LETTER TO THE EDITOR

The appearance of magnetospheric instability in flaring activity at the onset of X-ray outbursts in A0535+26

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ABSTRACT

We argue that X-ray flaring variability observed in the transient X-ray pulsar A0535+26 is due to low-mode magnetospheric instability. This instability develops at the onset of accretion, in the thin boundary layer between the accretion disk and neutron star magnetosphere. As a result, the matter collected in the boundary layer can rapidly fall onto the NS surface close to the magnetic poles, but not exactly along the field lines by which the stationary accretion proceeds. This explains the shift in cyclotron line energy measured using RXTE data in a pre-outburst spike, with respect to the line energy observed during the main outburst. Furthermore, the instability can account for the difference in pulse profiles, and their energy evolution that is different in the pre-outburst flare and main outburst.

Key words. accretion, accretion disks – stars: neutron – X-rays: binaries

1. Introduction

The transient X-ray binary pulsar A0535+26 was discovered by the Ariel V satellite during a giant outburst (Coe et al. 1975; Rosenberg et al. 1975). The neutron star (NS) rotates with a period \( P \approx 103 \) s and is in an eccentric (\( e = 0.47 \)) orbit about a massive O9.7IIIe star with an orbital period of \( P_{\text{orb}} \approx 110 \) d (Coe et al. 2006). The X-ray activity of this transient source is complicated: several giant outbursts were observed in 1975, 1980, 1983, 1989, 1994 and 2005, with weaker outbursts sometimes observed at successive periastron passages. This type of X-ray activity is common for Be/X-ray binary systems, which represent the largest subclass of massive X-ray binaries. The giant (type II, according to Stella et al. 1986) outbursts can take place at any orbital phase and most probably are triggered by the enhanced activity of the optical star (Coe et al. 2006). More regular, weaker type I outbursts are associated with enhanced interaction of the neutron star with a circumstellar disk surrounding the Be-companion (Okazaki & Negueruela 2001). A0535+26 did not show outbursting activity between 1994 and 2005. The last giant outburst of A0535+26 occurred after a prolonged quiescence period in May–June 2005 (Tueller et al. 2005). In September 2005, the subsequent normal type I outburst was extensively studied by RXTE and INTEGRAL (Caballero et al. 2007, 2008). These observations revealed somewhat unexpected features, which we summarize below.

Feature 1. A short (fraction of a day) pre-outburst X-ray spike, with a luminosity comparable to the outburst maximum, is observed during the rise of the outburst.

Feature 2. The NS pulse period at the onset of the outburst, remained constant within the margins of error, but rapidly decreased after the periastron passage.

Feature 3. RXTE data shows that the energy of the cyclotron resonance scattering feature (CRSF) during the spike at 90% confidence is \( 52.0^{+1.6}_{-1.4} \) keV (Caballero et al. 2008), which is notably higher than the value \( 46.1 \pm 0.5 \) keV measured during the main outburst at the same level of X-ray luminosity. The latter value is consistent with INTEGRAL measurements (Caballero et al. 2007).

Feature 4. The CRSF energy in the main outburst (within the margins of error) is independent of the X-ray luminosity.

Feature 5. The X-ray pulse profiles during the spike are different from the pulse profiles observed during the main outburst. Pulse profiles during the outburst show an abrupt change at energies above the cyclotron resonance, while those in the pre-outburst spike do not.

The additional inspection of the Swift BAT (15–50 keV) light curve of the source (Fig. 1) reveals that the pre-outburst spike observed by RXTE is only one of a collection of flares, with the characteristic time up to a few times \( 10^4 \) s, appearing at the rising part of the outburst. The flux evolution then proceeds more smoothly during the spin-up of the NS (Feature 6), which begins close to periastron passage. A similar flaring activity was observed during the onset of the preceding giant outburst, at the same flux level, in April 2005, and at the next periastron passage in December 2005.

In this Letter we argue that the flaring activity and pre-outburst spikes are most likely due to magnetospheric instability. This would take place at the onset of a smooth increase in the mass-accretion rate through the accretion disk surrounding the NS, close to periastron passage. This instability would cause plasma that had accumulated in the thin boundary layer, between the accretion disk and NS magnetosphere, to fall onto the NS surface as large blobs. These blobs would be channeled to regions close to the NS magnetic poles by different magnetic field lines than those guiding the accretion flow smoothly increasing from the disk.
2. The model

Since the 1970s, it has been known that matter can penetrate the NS magnetosphere, and be accreted onto magnetized NSs, via various instabilities. The gravitational interchange instability (Rayleigh-Taylor, or Kruskal-Schwarzschild [KS] for plasma in magnetic field) of cold plasma at the magnetospheric boundary (see Emsler & Lamb 1976; Arons & Lea 1976a), in particular, mediates quasi-spherical accretion. In this case, close to the magnetic equator where KS instability is more likely, plasma enters the magnetosphere as bubbles or filaments that fall deeper towards the NS. All or part of these filaments, broken up into smaller pieces by Kelvin-Helmholtz instabilities (Arons & Lea 1976a), can then be entrained by the magnetic field and channeled toward the magnetic polar region on the NS surface.

During disk accretion onto a rotating magnetized NS the Kelvin-Helmholtz instability between the disk material and the magnetosphere is also important (Anzer & Börner 1980, 1983). The transition between the accretion disk and the rotating NS magnetosphere (for the aligned magnetic dipoles) was studied by Ghosh & Lamb (1978, 1979), Scharlemann (1978), Anzer & Börner (1983) and later by Lovelace et al. (1995) using more realistic assumptions. In the latter model, the twisting of the stellar magnetic field by the differentially rotating disk leads to the appearance of open magnetic field lines extending outward from both the star and the disk. The accretion process may then be maintained by an MHD outflow from the disk that transports away angular momentum. Numerical MHD simulations of the disk interaction with an inclined magnetic dipole (Romanova et al. 2003) confirmed the basic features of the disk-magnetospheric interaction. Accretion onto NSs can be unstable, leading to outbursts and flares, because of instabilities in the magnetosphere (Baarn 1979; Spruit & Taam 1993). The KS instability affects accretion onto magnetized NSs at both large and small accretion rates. At small accretion rates, matter accumulates at the boundary layer and flaring events are expected. At large accretion rates, matter is accreted more steadily.

In the case of A0535+26 we deal with non-stationary accretion triggered by enhanced NS interaction with the circumstellar disk and the wind of the Be-companion at binary periastron passage. BATSE observations of this source (Bildsten et al. 1997) indicated the strong disk accretion spin-up during type II (giant) outbursts, while no significant spin-up was observed during a series of type I outbursts, at successive periastron passages both before and after the giant outburst. Moreover, the average spin-down of the NS rotation is clearly seen in the BATSE data before and after the giant outburst, suggesting that a propeller-like mechanism operates between accretion episodes close to periastron. We expect similar long-term spin-up/spin-down behavior of magnetized NSs in eccentric Be X-ray binaries on very general grounds (Stella et al. 1986). The magnetic propeller regime was investigated by Lovelace et al. (1999). Numerical MHD simulations (Ustyugova et al. 2006) revealed the non-stationary character of mass outflow during the propeller stage. Clearly, the transition from propeller to accretion stage is the most complicated for the analysis. Here we suggest that the non-stationary features observed in the outburst of A0535+26 relate to the magnetospheric instability which develops during the transition to the accretion stage.

The pre-outburst X-ray flaring activity is not an exceptional feature of the 2005 outbursts in A0535+26. Hints of other flares in A0535+26 are apparent for several other type I outbursts in BATSE light-curve data for its giant outburst in 1994 (see Fig. 1 of Finger et al. 1996). Similar pre-outburst spikes are observed in other Be/X-ray binaries, e.g. in BATSE observations of GS 1843-02 (Finger et al. 1999) and INTEGRAL observations of EXO 2030+375 (Camero Arranz et al. 2005). A plausible picture may be delineated as follows.

1) We assume that an accretion disk surrounds the NS in A0535+26. It is definitely the case during the giant outbursts, as the spin-up measurements and QPO observations suggest (Sembay et al. 1990; Finger et al. 1996). The disk can survive for several orbits after the giant outburst. The observed strong spin-up during the main part of the August/September 2005 outburst (Caballero et al. 2008 and Fig. 1) confirms the presence of the disk.

2) When the accretion rate onto the NS increases as it approaches orbital periastron, the magnetospheric radius $R_m$ determined by magnetic pressure balancing plasma pressure, decreases according to the proportionality $R_m \propto M^{-27}$. Accretion occurs when the stopping radius of matter $R_s$, generally of the order of $R_m$, becomes smaller than the corotation radius $R_c = (G M / \omega^2)^{1/3}$, where $M$ is the NS mass and $\omega = 2 \pi / P$ is its spin frequency. In all models of the disk-magnetospheric interaction a thin boundary layer between the disk and the rotating NS magnetosphere does exist in which the matter becomes gradually captured by the magnetic field lines. The width of this region is model dependent, but is of the order of the disk thickness (e.g. $< 20 c_s / \omega_K$ in Anzer & Börner 1983, or $\sim 5 c_s / \omega_K$ in Lovelace et al. 1995; here $c_s$ is the sound speed and $\omega_K$ is the Keplerian frequency). So for an estimate we can assume $\Delta l \sim h = 0.1 R_s$. The amount of mass accumulated in this layer can be roughly evaluated assuming the standard $\alpha$-theory (Shakura & Sunyaev 1973):

$$\Delta M = \rho 2 \pi R_s^2 \delta h \Delta \varpi \approx (4 \times 10^{10}) g \Delta \varpi \alpha^{3/2} \alpha^{-4/5} M_\odot^{-3/5} (1 - \xi)^{3/5},$$

where $R_s \varpi$ is the stopping radius in units of $10^6$ cm, $M_\odot$ is the mass accretion rate in units of $10^{-10}$ $M_\odot$/yr, $\xi = J / (M \sqrt{G M R_s^2})$.
is the angular momentum flux through the disk normalized to the flux from the stopping radius. Here we have assumed the gas pressure to dominate over the radiation pressure in the boundary layer and the main opacity to be due to Thomson scattering. Of course, the disk is already not Keplerian at this radius (dω/dr → 0 at Rg), but for the case of interest Rg ∼ Rc we neglect the deviation from the Keplerian motion. At the onset of accretion ξ = 0, the viscosity parameter can be very small, α ∼ 0.01 or smaller, so the amount of matter in the boundary layer may be as high as ∼10^3 g.

3) As inferred from the analysis by Baan (1979), at small accretion rates (1 × 10^{-10} M_{⊙}/yr ≈ 10^{-6} g/s) the magnetopause in A0535+26 with P ∼ 104 s may be on the verge of a KS instability. The model by Baan (1977, 1979) has successfully described the statistical properties and the burst waiting time – luminosity correlation of type II outbursts in the rapid burster A0535+26. The considerable magnetospheric instability can break-up the entire boundary layer in the disk. All material stored in the boundary layer may then rapidly enter the magnetosphere. Our estimate above indicates that up to ∼10^{31} g can fall onto the NS surface on the free-fall time scale (of the order of 20 s) producing short X-ray spikes with a maximum X-ray luminosity of up to 5 × 10^{36} erg/s (feature 1 from the Introduction). The amount of matter falling onto the NS surface during the spikes in the considered outburst of A0535+26 can be estimated from the light curve (Fig. 1) and is found to be ΔM = ∫ Mdt < 10^{22} g in each spike. The characteristic timescale of the spikes is ∼10^4 s and agrees with the time required to replenish the boundary layer ∼ΔM/M. The angular momentum supply from the disk during the spikes changes the NS spin period by the fractional amount ΔP/P = ΔM/2GMcP(2πt) / (2πt) < 7 × 10^{-6} where we assume that the NS moment of inertia is I = 10^{45} g cm^2 and Rg = Rc = 10^9 cm. This is within the uncertainty of the period measurement (ΔP/P ∼ 5 × 10^{-6}, Caballero et al. 2008), which explains the lack of noticeable spin-up of the NS at the initial phase of the outburst (feature 2 from the Introduction); see also the BATSE observations of A0535+26 presented in Bildsten et al. (1997), and of GS 1843-02 in Finger et al. (1999).

5) The plasma entering the magnetosphere via the low-mode KS instability may become frozen into the magnetic field more close to the NS than the main accretion flux and hence fall along different magnetic field lines than those by which the quasi-stationary accretion is channeled. This explains the observed difference in the cyclotron line energy during the initial X-ray spike and the remainder of the outburst (feature 3 from the Introduction). Similarly to Her X-1 (Staubert et al. 2007), the absence of a radiation-dominated accretion column in A0535+26 is suggested by the independence of the CRSF energy late in the outburst from the observed X-ray luminosity (feature 4 from the Introduction). The height of the emission region above the NS surface is then about several hundred meters. To change the CRSF energy by the fractional amount of ΔE_c/E_c ∼ 10%, the emission region during the spike is required to move towards the NS surface by the amount ΔR/Rns ∼ 3% (assuming the dipole magnetic field), i.e. by about 300 meters. Therefore, the emission from the spike is likely to originate very close to the NS surface. This explains the different pulse profiles during the spike, especially in hard X-rays (feature 5 from the Introduction).

The smooth change in pulse profile shape at energies above the cyclotron resonance (as in Her X-1, Kloeckhov et al. 2008) may correspond to a pencil-beam diagram of emission during the flare. The photon cross-section may then change smoothly, at the cyclotron resonance energy, in the strong magnetic field along the direction of the field. In the main outburst, however, the accretion column is higher (see above), the density increases such that it can become optically thick in the direction normal to the field, and if there is a temperature gradient to the center, a fan-like beam can be additionally formed by extraordinary photons. The cross-sections of extraordinary photons far from the resonance (E ≪ E_c) are proportional to σ_⊥ = σ_∥(E/E_c)^2, which is a smaller cross-section than that of ordinary photons.

1 Ordinary polarized photons have electric field vector E lying in the plane formed by the magnetic field and the wave vector of the photon; the E-vector of extraordinary photons is perpendicular to this plane.
photon $\sigma_T \approx \sigma_T(\sin^2 \theta + \cos^2 \theta (E/E_0)^2)$. The different behaviors can escape effectively from larger optical depth. (Here $\sigma_T$ is the Thomson scattering cross-section and $\theta$ is the angle between the incident photon and the magnetic field; see Harding & Lai 2006). Above cyclotron resonance, $\sigma_T \approx \sigma_T \approx \sigma_T$ and photons escape from small optical depths. This can explain the appearance of the large hump at pulse phase $\sim 0.7$ after crossing the CRSF energy (Fig. 3 in Caballero et al. 2008). The model by Hayasaki & Okazaki, however, ignores the phase-dependent mass accretion. Such accretion disks can potentially produce one-armed spiral structures of the accretion disk, induced by a phase-dependent mass accretion. Such accretion disks can reappear after the spin-up stopping, for which there is indeed a hint in the light curve of the A0535+26 outburst during September 13–15, 2005. At this time the NS had stopped spinning-up (see Fig. 1).

3. Discussion

The magnetospheric instability model proposed for the pre-outburst flares in A0535+26 is generic and can be applied to other transients. The prerequisite, however, is that the source must be on the verge of low-mode instability, which depends on the NS magnetic field, the spin period, the accretion rate and possibly other parameters (e.g., the misalignment of the magnetic dipole and/or NS spin axis relative to the orbital angular momentum). It is possible that the transition from propeller to accretion stage can occur without a strong KS instability being present. The model predicts changes in pulse profiles and in the cyclotron line energy during the short flares, as observed in A0535+26 (Caballero et al. 2008), which can be compared with observations of other sources.

Are there other possible explanations for the observed pre-outburst X-ray spikes? The SPH modeling of an accretion disk surrounding the NS (Hayasaki & Okazaki 2006) reproduces normal outbursts at successive periastron passages. In some instances the modeling shows a single peak preceding outburst maximum. The accretion disk is formed from the Roche lobe overflow of the coplanar circumstellar disk surrounding the Be companion star. The important feature of these SPH simulations is the transient, one-armed spiral structure of the accretion disk, induced by a phase-dependent mass accretion. Such accretion disks can be responsible for mass transfer enhancement close to periastron. The model by Hayasaki & Okazaki, however, ignores the disk-magnetosphere interaction critical to transient accretion onto magnetized NS, and can not reproduce the observed flaring activity.

Spruit & Taam (1993) also found a viscous, disk-magnetosphere instability that was associated with the magnetospheric boundary around the corotation radius. This instability results in a cyclic enhancement of the mass accretion rate on the viscous time scale at the magnetospheric boundary. While this timescale can be as short as $10^8$ s for the corotation radius $10^9$ cm, the chaotic behavior of flares observed in A0535+26 and, most importantly, other features (different pulse profiles and CRSF energy, and absence of the flaring during the NS spin-up phase) imply that this model can not provide the correct explanation.

Our model for short flares observed at the onset of outbursts in the transient X-ray pulsar A0535+26 is based on magnetospheric instability. It successfully explains all features of the outburst observed during August–September 2005 by RXTE and INTEGRAL, and makes clear predictions for future observations. The present model should provide a framework for line measurements in accreting neutron stars, precise timing analysis and evolution of X-ray pulse shapes with luminosity at different energies, have become the working tools to probe the non-stationary accretion onto magnetized neutron stars.

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2 A similar dependence holds for free-free absorption cross-sections (Kaminker et al. 1983).