









# Relativistic precessing jets powered by an accreting neutron star

F. J. Cowie<sup>1</sup>   R. P. Fender<sup>1,2</sup> I. Heywood<sup>1,3</sup> A. K. Hughes<sup>1</sup>  K. Savard<sup>1</sup>  P. A. Woudt<sup>2</sup>  
 F. Carotenuto<sup>4</sup>  A. J. Cooper<sup>1</sup>  J. van den Eijnden<sup>5</sup>  K. V. S. Gasealahwe<sup>2,6</sup> S. E. Motta<sup>1,7</sup>  and  
 P. Saikia<sup>8</sup>

<sup>1</sup>*Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*

<sup>2</sup>*Department of Astronomy, University of Cape Town, Private Bag X3, 7701 Rondebosch, South Africa*

<sup>3</sup>*Centre for Radio Astronomy Techniques and Technologies, Department of Physics and Electronics, Rhodes University, PO Box 94, Makhanda 6140, South Africa*

<sup>4</sup>*INAF, Osservatorio Astronomico di Roma, Via Frascati 33, I-00078 Monte Porzio Catone, Italy*

<sup>5</sup>*Anton Pannekoek Institute for Astronomy, Universiteit van Amsterdam, Science Park 904, NL-1098 XH Amsterdam, the Netherlands*

<sup>6</sup>*South African Astronomical Observatory, P.O. Box 9, 7935 Observatory, Cape Town, South Africa*

<sup>7</sup>*Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate (LC), Italy*

<sup>8</sup>*Center for Astro, Particle and Planetary Physics, New York University Abu Dhabi, PO Box 129188 Abu Dhabi, UAE*

Accepted 2025 September 8. Received 2025 September 5; in original form 2025 July 3

## ABSTRACT

Precessing relativistic jets launched by compact objects are rarely directly measured, and present an invaluable opportunity to better understand many features of astrophysical jets. In this Letter we present MeerKAT radio observations of the neutron star X-ray binary system (NSXB) Circinus X-1 (Cir X-1). We observe a curved S-shaped morphology on  $\sim 20$  arcsec ( $\sim 1$  pc) scales in the radio emission around Cir X-1. We identify flux density and position changes in the S-shaped emission on year time-scales, robustly showing its association with relativistic jets. The jets of Cir X-1 are still propagating with mildly relativistic velocities  $\sim 1$  pc from the core, the first time such large scale jets have been seen from a NSXB. The position angle of the jet axis is observed to vary on year time-scales, over an extreme range of at least  $110^\circ$ . The morphology and position angle changes of the jet are best explained by a smoothly changing launch direction, verifying suggestions from previous literature, and indicating that precession of the jets is occurring. Steady precession of the jet is one interpretation of the data, and if occurring, we constrain the precession period and half-opening angle to  $> 10$  yr and  $> 33^\circ$ , respectively, indicating precession in a different parameter space to similar known objects such as SS 433.

**Key words:** stars: jets – stars: neutron.

## 1 INTRODUCTION

Relativistic jets are amongst the most important phenomena in astrophysics, associated with accretion on a vast range of scales from gamma-ray bursts to supermassive black holes. Observations of different astrophysical jets have shown that in some cases the direction in which they are launched can change with time. On large spatial scales this phenomenon is used to explain the morphology of certain radio galaxies (Horton, Krause & Hardcastle 2020), but it is only on smaller scales where the change in the jet launch axis with time can be directly observed. This has only been seen in a handful of systems, but over a range of size scales, from the supermassive black hole in M87 (Cui et al. 2023) to the stellar mass compact object in the microquasar SS 433 (Abell & Margon 1979; Fabian & Rees 1979; Milgrom 1979).

Astrophysical jet systems with measurable changes in jet launch direction, though rarely directly observed, are invaluable for probing key unknowns in jet physics. They allow conditions close to the jet launching region to be understood, and allow for insight into

the mechanism powering the jet. Furthermore, jets which change direction are more efficient at transferring energy to the ambient medium due to the increased interaction area (Monceau-Baroux et al. 2014). If jets which change direction are a widespread phenomenon this then has consequences for particle acceleration (Britzen et al. 2019, H. E. S. S. Collaboration 2024) and feedback (Vernaleo & Reynolds 2006, Li & Bryan 2014). Steady precession of the jet launch axis is the common model invoked to explain changing jet directions, whether due to Lense–Thirring precession of the inner accretion disc (Lense & Thirring 1918, Liska et al. 2018), or tidal effects of a binary companion on a misaligned accretion disc (Larwood 1998). Jets can show changing directions from other effects, such as motion of the compact object through the ISM/IGM (Heinz et al. 2008), or from interactions with a strong wind (Yoon & Heinz 2015), but in these cases the intrinsic jet *launch* direction is not changing.

X-ray binaries (XRB) are a unique laboratory for probing accretion and relativistic jets, due to their stellar scale size leading to evolution on human accessible time-scales when compared to their supermassive counterparts. The canonical example of a precessing jet is that of the XRB SS 433 (Margon 1984 and references therein), precisely measured using radio imaging (Hjellming & Johnston

\* E-mail: [fraser.cowie@physics.ox.ac.uk](mailto:fraser.cowie@physics.ox.ac.uk)

1981; Blundell & Bowler 2004) and spectral lines (Margon 1984; Eikenberry et al. 2001). Position angle variations in the jet from the black hole XRB V404 Cyg have also been observed and attributed to Lense–Thirring precession (Miller-Jones et al. 2019). Hints of a narrow precession in the jets of 1E 1740.7-2942 (Luque-Escamilla, Martí & Martínez-Aroza 2015) and Sco X-1 (Fomalont, Geldzahler & Bradshaw 2001b) have also been reported. In many cases the observation of certain quasi-periodic oscillations (QPOs) in XRB systems has been used to suggest the presence of a precessing jet (Ingram & Motta 2019; Zhang et al. 2023; Yang et al. 2024). Identifying more of these rarely observed precessing jets, with high-quality observations, is vital to better understand this phenomenon and will allow these systems to be better used as accretion and jet laboratories.

Circinus X-1 (Cir X-1) is a peculiar neutron star X-ray (NSXB) binary system which defies conventional classification. Discovered in 1969 (Margon et al. 1971), it has been monitored and studied for over 50 yr in X-ray, optical, infrared, and at radio wavelengths (e.g. Whelan et al. 1977; Glass 1994; Johnston et al. 2001; Yu et al. 2024). At all these wavelengths it has a periodic light curve of approximately 16.5 d (Glass 1978; Calvelo et al. 2012a; Johnston; Soria & Gibson 2016; Tominaga et al. 2023). The X-ray properties of Cir X-1 are similar to low mass NSXBs, with Z and Atoll behaviour (Soleri et al. 2009), and QPOs (Boutloukos et al. 2006). Type I X-ray bursts from the system confirmed a neutron star accretor (Tennant, Fabian & Shafer 1986; Linares et al. 2010). Cir X-1 is surrounded by its natal supernova remnant (SNR), known as the Africa nebula (Gasealahwe et al. 2025), indicating the system is less than 4600 yr old, making it the youngest known XRB (Heinz et al. 2013). The nature of the companion star is uncertain (Jonker, Nelemans & Bassa 2007; Johnston et al. 2016; Schulz et al. 2020). Observations of dust scattering rings suggest a distance of  $\sim 9.4$  kpc, implying Cir X-1 frequently exceeds the Eddington limit for a  $1.4 M_{\odot}$  neutron star.

Overall, the system can be modelled as a neutron star in an eccentric orbit with a companion star, where at periastron increased mass transfer and accretion rate leads to an X-ray flare and the launch of a transient relativistic jet (Murdin et al. 1980; Moin et al. 2011). The launch of the jet leads to a radio flare which shows an optically thick to thin synchrotron evolution, consistent with an expanding synchrotron emitting plasma (Haynes et al. 1978, 1979; Calvelo et al. 2012a). There is also some evidence of radio flaring at apastron (Fender et al. 1998; Tudose et al. 2008). VLBI observations of Cir X-1 around periastron showed a resolved symmetric jet-like structure at milliarcsecond (mas) scales, constraining the jet collimation angle to be  $< 20^{\circ}$  (Miller-Jones et al. 2012). These observations suggested a mildly relativistic jet inclined close to the plane of the sky. However, other observations suggest the presence of an unseen ultrarelativistic flow (URF), launched close to the plane of the sky during flaring of the source, energizing downstream material in the jet (Fender et al. 2004), behaviour also seen in the XRB Sco X-1 (Fomalont, Geldzahler & Bradshaw 2001a). However, the nature of the recurrent flaring of Cir X-1 could potentially complicate the interpretation of these core-lobe time delays used to infer the presence of this URF.

Observations in the literature show evolution in the morphology and luminosity of the jets over time-scales from days to years, including tentative variation in the jet position angle direction (Tudose et al. 2008). Calvelo et al. (2012b) presented the first millimetre wavelength observations of the source, finding morphology and flux density variations which again suggested that the jet position angle had changed from previous observations. Coriat et al. (2019) showed that the jet position angle appears to change with distance from the core. Long term secular evolution has also been observed in the

radio and X-ray luminosities (Armstrong et al. 2013; Yu et al. 2024). Potential jet interaction regions with the ambient medium have been found aligned with the historical jet axis. These include wide angled ‘cap’ structures within the bounds of the SNR (Sell et al. 2010) and asymmetric bubbles where the jet has punched through the SNR (Gasealahwe et al. 2025).

Currently it is difficult to imagine a single simple model which can explain the various and often contradicting phenomenology of Cir X-1 and its jets. The many peculiar features of the jets of Cir X-1, strongly motivates their further detailed study.

## 2 OBSERVATIONS AND DATA PROCESSING

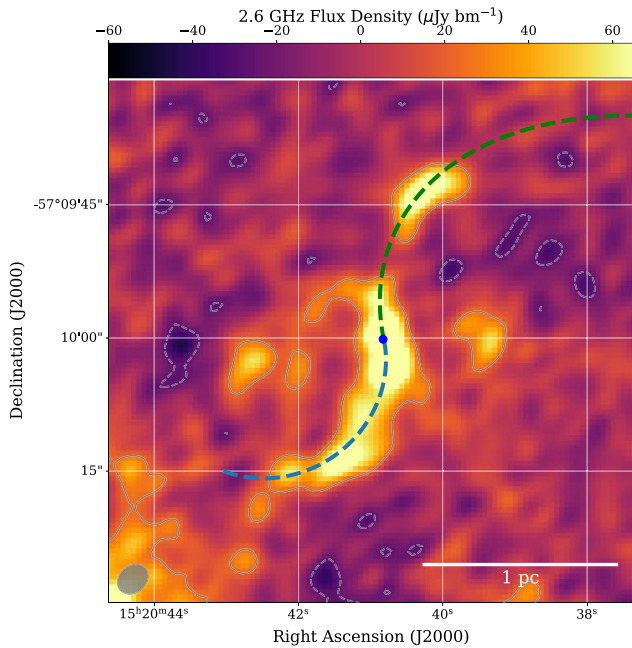
We observed Cir X-1 and the surrounding field using both the *L*-band (856–1712 MHz) and the *S*-band (1.75–3.5 GHz, 875 MHz instantaneous bandwidth) receivers on the MeerKAT radio telescope (Jonas & MeerKAT Team 2016; Barr 2018). These observations were made as part of the ThunderKAT (Fender et al. 2016), and X-KAT programmes (MeerKAT Proposal ID: SCI-20230907-RF-01).

In time order the observations taken were: 45 min *L*-band (1.3 GHz) observation on 2018 October 27;  $3 \times 15$  min *S2*-band observations (2.6 GHz) from 2023 August 11 with daily cadence; 15 min *L*-band observation on 2024 February 4; 60 min *S4*-band (3.1 GHz) observation on 2024 October 26; 60 min *S2*-band observation on 2025 May 31. The length of observation refers to the total on source time, composed of scans up to 30 min long sandwiched by 2 min secondary calibrator (J1427–4206) scans. Each observation began and ended with a 5-min scan of J1939–6342, the primary calibrator.

The observational data were reduced using the semi-automated pipeline OXKAT<sup>1</sup> (Heywood 2020). The software packages used in this pipeline were accessed using SINGULARITY for software containerization (Kurtzer, Sochat & Bauer 2017). First generation calibration (applying corrections from the primary and secondary calibrators, see Heywood et al. 2022) and iterative RFI flagging was done using CASA (CASA Team 2022). The target field was flagged further using TRICOLOUR (Hugo et al. 2022) and then imaged using WSCLEAN (Offringa et al. 2014). A deconvolution mask was manually made and iteratively improved through further imaging and use of the mask making tool BREIZORRO (Ramaila, Smirnov & Heywood 2023), before phase and delay self-calibration were performed using CUBICAL (Kenyon et al. 2018).

Joined frequency channel deconvolution using 8 channels and a Briggs weighting of  $-0.3$  was used (Briggs 1995). For the images at *S2* and *S4*-band an inner Tukey taper from 0 to  $10^4 \lambda$  was applied to the weighting of the visibilities in the *uv*-plane and at *L*-band an inner Tukey taper from 0 to  $5 \times 10^3 \lambda$  was used. Tapering allowed for down-weighting of the diffuse background emission from the SNR. In all images a known background source to the SE was subtracted (see Sell et al. 2010; Calvelo et al. 2012a; Coriat et al. 2019). The source subtraction was done by fitting an elliptical Gaussian with fixed size given by the restoring beam, plus a flat background, allowing the flux density of the Gaussian component and background to vary, and allowing the position of the component to vary only  $\pm 0.5$  pixels from the known position of the background source from our high resolution uniformly weighted images. We investigated systematic astrometric errors by examining the variability in the best-fitting positions of 10 background sources of varying flux density relative to their mean positions. Combining the offsets across the sample,

<sup>1</sup><https://github.com/IanHeywood/oxkat>

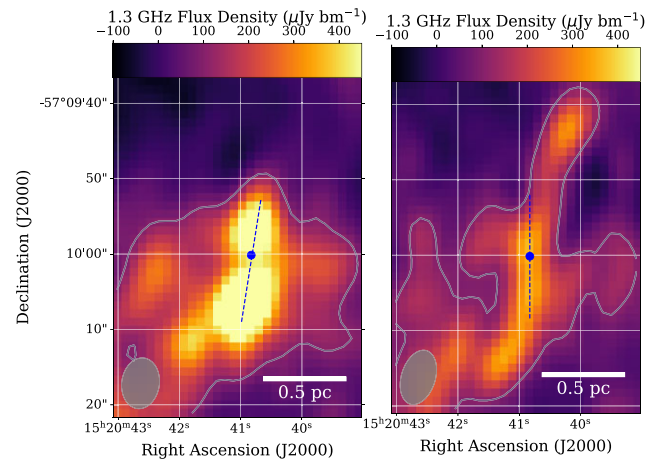


**Figure 1.** S2-band image of the jets of Cir X-1 in August 2023, the known background source to the SE has been subtracted. The core of Cir X-1 is marked by a blue dot. This image is the result of combined imaging of  $3 \times 15$  min observations taken within a 48 h period in August 2023. The dashed line is a fit to a ballistic precession model. The noise level in the region surrounding Cir X-1 is  $8 \mu\text{Jy beam}^{-1}$ ,  $-3\sigma$ ,  $3\sigma$  contours are shown.

we find a standard deviation of  $\sim 0.07$  arcsec, which is significantly smaller than our adopted systematic uncertainties throughout this letter. This indicates that our interpretations are robust under the conservative assumption that astrometry is limited to 10 per cent of the synthesized beam (i.e.  $\sim 0.3$  arcsec). The source subtraction was implemented using the *ASTROPY* (Astropy Collaboration 2022) and *LMFIT* packages (Newville et al. 2014). In some images a point source was subtracted using the same process from the known core position of Cir X-1 (Moneti 1992), in order to more clearly show any resolved underlying structure. We note that the position of the core of Cir X-1 in our high resolution images agrees with the known position of the optical counterpart (Moneti 1992). Throughout this Letter a distance of 9.4 kpc is assumed, and the uncertainty on this distance (Heinz et al. 2015) does not affect any conclusions.

### 3 RESULTS

Fig. 1 clearly shows that the radio emission surrounding Cir X-1 has a curved symmetric S-shaped morphology on parsec scales. This morphology is particularly clear in these  $3 \times 15$  min epochs taken in August 2023 as the orbital phase was  $\sim 0.8$  (using an updated radio ephemeris, Nicolson priv. comm.), meaning there is no/minimal radio emission from the core (Calvelo et al. 2012a). The lack of core flux density variability allows them to be combined during imaging despite being taken 48 h apart. Other observations during the campaign, including longer contiguous observations, showed the same curved morphology but an increased core flux density meant that source subtraction of the core was required to see these features more clearly. Furthermore, we note that the radio emission within  $\sim 3$  arcsec of the core of Cir X-1 is extended along an axis. The position angle of this core emission in Fig. 1 is  $13 \pm 3^\circ$  E of N. The



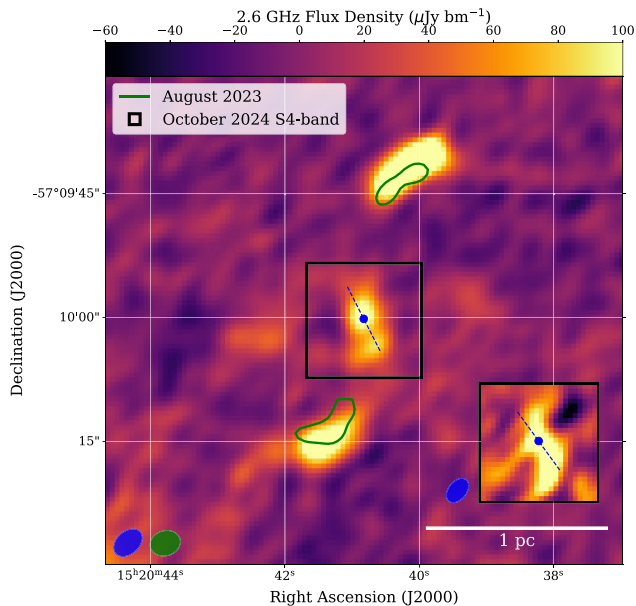
**Figure 2.** Left: *L*-band image of the jets of Cir X-1 in 2018 the core (marked by a dot) and SE background source have been subtracted. Right: *L*-band image of the jets of Cir X-1 in 2024 with the same subtractions. The position angle of the core emission,  $-9 \pm 3^\circ$  E of N in 2018 and  $\sim 0^\circ$  E of N in 2024, is indicated by a dotted line. Between the two images, there is variability in the position angle, morphology and flux density of the emission close to the core and at larger distances. The noise level in the region surrounding Cir X-1 is  $35 \mu\text{Jy beam}^{-1}$  in both images,  $-3\sigma$ ,  $3\sigma$  contours are shown.

jet emission has had position angle measurements made over the past 20 yr, but has never been observed at this angle before.

If the curved symmetric S-shape radio morphology is associated with the jets from Cir X-1 then we find some form of precession the most plausible scenario (see Section 4). Ballistic precession is one such geometric precession model, where the precession parameters are stable and no deceleration of the jet occurs. Fig. 1 shows a fit to a ballistic precession model (Hjellming & Johnston 1981). Data points were placed evenly along the S-shape, and the differential evolution algorithm (Storn & Price 1997), implemented in *SCIPY.OPTIMIZE* (Virtanen et al. 2020), was used to minimize the 2D on-sky distance between data and model. The jet speed and geometric parameters describing the precession cone are detailed in Table A1. However, due to degeneracy these are not to be taken as the precession parameters (see Section 4).

It is clear that there is much complex radio structure close to Cir X-1, not all of which may be attributable to relativistic jets. However, we can show using additional data that the S-shaped radio morphology is unambiguously associated with relativistic jets. The left of Fig. 2 shows the 2018 *L*-band observation with the core and background source subtracted. The right of Fig. 2 shows the 2024 *L*-band observation with the same subtractions. Both the 2018 and 2024 data show a clear extended structure of emission close to the subtracted core. In the 2018 case the structure is bipolar. In 2024 on larger scales hints of the S-shape seen more clearly in Fig. 1 are present. In 2018 the position angle of the core emission is  $-9 \pm 3^\circ$ . This is significantly different from the position angle on a similar size scale of core emission measured in 2023, shown in Fig. 1. The position angle of the core structure in the 2024 *L*-band data is difficult to measure accurately due to low flux density when compared to background emission, but appears to be close to  $0^\circ$  E of N.

An important conclusion from the comparison of images at the same frequency in 2018 and 2024 in Fig. 2 is the clear variability of flux density and structure of the emission both close to the core and on parsec scales. Notably, the northern and southern components of the S-shape are not present in 2018. While the cause of the variability



**Figure 3.** S2-band image of the jets of Cir X-1 in May 2025, with known background source and core subtracted. The lower right inset shows the higher resolution S4-band view of the jets close to the subtracted core in October 2024, where a miniature S-shape can be seen.  $10\sigma$  contours from the observation shown in Fig. 1 are plotted, illustrating movement of components in the S-shape. The core is marked by a dot and the position angle of emission surrounding the core is  $36 \pm 4^\circ$ , indicated by a dotted line. Contours from the central part of the image have been removed for clarity. The noise level in the region surrounding Cir X-1 is  $9 \mu\text{Jy beam}^{-1}$  in both the image and the inset. The ellipse in the bottom left represents the beam in the 2025 image displayed, while the ellipse to the right represents the beam for the 2023 observation, for which contours are shown. The ellipse next to the inset region is the beam for the 2024 observation shown in the inset.

close to the core may be short or long term, as these observations were taken at different phases in the binary orbit, the variability far from the core confirms that this emission is associated with Cir X-1, not the surrounding SNR.

We can then compare the S2-band observations in 2023 in Fig. 1 to S2-band observations taken nearly 2 yr later in 2025. Furthermore, we can also use the highest frequency and resolution S4-band observations from 2024 to investigate the structure of the emission very close to the core, after core subtraction. Fig. 3 shows the image from the S2-band 2025 observations, with an inset showing the core in the 2024 S4-band observations. Finally,  $10\sigma$  contours from the 2023 observation shown in Fig. 1 are plotted in order to illustrate movement of the northern and southern components of the S-shape between 2023 and 2025.

In order to measure the positional difference in the north (N) and south (S) components of the S-shape between 2023 and 2025 we use 2 methods as no simple image plane model is appropriate to fit. We first define two axes along which positional differences will be measured, one for the N component and the other for the S component. This is done by connecting the brightest pixel in Fig. 1 for each component and the core position. One measurement method is then to simply identify the brightest pixel in Fig. 3 in each component along the respective axis, and calculate the distance from the brightest pixel in Fig. 1. A more advanced method to measure the positional differences uses the gradient based method of Canny edge detection (Canny 1986) to identify the leading edge of the emission in 2023 and 2025. Then along the the respective axes the positional difference of

the edge in 2023 and 2025 was measured. The edge detection was implemented using the SCIKIT-IMAGE package (van der Walt et al. 2014), and the parameters used to run the edge detection were a low threshold of  $40 \mu\text{Jy beam}^{-1}$  and a high threshold of  $70 \mu\text{Jy beam}^{-1}$ . No Gaussian blur was applied to the image beforehand.

The brightest pixel method gave positional differences of  $2.1 \pm 0.4$  and  $1.8 \pm 0.4$  arcsec for the N and S components, respectively, where a positive difference in position corresponds to increasing distance from the core. The edge detection method gave a difference in position of  $2.4 \pm 0.4$  arcsec for both the N and S components. In all cases the uncertainties have been estimated by calculating the uncertainty which would be present on an elliptical Gaussian fit to a point source with the same SNR as the N and S components (Condon 1997), including a 10 per cent systematic error (which dominates) to ensure the uncertainty estimates are conservative. Other studies using MeerKAT have found this systematic error to be significantly less than 10 per cent (Hughes et al. 2024), suggesting that the uncertainties on the position differences are likely very conservative.

Our analysis shows strong evidence that the outer parts of the S-shaped emission are propagating away from the core of Cir X-1 with proper motions of approximately  $3.5 \pm 0.6 \text{ mas d}^{-1}$  (taking the positional difference derived from the edge detection method). At a distance of  $\sim 9.4 \text{ kpc}$  (Heinz et al. 2015), this corresponds to an mildly relativistic apparent velocity of  $0.19 \pm 0.04c$ . Then making the usual assumption (which appears to hold for SS 433 and other sources e.g. Hjellming & Johnston 1981) that the brightest point in the jet is conserved, we can say this value is the apparent bulk velocity of the material within the jet. This result, combined with the observed variability, shows unambiguous evidence that the S-shaped emission is associated with a relativistic jet from Cir X-1, which is still propagating mildly relativistically out to parsec scales.

We also observe strong variability in the flux density of the northern and southern components between the 2023 and 2025 observations at S2-band, with the northern jet component brightening by a factor of  $> 3$ . While the large scale S-shape is overall fairly symmetrical, we see that in Figs 1 and 3, for a given position angle, the N component of the S-shape is further from the core than the S component, by  $\sim 3$  arcsec. In Fig. 3, following the S-shape morphology towards the south-east, we observe a tentative hint of an inflexion in the morphology. Future observations will be needed to confirm if this emission is associated with the jets.

In Fig. 3 the position angle of the core emission in 2025 is  $28 \pm 4^\circ$ . In the inset of Fig. 3, showing higher resolution 2024 data, emission surrounding the core is not symmetric but shows an asymmetric miniature S-shaped morphology. Therefore, we measure the position angle of the core emission in this case by using the emission to the south-west of the core, which is brighter and more extended than the emission to the north. The measured position angle of the core emission in this case is  $36 \pm 4^\circ$ . The significance of these residuals ( $> 80 \mu\text{Jy beam}^{-1}$ ) was examined by performing a similar core subtraction on background point sources of comparable flux density. Despite the test sources being off-axis (and thus more prone to calibration systematics), our tests revealed no comparable residual structure, strongly suggesting that the mini S-shaped morphology is intrinsic to the source and not an artefact. Measurements of the core emission position angle on arcsecond scales are not necessarily indicative of the jet launch axis position angle at that time, but instead measure the jet launch position angle at some time in the past. However, we can, by combining our position angle observations with an estimate of the jet velocity, and the large scale S-shape, build up an overall picture of the jets in the system.

Since 2015 the position angle of the jet launch axis on the sky has rotated from  $\sim -10^\circ$  to at least  $\sim 36^\circ$  E of N. On average the position angle of the jet launch axis has changed by  $\sim 5^\circ \text{ yr}^{-1}$ . Archival observations of the position angle of core emission show variation between  $\sim -75^\circ$  and  $\sim -35^\circ$  E of N at 8.6 GHz on scales of  $\sim 2$  arcsec (Tudose et al. 2008), a position angle of  $\sim -68^\circ$  E of N on  $\sim 20$  mas scales (Miller-Jones et al. 2012), and angles between  $\sim -15^\circ$  and  $\sim -60^\circ$ , on scales of  $\sim 2$  and  $\sim 10$  arcsec, respectively (Coriat et al. 2019). Therefore, we can concretely say that the projected jet launch axis on the sky, has varied by *at least*  $\sim 110^\circ$  over the past 25 yr a rather extreme and unusual position angle change for a jet launch axis compared to other sources.

Finally, in all our observations we see faint diffuse emission (at a significance of  $6\sigma$  in Fig. 1), oriented in an E-W direction, roughly perpendicular to the current jet launch axis, at a distance of  $\sim 10$  arcsec ( $\sim 0.5$  pc) and approximately symmetrical about the core. Tentative hints of variability, most obvious in Fig. 2, suggest that this emission may also be related to the relativistic jets.

#### 4 DISCUSSION

In Section 3 we showed that there is a symmetric parsec scale S-shaped morphology in the relativistic jets of Cir X-1. There are several scenarios which can explain a such a jet:

- (i) The jet itself is straight but has fluid elements travelling along curved trajectories due to instabilities (Nikonov et al. 2023).
- (ii) The jet follows a curved path due to interactions with the surrounding medium (Miller & Brandt 2009).
- (iii) The jet travels in a straight line but the launch axis has changed over time.

Scenario (i) is expected to produce sharp small bends in the jet (Perucho et al. 2012; Misra et al. 2025), this is disfavoured due to the absence of these effects, and the observation of a well collimated curved jet out to large scales relative to the size of the system. The ambient environment of Cir X-1 is likely to be complex but low density in comparison to the interstellar medium (ISM) given the SNR. However, (ii) is disfavoured due to the requirement of the medium to be both inhomogeneous and symmetric being unlikely and it being unable to explain the time evolution of the core emission axis. This leaves scenario (iii) as the most likely. A caveat is that if a sufficiently powerful wind exists, with a changing launch direction, then jets could be redirected by this wind, creating the appearance of a changing jet launch direction. This mechanism has been invoked to explain the precession of the jet in SS 433 (Begelman, Blandford & Rees 1980), but would require Cir X-1 to have a remarkably powerful wind-like outflow, and therefore have a hyper-Eddington mass transfer rate.

We were able to reproduce the observed S-shape morphology using a simple ballistic jet model (no deceleration; Hjellming & Johnston 1981) in which the jet launch direction precesses over time. The model provides a good qualitative match to the morphology, but the similarity between a fast jet precessing on a short time-scale and a slower jet on a longer time-scale, the degeneracy between the opening angle and the position angle of the precession cone, and the coupling between intrinsic jet velocity and the line-of-sight inclination of the precession cone render the fitted parameters largely unconstraining. These degeneracies arise due to our observational data being limited to a small window of time relative to the precession period, and the lack of identification of an inflexion point in the S-shape, which would identify the edge of the precession cone.

Furthermore, in the case of Cir X-1 we note several features that may make this simple ballistic precession model unsuitable. To begin with, the measured combined proper motion of the parsec scale jets is significantly less than the value measured from VLBI observations (Miller-Jones et al. 2012). This could be either due to different inclination angles relative to the line of sight, or a reduction in the jet speed, likely due to deceleration on parsec scales. We know that the S-shaped emission on large scales must be caused by *in situ* particle acceleration as the initial synchrotron flare fades on day time-scales before the jet propagates to large distances. This particle acceleration could occur via a reverse shock or from interactions between the ambient medium and jet (Cooper et al. 2025; Matthews et al. 2025; Savard et al. 2025). This makes deceleration a likely possibility and means the ballistic precession model is unsuitable. For a proper treatment where ambient medium interactions are important, hydrodynamic simulations are needed. These have been performed for the case of radio galaxies (Horton et al. 2020; Nolting, Ball & Nguyen 2023) and SS 433 (Goodall, Alouani-Bibi & Blundell 2011b; Monceau-Baroux et al. 2014), showing that hydrodynamic effects and deceleration play an important role in determining the morphology of the emission from precessing jets.

Secondly, as noted throughout the literature, Cir X-1 undergoes dramatic secular changes in its behaviour on time-scales of decades (Armstrong et al. 2013). Cowie et al. (in preparation) show that these changes likely reflect a long-term evolution in jet power, suggesting that the jet properties may not remain constant over long time-scales. Furthermore, jet interaction features such as the bubbles (Gasealawhe et al. 2025), suggest that the jet was not always precessing in the past. It may be the case that Cir X-1 switches jet modes between launching a precessing jet and a fixed axis jet, or that two jets are active in the system simultaneously. The observation of an URF from Cir X-1 (Fender et al. 2004), is further evidence that multiple jets with different properties exist in this source, as it is not possible to reconcile the mildly relativistic jets we observe with this URF. If multiple jet modes do exist then it becomes difficult to tell which past measurements of the jet launch axis are suitable to include when fitting a precession model. Even if multiple jet launch modes do not exist, a jet-redirecting powerful wind, launched by a precessing disc only at certain times, can result in a jet which sometimes exhibits precession and other times does not. Finally, we do not discount the possibility that there is no steady precession with a fixed period or axis. Cir X-1, the youngest known XRB, underwent a recent cataclysmic disruption during a supernova (Heinz et al. 2013). The jet launch axis may be varying chaotically, or through other non-precession processes, as the system has not had time to settle into a steady state. Despite these facts, it seems that precession of some form, whether stable or unstable, remains the only viable option to explain the changes in the jet launch direction observed over the past 2 decades.

Despite the absence of a confident fit to a steady precession model, this could still describe the behaviour of Cir X-1. The S-shaped emission, and core emission position angle changes since 2018, can be explained by a scenario where the jet launch axis position angle has changed by an average of  $\sim 5^\circ$  per year. Similar rates of evolution are seen in fig. 4 of Tudose et al. (2008), from 1998 to 2003. Given that we have observed the jet axis position angle to vary by at least  $110^\circ$ , assuming this variation arises from precession. We can then constrain the precession period to be  $> 10$  yr, substantiated by the range of ballistic precession models fitted to the S-shape, with none having periods  $< 10$  yr. We note an apparently faster evolution in the position angle between 2010 (Miller-Jones et al. 2012) and 2011 (Coriat et al. 2019). Finally, given the S-shape and numerous observations over

the course of a year (Tudose et al. 2008, this work) it is very unlikely we are undersampling in time, leading to an overestimate of the precession period.

The half-opening angle of the precession cone,  $\psi$ , can also be constrained by considering the lack of asymmetry in the VLBI images, leading to the conclusion that at this epoch, for a jet speed of  $0.5c$ , the instantaneous jet inclination to the line of sight must have been  $i' > 75^\circ$ , to ensure  $\left(\frac{1+\beta \cos i'}{1-\beta \cos i'}\right)^3 < 2$ . Therefore, throughout the precession, the instantaneous inclination to the line of sight of the jet axis must reach at least this value, meaning  $\psi + i > 75^\circ$ , where  $i$  is the inclination of the precession cone to the line of sight. Furthermore, given the observed range of jet position angles, we can use the equations for the steady precession model in Hjellming & Johnston (1981) to form the inequality:

$$90^\circ - \arctan \frac{\sqrt{\cos 2\psi - \cos 2i}}{\sqrt{2} \sin i} > \frac{110^\circ}{2}. \quad (1)$$

Solving these inequalities together gives  $\psi > 33^\circ$ . If steady precession is the correct model for the jets in this system, then these constraints place Cir X-1 in a unique parameter space with respect to the few other X-ray binaries which show precession. The most relevant comparison for Cir X-1 is the system SS 433. SS 433 and Cir X-1 are both X-ray bright, peculiar X-ray binaries, embedded in their natal SNR (Heinz et al. 2013; Bowler & Keppens 2018). Signs of jet interactions with the ambient medium can be seen in both systems (Sell et al. 2010; Goodall; Blundell & Bell Burnell 2011a; Goodall et al. 2011b; Gasealahwe et al. 2025; Cowie et al., in preparation). SS 433 is an older system compared to Cir X-1, aged at  $10^4 - 10^5$  yr (Goodall et al. 2011b) potentially making Cir X-1 the younger analogue of SS 433. Finally, both launch relativistic jets with axes which change with time, leading to curved radio morphologies (Blundell & Bowler 2004). The precession period of Cir X-1 is inferred to be at least 25 times greater than the 162-d period in SS 433. Additionally, the precession half opening angle of SS 433 is  $20^\circ$ , at least 1.5 smaller than in the Cir X-1 case.

The constraint on the precession period rules out certain driving mechanisms. If precession is occurring we should expect some misalignment of angular momentum in the system. Evidence for a misalignment between the neutron star rotation axis and the orbital plane has recently been found through X-ray polarization observations (Rankin et al. 2024). Misalignments in Cir X-1 are plausible, given the system was recently disrupted by a supernova explosion.

Precession of the accretion disc can drive precession of the jet, either through the launch axis of the jet being linked to the accretion disc, or through re-direction of a fixed axis jet by a powerful wind-like outflow. The accretion disc can precess due to a variety of effects (Caproni et al. 2006). Magnetically driven precession occurs when the neutron star spin is misaligned with the accretion disc angular momentum (Lai 1999), however over a wide parameter space this cannot produce long period precession in neutron star systems (Veresvarska et al. 2024). The accretion disc can also precess due to tidal effects from the companion in the binary, if the accretion disc is initially misaligned with the orbital angular momentum (see Katz 1973; Bardeen & Petterson 1975; Schandl & Meyer 1994; Fragile, Mathews & Wilson 2001 for various mechanisms). Given the unknowns in the system we find that tidal precession can create a period on the order of 10 yr, but only for a low mass companion, large half opening angle, or a small accretion disc size (using equation 4 from Coriat et al. 2019). The Lense–Thirring effect can also cause precession of the accretion disc (Lense & Thirring 1918). However,

this mechanism can only produce precession periods of a few days or less (Massi & Zimmermann 2010). The jet direction may also be set by the neutron star spin, which may also precess. This can occur either through geodetic precession due to misalignment with the orbital angular momentum (Boerner, Ehlers & Rudolph 1975) or free precession (Shaham 1977, Fabian 1980). Geodetic precession leads to a precession period several orders of magnitude too large to explain the jet precession and free precession is poorly understood so is difficult to assess in terms of viability.

We can compare the jets of Cir X-1 to precessing jets seen on much larger scales in radio galaxies. In this case jet precession is thought to occur through precession of the accretion disc or geodetic precession of black hole spin (Begelman et al. 1980). While the scales are vastly different, the morphology of the jets in Cir X-1 bears a striking resemblance to some radio galaxies, e.g. PKS 2300-18 (Misra et al. 2025). Furthermore, a feature common to several S-shaped radio galaxies is the existence of diffuse, lower surface brightness wings of emission, misaligned from the jet axis. We note that a qualitatively similar structure has been observed in SS 433, referred to as the radio ruff (Paragi et al. 1999; Blundell et al. 2001). However, this is interpreted to be a wind-like outflow, and is observed on  $10^{-3}$  pc scales rather than the parsec scales of the diffuse emission in Cir X-1. Overall, similarities in the morphology between Cir X-1 and radio galaxies suggest a certain degree of scale invariance in these objects. However, this is contrary to theoretical expectations from considerations of the different environments these jets propagate into (Heinz 2002).

Finally, the fact that jets of Cir X-1 are still propagating mildly relativistically around 1 pc away from the system has significant implications. Over the past 2 decades, several black hole X-ray binaries have been observed to launch the so-called large scale jets (see e.g. Carotenuto et al. 2024). However, no detection of moving large scale jets from any confirmed NSXB has been seen until Cir X-1. Other NSXBs binaries have shown resolved jets on smaller scales, e.g. the jets in Cyg X-2 observed out to  $\sim 60$  AU (Spencer et al. 2013). In the case of Cir X-1 the jets are still propagating and detected out to  $\sim 1$  pc, which is roughly the same distance as the furthest known black hole XRB jets (Russell et al. 2019). This indicates that the jets from Cir X-1 are comparable, in terms of energy, to the large scale jets from some of the most powerful black hole X-ray binaries, if the sources exist in similar ISM environments.

## 5 CONCLUSIONS

By combining the most detailed radio observations of the NSXB Cir X-1 to date, with observations in the literature going back over 20 yr, we have revealed several unique features of the relativistic jets. We have found a parsec-scale S-shaped morphology in the radio emission around Cir X-1 which can be robustly attributed to relativistic jets interacting with the ambient medium. This makes Cir X-1 the second ever X-ray binary, and first confirmed neutron star X-ray binary, to show this type of jet morphology.

We have found evidence for movement of jet components within this morphology, demonstrating the jets launched by the neutron star in Cir X-1 are still propagating mildly relativistically at least 1 pc from the system. This is the first observation of dynamic large scale jets from an accreting neutron star, and potentially implies similar jet powers to transient large scale jets launched by black hole X-ray binary systems (see also Gasealahwe et al. 2025).

Comparison to data going back over 20 yr shows a  $110^\circ$  range of jet position angles on sky, the largest range of jet position angles seen from any X-ray binary, indicating the jet launch axis of Cir X-1

has changed direction by a large degree. This is the first case where this has been observed from a neutron star X-ray binary. Precession of the jets is the most likely scenario explaining this behaviour. If stable precession is occurring we can constrain the precession period to be  $> 10$  yr and the half opening angle of the precession cone to be  $> 33^\circ$ , placing Cir X-1 in a unique area of parameter space compared to the few other X-ray binary systems with precessing jets.

## ACKNOWLEDGEMENTS

We thank the anonymous referee for their detailed comments which helped significantly improve the manuscript. FJC was supported by STFC grant ST/Y509474/1. RF acknowledges support from UK Research and Innovation, the European Research Council, and the Hintze Charitable Foundation. JvdE was supported by funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101148693 (MeerSHOCKS). The MeerKAT telescope is operated by the South African Radio Astronomy Observatory, which is a facility of the National Research Foundation, an agency of the Department of Science and Innovation. This work has made use of the 'MPIfR S-band receiver system' designed, constructed, and maintained by funding of the MPI für Radioastronomie and the Max-Planck-Society. We acknowledge the use of the ilifu cloud computing facility – www.ilifu.ac.za, a partnership between the University of Cape Town, the University of the Western Cape, Stellenbosch University, Sol Plaatje University, and the Cape Peninsula University of Technology. The ilifu facility is supported by contributions from the Inter-University Institute for Data Intensive Astronomy (IDIA – a partnership between the University of Cape Town, the University of Pretoria, and the University of the Western Cape), the Computational Biology division at UCT and the Data Intensive Research Initiative of South Africa (DIRISA). This work made use of the CARTA (Cube Analysis and Rendering Tool for Astronomy) software (DOI 10.5281/zenodo.3377984 - https://cartavis.github.io). The authors would like to thank Lilia Tremou, Andrew Hughes, Francesco Carotenuto, and Payaswini Saikia for scheduling the MeerKAT observations.

## DATA AVAILABILITY

The data availability will be subject to the ThunderKAT LSP and X-KAT XLP data release conditions.

## REFERENCES

Abell G. O., Margon B., 1979, *Nature*, 279, 701  
 Armstrong R. P. et al., 2013, *MNRAS*, 433, 1951  
 Astropy Collaboration, 2022, *ApJ*, 935, 167  
 Bardeen J. M., Petterson J. A., 1975, *ApJ*, 195, L65  
 Barr E. D., 2018, in Weltevredre P., Perera B. B. P., Preston L. L., Sanidas S., eds, Proc. IAU Symp. 337, Pulsar Astrophysics the Next Fifty Years. Cambridge Univ. Press, Cambridge, p. 175  
 Begelman M. C., Blandford R. D., Rees M. J., 1980, *Nature*, 287, 307  
 Blundell K. M., Bowler M. G., 2004, *ApJ*, 616, L159  
 Blundell K. M., Mioduszewski A. J., Muxlow T. W. B., Podsiadlowski P., Rupen M. P., 2001, *ApJ*, 562, L79  
 Boerner G., Ehlers J., Rudolph E., 1975, *A&A*, 44, 417  
 Boutloukos S., van der Klis M., Altamirano D., Klein-Wolt M., Wijnands R., Jonker P. G., Fender R. P., 2006, *ApJ*, 653, 1435  
 Bowler M. G., Keppens R., 2018, *A&A*, 617, A29  
 Briggs D. S., 1995, PhD thesis. New Mexico Institute of Mining and Technology

Britzen S., Fendt C., Zajaček M., Jaron F., Pashchenko I., Aller M. F., Aller H. D., 2019, *Galaxies*, 7, 72  
 Calvelo D. E., Fender R. P., Tzioumis A. K., Kawai N., Broderick J. W., Bell M. E., 2012a, *MNRAS*, 419, 436  
 Calvelo D. E., Fender R. P., Tzioumis A. K., Broderick J. W., 2012b, *MNRAS*, 419, L54  
 Canny J., 1986, *IEEE Trans. Pattern Anal. Mach. Intell.*, PAMI-8, 679  
 Caproni A., Livio M., Abraham Z., Mosquera Cuesta H. J., 2006, *ApJ*, 653, 112  
 Carotenuto F., Fender R., Tetarenko A. J., Corbel S., Zdziarski A. A., Shaik G., Cooper A. J., Di Palma I., 2024, *MNRAS*, 533, 4188  
 CASA Team 2022, *PASP*, 134, 114501  
 Condon J. J., 1997, *PASP*, 109, 166  
 Cooper A. J., Matthews J. H., Carotenuto F., Fender R., Lamb G. P., Russell T. D., Sarin N., Savard K., 2025, *MNRAS*, 541, 3518  
 Coriat M., Fender R. P., Tasse C., Smirnov O., Tzioumis A. K., Broderick J. W., 2019, *MNRAS*, 484, 1672  
 Cui Y. et al., 2023, *Nature*, 621, 711  
 Eikenberry S. S., Cameron P. B., Fierce B. W., Kull D. M., Dror D. H., Houck J. R., Margon B., 2001, *ApJ*, 561, 1027  
 Fabian A. C., 1980, *MNRAS*, 192, 11P  
 Fabian A. C., Rees M. J., 1979, *MNRAS*, 187, 13P  
 Fender R., Spencer R., Tzioumis T., Wu K., van der Klis M., van Paradijs J., Johnston H., 1998, *ApJ*, 506, L121  
 Fender R., Wu K., Johnston H., Tzioumis T., Jonker P., Spencer R., van der Klis M., 2004, *Nature*, 427, 222  
 Fender R. et al., 2016, in *MeerKAT Science: On the Pathway to the SKA, Proceeding of Science*, Trieste, p. 13  
 Fomalont E. B., Geldzahler B. J., Bradshaw C. F., 2001a, *ApJ*, 553, L27  
 Fomalont E. B., Geldzahler B. J., Bradshaw C. F., 2001b, *ApJ*, 558, 283  
 Fragile P. C., Mathews G. J., Wilson J. R., 2001, *ApJ*, 553, 955  
 Gasealahwe K. V. S. et al., 2025, *MNRAS*, 541, 4011  
 Glass I. S., 1978, *MNRAS*, 183, 335  
 Glass I. S., 1994, *MNRAS*, 268, 742  
 Goodall P. T., Blundell K. M., Bell Burnell S. J., 2011a, *MNRAS*, 414, 2828  
 Goodall P. T., Alouani-Bibi F., Blundell K. M., 2011b, *MNRAS*, 414, 2838  
 H. E. S. S. Collaboration, 2024, *Science*, 383, 402  
 Haynes R. F., Jauncey D. L., Murdin P. G., Goss W. M., Longmore A. J., Simons L. W. J., Milne D. K., Skellern D. J., 1978, *MNRAS*, 185, 661  
 Haynes R. F., Jauncey D. L., Lerche I., Murdin P. G., 1979, *Aust. J. Phys.*, 32, 43  
 Heinz S., 2002, *A&A*, 388, L40  
 Heinz S., Grimm H. J., Sunyaev R. A., Fender R. P., 2008, *ApJ*, 686, 1145  
 Heinz S. et al., 2013, *ApJ*, 779, 171  
 Heinz S. et al., 2015, *ApJ*, 806, 265  
 Heywood I., 2020, record ascl:2009.003  
 Heywood I. et al., 2022, *MNRAS*, 509, 2150  
 Hjellming R. M., Johnston K. J., 1981, *ApJ*, 246, L141  
 Horton M. A., Krause M. G. H., Hardcastle M. J., 2020, *MNRAS*, 499, 5765  
 Hughes A. K., Sivakoff G. R., van den Eijnden J., Fender R., Miller-Jones J. C. A., Tremou E., 2024, *MNRAS*, 527, 9359  
 Hugo B. V., Perkins S., Merry B., Mauch T., Smirnov O. M., 2022, in Ruiz J. E., Pierfedereci F., Teuben P., eds, ASP Conf. Ser. Vol. 532, Astronomical Data Analysis Software and Systems XXX. Astron. Soc. Pac., San Francisco, p. 541  
 Ingram A. R., Motta S. E., 2019, *New Astron. Rev.*, 85, 101524  
 Johnston H. M., Wu K., Fender R., Cullen J. G., 2001, *MNRAS*, 328, 1193  
 Johnston H. M., Soria R., Gibson J., 2016, *MNRAS*, 456, 347  
 Jonas J., Team MeerKAT, 2016, in *MeerKAT Science: On the Pathway to the SKA, Proceeding of Science*, Trieste, p. 1  
 Jonker P. G., Nelemans G., Bassa C. G., 2007, *MNRAS*, 374, 999  
 Katz J. I., 1973, *Nat. Phys. Sci.*, 246, 87  
 Kenyon J. S., Smirnov O. M., Grobler T. L., Perkins S. J., 2018, *MNRAS*, 478, 2399  
 Kurtzer G. M., Sochat V., Bauer M. W., 2017, *PLoS ONE*, 12, e0177459  
 Lai D., 1999, *ApJ*, 524, 1030  
 Larwood J., 1998, *MNRAS*, 299, L32  
 Lense J., Thirring H., 1918, *Z. Phys.*, 19, 47

- Li Y., Bryan G. L., 2014, *ApJ*, 789, 54
- Linares M. et al., 2010, *ApJ*, 719, L84
- Liska M., Hesp C., Tchekhovskoy A., Ingram A., van der Klis M., Markoff S., 2018, *MNRAS*, 474, L81
- Luque-Escamilla P. L., Martí J., Martínez-Aroza J., 2015, *A&A*, 584, A122
- Margon B., 1984, *ARA&A*, 22, 507
- Margon B., Lampton M., Bowyer S., Cruddace R., 1971, *ApJ*, 169, L23
- Massi M., Zimmermann L., 2010, *A&A*, 515, A82
- Matthews J. H. et al., 2025, *MNRAS*, 539, 2665
- Milgrom M., 1979, *A&A*, 76, L3
- Miller B. P., Brandt W. N., 2009, *ApJ*, 695, 755
- Miller-Jones J. C. A. et al., 2012, *MNRAS*, 419, L49
- Miller-Jones J. C. A. et al., 2019, *Nature*, 569, 374
- Misra A., Jamrozy M., Weżgowiec M., Koziel-Wierzbowska D., 2025, *MNRAS*, 536, 2025
- Moin A., Reynolds C., Miller-Jones J. C. A., Tingay S. J., Phillips C. J., Tzioumis A. K., Nicolson G. D., Fender R. P., 2011, *MNRAS*, 414, 3551
- Monceau-Baroux R., Porth O., Meliani Z., Keppens R., 2014, *A&A*, 561, A30
- Moneti A., 1992, *A&A*, 260, L7
- Murdin P., Jauncey D. L., Haynes R. F., Lerche I., Nicolson G. D., Holt S. S., Kaluzienski L. J., 1980, *A&A*, 87, 292
- Newville M., Stensitzki T., Allen D. B., Ingargiola A., 2014, *LMFIT: Non-Linear Least-Square Minimization and Curve-Fitting for Python*, recordascl:1606.014
- Nikonov A. S., Kovalev Y. Y., Kravchenko E. V., Pashchenko I. N., Lobanov A. P., 2023, *MNRAS*, 526, 5949
- Nolting C., Ball J., Nguyen T. M., 2023, *ApJ*, 948, 25
- Offringa A. R. et al., 2014, *MNRAS*, 444, 606
- Paragi Z., Vermeulen R. C., Fejes I., Schilizzi R. T., Spencer R. E., Stirling A. M., 1999, *A&A*, 348, 910
- Perucho M., Martí-Vidal I., Lobanov A. P., Hardee P. E., 2012, *A&A*, 545, A65
- Ramaila A. J., Smirnov O., Heywood I., 2023, record ascl:2305.009
- Rankin J. et al., 2024, *ApJ*, 961, L8
- Russell T. D. et al., 2019, *ApJ*, 883, 198
- Savard K., Matthews J. H., Fender R., Heywood I., 2025, *MNRAS*, 540, 1084
- Schandl S., Meyer F., 1994, *A&A*, 289, 149
- Schulz N. S., Kallman T. E., Heinz S., Sell P., Jonker P., Brandt W. N., 2020, *ApJ*, 891, 150
- Sell P. H. et al., 2010, *ApJ*, 719, L194
- Shaham J., 1977, *ApJ*, 214, 251
- Soleri P., Tudose V., Fender R., van der Klis M., Jonker P. G., 2009, *MNRAS*, 399, 453
- Spencer R. E., Rushton A. P., Bałucińska-Church M., Paragi Z., Schulz N. S., Wilms J., Pooley G. G., Church M. J., 2013, *MNRAS*, 435, L48
- Storn R., Price K., 1997, *J. Global Optimization*, 11, 341
- Tennant A. F., Fabian A. C., Shafer R. A., 1986, *MNRAS*, 221, 27P
- Tominaga M., Tsujimoto M., Ebisawa K., Enoto T., Hayasaki K., 2023, *ApJ*, 958, 52
- Tudose V., Fender R. P., Tzioumis A. K., Spencer R. E., van der Klis M., 2008, *MNRAS*, 390, 447
- van der Walt S. et al., 2014, *PeerJ*, 2, e453
- Veresvarska M. et al., 2024, *MNRAS*, 534, 3087
- Vernaleo J. C., Reynolds C. S., 2006, *ApJ*, 645, 83
- Virtanen P. et al., 2020, *Nat. Methods*, 17, 261
- Whelan J. A. J. et al., 1977, *MNRAS*, 181, 259
- Yang Z.-X. et al., 2024, *ApJ*, 970, L33
- Yoon D., Heinz S., 2015, *ApJ*, 801, 55
- Yu Z. L. et al., 2024, *MNRAS*, 527, 8029
- Zhang P. et al., 2023, *A&A*, 677, A178

## APPENDIX A: PRECESSION FIT PARAMETERS

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.  
**Table A1.** Parameters for the ballistic precession model shown in Fig. 1. These parameters should not be interpreted as uniquely constraining.

| Command                              | Output      |
|--------------------------------------|-------------|
| $P$ , period (d)                     | 8160        |
| $v_j$ , jet velocity                 | $0.7c$      |
| $\psi$ , opening angle               | $35^\circ$  |
| $\chi$ , position angle E of N       | $300^\circ$ |
| $i$ , inclination                    | $37^\circ$  |
| $\phi$ , precession phase            | 0.58        |
| $s_{\text{rot}}$ , sense of rotation | -1          |