Abstract. Multifrequency VLA and OVRO observations of the radio outburst of Cygnus X-3 in September 2001 are presented, illustrating the evolution of the spectrum of the source over a period of six days. An estimate of the magnetic field in the emitting region is made from the spectral turnover and possible explanations for the spectral evolution are suggested.

1. Introduction

Cygnus X-3 is an X-ray binary system located in the Galactic plane at a distance of ≈10 kpc (e.g. [1], [2]) in or behind one of the spiral arms. There is ongoing debate as to the nature of the compact object (e.g. [3],[4]). The large interstellar extinction to the source precludes any optical spectroscopy, making it difficult to obtain a reliable mass function and hindering identification of the companion star. Analysis of infrared spectra [5] suggests that the companion is a WN7 Wolf-Rayet star, although more recent observations [6] indicate a WN8 subclass. The orbital period, as confirmed in X-ray and infrared flux modulations, is 4.8 hours (e.g. [7]). The source occasionally undergoes huge radio outbursts where the flux density increases to a level of up to 20 Jy. Two-sided jets have been seen on arcsecond scales in a N-S orientation [8], whereas a highly-relativistic ($\beta \geq 0.81$) one-sided jet with the same orientation has been reported on milliarcsecond scales with the VLBA [9].

2. Observations of spectral evolution

Cygnus X-3 went into flare during September 2001, with the RATAN monitoring programme detecting the start of the outburst on 14th September [10]. Brief 2-3 minute VLA snapshot observations were made every day between 18th and 24th September, and then every few days until the end of October. The VLA was in its most compact “D” configuration, meaning that the source was unresolved, yet that none of the emission was resolved out. Data were taken at seven different frequencies between 74 MHz and 43 GHz. Between the 20th and 26th September, data were also taken at 100 GHz at OVRO, extending the frequency coverage to span three decades in frequency. In addition, six longer observations were made with the VLBA between the 18th and the 23rd September, and appear as before to show a one-sided jet [11].
The high-frequency spectral indices taken in the first week of observations are shown in Figure 2. The spectra display the power-law form characteristic of synchrotron emission at high frequencies, together with a low-frequency cutoff, which moves to lower frequencies as time progresses.

After the outburst the source flux decreases, and the spectral index of the power law increases from $\alpha = 0.3$ on the 18th to a terminal value of $\alpha = 0.6$ (implying an electron index of $p = 2.2$) by the 21st September, after which $\alpha$ remains approximately constant. This is shown in Figure 2. Such behaviour (the increase during the outburst of the spectral index to a terminal value) was observed in the outburst of 1972 ([12], [13], [14], [15]). Various explanations were invoked, including synchrotron losses [17], repeated sporadic electron injection [13, 14], and bremsstrahlung losses [12]. It has also been seen in later outbursts (e.g. [16], [10]).

![Figure 1. Spectra of Cygnus X-3 during the first week of observations following the flare of September 2001](image-url)
Figure 2. Evolution of the spectral index of Cygnus X-3 during the flare of September 2001

varied with each injection event in a contrived manner, the same difficulties arise as for the superposition model.

One possibility is that bremsstrahlung emission from the synchrotron-emitting population is causing Coulomb cooling of the electrons. Since the power emitted in bremsstrahlung radiation scales as $\rho^2$, where $\rho$ is the ionised plasma density, then as the source expands, $\rho$ decreases and the effect becomes less significant. This could also in principle explain the cessation of the steepening of the spectral index. The energy loss rate by bremsstrahlung emission for ultra-relativistic electrons in a fully ionised plasma is proportional to the electron energy. This would ensure that the highest-energy electrons lost energy fastest, leading to a steepening of the spectral index as required. A similar scenario was first put forward by [12], who also invoked neighbouring thermal plasma to generate the bremsstrahlung emission. While this is plausible, given the strong stellar wind of the Wolf-Rayet companion, electron motion between mirror points in an extended stellar atmosphere is additionally required in their model.

We are currently exploring other physical models which replicate the details of Cygnus X-3’s behaviour in intensity and spectral evolution over the appropriate timescales.

3. Source parameters

As time passes, the low-frequency turnover gradually moves to lower frequencies. Assuming that this is due to synchrotron self-absorption, and fitting the data with a steep and an inverted power-law, the turnover frequency may be found, given the flux density at this frequency. From [24], these parameters, together with a source size, may be used to place an upper limit on the magnetic field in the plasmon.

$$B = 10^{-5} b(\alpha) \theta_d^{4} \nu_m^5 F_m^{-2} \delta_{\max} G$$

where $\theta_d$ is the angular diameter of the source in mas, $\nu_m$ is the turnover frequency in GHz, and $F_m$ is the source flux density (in Jy) at the turnover frequency. $b(\alpha)$
is a dimensionless function tabulated in [24], \( \delta_{\text{max}} \) is a beaming parameter, taken as 2 [25], and the angular size is assumed to be 1 mas [9]. With the fitted turnover frequencies and flux densities, the turnover was found to be at 2.4 GHz on the 18th and at 0.74 GHz on the 23rd, giving a magnetic field of 12 \( \mu \)G on the 18th and 5 \( \mu \)G on the 23rd. Assuming flux conservation holds, \( B \propto r^{-2} \), which implies expansion of the plasmon by a factor 1.6 over the 5 days. As a consistency check on the magnetic field, it is possible to use the ratios of the flux densities and the frequencies of the self-absorption turnovers on the two days to derive an expansion factor \( F \). 

\[
\Delta(\log \nu) = 2 \log F \tag{2}
\]

\[
\Delta(\log S_\nu) = 4 \log F \tag{3}
\]

This method gives an expansion factor \( F \) of 1.3 and 1.9 respectively for the frequency and flux estimates. This is remarkably consistent with that derived from the magnetic field and inspires confidence in the field derivation, since the methods are wholly independent.

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