Postprint: Research Advances on the Collimation Mechanism of Radio Galaxy Jets

Authors: Shen Yuling[1], Cui Lang[1], An Tao[1,2], Liu Xiang[1]

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Abstract

Radio galaxies are an important subclass of radio-loud active galactic nuclei (AGN), with relativistic radio jets being one of their typical observational features. The acceleration process, collimation mechanism of radio jets, and the role played by magnetic fields have always been key focuses of attention for astronomers. In recent years, with the development of high-resolution VLBI observation technology, radio astronomical observation instruments have been able to probe the core regions of AGN, thereby enabling the study of the internal structure and physical processes of jets. Thanks to this, astronomers have made significant progress in observational studies of jet collimation mechanisms in nearby radio galaxies. First, mainstream jet formation models are introduced, then through typical research cases, the latest progress in research on collimation mechanisms for the two classes of radio galaxies, FR-I and FR-II, is elaborated, and finally, a summary and outlook for research on radio galaxy jet collimation mechanisms is provided.

Full Text

Progress in the Study of Jet Collimation Mechanisms in Radio Galaxies

SHEN Yuling[1], CUI Lang[1], AN Tao[1,2], LIU Xiang[1]

[1] Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011, China
[2] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

Abstract

Radio galaxies represent an important subclass of radio-loud active galactic nuclei (AGN), with relativistic radio jets being one of their typical observational characteristics. The acceleration process of radio jets, their collimation mechanisms, and the role of magnetic fields have long been focal points for astronomers. In recent years, advances in high-resolution VLBI observational techniques have enabled radio astronomical instruments to probe the nuclear regions of AGN, facilitating studies of the internal structure and physical processes of jets. Consequently, astronomers have made significant progress in the observational investigation of jet collimation mechanisms in nearby radio galaxies. This paper first introduces mainstream jet formation models, then reviews recent advances in collimation mechanism studies for both FR-I and FR-II radio galaxies through typical case studies, and finally provides a summary and outlook for future research on radio galaxy jet collimation mechanisms.

Keywords: radio galaxies; jet; collimation mechanism; VLBI

1 Introduction

Active galactic nuclei (AGN) are a particularly special class of extragalactic objects characterized by intense activity and complex, extreme astrophysical processes in their cores [1-3], making them important research targets for frontier topics such as galaxy-black hole coevolution [4]. The main components of AGN include a central supermassive black hole (SMBH), an accretion disk formed by matter accreting onto the black hole, hot gas present on the accretion disk (called the corona), broad-line region (BLR) and narrow-line region (NLR) surrounding the accretion disk, a torus structure composed of dust and gas, and jets existing at the poles of the black hole, as shown in Figure 1 [Figure 1: see original paper] [5, 6].

It is widely believed that the accretion activity of the central supermassive black hole in AGN serves as the "engine" for relativistic jets, generating high-speed, collimated jets composed of non-thermal plasma at the poles of AGN [6, 7]. In fact, jet phenomena were discovered in the M87 galaxy as early as 1918 [8], and AGN relativistic jets have fascinated astronomers for an entire century. The mechanisms of jet production, acceleration, and collimation remain among the most challenging research topics in astrophysics [9, 10]. In the unified model shown in Figure 1, both strong and weak unified models can be seen [2]. The strong unified model has only one intrinsic parameter: the orientation of the observer' s line of sight relative to the AGN symmetry axis. According to this model, differences among various types of AGN are entirely determined by orientation (i.e., jet direction), with different orientations corresponding to different AGN types. The weak unified model includes additional parameters [2]. Most commonly, besides orientation effects, another parameter is taken as the ratio of radio luminosity to optical luminosity. In the complete unified model, AGN include two basic types: radio-loud AGN and radio-quiet AGN. Radio-loud AGN account for about 10% of all AGN, with relativistic radio jets being a typical characteristic of radio-loud AGN [10]. Among them, radio galaxies are an important subclass of radio-loud AGN, with jet directions forming relatively large angles with our line of sight (generally exceeding 10°) and relatively weak Doppler boosting effects, often exhibiting a morphology of a radio core plus bilateral jets—making them ideal targets for studying jet formation regions and collimation processes near supermassive black holes [11].

Radio galaxies are further divided into FR-I and FR-II types based on morphology [12], with these two types showing clear differences in radio luminosity. FR-I galaxies have weaker jet luminosities ($L_{178 \quad 2} \leq 2 \times 10^{25}\ \mathrm{W \cdot Hz^{-1}}$), displaying edge-darkened morphologies where jet intensity weakens with increasing distance from the core. FR-II galaxies have higher jet luminosities, showing edge-brightened morphologies where radio lobes are brightest farthest from the core, with bright hotspots visible at outer edges. Typical jet morphologies of these two types are shown in Figure 2 [Figure 2: see original paper]. Since this classification scheme was proposed, researchers have investigated characteristics of these two basic morphologies in various aspects [13-18]. For example, FR-II types mostly have rotating gas disks with emission lines, sometimes including chaotic and turbulent dust disks, while FR-I types may lack these features [19]; the black hole spins may differ between the two types (low spin for FR-I, high spin for FR-II) [14]; there is a relationship with host galaxy mass, where more massive elliptical galaxies tend toward FR-I morphology [15], among other models based on differences in jet interactions with surrounding media [20]. However, the differences in acceleration and collimation mechanisms for the many highly collimated relativistic jets observed remain unclear.

Research on jet collimation processes is based on jet formation and acceleration models. Researchers have proposed many jet formation and acceleration models, with the most representative being the Blandford-Znajek (BZ) process [7] and the Blandford-Payne (BP) process [22]. Many scholars have conducted comparative studies of magnetic fields in these two energy extraction processes from black hole and accretion disk systems (BZ vs. BP) (see Chapter 2 for details) and discussed the relative importance of the BZ process [23]. Although which process dominates jet formation and collimation remains debated, the view that magnetic fields connecting the black hole and accretion disk drive jets has been accepted by most scholars [24-29]. These models have laid the foundation for numerous subsequent theoretical and numerical simulations of jet acceleration and collimation [30-33].

Nevertheless, studies of AGN jet structure remain extremely challenging for two main reasons. (1) The physical mechanisms involved in jet dynamics are highly complex. Since AGN jets are excited by relativistic magnetized fluids emitted near supermassive black holes and partially by internal magnetized accretion flows, potentially extending to megaparsec (Mpc) scales to form giant radio lobes, understanding black hole accretion-driven systems requires general relativistic magnetohydrodynamics (GRMHD) equations to describe the fluid dynamics near relativistic jet launch regions. These equations are extremely complex and difficult to solve analytically. In recent years, rapid development of numerical simulations has made such research possible [31, 34], such as analytical studies of strongly magnetized jets [35], but the processes of particle acceleration and energy dissipation and their roles in jets remain without clear conclusions [36-39]. (2) Important physical processes in jets involve different spatial scales. Current theoretical models of jet formation (BZ and BP models) [7, 22] propose that jets are driven by strong magnetic fields, initially produced at slow speeds, with magnetic fields amplified by rotating black holes or accretion disks, after which the magnetic energy of the rotating field is converted to kinetic energy to accelerate the jet. Theoretical models place the acceleration and collimation zone (ACZ) in the region approximately 10 R - 10^5 R from the black hole [40]. For a nearby AGN jet (redshift $z < 0.1$), this corresponds to angular scales of milliarcseconds (mas) or even microarcseconds (as). Additionally, structural changes corresponding to rapid variability observed in X-ray and γ-ray bands require sub-parsec (pc) scale or even higher spatial resolution—difficult to achieve directly with optical, X-ray, or γ-ray telescopes. To address the challenges of imaging compact objects, very long baseline interferometry (VLBI) in radio bands emerged and rapidly developed. As early as the 1960s, astronomers at the Lebedev Physical Institute of the Soviet Academy of Sciences first formally published the VLBI concept of "independent local oscillators and tape recording"long-baseline interferometers [41]. During the 1970s-80s, VLBI observations were conducted with temporarily assembled arrays, revealing pc-scale structures in several bright radio sources [42-44] and uncovering morphological characteristics of jet cores and apparent superluminal motion of jet components. In the 1990s, the European VLBI Network [45] and the U.S. Very Long Baseline Array (VLBA) [46, 47] greatly advanced high-resolution observational studies of AGN jets. Subsequently, the establishment of the Australian Long Baseline Array (LBA) [48], Japanese VERA (VLBI Exploration of Radio Astrometry) [49], and East Asia VLBI Network (EAVN) [50] further improved global VLBI network coverage. The Global mm-VLBI Array (GMVA), Event Horizon Telescope (EHT) [51], and Korean VLBI Network (KVN) [52] expanded research to higher frequencies (86, 129, 230 GHz). The rapid development of the Event Horizon Telescope (EHT), in particular, enabled humanity' s first photograph of a black hole, opening a new era for observational studies of AGN and supermassive black holes with unprecedented angular resolution.

The collimation mechanism of relativistic jets remains an incompletely solved problem in astrophysics. However, in recent years, high-resolution VLBI observational techniques have allowed researchers to not only obtain parameters such as jet velocity and acceleration magnitudes but also penetrate internal regions to acquire fine structures within jets. Thanks to these advances, significant progress has been made in observational studies of nearby AGN jet structures.

Due to space limitations, this paper focuses on recent progress in studies related to radio galaxy jet collimation mechanisms, emphasizing the unique role played by VLBI technology. The article is structured as follows: Chapter 2 briefly describes current mainstream jet models and collimation mechanisms; Chapters 3 and 4 present typical case studies detailing recent advances in jet collimation mechanisms for FR-I and FR-II radio galaxies, respectively; Chapter 5 provides a summary and future outlook.

2 Jet Formation Models and Collimation Mechanisms

2.1 Jet Formation Models

Regarding AGN jet formation and acceleration mechanisms, scientists have proposed numerous models over the past decades, with the most influential being two magnetic-field-driven jet models: the Blandford-Znajek (BZ) model [7] and the Blandford-Payne (BP) model [22]. The primary difference is that the BZ model mainly extracts black hole rotational energy, resulting in jets with minimal matter content dominated by Poynting flux, whereas the BP model primarily extracts energy from the accretion disk surrounding the black hole, producing jets dominated by matter content [53].

2.1.1 BZ Model The BZ model, proposed by Blandford and Znajek in 1977 [7], posits that AGN jets are driven by rotating black holes with accreting magnetic flux, where the accretion system extracts black hole rotational energy through magnetic fields connected to the black hole. The angular momentum of supermassive black holes is typically called spin angular momentum, and its gravitational influence extends over large regions. Accretion flows create a magnetosphere around rotating supermassive black holes, subsequently forming magnetized plasma. Interaction between supermassive black hole spin and magnetic fields alters the magnetic field structure, accelerating the plasma. Tchekhovskoy et al. [34] found through numerical simulations that the BZ process can extract energy from supermassive black holes under conditions of highly magnetized accretion flows and high black hole spin. The energy extracted through the BZ process depends on the magnetic flux and spin of the supermassive black hole. Initially, this process successfully explained energy extraction from black holes via magnetic fields in quasars and AGN, capable of extracting up to 29.3% of rotational energy—an extremely efficient energy extraction mechanism [54]. The BZ process also provides good explanations for relativistic jet production [55].

2.1.2 BP Model In addition to magnetic field configurations connecting to black holes as in the BZ process, large-scale ordered magnetic fields connecting to accretion disks also exist [55]. In 1982, Blandford and Payne [22] proposed the BP model, assuming large-scale magnetic fields are "frozen" into the accretion disk. They argued that due to the disk' s rotation, magnetic field lines on the accretion disk rotate with the accreting matter around the black hole. When the angle between the magnetic field and the disk surface is less than 60°, centrifugal forces can drive plasma outflows. At distances far from the disk surface, toroidal magnetic field components collimate the outflowing material. Unlike the BZ process, jets produced by the BP process carry substantial baryonic matter, explaining low-velocity outflows observed in some AGN. Additionally, matter outflows in the BP process significantly reduce disk luminosity; when jets appear, the disk’ s X-ray radiation flux consequently decreases [56].

2.2 Collimation Mechanisms

For the observed large-scale collimated jet structures, two primary factors have been proposed as causing collimation: magnetic fields and interstellar medium.

Magnetic fields are ubiquitous in the universe [53, 57-62], though generally weak. However, magnetic fields in accretion disks can be amplified through the “magnetorotational instability” effect [63]. This effect arises because accretion disks are always differentially rotating—angular velocity is greater at smaller radii. In such unstable disks, gas becomes turbulent and magnetic fields are amplified. The mainstream jet formation models mentioned earlier all feature large-scale poloidal magnetic fields near the black hole rotation axis. In the BZ model, differential rotation generates a helical magnetic field around the rotation axis [64, 65], with helical magnetic field lines driving “trapped” plasma outward, during which the corresponding forces point toward the rotation axis. Depending on the relative strengths of magnetic fields, plasma density, and rotation, different outcomes result, such as non-collimated winds, slow outflows, or relatively collimated jets. This magnetohydrodynamics (MHD) process is generally considered the initial acceleration and collimation mechanism for jets. Recently, the analytical model by Chen and Zhang [35] quantitatively illustrated this process (as shown in Figure 3 [Figure 3: see original paper]), providing quantitative analytical calculations of how magnetic field lines wrap and how helical jets accelerate. In the BP model, magnetic fields are dominated by the poloidal component near the accretion disk, while at large distances from the disk, the disk rotation cannot drive magnetic field lines synchronously, resulting in a toroidal component that can collimate the jet [22].

Additionally, interstellar medium pressure can also collimate jets, though its range of action differs from magnetic fields. Simply put, as jets propagate, their fast flow and low gas density result in pressure lower than that of the surrounding interstellar medium, causing the interstellar medium to exert pressure on the jet gas and thereby collimate it [53, 66]. This pressure may originate from gas, radiation, or shocks in the interstellar medium. In this scenario, environmental differences around different galaxies lead to different jet structures.

Research on relativistic jet collimation mechanisms has long been challenging because multiple mechanisms often operate simultaneously in a single galaxy, yet it is precisely this complexity and interconnection of various characteristics that makes the research valuable.

Below, we elaborate on recent research progress for FR-I/FR-II radio galaxies. As case studies, we present several nearby radio galaxies where high-resolution imaging observations provide insights into regions near jet origins at their cores.

3 FR-I Type Radio Galaxies

3.1 M87

Since the discovery of the M87 jet [8], it has been monitored for over a century. Its proximity (D = 16.8 Mpc [67]) and strong radiation across the entire electromagnetic spectrum from radio to γ-rays make it an excellent target for studying relativistic jet physics, including large-scale jet morphology [68], jet formation and related properties [69, 70], and the origin of high-energy X-ray emission [71-73]. Additionally, the central supermassive black hole mass is relatively large, reaching 6.5×10^9 M [74-76] (M is solar mass). The combination of relatively close distance and large black hole mass means that 1 mas angular scale in this galaxy corresponds to 0.08 pc (approximately 140 R) [77], enabling detection of structures 10-100 times finer than in distant quasars or blazars. Consequently, M87 has consistently been a top priority target for black hole shadow imaging [78] and VLBI studies of relativistic jet formation and structure.

Over the past decades, extensive and in-depth studies of the M87 jet using VLBI technology at various scales have yielded important progress. In the (10-100) R scale range, Hada et al. [77] reported in 2016 on GMVA 86 GHz observations of M87 using the high-sensitivity array (HSA), with resulting images showing a wide-opening-angle jet base with clear edge-brightened structure [79], consistent with magnetically-driven jet models from rotating black holes [80-83] (i.e., the BZ model). At the same scales, Walker et al. [84] used 43 GHz VLBA observations in 2018 to produce polarization images revealing helical magnetic fields at these scales, indicating the magnetic field configuration. Beyond 100 R from the black hole, up to where the bright knot HST-1 appears (approximately 10^6 R) [85-87], Nakamura et al. [82] in 2018 produced multi-frequency VLBI images at 1-43 GHz showing the M87 jet has a parabolic shape (or quasi-parabolic, as it is not a standard parabola; however, this paper focuses on distinctions and transitions between various jet morphologies, so we do not strictly differentiate and collectively refer to it as parabolic). Beyond HST-1, the jet becomes conical (see Figure 4 [Figure 4: see original paper]).

A series of observational results support magnetic collimation mechanisms for the M87 jet—namely, MHD processes. Notably, the change in M87 jet morphology coincides with the location of bright knot HST-1. Addressing this feature, Asada and Nakamura [85] speculated that this may relate to changes in environmental pressure distribution and recollimation shocks produced by pressure drops and sudden expansions. To test this hypothesis, they discussed possible physical relationships between jet confinement and radial distribution changes in environmental pressure. Their analysis indicated that magnetohydrodynamic jets are initially constrained by external gas influenced by supermassive black hole gravity, after which the jet expands freely in a conical shape. In 2015, Asada et al.' s speculation received support from external medium pressure measurements by Russell et al. [88]. Moreover, recent observational studies show similar situations in another radio source, 1H0323+342 [89]. On the other hand, single power-law pressure models can also predict jet morphology changes. For example, Lyubarsky' s analytical model in 2009 [90] predicted the transition region from parabolic to conical jet shapes and quasi-oscillations in jet shape within conical regions. Levinson and Globus [91] in 2017 applied this method to study recollimation shock characteristics in M87. Collectively, these studies demonstrate that recollimation shocks also significantly influence jet collimation.

In typical AGN systems, winds have important astrophysical significance. Since winds can cause mass loss, the accretion rate onto the central massive black hole in a given AGN system may be far smaller than that measured via X-rays at the Bondi radius. Compared to the luminosity predicted by the accretion rate determined at the Bondi radius (M_B 0.2 M • yr^{-1}) [88, 92], M87' s nucleus is extremely faint (L_{bol} 10^{-6} L_{Edd}, where L_{bol} is the nuclear radiative luminosity and L_{Edd} is the Eddington luminosity) [93], indicating very low radiative efficiency of the central black hole' s accretion state, or that the accretion rate M near the event horizon is much lower than M_B.

In 2014, Kuo et al. used the Submillimeter Array (SMA) at 230 GHz to conduct Faraday rotation measure (RM) observations of M87' s nucleus, showing accretion rates near the black hole of M $\leq$ 10^{-3} M • yr^{-1}, at least two orders of magnitude lower than M_B [94], demonstrating that accretion rates in the inner accretion flow region are significantly suppressed and confirming that M87 is indeed a low-luminosity AGN. However, no studies or reports have yet addressed the specific processes responsible for the enormous mass loss between the Bondi radius and black hole scales.

In this context, Park et al. [95] in 2019 collected multi-frequency VLBA data to study RM in M87' s jet within the Bondi radius in detail. By analyzing RM values at each frequency, they found that RM magnitudes between (5 $\times$ 10^{3} - 2 $\times$ 10^{5}) R from the black hole decrease with increasing distance (see Figure 5 [Figure 5: see original paper]), with slopes well-represented by a hot gas density profile r^{-1}, where r is the distance from the black hole.

Non-relativistic, non-collimated gas flows out from the hot accretion flow, consistent with various numerical simulation results. The pressure profile derived from the density profile is significantly flatter than typical pure advection-dominated accretion flows (ADAF), capable of both collimating jets and gradually accelerating them in MHD processes. Figure 5 matches well with observed gradual collimation and acceleration of the M87 jet within the Bondi radius. Additionally, RM results confirm that the wind' s pressure profile is shallow enough to confine M87' s jet to a parabolic shape up to the Bondi radius, indicating that wind is a major external source of jet confinement.

3.2 3C 84

3C 84 is a bright radio source in the elliptical galaxy NGC 1275 near the Perseus cluster. Classified as an FR-I source based on radio luminosity [96], it has been well-studied due to its brightness and proximity, known to have multi-lobe morphology from pc to 10 kpc scales [97] with documented periodic jet activity. Between 2005 and 2008, γ-ray emission from the source' s core significantly increased [98], and a new radio component "C3" was ejected southward from the core on sub-pc scales [99, 100]. These phenomena prompted multi-wavelength observational campaigns that continue today. The galaxy' s rich observational data indicate a very complex gaseous environment around the nucleus [101-104]. These characteristics make 3C 84 an ideal target for studying jet formation, γ-ray production, supermassive black hole accretion, and feedback phenomena.

Recent high-resolution VLBI imaging of 3C 84 has further refined our understanding of jet transverse structure from sub-pc to pc scales. In 2014, Nagai et al. used VLBA 43 GHz data to study 3C 84's sub-pc scale jet structure, revealing a clear, bright jet morphology [105]. Their results showed that within the (10^3 - 10^5) R scale range, the jet width profile is rapidly collimated, not parabolic. Additionally, in 2018, Giovannini et al. used space VLBI observations to resolve brightness structures near the jet base down to 50 as scales (corresponding to approximately 200 R) [106] (see Figure 6 [Figure 6: see original paper]).

As seen in Figure 6, near the nuclear region the jet is wide, meaning it has a large opening angle—similar to M87—but differs in that 3C 84' s jet collimation profile approaches a cylindrical rather than parabolic shape. Since relativistic MHD jet profiles are constrained by external media and this galaxy is gas-rich, this phenomenon likely results from differences in the jet propagation environment.

However, many properties of the nuclear or circumnuclear region remain unanswered at smaller scales (e.g., pc scales). Moreover, Giovannini et al. [106] suggested based on their results that if 3C 84' s jet were in pressure equilibrium with the external medium, the corresponding density profile would flatten, which seems unlikely for disk-like accretion flows with flat density profiles along the inner edges of geometrically thick disks. Therefore, the jet is likely in non-equilibrium pressure with other layered components of the accretion flow or interstellar medium.

Building on this, long-term monitoring of the bright radio component C3 in the jet revealed clues about the pc-scale nuclear environment: after being ejected, C3 moved continuously southward [107], but in 2015, C3 suddenly changed direction and began moving eastward (see Figure 7 [Figure 7: see original paper]) [108], with both total flux [108, 109] and polarized flux [110] increasing. This peculiar kinematics is difficult to explain through internal jet motion but can be naturally explained by C3 interacting with non-uniform, dense clumpy media [111]. Furthermore, recent monitoring of the counter-jet 2 mas north of the source's nucleus also indicates the presence of dense media on sub-pc to pc scales [112]. On the other hand, high-density circumnuclear environments may complicate the relationship between original jet characteristics and jet production, requiring higher-resolution VLBI technical support.

3.3 NGC 4261

NGC 4261 (3C 270) is another nearby FR-I radio galaxy characterized by nearly symmetric kpc-scale bilateral jets [113]. At a distance of 31.6 Mpc from Earth [114], corresponding to 0.15 $\mathrm{pc} \cdot \mathrm{mas}^{-1}$, its relative proximity creates opportunities to study fine structures within 1 pc of the central black hole. NGC 4261' s central black hole mass is $4.9 \pm 1.0 \times 10^8$ M [115]. Hubble Space Telescope observations also reveal a gas and dust disk approximately 300 pc in diameter at NGC 4261' s center [116]. VLBI observations reveal another characteristic of NGC 4261: pc-scale bilateral jets parallel to the rotation axis of the dust disk [117]. The western jet points toward the observer, while the eastern jet points away—the latter called the counter-jet—with both jet brightnesses slightly affected by relativistic beaming.

In 2018, Nakahara et al. [118] used multi-frequency images from the Very Long Baseline Array (VLBA) and Very Large Array (VLA) to obtain new observational data on jet width and radiation profiles along the jet within (10^3 - 10^9) R . VLBA images show that at approximately 10^4 R from the central black hole, both jet and counter-jet width profiles exhibit transitions from parabolic to conical shapes (see Figure 8 [Figure 8: see original paper]); radiation profiles near the jet also change at this same location. The consistency of transition locations indicates that physical environmental conditions change for NGC 4261' s jet at this distance. Evidently, the previously reported phenomena of jets transitioning from internal to external regions and from acceleration to expansion found in M87 and NGC 6251 also exist in NGC 4261. Additionally, this study discovered another radiation profile transition in the conical region at approximately 3×10^6 R . Whether another major change exists in the jet' s external environment warrants further investigation.

NGC 4261 is the first galaxy where structural changes in jets have been observed in both the jet and counter-jet, suggesting that AGN jet collimation processes may be caused by global distributions of surrounding environmental pressure rather than local interactions between jets and surrounding media. Specific influence mechanisms require discussion of jet environment evolution regarding particle acceleration, cooling, dissipation, and pressure balance with surrounding hot gas. On the other hand, like M87 and NGC 6251, jet width and radiation intensity both transition at nearly the same location, with jet shape changing from parabolic to conical. Based on equipartition assumptions, Nakahara et al. [118] derived jet pressure distributions consistent with X-ray-based hot gas pressure estimates, observationally supporting jet pressure equilibrium with environmental pressure.

4 FR-II Type Radio Galaxies

4.1 Cygnus A

Cygnus A is a typical FR-II radio galaxy [119] at redshift z = 0.056075 [120]. Optical and near-infrared spectroscopic data indicate its central black hole mass is approximately 2.5×10^9 M [121]. Its jet maintains a parabolic shape overall from 0.3 pc to 60 kpc [122], which is remarkable because the jet' s parabolic morphology persists across eight orders of magnitude in gravitational radii, far beyond the central black hole' s gravitational influence range—implying that high-power jets can penetrate surrounding media while maintaining their shape [123].

In 2016, Boccardi et al. [124] studied the kinematic properties and transverse structure of Cygnus A' s bilateral jets based on VLBI 43 GHz data, finding that the power-law dependence of jet width profiles on sub-pc scales can be expressed as W(r) $z^{0.55\$\pm0.07,}$*whereW(r)isjetwidthandzisprojecteddistancefromthecore—indicatingaparabolicjetshapeuptoapproximately* R . In 1991, Carilli et al. [125] used VLBI 4.9 GHz imaging to show the source' s jet width remains constant at 2.2 mas at 4-20 mas (corresponding to approximately 10^4 R - 10^5 R). In 2019, Nakahara et al. [122] used VLA archival data and publicly available VLBI measurements to study changes in Cygnus A' s jet radial width profile: as shown in Figure 9 [Figure 9: see original paper], multi-frequency imaging results reveal gradual jet collimation—smoothly decreasing opening angles with increasing distance—maintaining an overall parabolic shape continuously to kpc scales. They also discovered clear discontinuities in the jet width radial distribution (at approximately 100 pc or 5×10^5 R), speculating that the jet cross-section expands and is recollimated due to loss of dynamic equilibrium or renewed oscillations under relatively stable environmental pressure conditions.

As mentioned previously, relativistic MHD jet profiles are constrained by external media, and general relativistic MHD simulations also show that jet parabolic profiles are influenced by external pressure [118]. Theoretical studies indicate that non-conical morphologies require transverse pressure from external media with radial dependence following p r^{-} [126, 127], where p is external medium pressure and r is distance from the core. In 2009, Komissarov et al. [128] showed that when external gas pressure follows $b \leq 2$, jets form parabolic shapes (power-law index $0.5 < a \leq 1$); when external pressure is insufficient, jets form conical shapes. For example, M87 and NGC 6251 jets transition from parabolic to conical at approximately 10^5 R , near their Bondi radii or central supermassive black hole influence ranges [85, 129]. Recent RM observations of M87 indicate surrounding winds satisfy $b < 2$, which would confine the jet [95]. Therefore, for Cygnus A, surrounding gas pressure support likely maintains its large-scale morphology unchanged.

In 1996, Carilli and Barthel [119] estimated Cygnus A' s jet pressure under minimum energy conditions (approximately 6×10^{-15} N · cm^{-2}), finding it exerts pressure on the environment. They used X-ray observational data to map hot gas pressure gradients on kpc scales: at 70-500 kpc from the nucleus, the clumpy medium' s radial profile corresponds to power-law index b 1.6; in regions relatively far from radio lobes (approximately 60 kpc), wide-field Chandra (X-ray telescope) observations indicate that if pressure is significant, surrounding hot gas will collimate the jet into a parabolic shape. In the same year, Reynolds and Fabian calculated pressure distributions of 10-500 kpc based on ROSAT (the ROentgen SATellite) observational data, showing profiles become flatter in radio-emitting regions [130]. According to Chandra data [131], hot gas pressure at 10-30 kpc distances is approximately $5 \times 10^{-15}\ \mathrm{N \cdot cm^{-2}}$, comparable to kpc-scale jet minimum pressures. Therefore, environmental pressure from X-ray-emitting hot gas is sufficient to balance minimum jet pressure, reasonably explaining why Cygnus A' s jet maintains a parabolic shape to kpc scales. Another possibility is that at such large scales for Cygnus A, the jet may achieve pressure equilibrium with environmental media through cocoons or backflows around hotspot regions—possibly a phenomenon unique to FR-II sources. However, better explanations for additional differences between FR-I and FR-II require increased FR-II research samples.

4.2 3C 111

3C 111 is another nearby FR-II radio galaxy at redshift z = 0.049. In June 1982, VLA data at 1.4 GHz, 4.9 GHz, and 15 GHz showed 3C 111 has a bright, compact nucleus, a highly collimated one-sided jet, and large-scale bilateral radio lobes [132]. Additionally, beginning in 1995, Lister et al. [133] used VLBA to implement the MOJAVE project (Monitoring of Jets in Active Galactic Nuclei with VLBA Experiments), conducting long-term VLBI monitoring at 15 GHz showing strong structural changes in 3C 111' s jet morphology on pc scales. Jorstad et al. [134], Chatterjee et al. [135], and Lewis et al. [136] also conducted VLBA monitoring of 3C 111 at 43 GHz, with all these observations demonstrating that 3C 111 is an excellent radio source for studying jet internal structure and collimation mechanisms, with its jet structures at different scales shown in Figure 10 [Figure 10: see original paper].

However, regarding the observed highly collimated jet, previous studies speculated that external medium pressure might be insufficient to confine such jets, with magnetic confinement being more likely. Due to limited technology at the time and insufficient attention to this issue, in-depth research was not conducted. Moreover, 3C 111' s jet displays a parabolic morphology on pc scales, transitioning from parabolic to conical near the central supermassive black hole' s gravitational influence range [139], similar to M87 and NGC 6251. Does this imply that common jet collimation mechanisms also apply to this source? What similarities and differences exist with the aforementioned FR-I sources? These questions require further research and confirmation.

5 Summary and Outlook

Recent research indicates that FR-I and FR-II galaxy jet collimation mechanisms have distinct characteristics but also common features, generally agreeing that combined magnetic field structure and environmental medium pressure effects produce jet collimation results. For FR-I galaxies, in addition to the work cited here, increasingly detailed studies of internal jet geometry have been conducted for many nearby FR-I radio galaxies, such as NCG 315 [140], NGC 6251 [129], 3C 120 [141, 142], and 3C 264 [143]. Most notably, jets in these galaxies all exhibit clear parabolic morphologies on sub-pc to pc scales. Many FR-II radio galaxies, such as 3C 111, Cygnus A, and 3C 445 [144], also have powerful jets with rich historical observational data, initially meeting conditions for detailed studies of FR-II radio galaxy jet collimation mechanisms. However, except for Cygnus A, which has received attention in the past two years, other FR-II radio galaxies have not been systematically studied, and details of their jet collimation processes remain unclear [145], necessitating increased research data on FR-II galaxies to improve sample completeness.

Next-generation radio array telescopes such as the Square Kilometre Array (SKA) [146] and the next-generation Very Large Array (ngVLA) [147] promise ultra-high dynamic range imaging capabilities that will provide more information about jet structure, magnetic fields, and dynamics [148, 149], substantially increasing samples for radio galaxy jet collimation mechanism studies and helping reveal similarities and differences in jet morphology and collimation mechanisms between FR-II galaxies, FR-I galaxies, and other radio-loud AGN, thereby improving our understanding of AGN jet characteristics.

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