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The proper motion and changing jet morphology of Cygnus X-3

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We present analysis of 25 years' worth of archival VLA, VLBA and EVN observations of the X-ray binary Cygnus X-3. From this, we deduce the source proper motion, allowing us to predict the location of the central binary system at any given time. However, the line of sight is too scatter-broadened for us to measure a parallactic distance to the source. The measured proper motion allows us to constrain the three-dimensional space velocity of the system, implying a minimum peculiar velocity of 9 km s^{-1}. Reinterpreting VLBI images from the literature using accurate core positions shows the jet orientation to vary with time, implying that the jets are oriented close to the line of sight and are likely to be precessing.

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1. Introduction

Cygnus X-3 is a high-mass X-ray binary system with a compact object accreting matter from a Wolf-Rayet donor star. The nature of the compact object is still under debate. The system is a persistent radio source, with a typical flux density of 80–100 mJy at GHz frequencies. Occasionally, it undergoes giant outbursts, in which the radio flux density initially quenches to a level of a few mJy before increasing by two to three orders of magnitude to peak at a level of several Jy. During such outbursts, VLBI observations have revealed the presence of moving, relativistic jets ([1, 2, 3]), predominantly aligned around a position angle 180° E of N. Hitherto however, analysis of the jet morphology has always been hindered by uncertainty in identifying the location of the central binary system; since VLBI observations were typically triggered on detection of a radio flare, the jets were already resolved by the time of the observations, often rendering an accurate identification of the core position difficult or impossible from the images alone.

2. Astrometric observations

To resolve the uncertainty in identifying the core position, we interrogated the NRAO archives for VLA and VLBA observations taken during core-dominated epochs (i.e. outside major flaring episodes), when the pointlike morphology of the source allowed us to accurately identify the core position. The VLA observations spanned the period 1983–2006, and we selected only data at frequencies of 8.4 GHz or higher, in the A-configuration of the array, to maximize the angular resolution. The VLBA observations were taken between 1997 and 2005. We also considered EVN data taken by our group, using the e-VLBI technique, between 2006 April and 2008 April, some of which has already been published [3]. Data were reduced according to standard procedures in AIPS, with imaging and self-calibration being performed using both AIPS and Difmap.

Standard linear regression performed on the full dataset (see Fig. 1) then gives proper motions in Right Ascension and Declination of

$$\mu_\alpha \cos\delta = -2.73 \pm 0.06 \text{ mas y}^{-1} \tag{2.1}$$

$$\mu_\delta = -3.70 \pm 0.06 \text{ mas y}^{-1}, \tag{2.2}$$

and a reference position on 2000 Jan 01 (MJD 51544.0) of $20^{\rm h}32^{\rm m}25^{\rm s}.7731(11)$, $+40^{\rm d}57'27''.951(12)$ (J2000). Owing to the strong scattering along the line of sight to Cygnus X-3, it was not possible to determine the source positions sufficiently accurately to measure a parallactic distance to the source; the expected signal for a distance of 9–10 kpc [4, 5] is of order 0.1 mas.

2.1 Peculiar velocity

Together with a line-of-sight systemic radial velocity and the distance to the source, the proper motion can be used to derive the full three-dimensional space velocity of the system [6]. However, the radial velocity of Cygnus X-3 is very poorly constrained, owing to the powerful stellar wind from the Wolf-Rayet donor star. The high visual extinction along the line of sight forces us to rely on infrared lines to measure the systemic velocity. The P Cygni line profiles from the outflowing wind, turbulence in the wind, and uncertainty as to where in the system the observed

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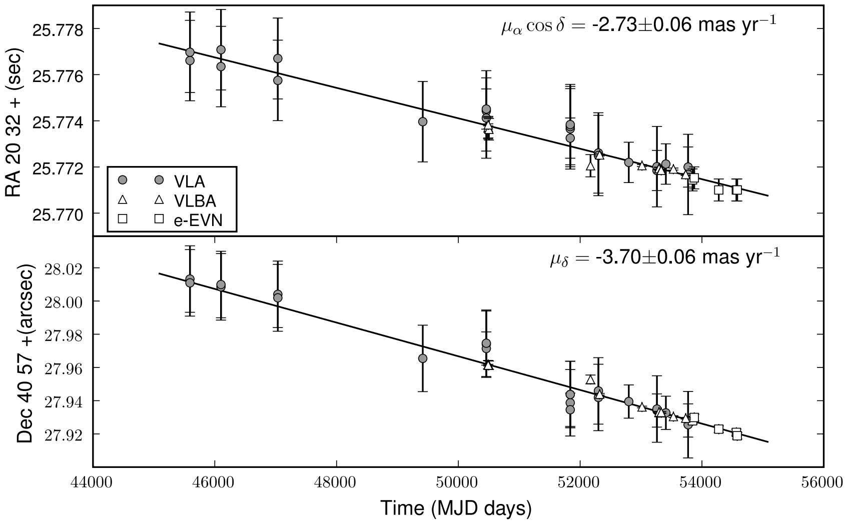

Figure 1: Variation in core position of Cygnus X-3 with time, in both RA (top panel) and Dec (bottom panel). The best-fitting proper motions are shown by the solid lines.

infrared lines arise, all hinder the determination of an accurate systemic radial velocity. [7] constrain its magnitude to $< 200\,\mathrm{km\,s^{-1}}$. For a given three-dimensional space velocity, we can derive the peculiar velocity of the source; the discrepancy from what would be expected assuming the source participates in the standard Galactic rotation. Computing the peculiar velocity for the full range of permitted systemic radial velocities (assuming a Galactocentric distance of 8.4 kpc and a Galactic rotational velocity of $254\,\mathrm{km\,s^{-1}}$ [8]) gives a minimum peculiar velocity of $9\,\mathrm{km\,s^{-1}}$ for a systemic radial velocity of $-47\,\mathrm{km\,s^{-1}}$. For a $200\,\mathrm{km\,s^{-1}}$ systemic radial velocity however, the peculiar velocity would be $250\,\mathrm{km\,s^{-1}}$.

The Wolf-Rayet nature of the donor star in Cygnus X-3 implies that the system is young (typical Wolf-Rayet lifetimes are of order a few Myr). It has therefore not had time to acquire a significant peculiar velocity through assorted gravitational interactions during its Galactocentric orbit, so the likelihood is therefore that any non-zero peculiar velocity arises from a natal kick during the supernova in which the compact object was formed. However, with such an uncertain systemic radial velocity, our limit on the peculiar velocity is not terribly constraining.

For such a young system, there is a chance of tracing the Galactocentric orbit of the system backwards in time to find the birthplace of the binary. However, owing to the large distance to the source and its location behind one of the Galactic spiral arms, it was not possible to identify a star cluster or supernova remnant from which Cygnus X-3 might have originated.

2.2 Implications for the jet morphology

With the fitted proper motion of the system, we can identify the position of the X-ray binary core at any given epoch. This allows us to more accurately interpret the observed jet morphology during outbursts of the source. We find that the jets were one-sided, and flowing to the south during the 1997 February outburst, in agreement with previous work [1]. During the 2001 September outburst [2], they were two-sided and oriented north-south, but brighter to the south, presumably owing to Doppler boosting of the approaching jet. However, during the 2006 May outburst, we find that the jets were one-sided and flowing to the north. In contrast with the previous interpretation [3], we are now able to identify "knot C" in their work as the true core.

The varying position angle of the jets supports the hypothesis that the jets are precessing [1], although the sampling is at present too sparse to place useful constraints on the precession period. However, the dramatic position angle changes imply that the jets are aligned very close to the line of sight, making Cygnus X-3 a good example of a Galactic microblazar.

3. Conclusions

We have measured the proper motion of Cygnus X-3 to be $4.60 \pm 0.09\,\mathrm{mas\,yr^{-1}}$. From the proper motion and source distance, we derive a minimum peculiar velocity of $9\,\mathrm{km\,s^{-1}}$, so we cannot significantly constrain the size of any natal kick received by the system when the compact object was formed. The ability to locate the central binary system at any given epoch allows us to re-interpret archival VLBI images, showing that the position angle of the jets can change by 180° with time, supporting previous evidence for jet precession and suggesting that the jets are oriented very close to our line of sight.

Acknowledgments

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