Quenched millimetre emission from Cygnus X-1 in a soft X-ray state

S.P. Tigelaar, R. P. Fender, R.P.J. Tilanus, E. Gallo, G.G. Pooley

Abstract

We present millimetre wavelength observations of the black hole candidate X-ray binary Cygnus X-1 which indicate a suppression, or quenching, of the emission as the source switches to a softer X-ray state. Combining the data with those for another black hole candidate, XTE J1118+480, we demonstrate that the millimetre emission shows the same coupling to X-rays as the radio emission, although with a much stronger sensitivity to spectral shape. We therefore confirm the association of the millimetre emission with the jets in low/hard state black hole candidate X-ray binaries.

Key words:

1 INTRODUCTION

In recent years a clear connection between the radio and X-ray emission from galactic black hole and neutron star X-ray binaries has been observed (e.g. Harmon et al. 1995, 1997; Fender et al. 1999; Mirabel & Rodríguez 1999; Klein-Wolt et al. 2002; Corbel et al. 2003; Gallo, Fender & Pooley 2003; Fender 2001, 2004). This connection is interpreted as reflecting the coupled processes of accretion and ejection in these systems, and analogous behaviour may be observed from supermassive black holes in active galactic nuclei on longer timescales (Marscher et al. 2002; Merloni, Heinz & di Matteo 2003; Falcke, Körödi & Markoff 2003; Maccarone, Gallo & Fender 2003), highlighting the importance of such studies.

Specifically, in the ‘low/hard’ X-ray state, characterised by an X-ray spectrum peaking at $\sim 100$ keV, little accretion disc emission and strong variability (e.g. McClintock & Remillard 2004), there seems to be always a steady radio jet (Fender 2001). This jet is characterised by a ‘flat’ or ‘inverted’ ($\alpha \sim 0$ or $\alpha > 0$ respectively, where the spectral index $\alpha = \Delta \log S_\nu / \Delta \log \nu$, i.e. $S_\nu \propto \nu^\alpha$) radio spectrum, and the (GHz) radio luminosity seems to be correlated with the X-ray luminosity as $L_{\text{radio}} \propto L_X$ where $b \sim 0.7$ (Corbel et al. 2003; Gallo, Fender & Pooley 2003).

The radio spectrum is further observed to extend smoothly through the millimetre bands to the near infrared based upon which it has been suggested that the emission in these bands can also be dominated by synchrotron emission from jets in the low/hard state. (Fender 2001, 2004; Fender et al. 2001; Corbel & Fender 2003; Chaty et al. 2003) When sources transit to disc-dominated ‘high/soft’ or ‘intermediate’ states at higher bolometric luminosities (Homan et al. 2001; McClintock & Remillard 2004) the radio emission is strongly suppressed or ‘quenched’ (Tanabam et al. 1972; Fender et al. 1999; Corbel et al. 2001; Gallo, Fender & Pooley 2003).

The millimetre properties of X-ray binaries have been well studied only for the brightest of sources (e.g. Baars et al. 1986; Paredes et al. 2000). These sources tend to be semi-continuously flaring and the association of the millimetre emission with the X-ray state is hard to determine, although millimetre oscillations are clearly associated with rapid quasi-periodic accretion rate changes in GRS 1915+105 (Fender & Pooley 2000). Fender et al. (2000) showed that the radio spectrum of Cygnus X-1 extended smoothly with a very flat spectrum ($|\alpha| \leq 0.15 (3\sigma)$) into the mm band. Fender et al. (2001) presented observations of the transient BHC XTE J1118+480 in which a rather steeply inverted radio spectrum ($\alpha \sim +0.5$) connected smoothly to detections in the mm band. Furthermore, once this source had faded the mm emission had also clearly declined, strengthening the inferred connection with the jet component. This behaviour was consistent with the correlated radio/X-ray behaviour observed in this state. In this paper we report the first evidence for the quenching of millimetre emission from a black hole binary, Cygnus X-1, when it enters a softer X-ray state.

2 OBSERVATIONS AND RESULTS

The analysis in this paper uses published millimetre fluxes for Cygnus X-1 (Fender et al. 2000) and XTE J1118+480 (Fender et al. 2001), plus a new observation. This was performed on 2002 April 27 16:00–18:00 UT (MJD 52391) with SCUBA (Holland et al. 1999) on the JCMT, operating at 350 GHz, and failed to detect Cygnus X-1 with a $3\sigma$ upper limit of 7.5 mJy. Note that although...
the observations of Cyg X-1 range from 89 – 350 GHz we compare them as if the spectrum was perfectly flat ($\alpha = 0$), based upon Fender et al. (2000). This means that for MJD 50964 we have averaged the 146 and 221 GHz measurements. While the radio–millimetre spectrum of XTE J1118+480 (Fender et al. 2001 and see below) indicates that assuming a flat spectrum is not always appropriate, we believe that for the study undertaken here it is a reasonable enough approximation.

We compare our millimetre measurements with contemporaneous X-ray and radio monitoring of Cygnus X-1. For X-rays we have used the publicly available RossiXTE all-sky-monitor (RXTE ASM; Levine et al. 1996) data for Cygnus X-1. These data measure the flux from the source in the interval 1.5–12 keV. For all of the epochs except MJD 50945 we have used the average of the individual RXTE ASM dwell measurements over an interval of ±0.25 days from the time of the millimetre observation. Around MJD 50945 the RXTE ASM sampling is very sparse and we have used the average count rate over five days centred on our millimetre observation. Inspection of the radio and X-ray light curves on longer timescales around the times of our mm observations gives us no reason to doubt that our interpretation of the state behaviour as presented here is correct. For the radio monitoring we have used 15 GHz radio flux densities obtained at the Ryle Telescope. More information on the radio monitoring of X-ray binaries with the Ryle Telescope may be found in Pooley & Fender (1997); the quenching of the radio emission in soft X-ray states is presented in Gallo, Fender & Pooley (2003). The measurements in all three bands are summarised in Table 1.

In Fig 1 we plot the millimetre, radio and X-ray hardness ratio HR1 as a function of X-ray count rate. The HR1 is also from the Rossi XTE monitoring data and is the ratio of counts in the energy range 3–5 keV to that in the range 1.5–3 keV. In the ‘low/hard’ state the mm and X-ray points are clearly correlated, although the errors are large. Quantitatively, excluding the measurement in the softer state (see below) the best power-law fit to the millimetre-X-ray correlation is of the form $F_{\text{mm}} = (0.2 \pm 0.2) F_X^{2.1 \pm 0.3}$, steeper at the $\sim 2\sigma$ level than the $L_{\text{radio}} \propto L_X^{0.7}$ found for the low/hard state (Gallo et al. 2003). Above 30–35 RXTE ASM ct/sec the source transits from the ‘low/hard’ to a softer ‘intermediate’ X-ray state (Belloni et al. 1996; Miller et al. 2002), clearly revealed by a drop in HR1. The well-established suppression (‘quenching’) of the radio emission in the softer X-ray state is evident, and the same effect appears to be apparent for the mm emission. The ‘quenched’ millimetre point lies $\geq 10\sigma$ below the best-fit relation for the ‘low/hard’ state given above. As a caveat we note that variability of synchrotron emission from X-ray binaries does tend to increase in amplitude at higher frequencies, and we may just have been observing a dip in the flux unrelated to the X-ray state of the source. However, given that the behaviour fits the pattern observed for the radio emission, we consider this to be unlikely. Note furthermore that the ‘quenched’ millimetre measurement is at the highest frequency (350 GHz) which were the spectrum inverted as in XTE J1118+480 (see below), at the time of our observations, this only strengthens the quenching effect. We conclude that these data reveal for the first time the suppression of the mm flux in soft X-ray states and links, as expected, the mm emission with the jet responsible for the radio emission.

Figure 1. (Sub-)millimetre (top) and radio (middle) flux densities and X-ray ‘hardness’ as a function of X-ray flux for Cyg X-1. At the highest X-ray luminosity, the source has made a transition to a softer X-ray state, and the mm and radio emission are ‘quenched’. This is the first demonstration of suppression of the mm flux in soft X-ray states and links, as expected, the mm emission with the jet responsible for the radio emission.

### Table 1. Millimetre and X-ray observations of Cygnus X-1.

Apart from the most recent, details of the millimetre observations can be found in Fender et al. (2000). The millimetre observations were obtained at a variety of frequencies with the JCMT; the radio data were all obtained at 15 GHz with the Ryle Telescope, and the X-ray fluxes are in 1.5–12 keV count rates obtained with the Rossi XTE all-sky-monitor. These data, plus X-ray hardness ratios, are plotted in Fig 1.

| MJD   | $\nu_{\text{mm}}$ (GHz) | $S_{\text{mm}}$ (mJy) | $S_{\text{cm}}$ (mJy) | $F_X$ (ct/s) |
|-------|------------------------|-----------------------|-----------------------|-------------|
| 50644 | 89                     | 15.9±4.9              | 10.9±2.5              | 32±2        |
| 50945 | 146                    | 9.2±3.5               | 6.3±2.5               | 20±3        |
| 50950 | 146                    | 5.8±3.2               | 12.0±2.5              | 16±1        |
| 50960 | 221                    | 11.6±2.1              | 11.5±2.5              | 23±2        |
| 50964 | 146/221                | 14.4±3.6              | 12.7±2.5              | 25±2        |
| 52391 | 350                    | 0.7±2.5               | 0.5±2.5               | 69±2        |

3 DISCUSSION

Cyg X-1 was already known to have a ‘very flat’ ($|\alpha| < 0.15$ ($3\sigma$)) spectrum from the radio (2 GHz) through mm (350 GHz) bands while in the low/hard X-ray state (Fender et al. 2000). This was naturally interpreted as a high-frequency extension of the self-absorbed synchrotron spectrum from a steady jet of the kind envis-
was very steep (spectral index \( \alpha \sim +0.5 \)), then we expect the mm flux densities to lie about one order of magnitude above the GHz radio data, as they do. Cyg X-1, with a flat spectrum, needs no correction, as is also evident from the plot, which also indicates that, just as in the radio band, the coupling in Cyg X-1 may be rather steeper and sharper than in other sources.

In softer states, the mm emission is quenched

In the low/hard state, the mm emission correlates with the X-ray flux

– this behaviour is exactly as observed for the relation between radio and X-ray emission.

We therefore conclude that the mm emission arises from the same physical component as the radio emission, most likely to be a jet-like outflow. At such high frequencies we are probing ~ 100 times closer to the base of the jet than in the radio band. The next step will be to see if infrared emission, probing another 100-1000 times closer, shows the same coupling to X-ray states. In this direction we suggest that the 10\( \mu \)m band, where new detectors are now available, and the thermal emission from companion stars and accretion discs should generally be weak.

ACKNOWLEDGEMENTS

We acknowledge with thanks the use of the quick-look X-ray data provided by the ASM/RXTE team. We thank the staff at MRAO for maintenance and operation of the Ryle Telescope, which is supported by the PPARC. The James Clerk Maxwell Telescope is operated by The Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

REFERENCES

Baars J.W.M., Altenhoff W.J., Hein H., Steppe H., 1986, Nat, 324, 39
Belloni T., Mendez M., van der Klis M., Hasinger G., Lewin W.H.G., van Paradijs J., 1996, ApJ, 472, L107
Blandford R., Konigl A., 1979, ApJ, 232, 34
Chaty S., Haswell C.A., Malzac J., Hynes R.I., Shrader C.R., Cui W., 2003, MNRAS, 346, 689
Corbel S., Fender R.P., 2002, ApJ, 573, L35
Corbel S. et al., 2001, ApJ, 554, 43

Figure 2. Millimetre flux density as a function of X-ray flux (at 1 kpc and absorption corrected), superimposed on the radio-X-ray plane from Gallo, Fender & Pooley (2003). Considering that in XTE J1118+480, the spectrum was very steep (spectral index \( \alpha \sim +0.5 \)), then we expect the mm flux densities to lie about one order of magnitude above the GHz radio data, as they do. Cyg X-1, with a flat spectrum, needs no correction, as is also evident from the plot, which also indicates that, just as in the radio band, the coupling in Cyg X-1 may be rather steeper and sharper than in other sources.
