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XMM-Newton observations of 1A 0535+262 in quiescence

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Abstract. Accretion onto magnetized neutron stars is expected to be centrifugally inhibited at low accretion rates. Several sources including 1A 0535+262, however, are known to pulsate in quiescence at luminosities below the theoretical limit predicted for the onset of the centrifugal barrier. Here we present the results of an analysis of a ~ 50 ks long *XMM-Newton* observation of 1A 0535+262 in quiescence. At the time of the observation, the neutron star was close to the apastron, and the source had remained quiet for two orbital cycles. In spite of this, we detected a pulsed X-ray flux of $\sim 3 \times 10^{-11}$ erg cm^{-2} s^{-1}. Several observed properties, including the power spectrum, remained similar to those observed in the outbursts. Particularly, we have found that the frequency of the break detected in the quiescent noise power spectrum follows the same correlation with flux observed when the source is in outburst. We argue that, along with other arguments previously reported in the literature, our results suggest that the accretion in quiescence also proceeds from an accretion disk around the neutron star.

1 Introduction

1A 0535+262 is one of the best studied high mass X-ray binaries (HMXBs) of the Galaxy. The system hosts a *Be* star [1] and a neutron star in an eccentric orbit with $e \sim 0.47$ and orbital period of ~ 111 d [2]. The neutron star is an accreting pulsar with spin period of ~ 103.3s [3], which exhibits outbursts associated with passage through the circumstellar disk of the primary in the vicinity of periastron. The magnetic field of the neutron star has been estimated to be $B \sim 5 \times 10^{12}$ G from the centroid energy of the so-called cyclotron resonance scattering feature (CRSF) observed at $E_{cyc} \sim 45$ keV in X-ray spectrum of the pulsar. Unlike many other sources, 1A 0535+262 exhibits no significant variation of the line energy with flux, suggesting that the line is formed close to the surface of the neutron star [4].

Like many accreting pulsars [5–7] lighcurves of 1A 0535+262 exhibit a break in power density spectrum. Using RXTE observations, [6] were able to show that the frequency of the break is correlated with flux, and proportional to the Keplerian frequency at the inner edge of the accretion disk, where it is disrupted by the magnetosphere.

Being a transient source, 1A 0535+262 is best studied at high luminosities. However it is also one of a few accreting pulsars observed to pulsate outside of outbursts at lower fluxes as well [8], which is commonly defined as quiescence. The origin of the residual quiescence emission is uncertain. In fact, it was suggested early on [9] that accretion should be inhibited by the rotation of the magnetosphere, which grows in size as the surrounding plasma thins out. As discussed by [10] and [11], outside of outbursts 1A 0535+262 is on the verge, if not below, this critical luminosity. It is, therefore, not clear whether the observed emission is accretion powered or if other scenarios have to be invoked. To clarify the origin of its quiescent emission, we observed 1A 0535+262 with *XMM-Newton* for 50 ks to investigate in detail the spectral and timing properties of the source in quiescence. The results are presented and discussed in this paper.

2 Observations and data analysis

We observed 1A 0535+262 with *XMM-Newton* for 50 ks on Feb. 28, 2012. At the time of observation, the neutron star was close to the apastron, and the source had shown no outbursts in the two preceding orbital cycles. Therefore, 1A 0535+262 was indeed deep in quiescence. We also used the archival *Suzaku* observation (ID. 100021010) performed at the end of a normal outburst in Sep. 2005 as a reference to compare the quiescent and outburst spectra in the 0.2-12 keV energy range. In addition, we used all available observations of 1A 0535+262 by the Proportional Counter Array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE) to investigate the aperiodic variability of the source at higher fluxes. The data reduction was carried out using the *XMM* SASv12.0[1] and HEASOFT 6.12[2] software packages.

In *XMM* data, the source was clearly detected with all three instruments with an average combined count-rate of about 5 counts/s and a factor of four more in a flare-like episode halfway through the observation, which corresponds to source flux of $\sim 2.7 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ and luminosity of $\sim 1.3 \times 10^{34}\,\mathrm{erg\,s^{-1}}$ assuming a distance of 2 kpc.

2.1 Timing analysis

The search for pulsations and a detailed study of pulse-profiles was one of the main goals of our observation. For timing analysis, the photon arrival times were corrected for the orbital motion in the solar system and in the binary system using the ephemeris by [2] with the adjusted epoch as provided by the Fermi GBM Pulsar project[3]. We then extracted the lightcurve in the 0.2-12 keV energy band with 1 s time bins using the data combined from all three EPIC cameras. For this lightcurve, the Lomb-Scargle periodogram reveals the single highly significant peak at $\sim$ 103.28 s coincident with spin period of neutron star, so we confirm that the X-ray flux is pulsed in quiescence.

We then folded the light curves in several energy ranges to obtain the pulse-profiles presented in Fig. 1. The pulse shape is sine-like and almost constant with energy in line with earlier reports for the observations of the source in quiescence [8, 10, 12]. As noted by [8], in comparison with outburst observations, this simple shape resembles hard rather than soft pulse profiles.

To investigate changes of the source spin during and between outbursts, we compared the obtained period value with the GBM Pulsar frequency values. To study the luminosity dependence of source spin, one also needs a source flux estimate, which is not trivial in case the of the *Fermi* GBM, which can only measure the amplitude of pulsed flux. To determine the energy flux and the accretion rate from the

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[1] http://xmm.esa.int/sas

[2] http://heasarc.gsfc.nasa.gov/docs/software/lheasoft

[3] http://gammaray.nsstc.nasa.gov/gbm/science/pulsars

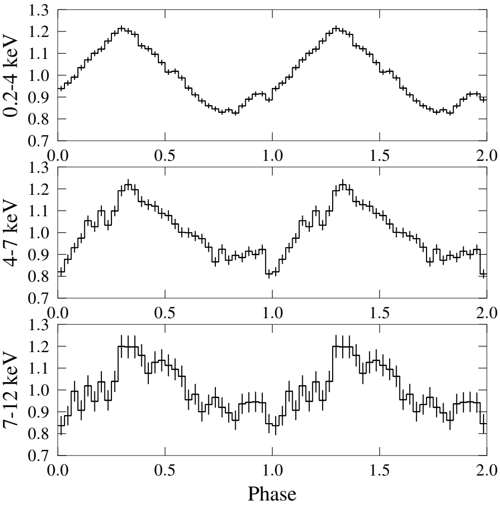

Figure 1. Normalized energy-resolved pulse profiles folded with best-fit period using all available PN and MOS data.

GBM amplitudes, we used the available RXTE observations contemporary to the GBM measurements in order to calibrate observed pulsed amplitudes with the source flux derived from spectral fits, which turned out to be well correlated. The resulting dependence of the pulse frequency derivative on flux is presented in Fig. 2 (left).

Motivated by the analysis of aperiodic variability in 1A 0535+262 presented by [6], we extended this study to *XMM* observation, and found that the break around the pulse frequency is immediately apparent in the resulting power spectrum. To compare *XMM* power spectrum with *RXTE* results [6], we re-analyzed all available *RXTE* observations following the same procedure as for the *XMM* data. In addition, we analyzed a single *BeppoSAX* observation of the source in quiescence, when pulsations were still detected [observation C in 12]. The results are presented in Fig. 2 (left). The correlation of the break frequency with flux reported by [6] is confirmed, and, moreover, seems to extend to the lowest fluxes where the pulsed flux from the source is still detected. Note, that in quiescence the break frequency approaches the spin frequency of the neutron star below which the accretion shall be inhibited centrifugally, which may explain non-detection of pulsations at lower fluxes in *BeppoSAX* observations [observations A and B in 12].

2.2 Spectral analysis

In order to determine whether quiescent X-ray spectrum differs significantly from outburst spectra we use a ~ 43 ks long *Suzaku* observation (ID. 100021010) of 1A 0535+262 carried out at the end of a normal outburst in Sep. 2005 as a reference point [13]. We restrict the analysis to X-ray Imaging Spectrometer (XIS) data, which has a similar energy range as the *XMM* EPIC cameras and combine the spectra from the three front illuminated XIS units.

For the analysis of the *XMM* data we also separately considered the large flare which occurred halfway the observation and lasted ~ 1.3 ks to probe for flux dependent spectral change in quiescence.

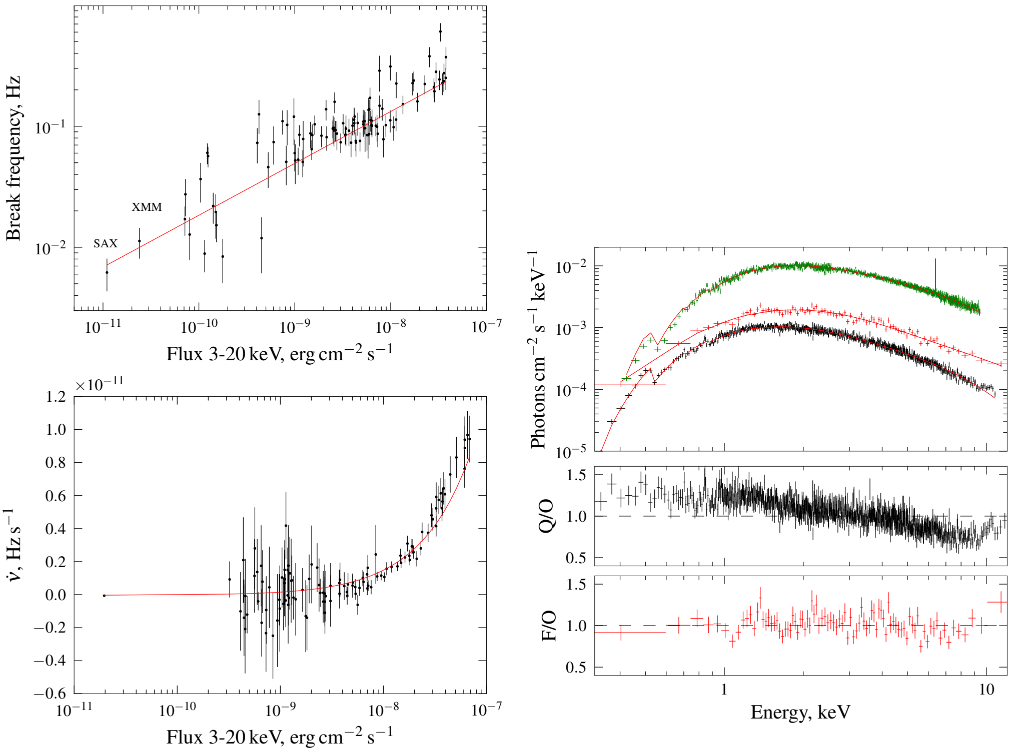

Figure 2. Left: Break frequency (top panel), and spin frequency derivative (bottom) as function of flux, and best-fit model prediction for the joint fit as described in the text (red lines). Right: Best fit outburst, flare and quiescent spectra (top to bottom in top panel) using the Suzaku XIS and XMM PN data, and ratio of *XMM* average (Q) and flare (F) spectra to best fit model for Suzaku XIS outburst spectrum (O) with adjusted absorption column and normalization.

Note, that similar events have been reported by [14] based on the *INTEGRAL* observations of the source. Flaring is probably normal for 1A 0535+262 in quiescence.

Both *XMM* and *Suzaku* XIS spectra are well fitted with either absorbed cutoff power law, and the comptonization model [*CompTT* in *Xspec*, see 15]. The unfolded spectrum and best-fit model parameters for *XMM* average, flare and the *Suzaku* XIS spectra are presented in Fig. 2 (right), and Table 1. In *XMM* observation the source flux in 0.2-12 keV energy range is $\sim 2-6\times10^{-11}$erg cm^{-2} s^{-1} (on average and during the flare respectively, i.e. at least factor of six less than in *Suzaku* observation), which corresponds to average luminosity of $\sim 1.3\times10^{34}$erg s^{-1} assuming a distance of 2 kpc. Besides a difference in the inferred absorption column, the spectra are similar in shape, although the source gets softer as the flux decreases.

Table 1. Best-fit spectral parameters for average and flare *XMM* and outburst *Suzaku* spectra fitted with *cutoffpl* and *CompTT* models), and for pulse-phase resolved *XMM* spectra fitted with *CompTT* model. The flux logarithm $\log_{10} F$ [$\mathrm{erg\,cm^{-2}\,s^{-1}}$] is the unabsorbed source flux in 0.2-12 keV energy range. Phase averaged spectra were fit simultaneously with common absorption column and seed photon temperature, which converged to phase-average values. The provided χ^2_{red} is for this combined fit.

Pulse-phase average

	cutoffpl			*CompTT*		
	XMM, all	*XMM*, flare	*Suzaku*	*XMM*, all	*XMM*, flare	*Suzaku*
N_{H} atoms cm^{-2}	0.380(7)	0.38(3)	0.516(8)	0.218(8)	0.20(3)	0.275(9)
Γ/τ	0.38(2)	0.2(1)	0.38(2)	23.3(5)	22(2)	20.7(4)
$E_{fold}/(T_0, kT)$, keV	4.2(1)	4.1(5)	5.6(1)	0.44(1), 1.98(3)	0.52(4), 2.3(3)	0.541(9), 2.57(5)
$\log_{10} F$	-10.530(2)	-10.19(1)	-9.410(2)	-10.576(2)	-10.221(1)	-9.442(2)
χ^2_{red}	1.15	1.4	1.17	1.11	1.4	1.18

3 Discussion

The analysis of the *XMM-Newton* observation of 1A 0535+262 in quiescence and comparison of the results with data from other satellites has revealed a phenomenology similar to that of the source in outburst:

- The source is highly variable, with the flux increasing by factor of ten during the flares. The average flux in quiescence also appears to vary upon comparison of the quiescence fluxes reported with different instruments.
- The X-ray spectrum, particularly during the higher flux flare episode, is similar to that in outburst (within the *XMM* energy range).
- Although the pulse profile is simplified in quiescence, some features typical of outburst profiles can still be tracked. The amplitude of the pulsed flux is also similar.
- The noise power spectrum exhibits the same broken power law shape as at higher fluxes, and the break frequency follows the same correlation with flux as at higher luminosities.
- The neutron star spins down in quiescence with average rate of $\dot{\nu} = -7 \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$.

First of all, these results, in line with previous reports [11, 16], confirm that the observed emission is powered by the accretion. However, in the case of the spherically symmetric accretion geometry, observed quiescent fluxes imply that the stationary accretion should be centrifugally inhibited [9, 16].

On the other hand, [17] considered a possibility that the accretion in quiescence might proceed from an accretion disk just like in outbursts, suggesting that plasma in circumstellar *Be* disk of the companion has sufficient angular momentum to form an accretion disk around the neutron star at all orbital phases. As a matter of fact, direct evidence for an accretion disk around the neutron star was reported by [18] based on the velocities derived from the observed doubling in the He I emission lines in the optical spectrum of the source.

Presence of a break in the noise power spectrum following the same correlation with flux both in outbursts and quiescence also suggests that the accretion geometry does not significantly change in quiescence, and the accretion still proceeds from disk.

It is easy to show, that spin evolution of the source is also consistent with this scenario, and the model by [19] for the case of disk accretion is able to reproduce the observed "spin-frequency derivative — flux" dependence. We assume that the neutron star has standard mass and radius, and the magnetic field of $B/10^{12}[\mathrm{G}] = (1+z)/11.57 \times 46[\mathrm{keV}] \sim 4.9 \times 10^{12}$ G, (where z is the gravitational redshift) derived from observed cyclotron line energy. The best fit is presented in Fig. 2 (left). The best-fit distance of $d = 1.85(2)$ kpc and model spin-down rate in quiescence $\dot{\nu} \sim -3.8 \times 10^{-14}\,\mathrm{Hz\,s^{-1}}$ are in good agreement with observations.

The break frequency is connected with the magnetospheric radius $f_b = \nu_{\mathrm{K}}(k \cdot R_m) = (GM)^{1/2}(k \cdot R_m)^{-3/2}/2\pi$, which can be constrained from the spin evolution of the neutron star. We can, therefore, find k (and the source distance) simultaneously, which yields $d = 1.85(3)$ kpc, and $k = 0.52(1)$, i.e. in line with predictions of the [19] model, so spin evolution and the break frequency changes are described self-consistently.

An independent estimate of the plasma velocity in the disk may be obtained from high resolution X-ray spectroscopy. Using *Chandra*, [20] derive velocities of $\sim 4000 - 5090(1000)\,\mathrm{km\,s^{-1}}$, which corresponds to break frequencies of 0.13-0.16 Hz in contemporary *RXTE* observations. The azimutal velocities in the disk for these frequencies are $v_\phi = (2\pi\nu_k GM)^{1/3} \sim 5500 - 6000\,\mathrm{km\,s^{-1}}$, i.e. consistent with direct measurements.

Several independent lines of evidence suggest, therefore, that in 1A 0535+262, the accretion disk around the neutron star powers the accretion, not only in outbursts, but also in quiescence. A similar scenario may be realized in other *Be* systems as well, and may be very important for understanding the spin evolution of enclosed neutron stars and the physics of quasi-periodic outbursts.

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