XMM-NEWTON OBSERVATIONS OF THE BE/X-RAY TRANSIENT A0538-66 IN QUIESCEENCE

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ABSTRACT

We present XMM-Newton observations of the recurrent Be/X-ray transient A0538-66, situated in the Large Magellanic Cloud, in the quiescent state. Despite a very low luminosity state of \((5-8) \times 10^{33}\) ergs/s in the range \(0.3-10\) keV, the source is clearly detected up to \(\sim 8\) keV and can be fitted using either a power law with photon index \(\alpha = 1.9 \pm 0.3\) or a bremsstrahlung spectrum with \(kT = 3.9^{+3.9}_{-1.7}\) keV. The spectral analysis confirms that the off-state spectrum is hard without requiring any soft component, contrary to the majority of neutron stars observed in quiescence up to now.

Key words: A0538-66; XMM-Newton; quiescent emission.

1. INTRODUCTION

The recurrent Be/X-ray transient A0538–66 (X 0535–668) was discovered in 1977 when two outbursts were observed with the Ariel 5 satellite (White & Carpenter 1978). In the following years several other outbursts were observed with HEAO 1 and Einstein (HEAO 2) (e.g. Johnston et al. 1980; Skinner et al. 1980) with coincident X-ray and optical flares showing a recurrence of 16.65 days (Skinner 1980) interpreted as the period of an eccentric binary orbit. This period has been confirmed as a by-product of the MACHO project by Alcock et al. (2001), who also found a longer optical modulation of 421 days. The optical counterpart, identified by Johnston et al. (1980), was found to be a member of the Large Magellanic Cloud (LMC) (Pakull & Parmar 1981). Optical and UV spectroscopy (Charles et al. 1983) classify the counterpart as B2 IIIe star.

Based on the distance to the LMC, the luminosity of the outbursts observed in the first years after detection can be estimated as around \(10^{39}\) ergs/s making this a super-Eddington source and one of the most powerful X-ray binaries known. An observation with Einstein (HEAO 2) 1980/81 during a strong outburst found 69 ms pulsations (Skinner et al. 1982; Ponman et al. 1984); up to this day this remains the only measure of the pulse period of this accreting pulsar. From the rapid spin period and the luminosity (Skinner et al. 1982) inferred an upper limit to the magnetic field of \(B \sim 10^{11}\) G assuming that matter accreted onto the polar caps uninhibited by a centrifugal barrier.

In later years the source has been mostly quiescent. Weak outburst activity at two to three orders of magnitude below the early observations was found in the ROSAT All-Sky Survey in 1990 (Mavromatakis & Haberl 1993) and in an ASCA observation in 1995 (Corbet et al. 1997); for details see Table [I] (Campana et al. 2002) observed the source in 1999 in quiescence with BeppoSAX finding very different results than in the previous observations. A 0538–66 was observed in the quiescent state in April 2002 by XMM-Newton. The goal of the observation was to use the unique collecting power of this satellite in order to obtain spectral data allowing to distinguish between different models of the quiescent emission, e.g., residual accretion to the surface or accretion stopped at the magnetosphere.

2. DATA ANALYSIS

The data were extracted with the XMM-Newton Scientific Analysis Software, version 5.4 from circles centered on the source, and from a background region with the same area. Separate spectra were extracted for single and double events, which allows to gauge potential calibration uncertainties.

The amount of photoelectric absorption is not strongly constrained and consistent with zero. We used a fixed value of \(N_H = 8 \times 10^{20}\) cm\(^{-2}\), as found by Corbet et al. (1997) and consistent with the ranges given in Mavromatakis & Haberl (1993) and Campana et al. (2002).
The spectra can be well fitted either by a power law with photon index $\alpha = 1.9 \pm 0.3$ and normalization $I_{1\text{keV}} = (4.9 \pm 0.6) \times 10^{-5}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$ ($\chi^2_{\text{red}} = 0.98$) or a bremsstrahlung spectrum with temperature $kT = 3.9^{+3.9}_{-1.7}$ keV and normalization $I = 6.3^{+1.1}_{-0.8} \times 10^{-5}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$ ($\chi^2_{\text{red}} = 1.03$). A blackbody spectrum is not consistent with the data, showing clear systematic deviations above $\sim 2$ keV ($\chi^2_{\text{red}} = 1.86$).

The spectrum reported by Corbet et al. (1997) for a weak outburst (see also Tab. 1, first spectrum) is not at all compatible with our data – even after allowing for free scaling, $\chi^2_{\text{red}} \approx 6.75$ for 29 d.o.f. We can exclude any significant contribution from an additional soft component or an iron line to the best fit spectra – at most such components could contribute 2–3% to the total flux. In summary our results match very well those obtained by Campana et al. (2002), but with the source in an even lower luminosity state.

A period search by epoch folding in the period range 10–100 ms found no pulsations in our dataset in line with previous observations at higher flux levels.

3. DISCUSSION

The observations reported here found A 0538–66 in a state of very low luminosity – with $(5-8) \times 10^{33}$ ergs/s this is the lowest state for which spectral results have been reported up to today. The results found by Campana et al. (2002) for the quiescent state – i.e., a relatively hard spectrum which can be described as a power law of photon index $\sim 2$ and no sign of pulsations – are confirmed and extended to even lower luminosity.

Several mechanisms to produce the residual luminosity of an accreting X-ray pulsar in quiescence are proposed by different authors:

- Residual accretion onto the neutron star surface at very low rates (e.g. Stella et al. 1994).
- Accretion down to the centrifugal barrier caused by the rotating magnetic field (Illarionov & Sunyaev 1975) with the main emission coming from the material outside or just at the magnetosphere boundary (Campana & Stella 2000).
- Thermal emission of the neutron star surface due to cooling of the core heated during phases of strong accretion (Brown et al. 1998).
- Rotational energy release via an activated radio pulsar either with a directly observed pulsar wind or X-ray emission originating in a shock front between the pulsar wind and the inflowing matter (e.g. Burderi et al. 2002, Campana et al. 2002).

From an observational point of view two groups of sources emerge: The majority of the reported results...
Table 1. Comparison of spectral fit results with previous observations of A 0538–66. While in the outbursts soft spectra or spectral components were observed, the available data in quiescence shows hard spectra without the need for any soft component. Over the years the maximum observed luminosities have decreased. The luminosities here are given for a distance of 52 kpc.

| Authors                     | Time of Observation | Luminosity [ergs/s] | Energy range |
|-----------------------------|---------------------|---------------------|--------------|
| Ponman et al. (1984)        | Dec 1980 & Feb 1981 | (2-5)×10^{38}       | 1.5–20 keV   |
|                            |                     | blackbody with $kT=2.4$ keV or Wuin law with $kT=2.4$ keV |
| Mavromatakis & Haberl (1993)| Nov 1990            | 4×10^{37}           | 0.1–2.4 keV |
|                            |                     | blackbody with $kT=0.25\pm0.04$ keV or bremsstrahlung with $kT=0.9^{+0.9}_{-0.3}$ keV or power law with $\alpha=2.6\pm0.7$ |
| Mavromatakis & Haberl (1993)| Dec 1990            | 2×10^{37}           | 0.1–2.4 keV |
|                            |                     | blackbody with $kT=0.22\pm0.02$ keV or bremsstrahlung with $kT=0.7^{+0.1}_{-0.2}$ keV or power law with $\alpha=2.9\pm0.3$ |
| Campana (1997)              | Oct 1993            | 1×10^{36}           | 0.1–2.4 keV |
|                            |                     | blackbody with $kT=0.22^{+0.07}_{-0.04}$ keV or power law with $\alpha=2.5^{+1.2}_{-0.9}$ |
| Corbet et al. (1997)        | Feb 1995            | 5×10^{36}           | 0.3–10 keV  |
|                            |                     | power law ($\alpha=2.04\pm0.15$) plus blackbody ($kT=2.69\pm0.15$ keV) and Fe line at 6.52±0.04 keV, or power law ($\alpha=2.05\pm0.15$) plus blackbody ($kT=2.69\pm0.15$ keV) and Fe lines at 6.4 and 6.7 keV, or power law ($\alpha=0.73\pm0.05$) plus bremsstrahlung ($kT=0.58\pm0.35$ keV) and Fe line at 6.52±0.04 keV |
| Campana et al. (2002)       | Sep 1999            | (1-3)×10^{35}       | 0.1–10 keV  |
|                            |                     | power law with $\alpha=2.1\pm0.6$, or bremsstrahlung with $kT=5.5^{+9.6}_{-2.3}$ keV |
| This study                 | April 2002          | (5-8)×10^{33}       | 0.3–10 keV  |
|                            |                     | power law with $\alpha=1.9\pm0.3$, or bremsstrahlung with $kT=3.9^{+3.8}_{-1.4}$ keV |
has a significant soft component, usually modeled as a blackbody spectrum, and sometimes a high energy tail, represented by a power law of photon index $\alpha \sim 1–2$ (e.g. Asai et al. [1998]). Only three neutron star systems have been observed with a quiescent spectrum dominated by hard power law: SAX J1808.4–3658 (Campana et al. [2002]), EXO 1745–248 (Wijnands et al. [2004]) and A 0538–66. It is interesting to note that two of these systems have a fast spin period: 69 ms for A 0538–66 and 2.5 ms for SAX J1808.4–3658.

Assuming that the low luminosity emission is caused by centrifugal inhibition of accretion, i.e. the so called “propeller” mechanism at work in A 0538–66, one would at first expect the spectrum to be dominated by a thermal component from a residual accretion disk up to the magnetospheric radius. Its absence is an indication that indeed a pulsar mechanism may be at work driven by the fast spinning neutron star.

REFERENCES

Alcock C., Allsman R.A., Alves D.R., et al. 2001, MNRAS, 321, 678
Asai K., Dotani T., Hoshi R., et al. 1998, PASJ, 50, 611
Brown E.F., Bildsten L., Rutledge R.E. 1998, ApJL, 504, L95
Burderi L., Di Salvo T., Stella L., et al. 2002, ApJ, 574, 930
Campana S. 1997, A&A, 320, 840
Campana S., Stella L. 2000, ApJ, 541, 849
Campana S., Stella L., Gastaldello F., et al. 2002, ApJL, 575, L15
Charles P.A., Booth L., Densham R.H., et al. 1983, MNRAS, 202, 657
Corbet R.H.D., Charles P.A., Southwell K.A., Smale A.P. 1997, ApJ, 476, 833
Illarionov A.F., Sunyaev R.A. 1975, A&A, 39, 185
Johnston M.D., Griffiths R.E., Ward M.J. 1980, Nat, 285, 26
Mavromatakis F., Haberl F. 1993, A&A, 274, 304
Pakull M., Parmar A. 1981, A&A, 102, L1
Ponman T.J., Skinner G.K., Bedford D.K. 1984, MNRAS, 207, 621
Skinner G.K. 1980, Nature, 288, 141
Skinner G.K., Shulman S., Share G., et al. 1980, ApJ, 240, 619
Skinner G.K., Bedford D.K., Elsner R.F., et al. 1982, Nature, 297, 568
Stella L., Campana S., Colpi M., Mereghetti S., Tavani M. 1994, ApJ, 423, L47
White N.E., Carpenter G.F. 1978, MNRAS, 183, 11P
Wijnands R., Heinke C., Pooley D., et al. 2004, submitted to ApJ. astro-ph/0310144