LETTER TO THE EDITOR

Radio jet precession in M 81*

S. D. von Fellenberg�, M. Janssen1, J. Davelaar3,4, M. Zajaček5, S. Britzen1, H. Falcke2, E. Körding2, and E. Ros1

1 Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, Bonn 53121, Germany
e-mail: sfellenberg@mpifr-bonn.mpg.de
2 Department of Astrophysics, Institute for Mathematics, Astrophysics and Particle Physics (IMAPP), Radboud University, PO Box 9010, 6500 GL Nijmegen, The Netherlands
3 Department of Astronomy and Columbia Astrophysics Laboratory, Columbia University, 550 W 120th Street, New York, NY 10027, USA
4 Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Avenue, New York, NY 10010, USA
5 Department of Theoretical physics and Astrophysics, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

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ABSTRACT

We report four novel position angle measurements of the core region M 81* at 5 GHz and 8 GHz, which confirm the presence of sinusoidal jet precession in the M 81 jet region, as suggested by Martí-Vidal et al. (2011, A&A, 533, A111). The model makes three testable predictions regarding the evolution of the jet precession, which we test in our data with observations from 2017, 2018, and 2019. Our data confirm a precession period of ∼7 yr on top of a small linear drift. We further show that two 8 GHz observation are consistent with a precession period of ∼7 yr but show a different time lag with respect to the 5 GHz and 1.7 GHz observations. We do not find a periodic modulation of the light curve with the jet precession and therefore rule out a Doppler nature for the historic 1998–2002 flare. Our observations are consistent with either a binary black hole origin for the precession or the Lense-Thirring effect.

Key words. galaxies: jets

1. Introduction

The galaxy M 81 appears as a bright radio source and is located at a distance of 3.36 ± 0.34 Mpc (Freedman et al. 1994). The black hole in the center of M 81 belongs to the class of low-luminosity active galactic nuclei (LLAGN) and exhibits relatively weak radio emission ($F_{\nu=4.8\text{GHz}} \sim 150 \text{mJy}$; e.g., Brunthaler et al. 2006). It is the closest LLAGN to Earth. Due to its low apparent luminosity, it serves as an optimal test bed for characterizing this class of accreting black hole (Markoff et al. 2008). As such, it may be the best candidate for bridging the accretion processes of LLAGN to that of Sgr A* (GRAVITY Collaboration 2020). M 81 shows slow changes in radio flux density on yearly timescales (e.g., Ho et al. 1999). Further, it shows fast intra-day flare-like variability at millimeter wavelengths (Sakamoto et al. 2001). This radio and millimeter behavior is consistent with the van der Laan expanding-blob scenario (van der Laan 1966). Here, the millimeter variability is created by blobs that expand as they move along the jet, where they become observable in the radio (Ho et al. 1999; Sakamoto et al. 2001). In the X-ray, M 81 is detected with a luminosity of $\sim 10^{36} \text{erg s}^{-1}$ and flux changes on the order of a few tens of percent (Ishisaki et al. 1996). The overall spectral energy distribution was modeled with a jet-dominated ADAF model by Markoff et al. (2008) using a set of simultaneous multiwavelength observations of M 81 and shows remarkable similarity to that of Sgr A* (e.g., von Fellenberg et al. 2018).

M 81*, the core region of M 81, is a regular target for global very-long-baseline interferometry (VLBI) observations, in particular since the explosion of the radio-luminous supernova SN 1993J (Ripero et al. 1993; Weiler et al. 2007). This supernova was located at a close angular separation from M 81* and was thus frequently used as a calibration source. In VLBI observations, M 81* is typically marginally resolved and shows a jet in the northeastern direction. Bietenholz et al. (2000) and Bietenholz et al. (2004) determined that M 81 is at rest with respect to SN1993J. Further, they found a frequency-dependent shift in the peak brightness of M 81*. This is consistent with the known core-shift effect of many active galactic nucleus jets (Marcaide & Shapiro 1984; Lobanov et al. 1998; Kovalev et al. 2008), which is believed to be caused by the synchrotron self-absorption of photons in the jet plasma. In this picture, the apparent shift in the luminous component results from the increasing opacity (and thus increasing luminosity) as a function of wavelength (Blandford & Königl 1979; Konigl 1981; Falcke & Biermann 1995; Marscher & Travis 1996; Davelaar et al. 2018). M 81* shows a decreasing core size (Θ) as a function of frequency, with an almost linear relationship: $\Theta \propto \nu^{0.9}$ (Bartel et al. 1982; Kellermann et al. 1976; Bietenholz et al. 2000; Markoff et al. 2008). This relationship holds down to millimeter frequencies, with a confirmation at 43 GHz (Ros & Pérez-Torres 2012) and one at 87 GHz (Jiang et al. 2018); the latter authors report a relation of $\Theta \propto \nu^{0.89 \pm 0.03}$. 

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Martí-Vidal et al. (2011) confirmed the basic findings reported in earlier works. They further showed that the M 81* intensity peak is shifted as a function of frequency along the direction of the jet using VLBI measurements from 1993 to 2005. Its size increases with decreasing frequency. The authors determined the location of the jet base to within 20 µas of the black hole, and they constrained the black hole mass to \( \sim 2 \times 10^7 M_\odot \) based on the strongly magnetized accretion flow scenario (Kardashev 1995). Alberdi et al. (2013) extended the temporal baseline of observations to the year 2012 and confirmed the basic findings reported in Martí-Vidal et al. (2011).

By fitting elliptical Gaussian models to the central source and, if detected, the jet component, they derived a sinusoidal modulation of the jet position angle. They found a precession period of \( \sim 7 \) yr on top of a linear increase in the position angle of \( \sim 0.5^\circ/\text{yr} \). They found this precession to be present both in their 5 GHz observations and in their 1.7 GHz observations. However, they found a lag of \( 1.9 \pm 0.4 \) years for the precession between the frequency bands, which they interpreted as a core-shift effect. In this picture, the jet shows a differential corkscrew-like precession, and different frequencies probe different regions along the jet. Lastly, they connected the observed jet precession with a four-year flare and argued that the increase in flux is caused by Doppler boosting of the jet along the line of sight.

Their model therefore provides three testable hypotheses: (1) a prediction of the position angle of the core component as a function of time; (2) a prediction of this modulation at different frequencies; and (3) a prediction of the expected flux level at a given time point.

In this Letter we investigate whether the three predictions hold against new VLBI observations of M 81* obtained in the years 2017, 2018, and 2019.

2. Observations and data reduction

In total, we analyzed four sets of observations of M 81*. The first set, obtained by the European VLBI Network (EVN) at 5 GHz in June 2017, was a dedicated observation to measure the position angle of M 81* (Prog. ID ED042, PI Jordy Davelaar). The second set consists of an observation at 8 GHz obtained in June 2018 at the Very Long Baseline Array (VLBA; Prog. ID BJ090, PI Wu Jiang), with the intent to obtain phase-referenced observations of the core-shift effect in M 81*. Lastly, we used 5 GHz and 8 GHz VLBI observations obtained in 2019 for the purpose of studying the jet components in M 81* (Prog. ID BJ099, PI Wu Jiang). All data were reduced using the rPicard\(^1\) VLBI pipeline version v7.1.5 (Janssen et al. 2019), which makes use of CASA v6.5 (THE CASA TEAM 2022) and the latest VLBI features (van Bemmel et al. 2022)\(^2\). To derive the position angle, we fit all data with a single Gaussian model using Difmap (Shepherd et al. 1997). In all cases, the source is marginally resolved; however, we opted for a simple description by a singular Gaussian component to derive a robust measurement of the position angle. Table 1 reports the dates, frequency bands, derived values, and the respective imaging \( \chi^2 \) values. The corresponding maps and models are shown in Appendix D.

In order to obtain an as complete picture of M 81* as possible, we searched the VLBA and EVN archives for available observations since 2012. Several observations at higher frequencies exist, which we do not study in this Letter (e.g., BJ086 and BB303). Three more observations in the L, S, or X band exist: RP023A (EVN), RP023B (EVN), and BD185 (VLBA). They, unfortunately, do not allow a determination of the position angle as the data quality is not sufficient. For RP023A, no long baseline stations participated in the observations. For RP023B, several telescopes suffered from sensitivity losses at the start of the scan, possibly due to being late on source. When the bad measurements were flagged, the scan durations were no longer long enough to obtain good fringe solutions. For BD185, we find large instrumental delay corrections of \( \sim 100 \) ns from the calibrator sources and only a few robust fringe detections on M 81 over the full Nyquist search window. These issues possibly originate from an error in the clock search at the correlator.

We further validated that we can reproduce the values published in Alberdi et al. (2013) with one example (BB293 B), which gives consistent results.

### 2.1. EVN observation

We analyzed a set of 5 GHz VLBI observations carried out by the EVN observatory, which were obtained on 21 June 2017 and which lasted for about 12 h. The IR, YS, TR, SH, NT, MC, WB, JB, and EF\(^3\) stations participated in the observations, and apart from a full loss of the right hand polarization at the EF station, no major technical difficulties occurred. The data were calibrated using observations of J0958+6533.

### 2.2. VLBA BJ090 observation

We analyzed the 8 GHz subset of the observations carried out in the VLBA BJ090 observation campaign from 10 June 2018. The data included the BR, FD, HN, KP, LA, MK, NL, OV, PT, and SC stations and used OJ287, J0954+658, and J1331+305 as calibration sources. No major technical difficulties occurred during the observations, with overall good data quality. The data were reduced in the same fashion as the EVN observations. In addition to the 8 GHz observations (X-band), the BJ090 observations included K-, Q-, and W-band observations, which we did not include in the analysis.

### 2.3. VLBA BJ099 observation

We analyzed the 5 GHz and 8 GHz subsets of the observations obtained as part of the VLBA BJ099 observation campaign, which was carried out on 4 November 2019. The data included the BR, FD, HN, KP, LA, MK, NL, OV, PT, and SC stations and used OJ287 and J0954+658 as calibration sources. While the 5 GHz observations showed overall agreeable data quality, the 8 GHz data set suffered from poor observations by the PT and SC stations. In order to derive a position angle measurement in

\[ \chi^2 \]

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2. For the sake of reproducibility, the pipeline parameters are uploaded to https://doi.org/10.5281/zenodo.7642852.

3. The full names and locations are given in Table E.1.
the 8 GHz band, we excluded the baselines to the PT and SC stations, the latter of which contributes the longest baselines. For both observations, the fit is relatively poor, with reduced $\chi^2$ of 1.9 yr in the 8 GHz observations, but in the opposite direction of 5 yr. This result is driven by the poor data quality. If one disregards the 2019 data, the observations are consistent with a shift of 1.9 years (see Fig. B.1). This illustrates that the available data set is insufficient to test this hypothesis, and future observations are required for a more definitive statement.

### 3.3. No precession-caused flux modulation

Martí-Vidal et al. (2011) proposed that the flare observed in the years 1998–2002 was caused by the variable Doppler boosting of the precessing jet as the viewing angle periodically changes in the linear drift model (Eq. (A.1)), including the new data from 2017 and 2019.

#### Table 2. Best-fit values of the sinusoidal and linear drift model derived from a $\chi^2$ fit to the observed data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sinusoidal model up to 2012</th>
<th>Sinusoidal model up to 2019</th>
<th>Linear drift model up to 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_0$</td>
<td>$(62.9 \pm 0.8)^{\circ}$</td>
<td>$(63.1 \pm 0.8)^{\circ}$</td>
<td>$(62.4 \pm 0.2)^{\circ}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$(0.4 \pm 0.1)^{\circ}/yr$</td>
<td>$(0.5 \pm 0.1)^{\circ}/yr$</td>
<td>$(0.2 \pm 0.2)^{\circ}/yr$</td>
</tr>
<tr>
<td>$A$</td>
<td>$(6.9 \pm 0.8)^{\circ}$</td>
<td>$(6.9 \pm 0.8)^{\circ}$</td>
<td>–</td>
</tr>
<tr>
<td>$T$</td>
<td>$(6.7 \pm 0.2)yr$</td>
<td>$(6.9 \pm 0.2)yr$</td>
<td>–</td>
</tr>
<tr>
<td>$1996 - t_0$</td>
<td>$-$(3.06 ± 0.24) yr</td>
<td>$(3.15 \pm 0.25) yr$</td>
<td>–</td>
</tr>
</tbody>
</table>

#### Notes. The first column shows the model parameters for the different models and data used. The second column shows the best-fit values derived from fitting a sinusoidal model (Eq. (1)) to the data up to 2012, i.e., based on the Martí-Vidal et al. (2011) and Alberdi et al. (2013) data. The third column shows values derived from the sinusoidal model, including the new data from 2017 and 2019. The third column shows the best values of the linear drift model (Eq. (A.1)), including the new data from 2017 and 2019.
3.4. A precession-nutation model for M 81*

Britzen et al. (2018) analyzed the precession and nutation of the resolved jet components of OJ287. In this section we follow their nomenclature in order to derive the intrinsic timescale of the system from the observed (projected) precession and nutation. In Sect. 3.1 we modeled this precession as a sinusoidal modulation plus a linear drift. In Sect. 3.1 we determined the posterior parameters of the model using the multi-frequency data of the core position angle. Thus, we cannot constrain the periodicity of the position angle for the observed modulation. We fit the temporal evolution of the position angle using Eq. (8) of Britzen et al. (2018) and refer the reader to Appendix C for the mathematical details. We determined the posterior parameters of the model using dynasty (Skilling 2006; Feroz et al. 2009; Skilling et al. 2004; Speagle 2020). Figure 4 shows the posterior distributions of the precession period, \( P_p \), the nutation period, \( P_n \), and the precession cone half-angle, \( \Omega_p \). As argued before, the nutation is driving the sinusoidal modulation of the position angle with a period \( P_n \sim 7 \) years, the trend is caused by a large-scale precession of the jet with a largely unconstrained period (i.e., more than 200 years and less than 1800 years), and the precession cone angle is constrained to be positive.

4. Astrophysical origin of precession

Jet precession is observed for many jetted active galactic nuclei, and its origin is typically attributed to being of a purely stochastic nature (i.e., without true periodicity), induced by disk instabilities in tilted accretion disks, or induced gravitationally by a pacemaker companion. Following the arguments presented by Vaughan et al. (2016), we cannot rule out a stochastic-nutation model, the linear trend describes (in the first order of a Taylor expansion) the precession and the additional sinusoidal modulation, the nutation term. The model presented in Britzen et al. (2018), which builds on the model introduced by Abraham (2000), has seven parameters, which are given in Table 3. While some of the older observations resolved the core structure, our prime observable is the position angle of the core on sky, \( \eta(t) \). Further, we do not detect a strong deviation from a linear trend of the core-position angle. Thus, we cannot constrain the periodicity of the jet precession, \( P_p \), directly; we can only constrain its value from the observed nutation and the linear trend. We fit the temporal evolution of the position angle using Eq. (8) of Britzen et al. (2018) and refer the reader to Appendix C for the mathematical details. We determined the posterior parameters of the model using dynasty (Skilling 2006; Feroz et al. 2009; Skilling et al. 2004; Speagle 2020). Figure 4 shows the posterior distributions of the precession period, \( P_p \), the nutation period, \( P_n \), and the precession cone half-angle, \( \Omega_p \). As argued before, the nutation is driving the sinusoidal modulation of the position angle with a period \( P_n \sim 7 \) years, the trend is caused by a large-scale precession of the jet with a largely unconstrained period (i.e., more than 200 years and less than 1800 years), and the precession cone angle is constrained to be positive.

Assuming that the observed modulation is truly periodic, we discuss two possible scenarios for its astrophysical origin. For an accretion disk that is not aligned with the black hole’s spin axis, Lense–Thirring precession (Thirring 1918) induces...
a nodal precession of test particle orbits. The strength of this effect is frequency dependent and thus results in a precessing warp of the accretion disk. Fragile et al. (2007) demonstrated that this can lead to a constant period precession of the disk around the black hole. Such a disk precession is thought to be the cause for the Type-C quasi-periodic oscillations observed in X-ray binaries (e.g., Stella & Vietri 1998) and can be used to estimate the black hole mass and spin using certain assumptions (e.g., Ingram & Motta 2014). Building on the simulations by Fragile et al. (2007), Liska et al. (2018) demonstrated that titled accretion flows are able to launch jets and that the jet precession is aligned with the precession of the disk. In this set of simulations, the amplitude of the jet precession depends on the separation from the black hole, dropping from 100″ at a separation of $R \sim 10R_g$ to ~50″ at 100$R_g$. Further, Fragile et al. (2007) found an empirical relation between the precession period of the disk, $T_p \sim 0.3(m/M_\odot)$ s, which corresponds to roughly 0.2 years assuming a black hole mass of $2 \times 10^7 M_\odot$. Both the amplitude of the oscillation and the precession period are in slight tension with the observed values ($2\Omega_p \sim 7''$, $P_p \sim 7$ yr). Assuming a precession-nutation model, the amplitude of precession is more similar to the expected value ($\sim 80''$); however, the much longer period in this case is even harder to contextualize. In this simple argumentation, however, we have not accounted for projection effects, none of the simulations have been tailored to M 81* (i.e., the unknown spin and the accretion-disk tilt), and we have ignored the fact that the disk precession timescales are dependent on the initial disk mass. We therefore suggest that the Lense–Thirring precession scenario may well be applicable in the case of M 81*.

Finally, a gravitational pacemaker may explain the observed precession of the M 81* position angle. Such a scenario has been found in the binary system SS433 (e.g., Stephenson & Sanduleak 1977; Clark & Murdin 1978), where two large-scale precessing jets create a corkscrew-like structure. For this system, the precession is thought to originate from the gravitational torque of the donor star on the accretion disk of a compact object, which is either a black hole or a neutron star (slaved disk model; Roberts 1974; Waisberg et al. 2019). A similar scenario has been proposed for OJ 287 and 3C 345, where an orbital modulation is present in both the light curve and the jet components (Lobanov & Roland 2005; Britzen et al. 2018). Further, Caproni et al. (2013) found a 12.1 yr precession period in BL Lacertae. Britzen et al. (2018) found a precession period of ~23 yr on top of a much faster ~1 yr nutation period and derived a binary separation of $0.001 \, pc < d < 0.1 \, pc$. For 3C 345, Lobanov & Roland (2005) found a precession period of ~10 yr for the position angle, which exhibited a linear trend; this is very similar to the behavior of M 81* (a short, ~7 yr, nutation period and a linear trend, which we interpret as a long-period precession of ~800 yr).

If we interpret the inferred seven-year period as the orbiting period of the companion object, we can derive the binary semi-major axis as well as the gravitational binary merger time. An orbiting secondary black hole induces gravitational torques on the accretion disk, which results in the precessing motion in the opposite direction of the disk rotation. The precessing motion is accompanied by the short-term nutation motion caused by the torque of a similar magnitude. However, the amplitude is smaller than for the precession by the ratio of the precession and the orbital frequencies. Following Katz et al. (1982, see also Caproni et al. 2013), the nutation angular frequency is equal to twice the difference of the orbital and precession angular frequencies,

$$\omega_n = 2(\omega_{orb} - \omega_p),$$

where $\omega_p$ is negative because of the opposite direction with respect to the orbital motion. Using Eq. (2), the orbital period can be expressed as

$$P_{orb} = \frac{2P_n}{1 - 2P_n/P_p} \approx 2P_n.$$ (3)

The putative supermassive black hole binary in M 81 has an orbital period of $P_{orb} \sim 14$ to 15 years for $P_p \geq P_n$, which seems to be the case based on the long-term linear drift. The semimajor axis of the binary system can be estimated from the third Kepler law,

$$a_{bin} \approx \frac{1573}{2 \times 10^7 M_\odot} \left( \frac{P_{orb}}{14 \, yr} \right)^{2/3} \text{AU},$$ (4)

which corresponds to $a_{bin} \sim 8000R_g$ ($R_g = GM_{tot}/c^2$) in gravitational radii if the primary supermassive black hole dominates the total mass. Using a primary mass fraction of $x_p = m_1/M_{tot} \sim 0.9$ (the secondary mass fraction is $x_s \sim 0.1$), the binary merger timescale is

$$\tau_{merge} = \frac{5}{256} \frac{a_{bin}^5}{G^3} \frac{\alpha_{bin}}{x_p x_s M_{tot}^3}$$ (5)

$$= 2.77 \left( \frac{a_{bin}}{1573 \, AU} \right)^5 \left( x_p 0.9 \right)^{-1} \left( x_s 0.1 \right)^{-1} \left( \frac{M_{tot}}{2 \times 10^7 M_\odot} \right)^{-3} \text{Gyr}. $$ (6)

For an even more extreme ratio, $x_p \sim 1$, $x_s \sim 10^{-2}$, we obtain $\tau_{merge} \sim 25$ Gyr, and hence the system would generally be long-lived.
5. Conclusions

We present novel observations of the core region M 81*. Our observations are consistent with a precession of the jet of this galaxy, which was first proposed by Martí-Vidal et al. (2011). The jet precession period is roughly 7 years. On top of the precession (amplitude \( \sim 5^\circ \)) the jet exhibits a small linear drift of roughly 0.5\(^\circ\)/yr. However, we cannot confirm that the flare observed in the years 1998–2002 is connected to the precession of the jet, for instance, through Doppler boosting. Our sparse flux measurements do not show elevated flux in the years 2017–2019. Further, historic data do not show any flaring activity since the end of the last flare in 2002. We can rule out a self-similar modulation of the light curve with the period of the modulation. However, the sampling of the light curve is too sparse to definitely rule out any modulation scenario. Thus, we consider it more likely that the flare observed in the years from 1998 to 2002 was not caused by variable Doppler boosting. Our observations are consistent with either a Lense–Thirring-induced precession of the jet or a binary-induced precession of the jet. They are therefore analogous to observations of other precessing jets, such as in 3C 345 and OJ 287, which both show a fast nutation-like component as well as a slower, but larger-amplitude, precession-like variation in the jet position angle. If Lense–Thirring precession is responsible for the observed jet precession in all three active galactic nuclei, the underlying coupling of the accretion disk precession to the jet precession would show a remarkable self-similar coupling through vastly different accretion regimes. While both 3C 345 and OJ 287 accrete close to their Eddington limit, M 81* belongs to the class of radiatively inefficient accretion flows. This may hint that the jet physics responsible for the observed precession in these systems is accretion-flow-rate and accretion-flow-state independent. On the other hand, if a binary black hole is responsible for the apparent precession, then it may be the closest supermassive or intermediate-mass binary black hole candidate known to date. However, more data are necessary to confirm the precessing nature of M 81*, and in particular the proposed frequency-dependent time lag.

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Appendix A: Best-fit model including the newest observation

In this appendix we show the best-fit model detailed in the third column of Table 2, as well as the linear drift model (fourth column of Table 2), defined as

$$\theta(t) = \beta \cdot (t - t_0).$$  \hspace{1cm} (A.1)

Fig. A.1. Same as Figure 1, but including the 2017 datum in the fit.

Appendix B: Frequency-dependent shift excluding the 2019 observations

Here we show the same plot as Figure 2 (Figure B.1), but with a model shifted by $-1.9$ years instead of $-3.5$ years. This is consistent with the well-determined 2018 8 GHz observation, but inconsistent with the 2019 observations.

Fig. B.1. Same as Figure 2, but with a -1.9 year shift of the 8 GHz model instead of -3.5 years.
Appendix C: Full posterior of the precession-nutation model

The full posterior of the precession-nutation model is given in Figure C.1

![Joint posterior of the precession-nutation model.](image)

**Fig. C.1.** Joint posterior of the precession-nutation model.
Appendix D: Observation maps

Below we plot the maps of the respective C- and X-band observations. Figure D.1 shows the C-band data, and Figure D.2 shows the X-band data. Table D.1 gives an overview of the observation details.

Table D.1. Achieved resolution and beam configuration for the four observations.

<table>
<thead>
<tr>
<th>Obs. date</th>
<th>Band</th>
<th>Beam size [mas]</th>
<th>Beam angle [°]</th>
<th>Clean residual RMS [Jy/beam]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017-06-21</td>
<td>C</td>
<td>0.902 × 0.86</td>
<td>−65.3</td>
<td>0.0004</td>
</tr>
<tr>
<td>2018-06-10</td>
<td>X</td>
<td>0.911 × 0.594</td>
<td>−12</td>
<td>0.0002</td>
</tr>
<tr>
<td>2019-11-04</td>
<td>C</td>
<td>1.78 × 1.2</td>
<td>−30.3</td>
<td>0.0003</td>
</tr>
<tr>
<td>2019-11-04</td>
<td>X</td>
<td>1.01 × 0.755</td>
<td>−29.1</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Fig. D.1. Maps of the observations obtained in the C band. The beam size is indicated by the gray ellipse. Panel (a) shows the C-band observation obtained with the EVN in June 2017. Panel (b) shows the C-band observation obtained with the VLBA in November 2019.

Fig. D.2. Same as Figure D.1, but for observations obtained in the X band. The beam size is indicated by the gray ellipse. Panel (a) shows the X-band observation obtained with the EVN in June 2018. Panel (b) shows the X-band observation obtained with the VLBA in November 2019.
Appendix E: Participating stations

Table E.1 gives the participating stations and their abbreviations.

Table E.1. Station names, abbreviations, and location of the participating EVN observatories.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Observatory name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF</td>
<td>Effelsberg</td>
<td>Germany</td>
</tr>
<tr>
<td>IR</td>
<td>Irbene</td>
<td>Latvia</td>
</tr>
<tr>
<td>YS</td>
<td>Yonsei</td>
<td>R. o. Korea</td>
</tr>
<tr>
<td>TR</td>
<td>Torun</td>
<td>Poland</td>
</tr>
<tr>
<td>SH</td>
<td>Shanghai Astronomical Observatory</td>
<td>P.R. China</td>
</tr>
<tr>
<td>MC</td>
<td>Medicina</td>
<td>Italy</td>
</tr>
<tr>
<td>WB</td>
<td>Westerbork Synthesis Radio Telescope</td>
<td>the Netherlands</td>
</tr>
<tr>
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