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Cygnus X-3 in the *INTEGRAL* era *

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Abstract Active throughout the entire electromagnetic spectrum, Cyg X-3 provides an excellent target for studying the multiwavelength behaviour of an accreting binary system. In this paper we present the results of the first *INTEGRAL* observations of the source in 2002 December, together with simultaneous *RXTE*/PCA-HEXTE observations and radio observations by Ryle and RATAN radio telescopes. The X-ray spectra were fitted with a thermal Comptonization model. The radio spectra from RATAN have the shape of a highly self-absorbed synchrotron spectrum with indications of a minor ejection event coinciding with the peak of an X-ray flare on the days before the *INTEGRAL* observations.

Key words: gamma rays: observations — stars: individual: Cyg X-3 — X-rays: binaries — X-rays: general — X-rays: stars

1 INTRODUCTION

The bright X-ray binary Cyg X-3 was discovered during an early rocket flight already in 1966 (Giacconi et al. 1967) but still remains poorly understood. The system is embedded in a dense wind from the donor star, presumably a massive nitrogen-rich Wolf-Rayet star with huge mass loss (van Keerkwijk et al. 1992). The galactic location and distance (eg. Predehl et al. 2000) of Cyg X-3 precludes any optical spectroscopy. Additionally the dense wind in this system makes

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using infrared or X-ray line spectroscopy to determine the mass function of the system difficult and unreliable. Despite several attempts to determine the masses (e.g. Schmutz, Geballe & Schild 1996; Stark & Saia 2003), the nature of the compact object - neutron star or black hole - remains unknown. In several aspects however, Cyg X-3 shows similar behaviour to the black hole binaries Cyg X-1 and GRS 1915+105.

2 X-RAY BEHAVIOUR

As an X-ray source, Cyg X-3 is one of the brightest in the Galaxy. It displays different states with high and low levels of emission at $\lesssim$10 keV (e.g. White & Holt 1982; Watanabe et al. 1994). The observed EF_E spectrum in the high/soft state peaks at a few keV and is highly variable, whereas in the low/hard state the peak is at $\sim$20 keV and there is less variability. The 1.5–12 keV flux is anticorrelated with the 20–100 keV flux (McCollough et al 1999) as well as with the 1.5–12 keV hardness, indicating a pivot in the spectrum somewhere between 12 and 20 keV. State transitions are frequent and Cyg X-3 spends a considerable amount of time in its high/soft state compared to eg Cyg X-1 (Zdziarski et al. 2002) but similar to what is observed for GRS 1915+105.

2.1 Broad-band X-ray spectrum

In spite of a large number of X-ray observations of Cyg X-3, the first physical modelling of its broad-band X-ray spectrum was presented in Vilhu et al. 2003, based on simultaneous *INTEGRAL* and *RXTE* observations in 2002 Dec 22–23, during *INTEGRALs* performance verification phase observations of the Cygnus region. Cyg X-3 was observed by all the X/γ-ray instruments aboard *INTEGRAL* – JEM-X (Lund et al. 2003), IBIS/ISGRI (Lebrun et al. 2003) and SPI (Vedrenne et al. 2003) as well as by *RXTE*/PCA-HEXTE, and the Ryle and RATAN radio telescopes. For details about the X/γ-ray observations and data reductions see Vilhu et al. 2003.

The resulting broad-band X-ray spectra were fitted with a model involving hybrid (thermal/nonthermal) Comptonization (Coppi 1999; Gierliński et al. 1999), Compton reflection, and complex absorption. For details about the spectral model and best-fit parameters see Vilhu et al. 2003. The results are shown in Fig. 1. We find all the studied spectra compatible with the hot plasma being completely thermal, and with $kT \ll 511$ keV. A comparison with a collection of spectra from 42 pointed RXTE observations between 1996–2000 (Szostek & Zdziarski 2004) shows that the 2002 December observations caught Cyg X-3 in one of its main spectral states, an intermediate one characterized by a medium level of $\lesssim$10 keV X-rays and a soft extended power law above $\sim$20 keV.

3 RADIO BEHAVIOUR

At the other end of the electromagnetic spectrum, Cyg X-3 is the strongest radio source ever associated with an X-ray binary, and shows huge radio outbursts and relativistic jets. Its radio behaviour varies between quiescence with flux levels $\sim$100 mJy, minor flaring with fluxes rising to a few hundred mJy and major flaring, where on timescales of days, the flux increases up to almost 20 Jy. The major flares are preceded by a quenched state when the radio emission falls below a few mJy, well below the normal quiescent level, for a period of a few days up to a few weeks (eg Waltman et al. 1994, 1995; McCollough et al. 1999; Trushkin et al. 2002). The radio activity and the production of jets seem to be closely linked with the X-ray emission and the

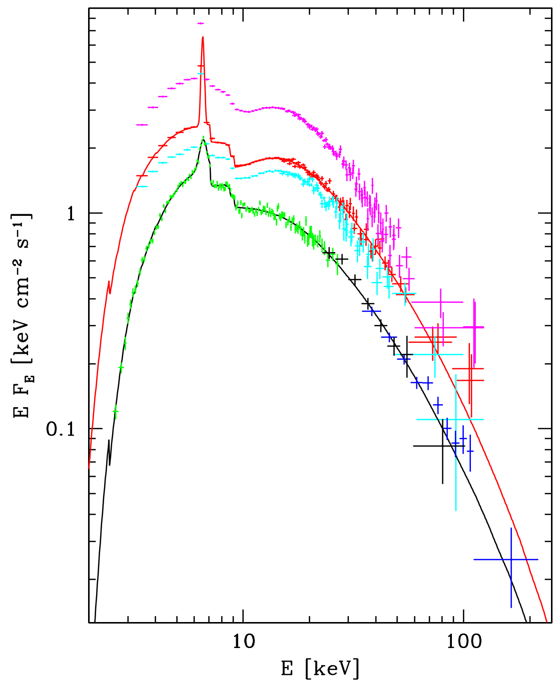


Fig. 1 Deconvolved spectra of Cyg X-3. The three top spectra correspond to the three PCA/HEXTE observations on Dec 22–23. Note that a part of the vertical extent covered by the spectra are due to the orbital modulation of the X-rays. The HEXTE spectra have been renormalized to the flux level implied by the PCA. The bottom spectrum represents the combined spectra from the JEM-X, ISGRI and SPI, respectively. For clarity the model spectrum is only shown for the middle RXTE spectrum and the *INTEGRAL* spectrum. The ISGRI and SPI spectra have been renormalized to the JEM-X data. The intensity levels of the *INTEGRAL* spectra, which were accumulated over several binary phases, should be close to the mean of the two lowest *RXTE* spectra. For a colour version of this spectral plot please see Vilhu et al. 2003.

different X-ray states (McCollough et al. 1999; Choudhury et al. 2002). It is interesting to note that all the major radio flares occur while the source is in its high/soft state (Watanabe et al. 1994). This is opposite to what is observed in most other radio active X-ray binaries where radio flares and jets are often associated with the low/hard state (eg Fender et al. 2001).

3.1 Radio Spectral Behaviour

The radio spectrum of Cygnus X-3 has been measured on several occasions, both during outbursts and quiescence (eg. Marti et al. 1992; Fender et al. 1995). The spectrum has been interpreted as that of synchrotron emission. The large radio flares are associated with major plasma injections into large-scale jets and the quiescent radio emission believed to be caused by a superposition of smaller amplitude flares, reflecting a continuous injection of relativistic electrons into the radio-emitting region.

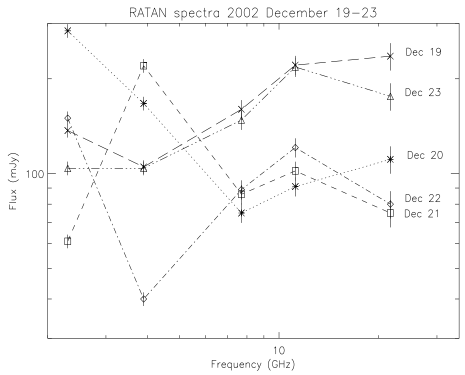


Fig. 2 RATAN spectra from 2002 Dec 19–23. The sudden transition of the spectrum between Dec 19 and 20 and back again on Dec 21 shows signs of the region becoming optically thin for a day before self absorption starts dominating the lower frequencies again.

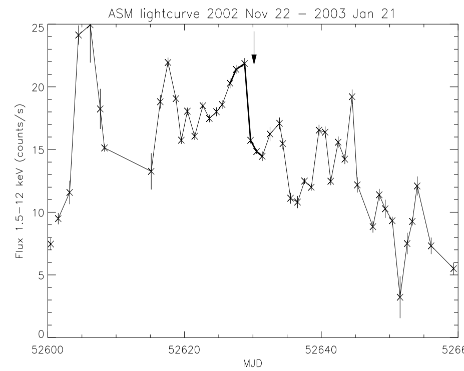


Fig. 3 The ASM lightcurve for 2002 December. The arrow shows the time of the *INTEGRAL* observations. The source is in a high state on the declining branch of an X-ray flare. The peak on Dec 20–21 (MJD 52628-29) corresponds to the transition in the radio spectrum.

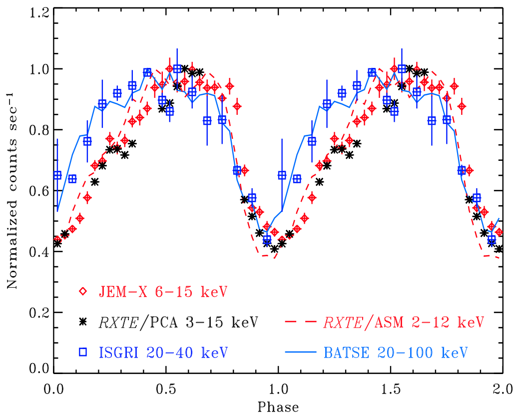
At the time of the *INTEGRAL* observations in 2002 December, Cyg X-3 was simultaneously monitored by RATAN at five radio frequencies; 2.3, 3.9, 7.7, 11.3 and 21.7 GHz as well as being observed by the Ryle telescope at 15 GHz. The 5-point spectra from daily observations between Dec 19 and 23 are plotted in Fig. 2. The spectrum of Dec 19 is inverted up to the highest observed frequency. On Dec 20 there is a sudden rise of the flux at the two lowest frequencies. On Dec 21 it has dropped drastically again at 2.3 GHz followed by a drop also at 3.9 GHz on Dec 22. During these three days, the flux at the highest frequencies becomes optically thin.

A study of the soft X-ray behaviour on the dates of the transition in the radio spectrum shows that it coincides with a small soft X-ray flare (see Fig. 3). This is consistent with the idea that the correlation between soft X-rays and radio is caused by the continuous ejection of matter from the system into the jets giving rise to minor flares in both energy bands.

4 ORBITAL MODULATION

One of the most striking features in the lightcurve of Cyg X-3 is a 4.8-hr quasi-sinusoidal modulation, present both in X-rays and infrared (eg. Mason et al. 1986). The modulation is believed to reflect the orbital motion of the binary with the emission from the X-ray source being scattered by the wind from the companion. Althought the depth of the modulation at different X-ray energies is almost exactly the same, the shape differs slightly between different X-ray bands. In Fig. 4, left panel, the lightcurves from the December observations are plotted folded on the orbital period (using the ephemeris of Singh et al. 2002), together with the *RXTE*/ASM (2–12 keV) and *CGRO*/BATSE (20–100 keV) 'templates' from monitoring of the source during 1996–2002 and 1991–2000 respectively.

In spite of several early claims of detection of a period in radio close to the X-ray period (eg. Molnar et al. 1984), no such modulation has been confirmed in later years. The Ryle lightcurve at 15 GHz from simultaneous observations on December 22–23 plotted in Fig. 4, right panel shows no modulation. The fact that the radio emission is not modulated could indicate that



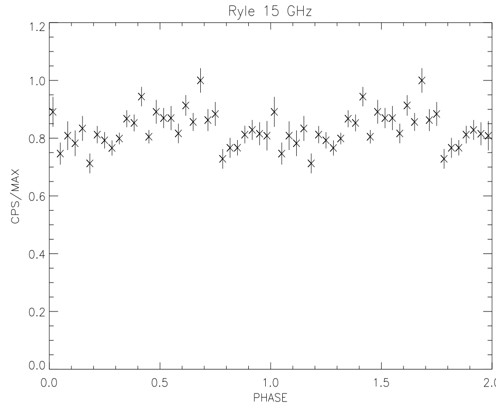


Fig. 4 *left*: The JEM-X 6–15 keV (diamonds) and ISGRI 20–40 keV (squares) lightcurves folded over the orbital period. We also show the *RXTE*/PCA 3–15 keV data (asterisks) from simultaneous observations as well as the *RXTE*/ASM 1.5–12 keV (dashed curve) and *CGRO*/BATSE 20–100 keV (curve) phase dependences averaged over several years of monitoring. The count rates are normalized to the respective maxima. *right*: The Ryle 15 GHz lightcurve December 21–24 folded using the same ephemeris shows no modulation.

either the radio emission is not affected by scattering in the wind, or that the bulk of the radio emission comes from ejecta moving away from the system and already outside the dense wind region.

5 CONCLUSIONS

Cyg X-3 was observed simultaneously with *INTEGRAL*, *RXTE*, RATAN and the Ryle telescope on 2002 December 22–23. The resulting broad-band X-ray spectra were fitted with a thermal Comptonization model showing the source in an intermediate spectral state, represented by a medium level of $\lesssim$10 keV X-rays and a soft extended power law above $\sim$20 keV. The ASM lightcurve shows that the source was caught in the declining phase of a soft X-ray flare with maximum the day before the *INTEGRAL* observations. The peak of this flare coincided with a rapid transition in the radio spectrum, indicating a minor ejection of matter from the system into the jets.

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