Pulsed Thermal Emission from the Accreting Pulsar
XMMU J054134.7-682550

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Abstract. Soft X-ray excesses have been detected in several Be/X-ray binaries and interpreted as the signature of hard X-ray reprocessing in the inner accretion disk. The system XMMU J054134.7-682550, located in the LMC, featured a giant Type II outburst in August 2007. The geometry of this system can be understood by studying the response of the soft excess emission to the hard X-ray pulses. We have analyzed series of simultaneous observations obtained with XMM-Newton/EPIC-MOS and RXTE/PCA in order to derive spectral and temporal characteristics of the system, before, during and after the giant outburst. Spectral fits were performed and a timing analysis has been carried out. Spectral variability, spin period evolution and energy dependent pulse shapes are analysed. The outburst ($L_X \approx 3 \times 10^{38}$ erg/s $\sim L_{EDD}$) spectrum could be modeled successfully using a cutoff powerlaw, a cold disk emission, a hot blackbody, and a cyclotron absorption line. The magnetic field and magnetospheric radius could be constrained. The thickness of the inner accretion disk is broadened to a width of 75 km. The hot blackbody component features sinusoidal modulations indicating that the bulk of the hard X-ray emission is emitted preferentially along the magnetic equator. The spin period of the pulsar decreased very significantly during the outburst. This is consistent with a variety of neutron star equations of state and indicates a very high accretion rate.

1. Introduction

Be/X-ray binaries consist of a neutron star orbiting a Be star. A Be star is defined as a non-supergiant B-type star whose spectrum shows (or showed, at some time) one or more Balmer lines in emission (Slettebak (1988)). Be/X-Ray binaries (Negueruela (2007)) display X-ray pulsations, a signature of the presence of a strong magnetic field ($B \sim 10^{12}$ G) of the neutron star orbiting a massive star companion. Most known Be/X-Ray binaries undergo outbursts in which their X-ray luminosity suddenly increases by a factor of $\sim 10^{-10^{4}}$ with respect to the quiescence level.

They can feature two types of outbursts: Type I (or normal) X-ray outbursts of moderate intensity ($L_X \sim 10^{36}$ erg s$^{-1}$) occurring during the periastron passage of the neutron star and Type II (or giant) X-ray outbursts of higher intensity ($L_X \sim 10^{37-38}$ erg s$^{-1}$) lasting for several weeks or even months. In general, type II outbursts start
shortly after the periastron passage, but do not show any other correlation with orbital parameters. A small fraction of Be/X-ray binaries are persistent sources (the prototype being X-Per), with a low luminosity $L_X \sim 10^{34}$ erg s$^{-1}$ at an almost constant emitting level.

The X-ray spectra of Be/X-Ray binaries are very close to those of accreting pulsars, although the dependence on the different physical conditions close to the neutron star. The spectra can be characterized by cutoff powerlaws. In a few systems, when the interstellar absorption is low, there is an evidence for soft excesses at low energies, often modeled as blackbody components. It has been showed that the soft excesses observed in luminous X-ray sources ($L_X > 10^{38}$ erg s$^{-1}$) can only be explained by reprocessing of hard X-rays by optically thick material, near the inner edge of the accretion disk (Hickox et al. (2004) and references therein). Many, if not all, bright sources with low absorption have shown this feature.

The observability of the soft excess depends on the absorbing column density ($N_H$) and flux. It is fair to suspect that soft excess may be present in other accreting pulsars but not be detectable due to low flux or high $N_H$ (Hickox et al. 2004). Sources far away from the galactic plane suffers less absorption than those in galactic plane. The following figure (fig. 1) shows plots of flux vs $N_H$ for a number of accreting pulsars. The left panel of figure 1 shows a sample of sources with detected soft excess (stars) or not detected (filled boxes). A clean boundary between the two kind of sources is seen. In the right panel, the over-plotted contour levels of $\chi^2_\nu$ fitted by a simple absorbed power law supports this idea. Sources with high $\chi^2_\nu$ shows soft excess while sources with $\chi^2_\nu \sim 1$ do not show soft excess. Thanks to the type II outburst and the position (LMC, low $N_H$) of XMMU J054134.7-682550 we are able to detect the soft excess.

Figure 1.: Left: Observed $N_H$ and unabsorbed fluxes for X-ray binary pulsars. Sources with soft excess are shows as stars, without soft excess with filled boxes. right: Observability of the soft excess as a function of $N_H$ and unabsorbed fluxes. The contours show the fits of simple absorbed power law. Figures are taken from Hickox et al. (2004)

XMMU J054134.7-682550, located in the Large Magellanic Cloud - LMC, has been proposed as a likely HMXB by Shtykovskiy and Gilfanov (2005). Palmer et al. (2007) found XMMU J054134.7-682550 in a flaring state during a routine scan of the Swift-BAT data on August 3, 2007 at a level of $\approx 50$ mCrab. Subsequent RXTE observations on August 9, 2007 revealed X-ray pulsations ($P_s \approx 61.601 \pm 0.017$ s) and cyclotron features at 10 keV (Markwardt et al. 2007). Assuming that this source is
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A Be system having a (giant) type II outburst, Markward et al. (2007) estimated an orbital period of about 80 days (within a factor of \(\sim 2\)) based on the Corbet diagram. The average PCA (Proportional Counter Array on board RXTE) spectrum could be fit with a cut-off power law, with photon index 0.47 and an e-folding cut-off energy of 16 keV (Markwardt et al. 2007).

2. The outburst

XMMU J054134.7 – 682550 has been observed during a type II (giant) outburst in August 2007, lasting for about 50 days, and reaching \(L_X \sim 10^{38} \text{ erg/s} \approx L_{\text{EDD}}\) (Manousakis et al. 2009). We have used data obtained with the Rossi X-ray Timing Experiment-RXTE (2 datasets) and XMM-Newton (4 datasets) in 2007; the reduction was carried out by following the standard procedure for RXTE, and by avoiding pile-up effects for XMM-Newton. The XMM-Newton and RXTE observations are quasi-simultaneous.

Figure 2 (left panel) shows the outburst\(^1\) spectrum by fitting an absorbed power law (\(\chi^2_\nu \approx 3\)). Residuals below 1 keV and spectral features at \(\sim 10\) keV can be seen. To account for the soft excess below 1 keV we added either a black body (\(kT=0.2\) keV) and/or a disk blackbody (\(kT=0.09\) keV) component. The combination of blackbody and disk blackbody can provide a \(\chi^2_\nu \approx 1.04\). The spectral features at 10 keV are fitted with a cyclotron absorption component. The cyclotron absorption line at \(E \approx 9.0\) keV indicates a magnetic field of \(\approx 10^{12}\) G. The power law is characterized by a photon index \(\Gamma \approx 0.2\), \(E_C \approx 12\) keV, typical of an accreting pulsar. The \(N_H\) is fixed to the galactic value towards this position, \(N_H = 6.32 \times 10^{20} \text{ cm}^{-2}\) (Dickey and Lockman (1990)). The inner radius of the disk blackbody is also fixed to the radius of the magnetosphere\(^2\).

Figure 2 (right panel) shows the unfolded spectrum and the model (solid line). The power law, disk emission, and hot blackbody components are shown with dashed lines. Above 5 keV the power law dominates the spectrum. At low energies, the dominant components are the disk emission and the hot blackbody.

We have obtained background corrected lightcurves in the energy bands 5-30 keV (from RXTE) and 0.2-0.5, 0.5-1, and 3-10 keV (from XMM-Newton). To search for pulsed thermal emission, we decided to obtain energy-dependent folded lightcurves (\(P_{\text{spin}} \approx 61.23\) s). The energy range of each dominant component is: 0.2-0.5 keV for the disk blackbody, 0.5-1 keV for the blackbody, and 3-10 keV for the power law. Figure 3 shows the folded lightcurves in the energy bands: 0.2 – 0.5 keV (top), 0.5 – 1.0 keV (middle), and 3 – 10 keV (bottom). Note that the lightcurves denoted with “(soft)” are corrected for the contribution of the cut off power law. The shape of the peak in the folded 3-10 keV lightcurve is sharper and narrower than in the “soft” lightcurves. The pulse in the middle panel shows a sinusoidal modulation (solid line).

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\(^1\)Exposure time for XMM-Newton: 7.5 ksec; Exposure time for RXTE: 3.5 ksec

\(^2\)The radius of the magnetosphere can be obtained by equating the kinetic energy density of the accreted material to the magnetic energy density
Figure 2: Left: Outburst spectrum obtained using EPIC/MOS1+2 and RXTE/PCA, fit with a simple absorbed cut-off powerlow model (const*wabs*cutoff). Right: $E \times f(E)$ outburst spectrum. The black solid line is the model described in the text. Cyan points are the unfolded spectrum. Blue, red, green dotted lines represent the cutoff powerlaw, hot blackbody and disk emission, respectively.

Figure 3: Folded lightcurves obtained from EPIC/MOS[1] in the 0.2 – 0.5 keV (top), 0.5–1.0 keV (middle), and 3–10 keV (bottom) energy bands, using the best spin period ($P \approx 61.23s$) found from RXTE/PCA data. The two soft lightcurves are corrected for the contamination of the cutoff powerlaw component. The solid curve in the middle panel shows a sinusoidal fit to the data. The zero epoch is set to MJD 54333.5.

Swift/UVOT, Swift/XRT (Palmer et al. 2007) and XMM/EPIC allows us to locate the optical-nearIR counterpart. The closest counterpart to XMMU J054134.7-682550
is the 2MASS 05413431-6825484. Using 2MASS and USNO-B1.0 magnitudes we can estimate a temperature of $\sim 13000$ K, compatible with a range of B-like stars.

3. The Geometry

Figure 4: The above sketch shows a schematic representation of the reprocessing geometry in the accreting pulsar XMMU J054134.7-682550 (the distance between the neutron star and the disk is not to scale).

In this model we assume that the hard X-rays are emitted (preferentially) towards the magnetic equator of the neutron star and that these photons illuminate the inner edge of the accretion disk. Subsequently, the illuminated disk re-radiates and features a soft X-rays sinusoidal modulation (see fig. 3, middle panel). The vertical line represents the rotation axis of the neutron star. The grey stripe indicates the reprocessing area on the inner edge of the accretion disk. The hard X-rays beam is indicated by dashed lines. The soft X-ray pulse evolves sinusoidally from left to right (fig. 4).

4. Conclusions

- The reprocessing region corresponds to the broadened inner edge of the accretion disk broadened to $\sim 75$ km.
- The soft X-ray pulse shape profile (0.5-1 keV) shows sinusoidal modulation, a signature of illumination of the broadened inner disk.
- The infrared-optical spectral energy distribution of the counterpart suggests a hot primary star of T$\sim 13000$K, likely a B-type star.

References

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