The Continuous Jets of Cygnus X-1

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October 15, 2000

Abstract. A resolved jet-like radio-emitting structure on mas scales has been found in Cygnus X-1. The jet emission is relatively smooth, and does not show the knots and blobs seen in Cygnus X-3, SS433 and GRS1915+105. This suggests that the jet production mechanism in Cyg X-1 is continuous, with the steady production of the energetic electrons and magnetic field required for the production of the radio emission. This is unlike the episodic jets seen in the other sources. The implications of these results for jet formation mechanisms will be discussed.

Keywords: X-ray binary stars, jets, Cygnus X-1.

1. Introduction

Cygnus X-1 (V1357 Cygni) was one of the earliest stars to be detected in the radio band (Braes and Miley 1971; Hjellming and Wade 1971). Its radio flux density has occasionally reached levels of 50 mJy in the 1970's, however it is mostly at the 12–15 mJy level with a flat ($\alpha = 0$) spectrum to mm wave frequencies (Fender et al. 2000a). The source also has long periods in the low/hard state (Brocksopp et al. 1999), with transitions to the soft state being associated with changes in the radio emission. It is one of the best candidates for a black hole compact companion. However its radio structure has remained a mystery until recent VLBI observations.

About a dozen of the radio emitting X-ray binary stars have been found to possess radio jets. Some sources show superluminal motion (e.g. GRS 1915+105; Fender et al. 1999), others have lower but still relativistic velocities (e.g. SS433, Paragi et al. this conference). They typically have very 'blobby' structures where the ejection of knots of emission can in some cases be related to changes in X-ray state (see review by Mirabel and Rodriguez, 1999). The flat spectrum and steady radio emission in the low/hard state of Cyg X-1 suggests that its radio properties may be somewhat different from these sporadic and transient sources.

Cyg X-1 is used as part of the astrometric reference frame, and the hint of resolution effects in trans-Atlantic VLBI measurements by Lestrade (priv. comm.) led us to propose VLBA observations on this source.

2. VLBA Observations

Initial observations were undertaken in March 1997 at 15 GHz. These showed the presence of a jet-like structure on the $\sim$ 1 mas scale (Stirling et al. 1998). More comprehensive follow-up observations were made in August 1998, over three epochs (10, 12 and 14 August) and at two frequencies (8.4 and 15 GHz). The results found previously at 15 GHz were confirmed, though the possible existence of emission in a direction perpendicular to the jet , again on the 1 mas scale, cannot be ruled out.

The 8.4 GHz observations however show a clear one-sided jet $\sim$ 15 mas (30 au if at 2 kpc) at position angle ~ -20 degrees present at each epoch. The emission along the jet varies smoothly, and is unlike the blobby jets seen in GRS1915+105 and SS433 (Stirling et al. 2000). However it should be noted that a compact jets exist in GRS 1915+105 when in the 'plateau' state (Dhawan et al. 2000). The properties of steady jets produced by both persistent and transient sources in the low/hard state are discussed in Fender (2000b).

A kink in the jet (see image presented by de la Force et al., this conference) stays consistent between the epochs, indicating a slow ($<$ 3000 km s^{-1}) jet, a backward moving shock feature or precession with non-ballistic flow. The smooth emission suggests a continuous jet, as described by the models of Blandford and Königl (1979) and where the fading of brightness down the jet is caused by adiabatic expansion rather than energy losses of the radiating electrons.

3. Jet Energetics

The brightness ratio of the jet to the counter-jet region in the map exceeds 64 to 1. If we interpret this as being due to Doppler boosting of a relativistic jet then $\beta \times cos(\theta) = 0.6$ for a spectral index of 0. The inclination angle for the binary has been proposed to be at 37 degrees, so if the jet is at the same angle then $\beta = 0.78, \gamma = 1.59$, and $\beta_{app} = 1.25$. We would therefore expect to see an apparent motion of 110 mas/day of the components in the jet.

Assuming synchrotron radiation, a cylindrical jet, unity filling factor, and ignoring the contribution from protons, we find a minimum energy of 10^{39} ergs. If the time to form the jet is equal to the time for material to travel down the length of jet then the power in the 15 mas jet is $\sim 3 \times 10^{34}$ ergs/sec. This is rather less than the minimum power required for discrete blob ejection in GRS1915+105 (10^{39} ergs/sec). However if the flat spectrum extends to infra-red frequencies the power increases to 10^{37} ergs/sec for the whole jet, which is comparable to the bolometric X-ray luminosity in this state.

The power required for continuous jets in persistent sources may be much less than that for sporadic jets in transient sources. We might therefore expect less dramatic physical changes in persistent sources as a result, consistent with long periods in the low/hard state.

The inner core of the jet (as shown in the 15 GHz images) is $\sim 1\times < 0.5$ mas^2 in size, or 2 au in length. The equipartition magnetic field B is then $\sim$ 300 mG, resulting in an electron lifetime, $t_{yr} = \frac{1}{(B^3 \nu_{GHz})^{0.5}}$, of 1.6 years at 15 GHz and 22 days at IR. These are very much greater than the travel times down the jet if the bulk motion is relativistic and show that the losses down the jet are primarily adiabatic. The typical energy of the electrons radiating at 15 GHz in this field is 100 Mev.

The expected magnetic field at the inner disk ($\sim 6r_g$) is 2×10^{11} G if $B \propto r^{-2}$ or 3×10^5 G if $B \propto r^{-1}$ as in the Hjellming and Johnston (1988) models. The jet power for the core region can be estimated from $L_j > \pi r^2 \Gamma^2 \beta c U_{min}$ where U_{min} is the minimum energy density. Ignoring the protons again gives 9×10^{34} ergs/sec for the inner jet, comparable with the figure found above for the jet as a whole.

Several mechanisms for the production of steady jets have been proposed. Ones which may be relevant here are the Blandford and Payne (1982) (BP) method which uses the twisting of magnetic fields generated in a disk to accelerate a jet, and the Blandford and Znajek (1977) (BZ) mechanism where the energy is extracted from a rotating black hole.

Expressions for the jet luminosity (in ergs/sec) in the two cases are:

$$BR : L = 1.6 \times 10^{38} (\frac{r_0}{r_g})^{3/2} B_8^2$$

$$BZ : L = 1.0 \times 10^{35} (\frac{J}{J_{max}})^2 (\frac{M}{M_\odot})^2 B_8^2$$

where r_0 is the inner radius of the disk, J the angular momentum of the black hole ($= J_{max}$ for a maximally rotating black hole) and B_8 the magnetic field at the inner disk radius in units of 10^8 G. For the given jet power and a maximally rotating 10 $M_\odot$ black hole we get $B = 6 \times 10^5$ G for BP and 3×10^7 G for BZ, both within range of expected fields derived earlier for the base of the jet. Other mechanisms may be important (e.g. Meier this conference) especially if an unstable state is reached with sporadic jets produced when the system changes to high/soft state.

4. Conclusions

We have found an apparently one-sided jet $\sim$ 30 au long in Cygnus X-1. The appearance is consistent with a Doppler boosted twin jet at 0.78c at around 40 degrees to the line of sight. A large proper motion $\gg$ beam size during the few hours of the observing runs is expected for such a velocity, so the jet image must be smeared. Multiple short snapshot observations are required to see if features do in fact move through the jet at the expected high proper motion. However these images will have lower signal to noise and have poorer mapping fidelity.

Standard jet production mechanisms for steady jets can produce the power required for a relativistic jet.

We note that the kink in the jet stays at a constant position; if this indeed indicates lack of motion along the jet then the jet is slow and must be intrinsically one-sided, and all the calculations above would have to be revised. Further observations are required to verify this feature.

It would be interesting to find the status of the jet when the source flares in the radio and in the transition to the high/soft X-ray state. Comparison with other episodic jet sources suggests that the jet should appear blobby and have a steep spectrum during this phase.

5. References

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