



Low-velocity Precessing Jets Can Explain Observed Morphologies in the Twin Radio Galaxy TRG J104454+354055

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Abstract

Our understanding of large-scale radio jets in merger systems has been drastically improved in the era of the Very Large Array, Very Long Baseline Array/European VLBI Network, upgraded Giant Metrewave Radio Telescope, and MeerKAT. Twin radio galaxies (TRGs) are rare interacting galaxy pairs where both supermassive black holes host kiloparsec-scale bipolar radio jets. Only recently was a third TRG discovered, and it shows significantly different jet morphologies than the previous two. Due to both the extreme paucity and complexity of such systems, the launching of their jets as well as their mutual interaction during the propagation through the ambient medium are not well understood. We have performed three-dimensional hydrodynamic simulations to study the bipolar jets in the third TRG, J104454+354055. Our study indicates that the precession of mutually tilted bipolar jets originating from the two galactic nuclei separated by tens of kiloparsecs and propagating at low velocities can explain the observed morphologies. The simulated jet precession timescales are short compared to the overall dynamical timescale of the jets, and could originate from Lense–Thirring effect in the accretion disks. This approach to understanding TRG jet dynamics could also be applied to other TRG systems with similar helical morphologies that may be discovered in the upcoming era of the Square Kilometre Array and its pathfinder surveys.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Active galaxies (17); Radio jets (1347); Galaxy jets (601); Quasars (1319); Quasar-galaxy pairs (1316); Supermassive black holes (1663)

1. Introduction

Most galaxies are believed to host a supermassive black hole (SMBH) at their centers (J. Kormendy & D. Richstone 1995; J. Magorrian et al. 1998), whose evolution is primarily thought to result from a sequence of galaxy mergers. These mergers channel large amounts of fresh matter toward the center, triggering an accelerated accretion process (P. C. Fragile et al. 2007; P. F. Hopkins et al. 2012). However, the complex interplay between matter accretion, SMBH growth, and matter ejection or outflows, both thermal and nonthermal, remains a key subject of frontier research (e.g., M. Gaspari et al. 2020).

Following the collision of two galaxies, it is expected that the SMBHs in each host will gradually sink toward each other in their orbits due to stellar dynamical friction and/or energy dissipation caused by the circumnuclear gas, ultimately forming a binary or a dual-SMBH system (see M. C. Begelman et al. 1980; J. Kormendy & L. C. Ho 2013, and references therein). When the approaching active SMBHs are separated by relatively small (<100 pc) distances, they are referred to as binary active galactic nuclei (BAGNs; see C. Rodriguez et al. 2006; K. Bansal et al. 2017; P. Kharb et al. 2017); when still separated by kiloparsec scales, they are called dual AGN (DAGNs; e.g., S. Burke-Spolaor et al. 2014; K. Rubinur et al. 2018).

Although several detections of DAGNs have been made, identifying binary systems remains challenging due to the

requirement of very-high-resolution observations across multiple frequency bands (see A. De Rosa et al. 2019; P. Breiding et al. 2022). Some candidates are even suspected to host BAGNs beyond the resolution capabilities of most contemporary telescopes (P. Kharb et al. 2019). Furthermore, different observational features, such as double-peaked optical spectra or curved morphologies of double radio lobes, once considered to be signatures for identifying such binary candidates, have been found to be explicable in terms of other astrophysical processes occurring around the violent nuclear environment (e.g., H. Fu et al. 2012; K. Rubinur et al. 2019). Regardless of these potential alternatives, the indirect signatures of DAGNs, such as S- or X-shaped radio galaxies (e.g., M. C. Begelman et al. 1980; H. Rottmann 2001; Gopal-Krishna et al. 2003; S. Nandi et al. 2017) or optical periodicity (e.g., M. J. Graham et al. 2015; T. Liu et al. 2015), continue to play a crucial role in identifying DAGN candidates among the vast population of jetted active galactic nuclei (AGNs). This set of systems provides a crucial step toward understanding the final stages of galaxy mergers (known as the final parsec problem), when SMBHs are separated by (sub)parsec scales and can emit gravitational waves contributing significantly to the gravitational-wave background (e.g., G. Agazie et al. 2023). Several multiwavelength surveys are now focusing on detecting such merger systems, with an emphasis on gravitational-wave detection as an emerging branch of astronomy (see K. N. Abazajian et al. 2009; E. L. Wright et al. 2010; C. P. Ahn et al. 2012, and references therein).

Depending on the quantity of gas that becomes available for accretion during a galaxy merger (wet versus dry merger),



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either one or both SMBHs in the binary orbit may launch relativistic plasma jets. While jet ejection from a single massive AGN is relatively common (M. Murgia et al. 2001; L. Bruno et al. 2019), simultaneous jet ejection from both AGNs is a rare phenomenon. Such a rare system is labeled as a twin radio galaxy (TRG) in the literature. The first case of such a dual jet-pair ejection was discovered four decades ago by F. N. Owen et al. (1985): 3C 75, near the center of the cluster A400 ($z = 0.023$), a wide-angle tail (WAT) radio source with an overall size of ~ 0.5 Mpc. Recall that the spectacular WAT morphology observed in 3C 465 was attributed to the high-velocity orbital motion of the jetted AGN about another massive galaxy with which it is merging (A. Wirth et al. 1982). The second TRG, discovered three decades ago, is PKS 2149–158, of size ~ 0.4 Mpc, located near the outskirts of A2382 ($z = 0.062$; P. Parma et al. 1991; D. Guidetti et al. 2008). Only recently a third TRG, J104454+354055 (hereafter TRG J104454), with $z = 0.162$, was discovered by Gopal-Krishna et al. (2022) using data from the upgraded Giant Metrewave Radio Telescope (uGMRT). In this TRG both radio jets are discernible up to ~ 0.1 Mpc scale, and the overall radio structure spans ~ 0.4 Mpc with a Fanaroff–Riley type I (FR I) morphology. Initially, this TRG was identified as a candidate for an X-shaped radio galaxy (R. Joshi et al. 2019; Y. Yang et al. 2019), but later it was classified as a TRG.

Note that possible evidence for DAGNs, with both galactic nuclei capable of ejecting jets, was also speculated from the anomalous spectral behavior observed in some X-shaped (winged) radio galaxies (D. V. Lal & A. P. Rao 2005; D. V. Lal et al. 2019). However, recent studies have proposed alternative explanations for this puzzling behavior, or have failed to confirm the reported spectral anomaly using radio maps with a wider radio-frequency coverage. This underscores the need for further investigation into the general applicability of such models (G. Giri et al. 2022b; D. Patra et al. 2023).

Given just the handful of TRGs discovered so far, much remains uncertain about these complex systems. Some open questions include the role of persistent accretion and SMBH dynamical and physical parameters on the jet ejections and their evolution; the relative stability of the gaseous halos of the interacting galaxies; and the impact of multiple radio jets in (de)stabilizing the surrounding environment.

To investigate the environmental influences on bipolar-jetted systems and also to understand the jet evolution phases of such systems, here we initiate a program of numerical modeling of the recently discovered source TRG J104454. Similar simulations have been conducted for the TRG 3C 75 (S. M. Molnar et al. 2017; G. Musoke et al. 2020). In comparison to the previously known TRGs, the configuration of TRG J104454 is distinctly neater since it does not appear to have any significant intracluster cross-wind (Gopal-Krishna et al. 2022). Note that the jets in the previous two TRGs eventually became C-shaped, most likely due to the effect of such cross-winds (F. N. Owen et al. 1985; D. Guidetti et al. 2008). Models have demonstrated that a variety of observed jet morphologies in an individual or twin galaxies can arise either from precession effects in jets (A. C. Gower et al. 1982) or gravitational interactions of the merging galaxies which can affect the jets (A. Wirth et al. 1982). TRG J104454 is likely exhibiting jet precession and potential lobe collisions at larger scales, but with an apparent lack of environmental cross-wind and consequent distortions of the lobe structures. Therefore, it

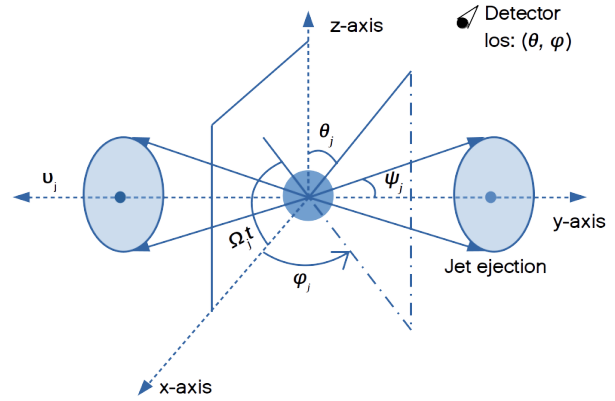


Figure 1. Three-dimensional illustration of the injection of a bipolar jet (similar to G. Giri et al. 2022b) based on our simulation configuration. The bipolar jet precesses around the y-axis at an angle Ψ_j with a precession period P_j , resulting in an angular velocity $\Omega_j = 2\pi/P_j$ in the x - z plane. Also sketched here is the line-of-sight position (θ, φ) along which the mock emission maps were generated.

is overall a simpler testbed for studying the nature of DAGNs as traced using their larger-scale radio structures. Regardless of the mechanism responsible for the precession of the jets, we performed simulations of the TRG under the premise of precessing jets and compared their outcomes with the observed uGMRT morphology of the present TRG.

In Section 2, we discuss the formulation of our simulations. In Section 3, the simulation results are discussed in terms of interpreting the properties recovered from observations of TRG J104454, including the possible origin of the inferred jet precession. We summarize our conclusions in Section 4.

2. Simulated Configuration

The bound pair of radio galaxies designated TRG J104454 measures ~ 220 kpc and beyond along the bipolar jet-flow axis, and has been identified as a low-powered jet-driven system (Gopal-Krishna et al. 2022). To simulate such an extended configuration, we employed the hydrodynamical module of the PLUTO code in a three-dimensional (3D) Cartesian system (A. Mignone et al. 2007). An illustration of the simulation configuration of a single bipolar jet is shown in Figure 1, where both the injection and precession of the jet are displayed. We note that the jet nozzles (through which the jet plasma is being injected) have not been assigned a specified opening angle, as we expect the jet structures observed at large scales to be governed by the overall dynamics and precession of the jets (G. Giri et al. 2022a). As discussed below, we choose the units for the three basic parameters to be a length (l_0) of 10 kpc, velocity (v_0) 6.9×10^7 cm s $^{-1}$ (sound speed in the jet), and density (ρ_0) 0.03 amu cm $^{-3}$ (at the center of the ambient gaseous halo). All other relevant parameters can be scaled based on these parameters, e.g., the simulation time can be scaled as (unit length/unit velocity), ≈ 14 Myr, and the kinematic luminosity ($L_{kin0} = \rho_0 l_0^2 v_0^3$) can be scaled as 1.5×10^{43} erg s $^{-1}$.

In order to describe the ambient medium through which the jets propagate, we use a spherical King density profile to mimic a rich galaxy group environment (e.g., M. J. Hardcastle & M. G. H. Krause 2013). This relies on the observation that the twin jets extend far beyond the stellar boundaries of their

host galaxies and evolve in a dynamically active galaxy group (Gopal-Krishna et al. 2022). This premise also holds true for the other two TRGs reported to date, although their radio structures show additional complicating features related to cluster cross-winds (Section 1). The gas density distribution is defined as

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta/2}, \quad (1)$$

where r is the radial distance from the center of the computing domain (also the center of the ambient medium) at $\{0, 0, 0\}$, taken as midway between the origins of the two injected bipolar jets, and is evaluated as $(x^2 + y^2 + z^2)^{1/2}$; ρ_0 is the (plasma) gas density of the ambient cluster medium at $r=0$ (adopted to be 0.03 amu cm^{-3}); r_c is the core radius, taken to be 125 kpc; and β is 0.55 (e.g., M. J. Hardcastle 2018; G. Giri et al. 2023). We adopted an ideal equation of state for the ambient gas and applied a constant pressure profile (of magnitude $2.5 \times 10^{-12} \text{ dyn cm}^{-2}$), in order to establish a static equilibrium of the ambient medium as the initial condition while the jets are being injected. These are typical parameter sets adopted for representing the large-scale jet environment (e.g., G. Musoke et al. 2020). The adopted sound speed in each jet, $v_0 = 6.9 \times 10^7 \text{ cm s}^{-1}$, corresponds to a jet temperature of $\sim 2.2 \text{ keV}$ (P. Kharb et al. 2019). Then a jet Mach number of $M_j = 65.2$ is adopted as a default parameter for the injected jets, which is equivalent to a jet velocity $v_j = 0.15c$ (selected to mimic a low jet power consistent with the estimates reported for TRG J104454), where c is the speed of light. The simulation domain extends from -70 kpc to $+70 \text{ kpc}$ in the x - and z -directions and -150 kpc to $+150 \text{ kpc}$ in the y -direction, with uniformly distributed $\{336 \times 720 \times 336\}$ grids. We employ outflow boundary conditions for the boundaries of the computational domain.

We inject two nonparallel bipolar jets with their origins separated by 30 kpc (Gopal-Krishna et al. 2022) from the center of the ambient medium configuration (also taken as the center of the simulation). Both pairs of jets are injected through cylindrical injection zones, which are divided into three launch regions: the top region (producing the flow of the jet primarily along the $+y$ -axis), the bottom region (for the flow mostly along the $-y$ -axis), and a neutral region (sandwiched between the two zones, where none of the parameters vary) around the center (similar to P. Rossi et al. 2017) with the injection radius (R_j) usually set to 4 kpc and the height of each cylinder (H_j) being 5 kpc. This relatively large value of R_j is necessary to resolve the jets with sufficient grid points and to generate enough mechanical power for the jet to overcome the resistance due to the environment. For the grid resolution mentioned above, the jet launching diameter contains around 10 grid cells (a convergence test has also been performed using a higher resolution; see Appendix A).

In our simulations, we continuously inject bipolar plasma jets from the cylindrical nozzles with velocities v_r and v_l . Here, the subscripts “ r ” and “ l ” denote left and right jets, respectively, as each injected jet is bipolar. Guided by the observed morphologies, we have tilted each jet at respective angles θ_r and θ_l (from the $+y$ -axis), with precession cone half-angles of $\Psi_{r,l}$ and periods P_r and P_l . We followed the

geometric model proposed by R. M. Hjellming & K. J. Johnston (1981) to implement the precession. Accordingly, both jets are tilted with respect to the y -axis and their precession axes are parallel to the y -axis. Therefore, the velocity components along all three axes of the precessing, tilted jets can be written as

$$\begin{aligned} v_{j,x} &= v_j \sin \Psi_j \cos(\Omega_j t) \sin \theta_j, \\ v_{j,y} &= v_j \cos \Psi_j \cos \theta_j, \text{ and} \\ v_{j,z} &= v_j \sin \Psi_j \sin(\Omega_j t), \end{aligned} \quad (2)$$

where $\Omega_j (= 2\pi/P_j)$ is the precession frequency for each jet, and the subscript “ j ” denotes the quantities for the left (l) and right (r) bipolar jets. The kinetic power of both these subrelativistic jets is estimated using the relation (M. J. Hardcastle & M. G. H. Krause 2014)

$$L_{\text{kin}} = \pi R_j^2 M_j \left(\frac{1}{2} M_j^2 \rho_j + \frac{5}{2} T_j \rho_j \right), \quad (3)$$

with T_j the jet plasma’s temperature.

Using the initial jet parameters, the estimated L_{kin} we considered ranges from $8.8 \times 10^{44} \text{ erg s}^{-1}$ for the minimum jet velocity, which was for $M_j = 60.9$, to $2.6 \times 10^{45} \text{ erg s}^{-1}$ for the maximum jet velocity examined, corresponding to $M_j = 87$. The parameters adopted for the selected TRG simulations, which are displayed in the following figures, are listed in Table 1. Note that the jet parameters, with the exception of Ψ_j , are taken independently for individual bipolar jets during each simulation. Implementing the above processes and grid resolutions, we checked how well the results converge for model S6. All results are presented for the grid distribution of $\{336 \times 720 \times 336\}$, taking into account the convergence of results with higher resolution (see Appendix A). Also, all snapshots are generated for a tracer that tracks the presence of jet material in a grid zone, set at a threshold of 0.5.

3. Results and Discussion

The left panel of Figure 2 shows the color-coded uGMRT map of TRG J104454 at 1.4 GHz (Gopal-Krishna et al. 2022). The other three panels of Figure 2 show the simulated synchrotron intensity maps for simulation S1 (Table 1) using the reference resolution at three different epochs during jet evolution. The synchrotron intensity, I_ν , is approximated using the relation (e.g., A. J. Mioduszewski et al. 1997; A. S. R. Antas et al. 2024)

$$I_\nu \propto \delta^{\alpha+2} \left(\frac{P}{\Gamma - 1} \right)^{(\alpha+3)/2} \nu^{-\alpha}, \quad (4)$$

where ν is the frequency at which the observation was made, α is the spectral index, δ is the relativistic Doppler boosting factor, which is $\simeq 1$ for the subrelativistic jet considered in this work, P is the jet pressure, and Γ is the adiabatic gas index. We adopted the synchrotron spectral index as $\alpha = 0.6$, typical for active radio jets (e.g., M. E. Jarvis et al. 2019; S. Silpa et al. 2022). We then integrate the emissivity data cube along the line of sight to obtain the intensity maps. We are viewing the structure along the z -axis (a tracer threshold of 0.5 is chosen to consider only emission from the zones predominantly composed of radio source plasma). All snapshots are rotated counterclockwise by 30° with respect to the sky-projected y -

Table 1
Input Parameters Adopted for the Selected TRG Simulations Presented in Figures 2 and 5

Setup	θ_l (deg)	θ_r (deg)	P_r (Myr)	P_l (Myr)	Ψ_j (Deg)	M_j (right)	M_j (left)	R_j (kpc)
S1	-45	40	49	28	20	65.2	65.2	4
S2	-45	-40	49	28	20	65.2	65.2	4
S3	-45	25	28	28	20	65.2	65.2	4
S4	-40	45	49	49	30	82.6	65.2	4
S5	40	45	35	35	30	87.0	60.9	4
S6	-45	-30	28	28	23	65.2	65.2	4
S7	-45	40	49	28	20	65.2	65.2	2

Note. For each simulation θ is the tilt angle of the bipolar jet at injection point relative to the y -axis, P is the precession period of the jet, Ψ_j is the precession angle, M_j denotes the Mach number of the jet, and R_j is the jet radius. We note that all of our simulations are carried out in dimensionless quantities, and then converted back into physical quantities by scaling with the respective units, adopted and derived.

axis for better visualization and comparison with the observed source.

Both bipolar jets are found to remain relatively straight with little wiggling during the early stages of their evolution (see the ~ 73 Myr snapshot in Figure 2). However, at later stages they diverge from symmetrical evolution due to differences in their precession parameters, which influence variations in their longer-term structures. During their growth, the two bipolar jets approach each other and thereby appear to influence their mutual dynamics and show more wiggling of the diffused material, as seen in the snapshot at time ~ 150 Myr. At later stages, they lose collimation and form diffuse radio lobes, as shown in the right panel of Figure 2, which also resembles the observed radio map of TRG J104454. The simulation timescale (~ 190 Myr) that matches the observed morphology is in rough agreement with the orbital timescale of the system, which is $t_{\text{orb}} = 2\pi(d^3/GM_*)^{1/2} \sim 230$ Myr, where d is the half-separation between two galaxies, and M_* is the total stellar mass, $\sim 5.4 \times 10^{11} M_\odot$ (Gopal-Krishna et al. 2022). However, the simulated jet precession timescales required for the observed jet wiggling seen in the uGMRT map are substantially shorter than this orbital timescale, and a possible origin of such timescales is discussed later in Section 3.3.

3.1. Jet Dynamics

As soon as the jets start propagating through the ambient medium in the denser core regime, their growth rate and dynamics are affected by the density profile of the ambient medium (e.g., Gopal-Krishna & P. J. Wiita 1987). We note that the present assumption, that the kinetic power of the jet is dominated by the synchrotron plasma in subrelativistic bulk motion, does not exclude the possibility that the primary source of the jet power lies in a relativistic spine.

We have measured the jet-head evolution for all four jets using x - y slices at different times. A tracer threshold of 10^{-4} is used to delineate the full dynamical extent of the lobes. The left panel of Figure 3 shows the head positions (along the $\pm y$ axes) for all four jets (left jet's upward arm in black, left jet's downward arm in red, right jet's upward arm in blue, and right jet's downward arm in green) during their temporal evolution, which was generated by the propagation of the jets through the denser ambient medium. The expansion of the upper jets (toward the $+y$ -axis) is slightly slower than that of the lower jets, which might explain the wider lobe formation by the jets along this direction compared to the $-y$ -axis. The northern jets ($+y$ -axis) and southern jets ($-y$ -axis) exhibit somewhat

different evolutionary patterns, which could be due to the mutual dynamical effects of the tilted bipolar jets. This results in varied impacts across different sections, further emphasizing the independent evolution of the jets. The right panel of Figure 3 shows the lateral movement of the jet heads. The same color convention as in the left panel has been followed. It can be seen that at the initial breakout stage all four jets had small lateral spreads, which however increased at later times. This can be understood as because of their higher thrust and more precise directionality at the time of launch compared to later times and the effect of precession. At the initial phase of their launch, the heads of all four jets are spatially distinct, but as time progresses the lobes begin to inflate and make contact among themselves, enhancing a greater lateral spread of the diffused material.

Helical structures arising from the precession of both jet pairs diminish at late time due to their apparent mutual dynamical interactions as well as their interactions with the heavier ambient medium. Nonetheless, the helical jet trajectories are still noticeable up to a certain spatial extent. At much later stages of evolution, however, the jets lose their collimated structures as they slow down, and start dispersing their material over a wider lobe region.

Note that although the present simulations cover a range of input parameters, as listed in Table 1, only the S1 setup most closely reproduces the observed TRG morphology. We also performed a similar simulation without incorporating the effect of jet precession; then all four jets were found to drill through the ambient medium keeping their initial injected directions, thereby failing to reproduce the observed jet-lobe structures. Therefore, we are confident that the observed morphology of TRG J104454 requires significant precession to be present in both jets.

To illustrate the evolved dynamical structure in 3D, we have plotted tracer values in 3D (Figure 4) representing the dominant jet-lobe structure (tracer values exceeding 50%) for the ~ 190 Myr snapshot in Figure 2. The collimated jets and their helical distortions are clearly visible in this visualization, along with their decollimation into tendril-like, wobbly structures after a certain spatial extent. The evolution of the northern and southern arms of the bipolar flows differ considerably: the northern arms interact and collide with each other, while the southern arms remain distinct, as revealed through a rotating view of the rendered image structure.

It is important to point out that the present simulations do not include magnetic fields. This simplification is partly justified by the fact that the magnetic field energies in such low-power systems are typically much lower than the kinetic

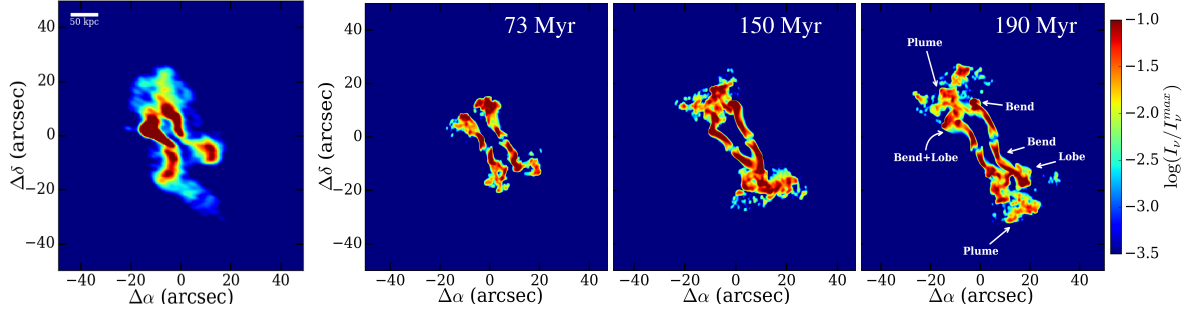


Figure 2. The leftmost panel reproduces the color-coded uGMRT map of TRG J104454 at 1.4 GHz (Gopal-Krishna et al. 2022; image used with authors' permission). The remaining three panels display the normalized synchrotron intensity maps of the simulated TRG at 1.4 GHz for model S1, obtained using emissivity data cubes of both jets. To produce the mock-intensity maps we use a value of $\alpha = 0.6$ (see Equation (4)). The approximate times of these simulation snapshots are shown in the respective images. The coordinates of the nuclei of the right and left bipolar jets in the simulation are $\{15, 0, 0\}$ kpc and $\{-15, 0, 0\}$ kpc, respectively. The simulated high-resolution maps have been convolved to a lower resolution using a Gaussian blur filter, with the filter size matching the uGMRT beam size. The last panel also marks the structural features of the jets.

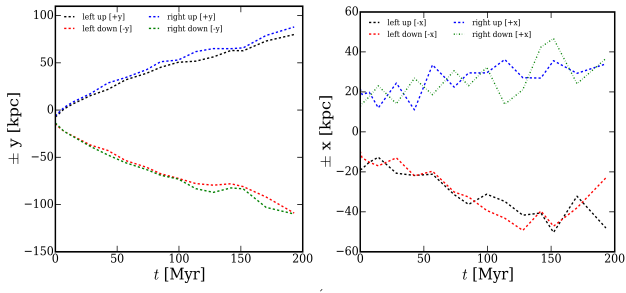


Figure 3. Temporal evolution of the jet head for all four jets in the x - y plane, for the S1 setup. The left and right panels show approximate $\pm y$ (linear) and $\pm x$ (lateral) positions of the jet heads. Both panels follow the same color conventions to indicate the four jets.

energy of the jet (G. Giri et al. 2025), rendering them dynamically less significant in this context. However, magnetic fields are likely to play a critical role in stabilizing the jets against decollimation and shielding them from ambient matter entrainment, potentially enabling the twin jets to persist over greater extents. Nonetheless, the role of magnetic fields is highly dependent on their strength and configuration, as they could also induce instabilities in the jets. This remains an open question, and warrants further investigation in future studies.

3.2. Jet Power and Black Hole Accretion Mode

The launching and powering of jets from SMBHs can be related to the properties of the central engine and its accretion states. Observations of jets from black hole X-ray binaries as well as in some AGNs provide evidence that jets can be produced in the advection-dominated accretion state and the collapse of the radio jets is observed when the flow transits from the hot to cool state (e.g., R. P. Fender et al. 2004). However, the collimation and powering of large-scale jets in powerful AGNs seem to require the extraction of rotational energy from the black hole (the Blandford–Znajek, or BZ, process; R. D. Blandford & R. L. Znajek 1977) and/or the accretion disk through magnetic fields (the Blandford–Payne, or BP, process; R. D. Blandford & D. G. Payne 1982). Since these processes can generate a wide range of jet power, different types of radio sources can be understood within this general framework.

The SMBHs ejecting radio jets in our simulations have masses of around $1.6 \times 10^{10} M_{\odot}$ (left source) and $2.0 \times 10^9 M_{\odot}$ (right source) (Gopal-Krishna et al. 2022). The L_{kin} values indicated by

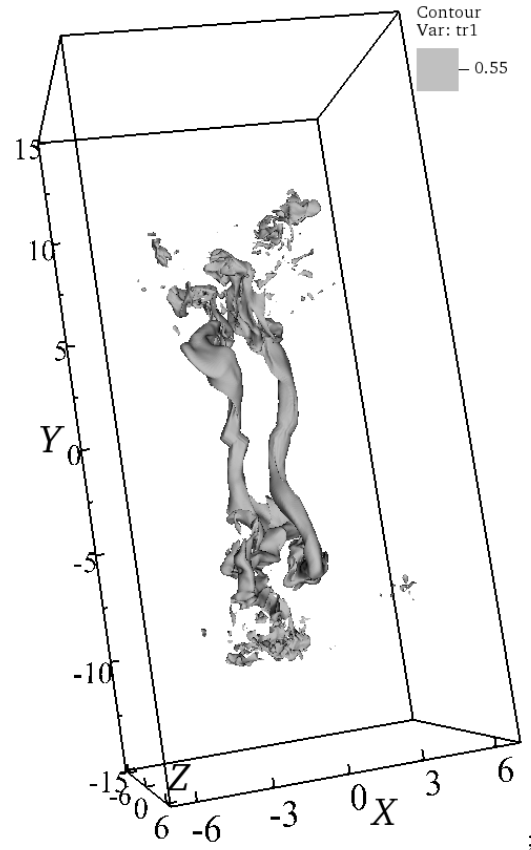


Figure 4. 3D gray-scale map of the tracer values (tracer values > 0.5) illustrating the primary jet structure, as well as its transition and decollimation into broader plumes. All axes are in the code unit.

the simulations suggest that both the SMBHs are accreting in the sub-Eddington regime, with mass-accretion rates $\sim 5 \times 10^{-4}$ and $\sim 4.2 \times 10^{-3} \dot{m}_{\text{Edd}}$ for the left and right sources, respectively, where the Eddington luminosity $L_{\text{Edd}} = 1.3 \times 10^{38} (M_{\text{BH}}/M_{\odot}) \text{ erg s}^{-1}$. For the present sources, where very sub-Eddington accretion is indicated, advection-dominated states are indeed expected (R. Narayan & I. Yi 1994).

3.3. Origin and Timescale of Jet Precession

Precession of radio jets (either bipolar or twin bipolar) may occur due to several underlying processes including magnetic

torques, warped disks, and gravitational torques in a binary (F. Pizzolato & N. Soker 2005). In a binary SMBH system, if either of the nuclei is actively accreting and generating radio jets, then the precession is induced around the orbital axis as the galaxies start to merge and the nuclei come closer to form a bound spiraling orbit (M. C. Begelman et al. 1980). Such processes can misalign the binary’s orbital axis and the SMBH spin axis. A. C. Gower et al. (1982) explored models of precessing twin jets for several observed systems for a range of bulk jet velocities that demonstrated the effect of orbital motion. Even without precession, spiraling jets can be formed from the combined effects of jet velocity and the orbital velocity of the system. Interestingly, 3C 315 in their sample required a longer precession period (~ 10 Myr) to match the observation, which was quite similar to our simulated precession periods. The radio jets in two galaxies separated by a few tens of kiloparsecs can be affected by the dynamical interactions arising from the large-scale galactic gas distribution and their orbital velocities. Occasionally, high-velocity circular orbits can even produce a WAT (e.g., 3C 465; A. Wirth et al. 1982), as was observed in the TRG 3C 75 (F. N. Owen et al. 1985).

Alternatively, precession can be associated with accretion disk instabilities such as Lense–Thirring (LT) or the related Bardeen–Peterson effects (J. M. Bardeen & J. A. Peterson 1975). The accretion disk may start precessing due to these instabilities if its angular momentum is misaligned with the angular momentum of the central spinning SMBH. Moreover, if the orientation of the disk determines the jet axis, then this would induce a precession in the jet axis (see M. Liska et al. 2018, for some general-relativistic simulations).

The precession period of the jets in an isolated AGN or a binary system can cover a broad range from a few years to a few tens of millions of years. A wide range of precession timescales results, depending on the scale of LT precession of the central SMBH due to the misalignment of the spin axis of the SMBH with the direction of the angular momentum vector of the accreting matter (P. A. G. Scheuer & R. Feiler 1996). Short precession periods of 11 and 7 yr were estimated for the cases of M87 and M81, which could have arisen from the misalignment of the black hole spin axes with the tilted disks (Y. Cui et al. 2023; S. D. von Fellenberg et al. 2023). However, in the case of large-scale structures, for example in galaxy clusters, the precession period can be a few tens of millions of years, as was inferred for 3C 84 (R. J. H. Dunn et al. 2006; D. Falceta-Gonçalves et al. 2010). These authors assumed that the precession was induced by the LT effect at a larger length scale, which is more likely since the accretion disks are connected with the merger processes, and therefore likely to be misaligned with the SMBH spin axis. On the other hand, Hydra A can be modeled with a shorter precession timescale of just ~ 1 Myr (M. A. Nawaz et al. 2016).

We have estimated the jet precession period in this work assuming that the LT effect allows the disk to warp at larger radii. The precession period can be written as (J. E. Pringle 1992; P. A. G. Scheuer & R. Feiler 1996)

$$P_j \sim \frac{\nu}{\dot{M}} \left(\frac{a_k c M_{\text{BH}}}{2\nu G} \right)^{\frac{1}{2}},$$

where $\nu = \alpha a_s H$, is the disk kinematic viscosity, which is estimated using the Shakura–Sunyaev prescription (SS 73 disk; N. I. Shakura & R. A. Sunyaev 1973), and G , c , and

$\dot{M}$ are the universal gravitational constant, the speed of light, and the disk mass-accretion rate, respectively. The sound speed (a_s) is calculated as $\sqrt{k_B T / m_p}$ for a typical cold disk temperature of 3×10^4 K. The scale height of the SS 73 disk (H) is given by a_s / v_ϕ , where v_ϕ is the angular velocity of the flow. For a standard warp radius, R_{warp} , of $150\text{--}1000 r_g$ ($=GM_{\text{BH}}/c^2$; P. A. G. Scheuer & R. Feiler 1996), BH spin $a_k = 0.8$, $\alpha = 0.2$ (Z. H. Xie et al. 2009; S. Mondal et al. 2022b; see for jetted sources), and M_{BH} , as well as the mentioned $\dot{M}$ in Section 3.2, the precession timescale falls in a range of $\sim 7\text{--}50$ Myr, which is consistent with the timescales used in our simulations. The estimated timescales also match with the viscous timescale ($t_\nu = t_{\text{dyn}}(H/R_{\text{warp}})^{-2}/\alpha$) of the accreting matter, where t_{dyn} is the dynamical timescale of the infalling matter. We thus surmise that LT precession may significantly warp the disk at rather large radii, where the inward advection is balanced by the viscous torque. Therefore, the jet launching and energy extraction to power the jets is more like a BP scenario. This can produce precession in large-scale radio jets with timescales of a few tens of millions of years. This supports the shorter precession periods of $\sim 7\text{--}50$ Myr for the jets inferred in this work, compared to the full dynamical timescale (~ 190 Myr), which produces agreement with the observed uGMRT morphology of TGR J104454.

In addition to uGMRT morphology, the present system also showed a larger arc-shaped morphology in LoTSS Data Release 2 data (see Gopal-Krishna et al. 2022), which is mostly diffused emission. It has been discussed by C. Nolting et al. (2023) that such large arc morphologies in jets may originate from a longer precession timescale and the drop-off in the surface brightness of the synchrotron plasma further away from the original jet direction. Due to this, the precession effects may no longer be detectable. Such a scenario can occur if the AGN activity persists for a time period of > 100 Myr (see R. J. Turner & S. S. Shabala 2015). We performed a simulation with a much longer precession period, which produced a larger arc in the original jet (see AS15 for these parameters in Table B1 in Appendix B). We note that orbital motion alone is unlikely to be able to produce the observed small-scale bends and lobes in the jets.

3.4. Search through the Parameter Space

We have verified that the simulated TRG morphology significantly deviates from the observation once the relevant model parameters depart substantially from model S1, as illustrated by the results for models S2–S6, shown in Figure 5. Particularly large deviations from the observed jet morphology are seen for S4 and S5, shown in Figures 5(c) and (d), when both bipolar jets are assigned different velocities. The initially higher-velocity jets are found to eventually advance more slowly. Furthermore, these jets also showed larger arcs in their jet morphology. These features of the subrelativistic jets may be understood as arising primarily from the precession they undergo: Faster jets make larger excursions sooner from their initial directions. This would result in their forward thrust spreading over a larger area, which can partially disrupt the jets, reshape them, and induce instabilities, thereby accelerating the transfer of the jet’s kinetic energy into the ambient medium. Additionally, higher-velocity jets have lower mass

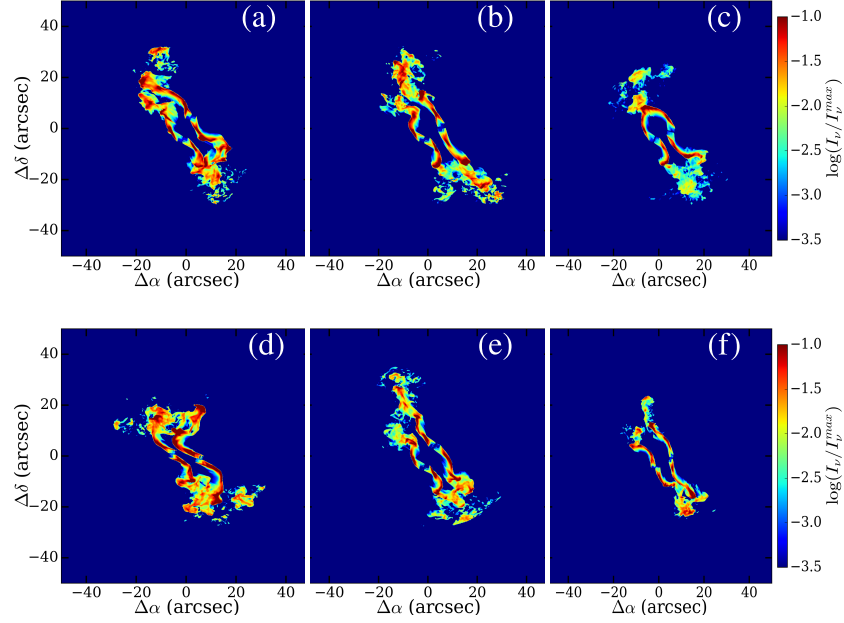


Figure 5. Same as Figure 2, but for the setups S2–S7 (from (a) to (f)) where the model parameters are varied individually and jointly. Snapshots are taken at 168 Myr (a, b, and e), 189 Myr (c), 176 Myr (d), and 136 Myr (f), respectively. The adopted jet parameters are given in Table 1.

loading, so that they more quickly accumulate equal amounts of swept-up mass, which slows them down (S. Mondal et al. 2022a).

Varying the inclination angle between the two bipolar jets can also affect the jet morphologies, as shown in the other panels (a), (b), and (e) of Figure 5. We see that for any of the substantial deviations in parameter values from those of S1 shown in Figures 5(a)–(e), the simulated TRGs deviate substantially from the observed morphology, although model S5 (panel (d)) comes fairly close. This makes it clear that numerical simulations serve as an effective tool for constraining the parameter space responsible for generating such complex structures, although they cannot provide unique solutions. Simulations of jets with narrower radii (S7) have also been tested. While there is a coarse agreement with the observed morphology, this simulation neither produces the wider lobe in the top-left jet nor the details of the wiggling pattern observed in this jet system (see Figure 5(f)). Such a consistency check further implies that the observed morphology depends not only on the jet–jet interaction but also on the internal dynamical parameters of the individual jets. Given the multiparameter nature of the system, we considered the possibility that different combinations of precession parameters might also reproduce a similar TRG morphology. To test this, we conducted an additional series of 15 simulations (AS1–AS15), exploring a broader parameter space (see Table B1 in Appendix B). However, reassuringly, none of these simulations yielded a better match than S1.

4. Conclusions

In this work, we have performed nonrelativistic hydrodynamic 3D simulations of two bipolar jets emanating from a gravitationally bound pair of host galaxies and propagating through an external medium of declining density. Our simulations were aimed to reproduce the observed morphology of the twin radio galaxy TRG J104454+354055. The main results obtained are as follows:

1. Injecting both bipolar jets without precession results in the jets simply drilling through the medium, without forming the observed helical or wiggling structures. This inconsistency with the observed radio morphology underscores the critical role of jet precession in explaining the morphology of TRG J104454. This further demonstrates that the precession can play a crucial role in the dynamical evolution of the jet pairs, even when their central engines are separated by (a few tens of) kiloparsec distances.
2. Low-velocity jets with different inclination angles and precessional periods can satisfactorily reproduce the observed morphology of TRG J104454.
3. For the optimal choice of input parameters among those we considered, the jet propagation along the $\pm y$ -axis was steady, while much random motion was observed in the $\pm x$ directions in the x – y plane. This arises from the effects of precession and the dynamics of the two bipolar jets.
4. Our study suggests the AGNs are in an advection-dominated accretion mode, with a preference for the BP mechanism for the jet launching.
5. The simulated jet precession timescales are substantially shorter than the full dynamical timescale of the jets and the orbital timescale of the system. Such precession timescales could arise from the LT effect due to misalignment of the black hole’s spin axis from that of the accretion disk feeding it.

In summary, the preferred simulation reproduces the observed complex morphologies of twin radio jets in TRG J104454 and underscores the significant role of precession in low-velocity jets. Moreover, these simulations highlight the importance of jet–ambient medium interactions in shaping their morphologies on a large scale in relatively undisturbed environments. Similar simulations can be used to probe the nature of any new TRGs with similar morphologies

expected to be revealed by next-generation telescopes, such as the Square Kilometre Array and its pathfinders.

However, not all TRGs necessarily exhibit precession; as seen in other discovered TRGs, external influences such as cluster winds likely play a key role. For instance, 3C 75 has been successfully modeled under the influence of cluster winds (G. Musoke et al. 2020), while the morphology of PKS 2149–158 can be attributed to buoyant motion (see, e.g., J. O. Burns & T. J. Balonek 1982, for a relevant buoyant evolution of a radio jet).

Since the present model allows for precession periods and angles as independent parameters for each bipolar jet, it can produce a broad range of jet morphologies. If precession is nonetheless found to be unimportant for future TRGs, the helical nature in their jet morphologies might be explained by the large-scale gas motion in the circumgalactic media associated with the interacting galaxy pair, or the orbital motion of the binary system, or continuous tidal interaction (A. Wirth et al. 1982), as appear to be required for the two previously known TRGs.

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Data Availability

Simulated data can be available upon reasonable request.

Appendix A Resolution Test

A resolution test is performed for the bipolar precessing jets (setup S6) with $\{x, y, z\}$ grids of dimensions $\{336 \times 720 \times 336\}$ and $\{504 \times 1080 \times 504\}$. The left and middle panels of Figure A1 show the emissivity maps for both reference and $1.5\times$ reference resolution grids. The right panel shows the temporal evolution of the total jet length (l_j), which is estimated for the $\pm y$ length where the first nonzero value of the tracer is obtained. The red and blue points in Figure A1 correspond to the reference and $1.5\times$ reference resolutions. As one can see, both resolutions give essentially similar results, with l_j values differing by only $\sim 4\%$. We note that these jet simulations do show different small-scale structures throughout their propagation in the ambient medium, so that aspect may not be very well converged. However, the similarities in the overall extents and morphologies appear to be sufficient for the purpose of this work (see discussions in R. P. Dubey et al. 2023).

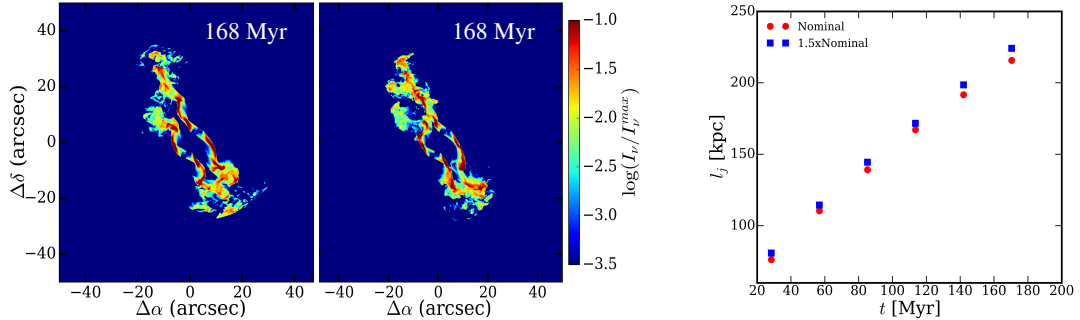


Figure A1. Comparison of the emissivity maps for two different resolutions for the S6 setup. The left and middle panels respectively show the nominal $\{336 \times 720 \times 336\}$ and high-resolution $\{504 \times 1080 \times 504\}$ maps. A comparison of the total length of the jet (l_j) for two resolutions is shown in the right panel. The red circles and blue squares correspond to the nominal and high-resolution cases, respectively.

Appendix B

Additional Simulations

We ran 15 additional simulations (not shown here) for different combinations of model parameters; however, none of these provided a better match to the observations. The parameters for those simulations are given in Table B1. From those simulations we noticed that a significant difference in jet velocities can almost stall the propagation of the low-velocity

jets, while the high-velocity one propagates much faster (e.g., model AS2). Moreover, jets that precess with shorter periods show more frequent curves in their helical structure, end up with diffuse emissions after traveling a shorter distance, and those diffuse emissions start interacting (e.g., in AS5). If two jets have opposite inclinations (as in AS8 and AS12) with positive inclinations of the left jet and a lower velocity compared to the right jet, then the low-velocity left jet remains nearly straight, without wiggling or developing lobes.

Table B1
Additional Setups Ran to Search for Possible TRG Matches with Observation

Additional Setups	θ_l (deg)	θ_r (deg)	P_r (Myr)	P_l (Myr)	Ψ_j (deg)	M_j (right)	M_j (left)	R_j (kpc)
AS1	−45	−30	28	28	20	65.2	65.2	4
AS2	−45	−30	28	28	23	87.0	43.5	4
AS3	−45	−35	28	28	20	65.2	65.2	4
AS4	−45	−35	53	28	20	65.2	65.2	4
AS5	−45	−30	7	7	20	73.9	73.9	4
AS6	−45	30	14	14	20	65.2	65.2	4
AS7	−45	40	49	28	20	87.0	87.0	4
AS8	15	−35	14	14	30	82.6	52.2	4
AS9	−30	45	49	49	30	82.6	65.2	4
AS10	−40	45	35	35	30	82.6	65.2	4
AS11	−40	45	28	28	30	65.2	65.2	4
AS12	20	−35	17	17	30	82.6	60.9	4
AS13	40	45	49	49	30	87.0	65.2	4
AS14	35	35	28	28	30	78.3	65.2	4
AS15	−45	40	140	84	20	65.2	65.2	4

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