}} = \frac{\dot{M}_{\rm c}}{\dot{M}_{\rm a}} t_{\rm ff}. \quad (14)$$

On the other hand, the cooling time of the envelope plasma due to the bremsstralung emission process is

$$t_{\rm c} \approx t_{\rm br} \simeq 633 \text{ s} \left(\frac{T}{10^9 \text{ K}}\right)^{1/2} \left(\frac{N}{10^{13} \text{ cm}^{-3}}\right), \quad (15)$$

where N is the particle number density, which at the base of the envelope can be expressed as

$$N(R_{\rm m}) = \frac{\mu^2}{4\pi R_{\rm m}^6 kT(R_{\rm m})}. \quad (16)$$

Combining Eqs. (14–16) I find that the energy input to the envelope due to accretion dominates the radiative losses if

$$\dot{M}_{\rm a} \gtrsim 5\ 10^{14} \text{ g s}^{-1}\ \mu_{31}^{2/7}\ M_{1.5}^{-1/14} \left[\frac{\dot{M}_{\rm c}}{10^{17} \text{ g s}^{-1}}\right]^{13/7}. \quad (17)$$

Comparing this value with that expressed by Eqs. (9) and (11) one can conclude that the envelope remains hot (and hence, quasi-stable) if the process of plasma penetration from the base of the envelope into the magnetic field of the neutron star is governed by the magnetic lines reconnection process. The luminosity of the envelope in this case is

$$L_{\rm x,env} \sim 3\ 10^{31} \text{ erg s}^{-1}\ \mu_{31}^{-4/7} M_{1.5}^{8/7} \left(\frac{\dot{M}_{\rm a}}{10^{15} \text{ g s}^{-1}}\right)^{9/7} \quad (18)$$

and it contributes the system radiation mainly in hard X-rays ($55 \div 150$ keV). The spin down of the neutron star due to its interaction with the envelope is expected to be of the order of $\dot{P} \approx 3\ 10^{-9}$ s s^{-1}. This accretion picture is called below as *reconnection driven accretion model.*

3.1. Average quiescent luminosity

In the frame of the reconnection driven accretion model the average quiescent X-ray luminosity of A0535+26 can be explained provided the mass capture rate by the neutron star of (see Eqs. (11) and (12))

$$\dot{M}_{\rm c} \sim 10^2 \dot{M}_{\rm a,q} = 1.5\ 10^{-9}\ M_\odot\ \text{yr}^{-1}. \quad (19)$$

Under this condition the magnetospheric radius of the neutron star is $R_{\rm m,q} \simeq 1.14\ 10^9$ cm $< R_{\rm cor}$, and hence, the star is in the state of *accretor*. Can this value of the mass capture rate be consistent with the parameters of the circumstellar disk in A0535+26?

The rate of mass capture by the neutron star from the stellar wind of the Be companion can be evaluated as

$$\dot{M}_{\rm c}(a) = \pi R_{\rm eff}^2(a)\ \rho(a)\ V_{\rm rel}(a), \quad (20)$$

where $R_{\rm eff}$ is the effective accretion radius of the neutron star, ρ is the plasma density in the wind, $V_{\rm rel}$ is the relative velocity between the neutron star and the surrounding gas and a is the orbital separation.

Following Lamers & Waters (1987) the density and velocity in the circumstellar disk can be expressed as

$$\left[\begin{array}{l} \rho(R) = \rho_0 (R/R_{\rm Be})^{-n}, \\ \\ V_{\rm wr}(R) = V_{\rm r0}(R/R_{\rm Be})^{n-2}, \end{array}\right. \quad (21)$$

where ρ_0 and $V_{\rm r0}$ are the density and velocity of plasma at the inner disk radius and the value of n lies within the interval $2.3 \div 3.3$.

Investigating the properties of Paschen emission lines in A0535+26 Clark et al. (1998b) have estimated the plasma density in the circumstellar disk of 10^{12} cm^{-3}. Assuming these lines to be generated in the inner part of the disk one finds $\rho_0 = (2 \div 3)\ 10^{-12}$ g cm^{-3}.

In order to evaluate the plasma radial velocity in the circumstellar disk I take into account that the accretion flow onto the neutron star magnetosphere during the quiescent state has a spherical geometry. This means that the circularization radius,

$$R_{\rm circ} \simeq \frac{\dot{J}^2}{\dot{M}_{\rm c}^2 GM_{\rm ns}}, \quad (22)$$

is smaller than the magnetospheric radius expressed by Eq. (1). Here $\dot{J}$ is the rate of accretion of angular momentum,

$$\dot{J} = \xi \dot{J}_0 = \xi \left(\frac{1}{2} \Omega_{\rm orb} R_{\rm eff}^2 \dot{M}_{\rm c} \right), \quad (23)$$

and $\Omega_{\rm orb}$ is the orbital angular velocity of the neutron star. Parameter ξ is the factor by which the average rate of accretion of angular momentum is reduced due to inhomogeneities (the velocity and density gradients) in the accretion flow. Numerical simulations of mass transfer in wind-fed close binaries (e.g. Anzer et al. 1987; Taam & Fryxell 1988; Matsuda et al. 1991) revealed the average value of this parameter to be $\bar{\xi} = 0.2$.

The effective accretion radius of a neutron star in a binary system is

$$R_{\rm eff} \simeq \begin{cases} R_\alpha = 2GM_{\rm ns}/V_{\rm rel}^2, & \text{for} \quad V_{\rm rel} > V_0, \\ R_{\rm L_{ns}}, & \text{for} \quad V_{\rm rel} \lesssim V_0, \end{cases} \quad (24)$$

where the velocity V_0 is determined by $R_\alpha(V_0) = R_{\rm L_{ns}}$ and in the case of A0535+26 is

$$V_0 \simeq 105 \text{ km s}^{-1} M_{1.5}^{1/2} \left(\frac{a}{1.7\ 10^{13} \text{ cm}} \right)^{-1/2}.$$

Combining Eqs. (1) and (22–24) one can express the condition for a spherically symmetrical accretion geometry in A0535+26 in the form:

$$V_{\rm rel} \gtrsim 120 \text{ km s}^{-1} \xi_{0.2}^{1/4}\ \mu_{31}^{-1/14}\ M_{1.5}^{11/28}\ P_{111}^{-1/4}\ \dot{M}_{17}^{1/28}, \quad (25)$$

where $\xi = \xi/0.2$, P_{111} is the orbital period expressed in units of 111 days and $\dot{M}_{17}$ is the mass capture rate by the neutron star expressed in units of 10^{17} g s^{-1}.

In the general case the relative velocity is

$$\boldsymbol{V}_{\rm rel} = \boldsymbol{V}_{\rm ns} + \boldsymbol{V}_{\rm w}, \quad (26)$$

where $\boldsymbol{V}_{\rm ns}$ is the linear velocity of the neutron star orbiting around Be companion:

$$V_{\rm ns}(a) = a\Omega_{\rm orb}, \quad (27)$$

and $\boldsymbol{V}_{\rm w}$ is the stellar wind velocity in the frame of the Be star:

$$\boldsymbol{V}_{\rm w} = V_{\rm wr} \boldsymbol{e}_{\rm r} + V_{\rm w\phi} \boldsymbol{e}_\phi. \quad (28)$$

Here $\boldsymbol{e}_{\rm r}$ and $\boldsymbol{e}_\phi$ are the unit vectors in the radial and azimuthal directions, respectively.

Finally, the tangential velocity component in the circumstellar disk can be limited as[3]

$$V_{\rm w\phi}(a) \lesssim \sqrt{GM_{\rm Be}/a}. \quad (29)$$

Thus, for a spherical accretion picture to be realized in the system the radial velocity of plasma in the circumstellar disk at the periastron should be

$$V_{\rm wr}(a_0) \gtrsim \sqrt{V_{\rm rel}^2 - (V_{\rm ns} - V_{\rm w\phi})^2} \simeq 110 \text{ km s}^{-1}. \quad (30)$$

Using the average value of density gradient $n = 3$ adopted by Clark et al. (1999) I find the wind velocity at the inner disk radius $V_{\rm r0} = 12$ km s^{-1}. This value lies within the interval suggested by Lamers & Waters (1987) for field Be stars and corresponds to the average value of the mass outflow rate in the disk, $5\ 10^{-8}\ M_\odot$ yr^{-1}, estimated by Clark et al. (1999)[4].

Putting the derived values of ρ_0 and $V_{\rm r0}$ to Eq. (21) and combining Eqs. (20), (21), (24) and (26–29) I find the mass capture rate by the neutron star in A0535+26 at the periastron ($R = a_0$):

$$\dot{M}_{\rm c}(a_0) \simeq 2\ 10^{17} \text{ g s}^{-1}\ M_{1.5}^2 \times \left(\frac{N(a_0)}{1.4\ 10^9 \text{ cm}^{-3}} \right) \left(\frac{V_{\rm rel}(a_0)}{180 \text{ km s}^{-1}} \right)^{-3}. \quad (31)$$

The mass capture rate at other orbital phases strongly depends on the circumstellar disk properties beyond $R = a_0 \simeq 9R_{\rm Be}$ which are rather uncertain so far. The detection of the quiescent pulsing X-ray emission around the orbital phase $\phi = 0.4$ (Motch et al. 1991) indicates that the high density low velocity structure in the Be star wind is extended at least up to the distance of $25R_{\rm Be}$. Otherwise the mass capture rate by the neutron star from the spherically symmetrical wind component at this distance is smaller than 10^{13} g s^{-1} (setting the total mass loss rate by the Be star to be of a few $\times 10^{-8}\ M_\odot$ yr^{-1} and the wind velocity to be of the order of the terminal velocity $V_\infty \simeq 600$ km s^{-1}: see Giovannelli & Graziati 1992).

The stronger limits to the disk parameters at the distance $R > a_0$ can be obtained from the reconnection driven accretion model. In this case, the observed X-ray luminosity, $L_{\rm x}(\phi = 0.4) \simeq 10^{35}$ erg s^{-1}, implies $(\rho/V_{\rm rel}^3)\ |_{\phi=0.4} \gtrsim 2\ 10^{-37}$ g s^3 cm^{-6}. Taking into account that the relative velocity cannot be smaller than 120 km s^{-1} (otherwise the disk accretion geometry is expected, see Eq. (25)) I get the lower limit to the plasma number density: $N(\phi = 0.4) \gtrsim 2\ 10^8$ cm^{-3}. This exceeds the number density of plasma in the spherical component at the same distance by two orders of magnitude. It also indicates that the density and velocity gradients in the outer part of the circumstellar disk differ from that currently adopted for its inner part. In our particular case the value of the gradient $n = 1.9$ can be suggested. This situation could be realized if an additional compression of the disk at large distances occurs. However a more detailed investigation of this possibility is required.

3.2. Low luminous state

In the frame of the reconnection driven accretion model the low luminous state of A0535+26 can be explained in the following way.

Putting the value of average X-ray luminosity observed from A0535+26 during August – November 1998 ($L_{\rm x} \simeq 4\ 10^{33}$ erg s^{-1}) to Eq. (19) I find the mass capture rate by

[3] Here I take into account that $M_{\rm ns} \ll M_{\rm Be}$.

[4] Here I adopted the disk opening angle of $\theta = 15°$.

the neutron star during this time as $\dot{M}_{\rm c,ll} \sim 2\ 10^{15}\ {\rm g\,s^{-1}}$. Under this condition the magnetospheric radius of the neutron star is smaller than its corotational radius and hence the state of the neutron star during this time can be classified as *accretor* (see Eq. (13)).

Plasma being penetrated into the magnetosphere at the boundary flows along the field lines onto the magnetic poles of the neutron star. The radius of the hot polar caps in this case is

$$R_{\rm pc} = 0.17\ {\rm km}\ \mu_{31}^{-2/7} M_{1.5}^{1/14} R_6^{3/2} \left[\frac{\dot{M}_{\rm c,ll}}{2\ 10^{15}\ {\rm g\,s^{-1}}}\right]^{1/7}.$$

This value is comparable with the radius of polar caps estimated by Negueruela et al. (2000).

If the circumstellar disk completely disappeared in August – November 1998 the spherically symmetrical outflow model of the Be star should be used. In this case however the mass capture rate by the neutron star at the orbital phase $\phi = 0.8$ (at which the X-ray radiation was observed) is of the order of $1.5\ 10^{13}\ {\rm g\,s^{-1}}$. This is insufficient to power the observed X-ray luminosity of the system even assuming that all captured material is accreted onto the neutron star surface.

An alternative possibility is that the circumstellar disk did not completely disappear but it became by some reasons invisible (for example, a decrease of the mass outflow rate or/and a small plasma density). In this case the required value of the mass capture rate can be explained provided the disk number density[5] (see Eq. (31))

$$N\mid_{(\phi=0.8)} \simeq 8\ 10^6\ {\rm cm^{-3}} \left(\frac{V_{\rm rel}(\phi=0.8)}{150\ {\rm km\ s^{-1}}}\right)^{-3}.$$

This value exceeds the density in the spherical wind component only by a factor of two.

Assuming the density gradient in the disk to be similar to that expressed by Eq. (21) I estimate the density in the inner part of the disk during the low luminous state of the system as $N(R_{\rm Be}) \sim 3\ 10^{10}\ {\rm cm^{-3}}$. This is smaller than the disk density during quiescent state by about two orders of magnitude as is comparable with the plasma density in the spherical wind component just over the surface of the Be star. This means that the emission measure and the mass outflow rate in the disk during August – November 1998 were smaller than the typical values by a factor of 10^4 and 10^2, respectively. Under this condition however the circumstellar disk is unlikely to be seen.

4. Conclusions

Magnetospheric boundary of the neutron star in A0535+26 during a quiescent state is stable with respect to interchange instabilities. The fastest mode by which the accreting plasma can enter the magnetosphere is the reconnection of the force lines. Under this condition the magnetosphere of the neutron star is surrounded by a hot quasi-stationary plasma envelope.

The quiescent X-ray emission of A0535+26 can be explained within the reconnection driven accretion model provided the average mass capture rate by the neutron star is $\dot{M}_{\rm c} \simeq 10^{17}\ {\rm g\,s^{-1}}$. This condition is definitely satisfied around the orbital phase $\phi = 0$ (periastron). For this condition to be satisfied at other orbital phases the density gradient in the circumstellar disk beyond $10 R_{\rm Be}$ should be $n \simeq 1.9$.

The suggested approach allows to interpret the 103-s pulsing X-ray emission with luminosity $4\ 10^{33}\ {\rm erg\,s^{-1}}$ observed from A0535+26 during the "disk loss" state in August – November 1998 within the canonical model of a spherical accretion onto a magnetized neutron star (Elsner & Lamb 1984). Following the reconnection driven accretion model I find the average mass capture rate by the neutron star during this phase of $\sim 2\ 10^{15}\ {\rm g\,s^{-1}}$. This means that the neutron star during this time was in the state of *accretor*. The radius of the hot polar caps at the neutron star surface estimated within this approach is of the order of that derived by Negueruela et al. (2000). The required mass capture rate by the neutron star is realized if the low velocity disk structure at the equatorial plane of the Be companion during this time was not completely disrupted. I find the plasma density in the disk during this state to be smaller than its average value by two orders of magnitude. This implies the emission measure to be reduced by a factor of 10^4 that makes the disk invisible in the optical/IR.

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