Multifrequency VLBI Observations of the M84 Inner Jet/Counterjet

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Abstract

Observational studies of the innermost regions of the edge-on jets in nearby active galactic nuclei (AGN) are crucial to understanding their kinematics and morphology. For the inner jet of the nearby low-luminosity AGN in M84, we present new high-sensitivity observations with very long baseline interferometry since 2019, as well as archival Very Long Baseline Array observations in 2014. We find that the compact core in M84 has an inverted-to-flat spectrum from 1.5–88 GHz. Based on the turnover frequency of 4.2 ± 0.2 GHz in the spectrum, we estimate a magnetic field strength of 1–10 mG and an electron number density of ~10^5 cm^-3 in the core region. Three inner jet components within ~3 mas of the core are identified and traced in the images at 22 GHz, whose apparent speeds are 0.11 c, 0.27 c, and 0.32 c, respectively. We calculate the viewing angle of 58° ± 15° for the inner jet based on the proper motion and the flux ratio of jet to counterjet. A propagating sinusoidal model with a wavelength of ~3.4 mas is used to fit the helical morphology of the jet extended to 20 mas (~2.2 × 10^4 Schwarzschild radii).

Unified Astronomy Thesaurus concepts: Relativistic jets (1390); Low-luminosity active galactic nuclei (2033); Very long baseline interferometry (1769)

1. Introduction

M84 (NGC 4374, 3C 272.1) (z = 0.00339, D = 18.4 Mpc) is an elliptical galaxy in the Virgo cluster with a low-luminosity active galaxy nucleus (LLAGN). The central supermassive black hole, with a mass of 8.5 × 10^8 M_☉ measured by the gas kinematics (Walsh et al. 2010), or 1.8 × 10^8 M_☉ estimated from the velocity dispersion (Ly et al. 2004), launches a weak Fanaroff–Riley type I radio jet. A two-sided jet was observed at radio and UV wave bands (Meyer et al. 2018). A large viewing angle of 74° ± 18° was calculated based on the outer jet at the hundreds of parsec scale with its jet-to-counterjet flux ratio and apparent speed. The inner jet at the sub-parsec scale near the compact core has been studied in the radio band using the very long baseline interferometry (VLBI) technique. Very Long Baseline Array (VLBA) observation at 5 GHz clearly showed two-sided extended structures (Nagar et al. 2002). A high angular resolution VLBI image at 43 GHz exhibited a compact core with a slight extension to the north (Ly et al. 2004). Nakahara (2014) adopted a dual-beam phase-referencing technique and successfully detected the radio emission from M84 at 22 and 43 GHz with the VLBI Exploration of Radio Astrometry. They also found a jet-like structure extended to the north at 22 GHz with a peak flux of 71 mJy, while the peak flux at 43 GHz was about 63 mJy.

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Among the nearby active galactic nuclei (AGN), M84 is one of the rare sources with obvious two-sided jets in the low-frequency VLBI images. Other similar sources such as Centaurus A (Janssen et al. 2021) and NGC 1052 (Baczko et al. 2019), have masses of one order of magnitude lower than M84. Previous VLBI studies on M84 focused on the basic structure and the emission of jet, without deeper studies and discussion of the kinematics and the morphology of the inner jet. The source with a large viewing angle provides an opportunity to study the disk-jet connection near the event horizon. Such a source will play an important role in understanding LLAGN with the improvement of the sensitivity and the angular resolution of VLBI.

In this paper, we present multifrequency and multi-epoch observations to probe the inner jet of M84. Our observational data and data reduction are described in Section 2; The results and a discussion of the proper motion, the viewing angle, and the ridge structure are presented in Section 3. These results are summarized in Section 4. We adopt an angular distance scale of 89 pc arcsec^{-1}. For the supermassive black hole mass of 8.5 × 10^8 M_☉ (Walsh et al. 2010), M84 has a Schwarzschild radius of ~0.9 μas. The apparent angular size of the black hole shadow of M84 assuming zero spin is 4.7 μas (Roelofs et al. 2019) (or even larger to 10 μas with a mass of 1.8 × 10^8 M_☉). The event horizon in M84 could be approached by a future submillimeter VLBI technique (Jiang et al. 2021; Raymond et al. 2021).
We observed M84 with VLBI arrays, including the VLBA at multifrequency, in three epochs and the East Asian VLBI Network (EAVN) at 22 GHz in one epoch. Additionally, data in two epochs at 1.5, 5, and 15 GHz from the public VLBA archive system were reanalyzed. The data we observed and reanalyzed in this paper are listed in Table 1.

**Table 1**

| Code      | Array  | Date (yyyy/mm/dd) | Frequency (GHz) | Beam (mas × mas, deg) | Core flux (Jy) | rms (mJy beam⁻¹) |
|-----------|--------|-------------------|------------------|------------------------|---------------|-----------------|
| bj094a    | VLBA   | 2019/6/22         | 22.0             | 1.37 × 0.40, −13.8     | 0.086 ± 0.011 | 0.11            |
| a19xw01a  | EAVN   | 2019/12/20        | 22.2             | 1.44 × 0.61, 17.8      | 0.101 ± 0.011 | 0.11            |
| bx014     | VLBA   | 2020/6/2          | 4.9 (b)          | 3.46 × 1.65, −5.1      | 0.125 ± 0.012 | 0.04            |
| bj094b    | VLBA   | 2021/3/31         | 44.1 (e)         | 0.56 × 0.23, −17.8     | 0.086 ± 0.012 | 0.15            |
| bh186d*   | VLBA   | 2014/3/26         | 1.5 (a)          | 12.9 × 6.43, 16.6      | 0.061 ± 0.009 | 0.08            |
|           |        |                   | 5.0              | 3.86 × 1.99, 18.3      | 0.080 ± 0.009 | 0.07            |
|           |        |                   | 15.5 (c)         | 1.26 × 0.65, 19.0      | 0.093 ± 0.012 | 0.11            |
| bh186e*   | VLBA   | 2014/5/8          | 1.5              | 10.4 × 4.97, −1.3      | 0.067 ± 0.008 | 0.06            |
|           |        |                   | 5.0              | 3.17 × 1.61, −1.4      | 0.091 ± 0.010 | 0.06            |
|           |        |                   | 15.5             | 1.07 × 0.55, −4.2      | 0.080 ± 0.011 | 0.10            |

**Note.** Columns (1)–(5) VLBA/EAVN legacy experiment code (* denotes data from the public archive), VLBI array, observing date, frequency, and FWHM of the synthesized beam under natural weighting, respectively. The letters in parentheses listed in the frequency column correspond to the same labels in Figure 1; (6) The flux of the core component; (7) The rms noise of images.

2. Observations and Data Reduction

We observed M84 with VLBI arrays, including the VLBA at multifrequency, in three epochs and the East Asian VLBI Network (EAVN) at 22 GHz in one epoch. Additionally, data in two epochs at 1.5, 5, and 15 GHz from the public VLBA archive system were reanalyzed. The data we observed and reanalyzed in this paper are listed in Table 1.

**VLBA data:** The frequencies in VLBA epochs we observed cover 5, 22, 44, and 88 GHz. All 10 antennas participated in the observation of bx014 (the VLBA legacy experiment code and the same below), while bj094a was without the antenna FD and bj094b was without the antennas SC and HN. The data were recorded at recording rates of 2, 2, and 4 Gbps. The total bandwidths were 512, 512, and 1024 MHz splitting into 8, 4, and 8 intermediate frequency (IF) bands in bj094a, bx014, and bj094b, respectively. Bright sources M87 and 3C 273 were used as the calibrators in all these epochs.

We also analyzed two epoch data in 2014 with an interval of 43 days from NRAO science data archive at 1.5, 5, and 15 GHz. These data were used as a complement to the spectrum analysis and the flux ratios of the jet to the counterjet.

**EAVN data:** We observed M84 with EAVN on 2019 December 20. There were nine antennas participating in the observation. It had an angular resolution of ~0.55 mas and an image sensitivity of ~75 μJy (Cui et al. 2021). The data were recorded at a recording rate of 1 Gbps in left-hand circular polarization with 8 IFs and each IF had a bandwidth of 32 MHz.

The VLBA data were correlated by the VLBA correlator in Socorro, New Mexico. The EAVN data were correlated by the Daejeon correlator at the Korea-Japan Correlation Center (Lee et al. 2015). The amplitude and phase were calibrated using the NRAO Astronomical Image Processing System (Greisen 2003). The phase at 88 GHz was calibrated with source-frequency phase-referencing and its image was reported in Jorstad et al. (2017). The data exported from AIPS were loaded into the DIFMAP software package (Shepherd 1997). The CLEAN and self-calibration procedures were used to obtain the final images. We present the self-calibrated and natural weighting images from 1.5–88 GHz in Figure 1. The self-calibrated data were then fitted with circular Gaussian components through the MODELFIT function to extract four parameters of each component (flux, distance from the core, position angle, and component size).

The flux of the core component in a19xw01a has been multiplied by a factor of 1.3 to correct the flux losses caused by the EAVN backend system and correlation (Lee et al. 2015). The self-calibrated fluxes in bj094a, bj094b, and bx014 are scaled up by a factor of 1.15 because all VLBA data obtained after 2019 April 15 have suffered a systematic decrease on all baselines (Lister et al. 2021). For the flux at 88 GHz, we refer to the nearby calibrator source M87, whose core fluxes at 86 GHz were reported in Kim et al. (2018). We adopt its average flux in the stable period according to the light curve because no flare has been reported during our observation. A scaling factor of 2.17 is used and a corrected flux of 0.083 ± 0.016 Jy is obtained for M84 at 88 GHz.

In this paper, the errors of fluxes are estimated from the brightness temperatures (Jorstad et al. 2017): σ_f ≈ 0.097σ_b,obs and the errors of positions are approximated as σ_x,y ≈ 1.3 × 10^{-4}σ_{b,obs}^{−0.6} plus a minimum error of one-fifth angular resolution.

3. Results and Discussion

3.1. VLBI Images

The VLBI images from 1.5–88 GHz are shown in Figure 1. The noise levels in the new images are significantly improved compared with previous studies because of the improvement in sensitivities. These images show richer structures such that we can identify the corresponding components in three epochs at 22 GHz. All images show a core-jet structure. The jet at 1.5 GHz extends to about 60 mas, or ~5.3 pc projected in the celestial plane, which shortens at higher frequencies due to the steep spectrum of the synchrotron radiation. These images, especially at frequencies less than 22 GHz, show an elongated and collimated jet whose overall direction is almost due north while the counterjet is southward. The jet directions at each frequency are consistent, including the image at 88 GHz, in which the extended structure is down at a distance of ~400 R_g along the jet from the core. Such a morphology coincides with the outer radio jet observed by the Very Large Array and the...
Atacama Large Millimeter/submillimeter Array (ALMA; Meyer et al. 2018). The jet is locally oscillating around the position angle of 0°, which is more obvious at higher angular resolution. Details on the ridge structure are discussed in Section 3.3.

The spectrum of the core components from 1.5–88 GHz is overall inverted to flat as shown in Figure 2. Some extra data points at 2.3, 5, 8.4, and 15.4 GHz are quoted from Hada et al. (2011) denoted by Hada+2011, as well as the data from the Astrogeo VLBI FITS image database10 for verification and to complement the spectral analysis. The data from ALMA at 230 GHz (Boizelle et al. 2017), whose relatively higher flux is due to the low angular resolution and the blended emissions from the accretion disk (Raiteri et al. 2014), and thus is referenced as an upper limit and not used for spectrum fitting. We fit the spectrum of the core following the flux-frequency equation described in Kosogorov et al. (2022) from 1.5–88 GHz. The spectral index in the low frequency is set as +2.5 due to the synchrotron radiation self-absorption. We

Figure 1. VLBI images of M84 with natural weighting from 1.5–88 GHz. The parameters of the images are listed in Table 1. The contours are plotted at increasing powers of $\sqrt{2}$ from 3σ. The beam is plotted in the right lower corner.

Figure 2. Spectrum of the M84 core. The blue circulars denote the core fluxes of this work and the green square denotes the core fluxes of Hada+2011 (Hada et al. 2011). The violet diamond denotes the data from the ALMA observation as a reference in the submillimeter wavelength. The gray triangle is the compact flux from the AstroGeo database. The black solid line is the fitted curve.

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10 http://astrogeo.org since 2014 denoted by Astrogeo.
obtain an inverted-to-flat curve and a spectral index of $\alpha_c = -0.12 \pm 0.02$ for the flat spectrum, which is consistent with the result reported in Nakahara (2014). The estimated turnover frequency is $\nu_m = 4.2 \pm 0.2$ GHz and the corresponding flux is $F_m = 0.105 \pm 0.010$ Jy. We obtain a magnetic field strength of the order of $1 \sim 10$ mG and an electron density of $\sim 10^5$ cm$^{-3}$ following the equations in Hirotani (2005) with an estimated angular diameter of the core $0.28 \pm 0.03$ mas, which is derived from the fitted relation between the core size and the frequency.

The components in the counterjet are found in most of images. Even in the image at 88 GHz with a large rms, the core appears to be slightly extended to the south.

### 3.2. Jet Proper Motion and Viewing Angle

The jet proper motion was monitored at 22 GHz in three epochs throughout 1 yr. The proper motion between bh186d and bh186e at 15 GHz is checked. The components in these two epochs with an interval of 43 days are a one-to-one correspondence with slight position displacements, which means the apparent speed is not too large to cause a dislocation of the components. Therefore, the adjacent components at 22 GHz in three epochs separated every 6 months could be recognized as the same components. The displacements of components are obvious in both the model fitting and the bright features in the images as shown in Figure 3.

Three components named Na, Nb, and Nc are identified in the jet, whose position parameters are listed in Table 2 and their increasing separations from the core over time are plotted in Figure 3. We also examine the flux profile along the ridge line, where we can find the corresponding components obtained from model fitting. The final fitting result of proper motions still has non-negligible uncertainties and a risk in calculating the apparent speeds. The uncertainties are mainly from the insufficient cadence of epochs and the model fitting. The fitted proper motions are about 0.36, 0.93, and 1.11 mas yr$^{-1}$, equivalent to apparent speeds of 0.11$c$, 0.27$c$, and 0.32$c$, respectively. These speeds are much less than that in the outerjet, $>3$ mas yr$^{-1}$ (Meyer et al. 2018).

A counterjet toward the south is obviously seen at frequencies below 22 GHz, whose direction is consistent with the kiloparsec-scale counterjet. For the two-sided jet, the flux ratio of jet to counterjet is used to calculate the viewing angle of the inner jet:

\[
R_{\text{flux}} = \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^{2-\alpha_c}.
\]

where $\alpha_c$ is the spectral index of the jet; $\beta$ is the intrinsic speed in units of $c$ and $\theta$ is the viewing angle. We restore the images with a circular beam and compute the flux ratio between slices that are equidistant from the core. The cutoff flux of counterjet larger than 15$\sigma$ along the ridge line is selected in bx014. We calculate the ratios in regions of 4.0 $\sim$ 5.4 mas at 5 GHz and 0.9 $\sim$ 1.2 mas at 22 GHz, where the ratios are 2.1 $\sim$ 5.0 and 1.6 $\sim$ 2.2, respectively. The former region is farther than Nc, whose increasing flux ratio with distance from the core indicates that the jet is accelerating, and thus has a larger apparent speed estimated as $0.4 \pm 0.1$ $c$. The latter one is between components Na and Nb, so its apparent speed is estimated as $0.2 \pm 0.1$ $c$. Combining Equation (1) with the

![Figure 3. Time evolution of M84 at 22 GHz. Green, blue, and red (or circulars) represent the components of Na, Nb, and Nc, respectively. The dotted lines are used to fit their speeds. The contours are plotted at increasing powers of $\sqrt{2}$ from 0.3 mJy. The circular beam is plotted in the left lower corner.](image)

| Component | Interval (day) | Distance (mas) | A. (deg) | FWHM (mas) |
|-----------|---------------|---------------|---------|------------|
| Na        | 0             | 0.58 ± 0.16   | 4.4     | 0.03       |
|           | 181           | 0.76 ± 0.17   | 7.9     | 0.03       |
|           | 346           | 0.96 ± 0.31   | 2.1     | 0.17       |
| Nb        | 0             | 1.25 ± 0.46   | 2.7     | 0.30       |
|           | 181           | 1.58 ± 0.46   | 6.1     | 0.27       |
|           | 346           | 2.13 ± 0.64   | −5.3    | 0.34       |
| Nc        | 0             | 2.22 ± 0.41   | 5.6     | 0.16       |
|           | 181           | 2.80 ± 0.53   | −2.5    | 0.26       |
|           | 346           | 3.20 ± 1.43   | 1.9     | 0.86       |

**Note.** Parameters of Gaussian components in three epochs at 22 GHz. The distance from the core, position angle, and FWHM of the circular Gaussian are listed under Columns 3–5, respectively.
equation of apparent speed

\[ \beta_{\text{app}} = \frac{\beta \sin \theta}{1 - \beta \cos \theta} \]  

(2)

We could constrain the viewing angle under the assumption of intrinsic symmetry between the jet and the counterjet. The spectral index of jet \( \alpha_j \) in Equation (1) is presumed to be the normal value of \(-1\). As shown in Figure 4, the viewing angle is \( 59^{+16}_{-26} \) at 22 GHz and \( 57^{+15}_{-17} \) at 5 GHz. These two results are similar, and are both smaller than the result from the outer jet (74\(^\circ\)\(^+9\)\(^-8\)) (Meyer et al. 2018). The overlapping angle from the two results is \( 58^{+17}_{-18} \).

The intrinsic speeds of the components in Table 2 after applying the viewing angle of \( 58^\circ \) to Equation (2) are 0.12 \( c \), 0.27 \( c \), and 0.32 \( c \), at an average de-projected distance of 980, 2100, and 3700 \( R_s \), respectively. The distribution of intrinsic speeds versus distance from the core in units of Schwarzschild radius is at the same level as that in NGC 1052 (Baczko et al. 2019).

### 3.3. Jet Oscillation

It is noticed that the jet morphology in M84 is oscillatory indicated by the changing orientation angle of the ridge line. We mainly focus on the images at 5 GHz, where the jet structure is reconstructed with a high sensitivity and thus a high dynamical range. The ridge lines of wave-like morphology in bx014 and bh186e restored with a circular beam under natural weighting are shown in Figure 5. In order to exclude the possibility that an oscillatory morphology might be caused by the sidelobes when we carried out the CLEAN and self-calibration procedures, we checked the ridge line in the image under a uniform weighting scheme, and found that the directions of the ridge line are consistent with the one under the natural weighting scheme shown in Figure 5. Moreover, such morphology is found in both bx014 and bh186e with a similar oscillatory wavelength. Thus, the oscillation in M84 is considered as a true structure.

An oscillatory jet is generally considered to have been caused by the precession of the central engine or by Kelvin–Helmholtz (KH) instability. For instance, a binary black hole system can generate the precession of jet due to the orbital motion of the primary black hole (Villata & Raiteri 1999), but M84 is an elliptical galaxy and shows no obvious clues about the existence of a binary black hole. KH instability is another general interpretation of the jet oscillation in many sources, such as 3C 273 (Lobanov & Zensus 2001), S5 0836+710 (Vega-García et al. 2020), and M87 (Hardee & Eilek 2011).

Following the model in Lobanov & Zensus (2001), the jet oscillation can be modeled by a combination of several helical waves. In our model, a single apparent pattern with a wavelength of \( \lambda_{\text{obs}} \approx 3.4 \) mas is used to characterize the oscillation of the ridge line. Figure 5 shows the fitting results between the jet ridge and a model of the single sinusoidal mode after \( 58^\circ \) projection in two epochs. Some discrepancies between the model and ridge lines can be interpreted as enlarged errors further away from the center of the image or the growing amplitudes of some other potential wave modes of KH instability. It is rare to find a single wave pattern of KH instability to characterize the jet oscillation. A superposition of several oscillatory patterns of KH instability is common in other sources (Vega-García et al. 2020). An explanation is that one pattern of KH instability is dominant, while other patterns are still growing and do not fully appear, especially considering that the observed region \( (10^\circ \sim 10^3 R_s) \) in M84 is the innermost jet. We find that the improvement of angular resolution will lead to an increased amplitude when comparing the images under different beam sizes, while the phase along the propagation direction does not change. This is reasonable as the flux distribution would be smoothed at a low resolution. The amplitude will reach an upper limit when the transverse jet is completely resolved. We check the image restored under uniform weighting, whose ridge line gradually tends to coincide more with that shown in Figure 5(b) along the jet. The jet in the downstream region could be considered to be completely resolved.

The model also works in the image at 22 GHz in bx014 with only an initial phase difference of \( \sim 40^\circ \) from the simultaneous image at 5 GHz (Figure 5(b)). If this difference is caused by the core shift, its approximate value between 5 and 22 GHz would be 0.38 mas. The magnetic field strength estimated from this core-shift value following Kosogorov et al. (2022) is also at the same level of several milligauss.

The Mach number in the jet \( M_j \) and in the ambient medium \( M_a \), as well as the the particle density ratio of the jet to the ambient medium \( \eta = M_j^2/M_a^2 \) can be calculated with accurate values of the characteristic wavelength, the jet radius, the viewing angle, the jet apparent speed, and the apparent pattern (or wave) speed (Vega-García et al. 2020). For the surface and helical mode, the characteristic wavelength is \( 1.5 \lambda_{\text{obs}} \). The only parameter that we could not determine is the apparent pattern speed. The phase difference between two images at 5 GHz (Figure 5) is \( \sim 130^\circ \). This indicates that the wave has propagated at least \( 130^\circ \) over 6 yr. If the wave has propagated \( n \) periods, the apparent pattern speed will be about
0.06 + 0.16c. Dedicated dense observations are required to measure the apparent pattern speed in the future.

4. Summary

In this paper, we report a detailed analysis of the inner jet/counterjet of M84 through multifrequency and multi-epoch observations. We present VLBI images from 1.5–88 GHz, whose morphologies show core-jet structures. We fit the fluxes in core components and obtain an inverted-to-flat spectrum from 1.5–88 GHz, whose magnetic field strength and electron number density are estimated based on the turnover frequency.

The apparent speeds for three components near the core are about 0.11c, 0.27c, and 0.32c. These different speeds and the distribution of flux ratios of jet to counterjet indicate that a significant acceleration is occurring in the inner region. This result is consistent with the general acceleration scale in other active galactic nuclei. Considering the relatively large viewing angle of 58°18′, the intrinsic speeds are moderately relativistic.

We use a single wave mode of the KH instability to explain the sinusoidal-like jet morphology at 5 GHz. The model with an apparent wavelength of about 3.4 mas can well fit the ridge line in two images. This wave-like ridge line and KH instability model in M84 should be examined with further dedicated observations.

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