SEARCHING FOR A PARSEC-SCALE JET IN THE CHANGING-LOOK AGN NGC 3516

Scientific Justification

Active galactic nuclei (AGN) are luminous centres of galaxies that are accreting matter on to supermassive black holes (Rees, 1984). Many AGN have been found to show high spectral variability, especially in the broad emission line components. The appearance or disappearance of the broad line in AGN spectra is known as a 'changing-look' event. These events could be explained by invoking either a clumpy torus which can periodically obscure the broad line region or a changing accretion rate which reduces the continuum and thus line emission flux (Ricci & Trakhtenbrot, 2023). Changing-Look (CL) AGN have seen an increase in multi-wavelength observation campaigns aimed at distinguishing between these scenarios. While the X-ray spectrum differs somewhat between these two scenarios, it is possible for changing accretion rate to mimick the effects of changing obscuration (Mehdipour et al., 2022).

In the presence of such uncertainty regarding the mechanisms involved in changing-look events, radio observations at parsec scales become crucial. The best way to probe parsec-scale structure is through the technique of Very long baseline interferometry (VLBI) which can give us angular resolutions of a few milliarcseconds. For nearby AGN ($z < 0.1$), this means probing parsec-scale structure. Examining the morphology as well as radio brightness of an AGN in the aftermath of a CL event at such scales would help us probe the nature of the CL event and help us distinguish between the two possible scenarios for such an event.

NGC 3516 is a barred spiral galaxy at a redshift of 0.0088 (Miyaji et al., 1992), and a changing-look Seyfert galaxy. It shows an S-shaped morphology in both radio outflows and emission line gas. Our investigation into the kiloparsec-scale structures of this galaxy revealed that the radio jet likely entrains the emission line gas causing it to follow the same morphology. We find that the bending of the radio jet itself can be well explained by precession of the jet ejection axis using the precessing jet model of Hjellming & Johnston (1981) as shown in Figure 1 (Ghosh et al, in preparation). The jet velocity obtained from this model is in good agreement with the velocity obtained using the jet to counter-jet flux density ratio and spectral index from archival VLA observations. Such precession can be best explained either by the presence of binary black holes or by accretion disk instabilities.

NGC 3516 also shows very high spectral variability in optical, UV and X-ray bands. While it was originally identified as a Type 1 Seyfert showing both broad and narrow lines, it showed a CL event in 2014 following which the broad line component entirely disappeared (Ilić et al., 2023). The extremely high variability observed in this AGN could be explained by accretion disk instabilities which would also explain the precession of the radio jet. In April 2020, there was a flare in hard X-rays observed with *Swift* XRT by Oknyansky et al. (2021) following which the optical and UV continuum also brightened. The broad line component started to brighten as well. This is considered to be the beginning of another changing-look event. While there are many long-term monitoring campaigns for this source, its radio variability has not been previously explored. Radio studies would enhance the understanding of the source that we have gained from the existing multi-wavelength studies. The emergence of a new radio jet coincident with the trend of broad-line brightening would indicate that the CL events and the precession of the jet have a common origin in accretion disk instabilities in this source.

Recently, Meyer et al. (2024) found evidence of a new radio jet in the CL AGN 1ES 1927+654. This source started to show high variability in the X-ray band following the changing-look event in 2017. In 2023, they observed the emergence of a new radio jet at parsec-scales using VLBI. This was concurrent with a steady increase in soft X-rays. The new radio outflow was detected about 1800 days after the CL event. This discovery further emphasises the need for long-term close radio monitoring of CL sources.

VLBI Observations of NGC 3516

NGC 3516 has been observed with the VLBA at $\sim$ 5 GHz in 2001, 2002 and at $\sim$ 5.6 GHz in 2020. We found that the peak core brightness of the source changed between the two epochs. While the core remained unresolved in 2001 (see Figure 2), extended emission is detected in 2020 (see Figure 2). Given the changes observed in its optical and X-ray spectra, it would be prudent to perform additional VLBA observations of this source. Radio variability at parsec-scales can reflect the evolution of jet components. Further, radio variability can help distinguish between the two possible mechanisms for changing-look events. VLBI observations would allow us to understand the current structure of this source, which would also aid time variability studies when compared with past observations in a similar frequency range. We thus propose to observe this source with dual frequency phase-referenced VLBI.

Questions we wish to address

Some of the interesting new questions that we hope to explore with our VLBI study of NGC 3516 are:

(1) What is the flux density and spectral index of the radio core? How has this changed as compared to similar observations in 2002 and 2020? There have been many changes in the X-ray and optical spectra during the same period, similarity between these and the radio luminosity would offer insights into the origin of the variability in this source. If the trend of broad line brightening reported in 2021 continues, these VLBI observations would also help us probe the nature of the changing-look events in NGC 3516.

(2) Does the VLBA core of NGC 3516 show a core-jet structure? The core appeared unresolved at 5 GHz in 2001 and 2002. However, some diffuse emission could be seen surrounding the core at 5 GHz in 2020 with some indication to the presence of a new inner jet component (see right panel of Figure 2). A follow-up observation would allow us to understand the evolution of this inner jet and confirm whether a new component is present.

Dual frequency VLBA observations would help us distinguish between the core, jet, and diffuse emission on the basis of the spectral indices of these features. We would expect the core to have a flat or inverted spectral index and the jet to have a spectral index of ~ -0.7. However, it is unclear what the spectral index of the diffuse emission in the north-south direction would be. For instance, high resolution observations of Cygnus A revealed a radio structure perpendicular to the jet with a spectrum consistent with free-free emission ($\alpha = -0.1$) and was suggested to be the obscuring torus by Carilli et al. (2019). The proposed observations would therefore allow us to probe a possible connection between the emergence of radio jet components and other changing-look events.

(3) In case an inner jet structure is visible, it could indicate a connection between the emergence of radio jet components and changing-look events, such as the one studied by Meyer et al. (2024). Observations of the inner jet would also allow us to probe the direction of the jet ejection axis and changes therein since 2020. This would allow us to further constrain the kpc-scale modelling of the radio jet as a precessing jet.

With our proposed observations of NGC 3516, we will obtain invaluable information about the radio core and jet of a changing-look AGN. This would supplement existing archival data and help us establish the origin of the changing-look behaviour in NGC 3516. Such a study is crucial to facilitate our understanding of AGN geometry, accretion and evolution.

Technical Justification

We propose to observe NGC 3516 with the ten antennas of the VLBA in a phase-referencing experiment at 1.4 and 5 GHz. We propose to observe the source for for 5 hours in each frequency. The nearby calibrator J1048+7143 will be used as a phase reference calibrator. The observation will be conducted in the "nodding" mode in a 7 minute cycle with 3 minutes on the calibrator and 4 minutes on the source for good phase calibration, in keeping with earlier phase-referenced

VLBA observations of this source. Thus, the total time spent on the source and the phase calibrator will be ~ 8.75 hours at each frequency.

In addition to the source and the calibrator, two or more 5 minute scans of a fringe-finder will be observed through the experiment. Therefore, observation time of 9 hours per frequency, and total observation time of 18 hours is requested. Using the EVN exposure time calculator[1] for the VLBA, we find that such an observation would have a thermal noise of ~ 7.4 μJy beam^{-1} at 5 GHz and ~ 10.2 μJy beam^{-1} at 1.4 GHz. This is lower than the noise levels in previous observations and will thus allow us to probe the evolution of the structures seen in previous observations at a higher sensitivity.

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[1] https://planobs.jive.eu/

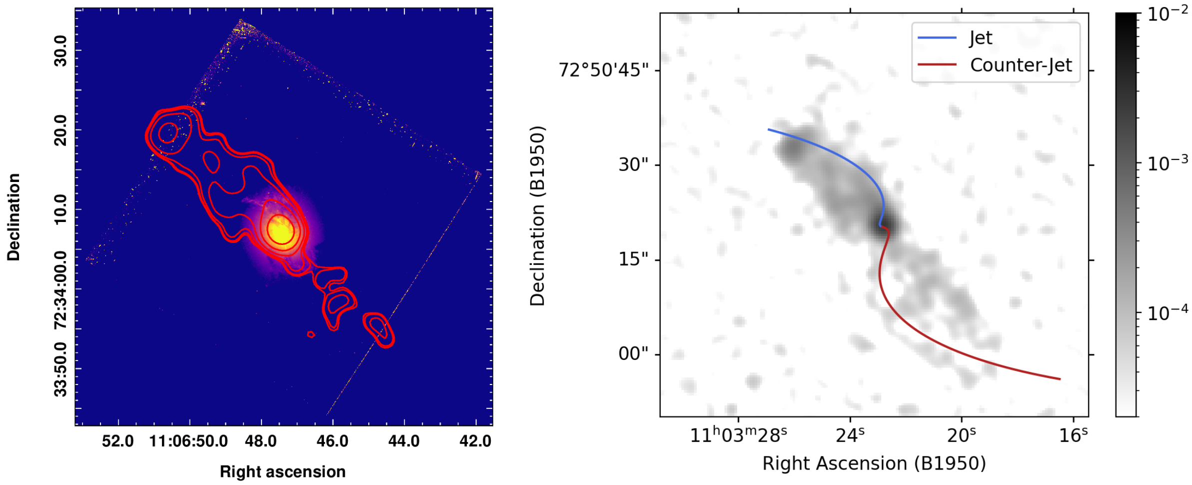

Figure 1: (Left) Contours from the VLA 8.5 GHz image (dataset with project code AB942) overlaid on Hubble Space Telescope (HST) WFPC2 [OIII] emission line image (Schmitt et al., 2003) showing correspondence in S-shape in the emission line gas as well as radio emission. (Right) Best-fit predictions of our precessing jet model overlaid on the VLA 8.5 GHz image shown alongside. The precession model closely predicts the trajectory of the jet spine terminating in a hotspot where the collimated jet breaks up into a more diffuse lobe (Ghosh et al, in preparation).

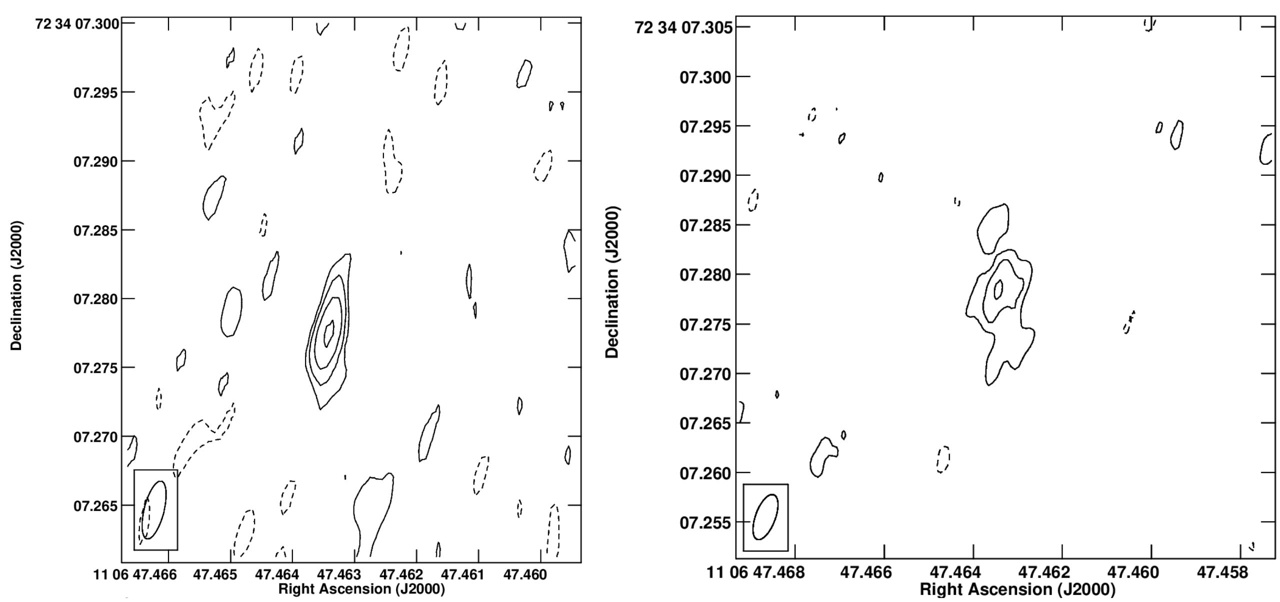

Figure 2: (Left) VLBA 4.98 GHz image from February 2002 showing a compact core with peak flux density 1.63 ± 0.1 mJy beam^{-1}, using archival dataset with project code BS104. The RMS noise level in the image is 0.1 mJy beam^{-1}. (Right) VLBA 5.68 GHz image from September 2020 showing diffuse emission in the North-South direction with a possible new jet component in the East-West direction. The core has peak flux density 0.76 ± 0.06 mJy beam^{-1}, using archival dataset with project code UC001D. The RMS noise level in the image is 0.06 mJy beam^{-1}.