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活动星系和类星体中的喷流 (I)

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摘要

自从人们获得河外射电源的第一个结构图像以来， 30 多年时间已经过去了。在这段时间的后半期，人们对许多源中的喷流状结构作了大量研究。目前，我们正在分析所获得的有关喷流的第一代结果，这包括高分辨率观测、数值模拟和理论研究等诸方面的成就。在本文中将详细地讨论河外射电源中的喷流。整个题目由两部分组成：第一部分将阐述一些基本概念，即喷流的定义、形式、产生和传播等方面；喷流的不对称性及其统一的解释模式也将在这一部分内讨论。有关喷流的形态和用 VLA 、 MERLIN 、 VLBI 和毫米波 / 亚毫米波 VLBI 观测所得到的高分辨率结果，将放在第二部分内阐述。

关键词 星系：活动星系 — 星系：喷流 — 类星体：一般 — 技术：干涉 — 射电连续辐射：星系

Jets in Active Galaxies and Quasars (I)

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Abstract

More than three decades have passed since our present picture of extragalactic radio sources began to unfold. The latter half of that time has witnessed the 'mapping' or 'imaging' of jet-like structures in many of these sources. We are now digesting the first generation of high resolution observations of extragalactic jets, the first generation of numerical simulations, and the first

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generation of theoretical studies. This paper will address the subject of extragalactic jets in a detailed and comprehensive manner. The topic consists of two parts. Part I will give us a basic concept. We will discuss the definition, types, production and propagation of jets. Also jet asymmetries and unified models will be included in this part. Features related to jets and high resolution imaging including the VLA, MERLIN, VLBI and mm-/submm-VLBI will be discussed in part II.

Key words galaxies: active—galaxies: jets—guasars: general—techniques: interferometric—radio continuum: galaxies

1 Introduction

One of the biggest puzzles for early radio astronomers was the nature of the bright "radio stars" found on sky surveys but which did not seem to have any relationship with known astronomical objects. As the resolving power of early radio telescopes improved it soon became clear that these objects were not "stars" at all, but could be identified with active galaxies radiating enormous power from regions far outside their apparent optical confines. In the past three decades the diversity of these objects has increased, and in addition to the classical "radio galaxies", we now have a zoo of rather exotic species of extragalactic sources of emission, such as, Seyfert galaxies, N galaxies, BL Lac objects, quasars, blazars, and QSOs.

It is now believed that all these objects are variations on a theme, and the main differences in their appearance lie in their different orientation with respect to an observer. They are known collectively as "active galaxies". In this article, we will be concerned with the observational aspect of one of the most intriguing and spectacular phenomena associated with active galactic nuclei (AGN), the presence of radio jets, that is, radio emission in the form of 'narrow linear jet'.

Jets have been known for 75 years[1], when a photograph of the giant elliptical galaxy, M87 revealed a narrow linear ('jet-like') feature protruding from its nucleus. In 1963, a similar feature was found in 3C273, the first quasar[2]. The existence of radio jets was 'justified' on the basis of the necessity of a more or less continuous supply of energy over the radio source lifetime to maintain the emission in the lobes far from the nucleus[3]. Relatively few optical jets have been found since then, but radio astronomers have found them in several hundreds of active nuclei of galaxies and quasars. Recently by using the Hubble Space Telescope it has also been possible to obtain optical images of jets in several AGNs with a resolution comparable to that obtained with VLA (see Figure 1: upper).

1.1 What are jets?

It is worth making a note on terminology concerning **beams** and **jets**. We always use the term **beam** to refer to figments of the theoristic imagination, and the term of **jet** to refer to observed structures. The latter term is now applied indiscriminately in the astronomical literature, and a number of authors have attempted to construct a 'code of practice' for its legitimate usage. Although no universal definition of the structural term 'jet' exists, Bridle and

Perley[4] suggest that for a feature to qualify as a jet it must be at least four times long as it is wide, distinctly bright or spatially resolved from other radio source features and be aligned with and closest to the core. However, the term 'jet' has come to refer to any roughly linear feature associated directly or remotely with the core of an active galaxy.

In the last decade, high resolution observations made with the VLA, MERLIN and VLBI have shown that jets can be found in most powerful radio sources, on scales ranging from a few parsecs up to many hundreds of kiloparsecs. An example of an extragalactic radio jet is the remarkable jet found in the powerful quasar 3C273 (see Figure 1: lower).

It is believed that these radio sources are powered by the associated active nuclei containing a (super)massive black holes (SMBH) and involve energies in excess of 10^{60} erg. Jets are now believed to be or associated with the channels (or beams) through which energy in the form of relativistic particles are transported from the radio source nucleus to the extended lobes[3,7]. It is noted that, apart from the detection of proper motions of jets on parsec–scales there is little or no observational evidence that actual flow process is involved in the jets seen in extragalactic radio sources. Such evidence, however, exists in galactic objects like SS433[8,9]. Jets display an extraordinary diversity, ranging from pencil–thin beams to enormous, flailing tendrils and billowing clouds.

Despite the deluge of observational data resulting from our ever improving instrumental capability and substantial progress in theoretical modelling and simulation of jets, we do not have a clear understanding of the nature of extragalactic radio jets[10]. The nature of the central engine driving the jets is not yet fully agreed upon, although the SMBH model is emerging as a strong candidate. A plethora of observed structural types makes a formulation of a 'unified scheme' for jet creation, collimation, and acceleration very difficult. Is there symmetric ejection

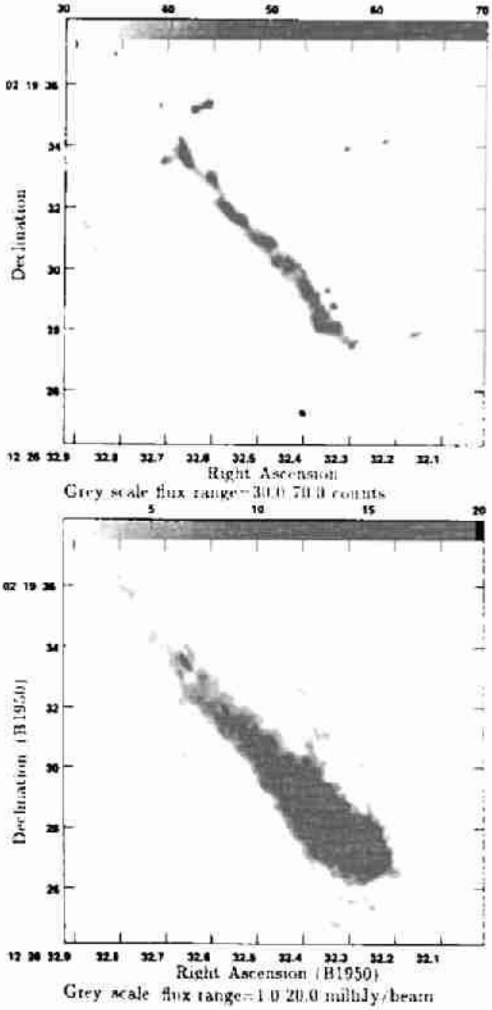

Figure 1 The remarkable jet in the quasar 3C273. Upper: a HST image[5]; lower: a MERLIN image[6].

(release) from the galactic nucleus or are the jets ejected (released?) on one side at a time? How is the initial acceleration and collimation of the jet obtained? Which particles are included in the makeup of the jet? Are the jets made up of a electron-positron mixture, or protons, or a combination of all or some of them? Are the jets heavy or light compared with their surroundings? What role does the surrounding play in the formation of various structural types?

1.2 Two types of jets

In classifying jets astronomers employ the now classical classification of radio sources by Cambridge scientists B. Fanaroff and J. Riley into two types according to the strength of the radio emission[11]. The more energetic sources with radio luminosity, $P \geq 10^{25}\mathrm{W}\cdot\mathrm{Hz}^{-1}\cdot\mathrm{sr}^{-1}$ are ‘Fanaroff & Riley class II’ (FRII) while the weak radio sources ($P \leq 10^{25}\mathrm{W}\cdot\mathrm{Hz}^{-1}\cdot\mathrm{sr}^{-1}$) are ‘FRI’. However, some objects with bordering and intermediate properties also exist. Jets in FRI sources look quite different from those in FRIIs. Also, the host galaxies of FRI and FRII radio sources are very different[12,13,14]. The host galaxies of FRIs are usually larger, brighter and are D or cD type objects; while the host galaxies of FRIIs are giant ellipticals, appear more ‘disturbed’ and do not usually reside in rich clusters[15].

Jets in the weaker FRI sources tend to be two–sided, widely spreading (with opening angles $\geq 7^0$) and merging directly into rather diffuse lobes without prominent hot spots. They are said to be edge–darkened. Also, polarization observations indicate that magnetic field direction is usually parallel to the jet axis[16]. The usual velocity structure of these sources, the disrupted nature of the jets and the associated plumes or lobes is believed to be a consequence of the relatively weak central powerhouse and the interaction of the radio beam with the interstellar medium (ISM). Typical examples are the twin–jets of the radio galaxy 3C449[17] and IC429[18], though the best studied jets in this class are those of M87 and 3C120 which are untypically one-sided and bright (see Figure 2).

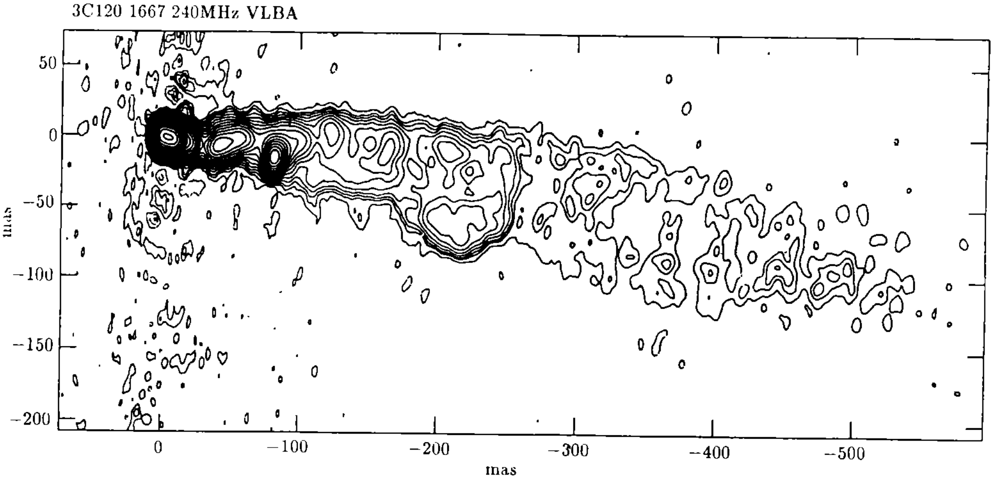

Figure 2 VLBA image of 3C120 based on 1.6 GHz data taken in June 1994
(R.C. Walker 1996, private communication)

More powerful FRII sources display more energetic jets which are usually one-sided, terminating in well-defined or prominent hot spots and sharp-edged lobes and so are edge-brightened (see Figure 3). These jets are, usually weaker than the lobe emission and magnetic fields derived from polarization measurements are parallel to the jet axis. Typical examples and some of the best studied examples are the prototype radio galaxy, Cygnus A[20] and the powerful quasar, 3C273[6].

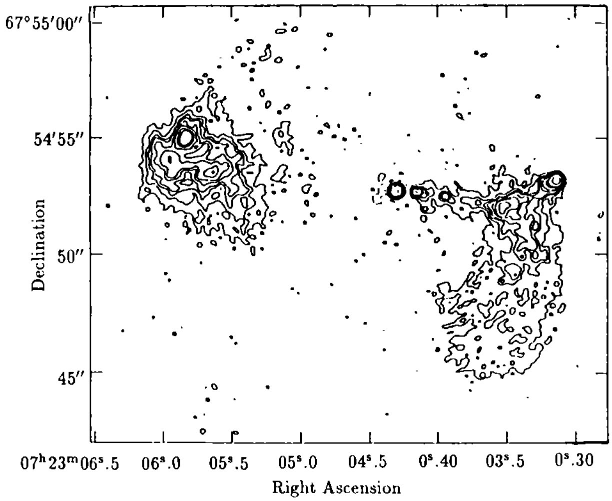

Figure 3 Combined MERLIN+VLA map of the twin-lobed quasar 3C179 at 1.67 GHz, showing bright jet and prominent hot spots[21].

2 Production of jets

How are the jets produced? Although different in appereance, they all seem to originate from a point-like core which is identified with the nucleus of the galaxy or quasar. No jets have been observed without the presence of a core. It is to this nucleus that astronomers look for the energy source that powers the jets and perhaps the history of the jet motion.

2.1 The energy source

Whatever the nature of this "central engine", it has to produce a prodigious amount of energy (the total luminosity of an active nucleus $\sim 10^{46}\mathrm{erg}\cdot\mathrm{s}^{-1}$) from a relatively small volume. After several decades of debate, a consensus is emerging that the most efficient energy source is gravitational, and the most likely candidate is a (super)massive black hole[22] with a mass anywhere a million and a billion times that of the Sun ($\sim 10^6 - 10^9 M_\odot$), though other contenders are supermassive stars and clusters of stars.

Some astronomers, however think that a central massive object is not necessary for an active nucleus[23]. They contend that the jet phenomenon can be produced through a 'dynamo effect' resulting from turbulence or some form of convection as we have within the stars.

There are many reasons given to explain why black holes are the 'prime movers' in the active galactic nucleus[24], some of which are somewhat circumstantial. For example, the jets on parsec and kiloparsec scales usually are fairly aligned. It is thought that a possible source of these sources must be able to keep memory of their direction over several years $\sim 10^6$yr, and could be the spin axis of massive black hole. Also, a prodigious amount of power is derived from an active nucleus $\geq 10^{48}\mathrm{erg \cdot s^{-1}}$.

A commonly agreed physical process, that can facilitate sufficient energies, is the release of potential energy by matter falling into a deep potential well. Matter falling from infinity into a potential well will have a velocity $v = (2GM/R)^{0.5}$ in a Newtonian gravity. Matter accreting to such a deep well can release ~30% of its rest mass as energy by thermalization of the gas, synchrotron radiation, or by some other non–thermal processes. In the case of the black hole the effective radius, where non–coherent emission is produced, is the radius of the accretion disc, $r \leq 10^{16}$ cm. An important parameter for accretion models is the "Eddington limit", defined at which radiation pressure on the free electrons balances gravity:

$$L_\mathrm{e} = \frac{4\pi GMm_pc}{\tau_T} \approx 1.3 \times 10^{47}\, M_\odot\, w \tag{1}$$

where $M_\odot$ is measured in solar masses (2×10^{30} kg). Masses of $10^8 - 10^9\, M_\odot$ are needed, to produce the observed luminosities. The Schwarschild radius of a massive black hole (MBH) is 1.5×10^{13} cm, well within the observed region at the core of quasars.

The required released energy is equivalent to the total conversion of L_e/c^2 into radiation energy, so nuclear (fusion) processes with efficiency of $\leq 1\%$ would be inappropriate source of the energy of AGNs as that would require enormous rate of 'consumption' of mass. However, accretion onto a massive black hole which permits the conversion into radiation of up to 32 persent of the rest mass of accreting matter seems to provide a viable mechanism.

More concretely, rapid intensity variations on very short timescales in optical ($\sim$ days) and X–ray ($\geq$ hours) point to the highly compact structure within the emitting regions in the galactic nuclei[25]. Moreover, observations of emission line widths indicate velocities $\sim$ 5000km $\cdot$ s^{-1} in the broad emission line region (BLR). Such large velocities on very small scales are thought to be strong indication of compact masses consistent with the massive black hole scenario.

In the black hole scenario, material is drawn towards the hole by the intense gravitational field, forming a accretion disc swirling around the hole rather like bathwater going down a plug hole. The infalling matter can release its potential energy in thermal and non–thermal processes. A small percentage of the infalling matter is accelerated by magnetic gradient and/or thermal or radiation pressure along the spin axis and escapes the black hole with very high velocities. This "twin–beam" model is the starting point for trying to understand the physics of jets, but we shall see there are still many questions left unanswered.

2.2 What are jets made of?

The emission from jets is in mainly synchrotron radiation, implying that the jets contain charged particles moving in a magnetic field at velocities close to the speed of light. A charged particle in a magnetic field will move along a curved path, radiating away its kinetic energy as electromagnetic radiation. The magnetic fields can be mapped by studying the polarization of the radio emission.

Apart from that, we know very little about the material that jets are made of. Presumably the electrons are accompanied by positively charged particles, but given ignorance of how jets are created, it would be a mistake to assume that they must be protons. Indeed, on one theory the jet is made of an electron–positron plasma. Pelletier & Roland[26] also have a model which explains some of the observed radio source properties in terms of jets containing two fluids—a non–relativistic electron–proton (thermal) component which carries most of the energy and contains the relativistic beam of electron–positron plasma.

There are reports of detections of spectral lines in the light from optical jets (e.g. Centaurus A), and if so this opens up the possibility of identifying atoms. With an observation of a spectral line, it would be possible to determine the velocity in respect to the local reference frame.

3 Propagation of jets

Rather more progress has been made in understanding how the jets carry energy from the core and deposit it in the lobes.

3.1 What is the speed of the jets?

Although superluminal motion, which is evidence of highly relativistic bulk motion seems to be very common in the nuclear jets of active galaxies, there is almost no conclusive detection of motion in the jets on large scale. Walker, Walker & Benson[27] using VLA observations reported the detection of motion ($v \sim 3.7c$) out to $\sim$ 2kpc of the jet in the powerful object 3C120, but later measurements of Muxlow & Wilkinson[19] using MERLIN observations did not confirm the detected motion.

However, estimates of jet speeds have been made using statistical consideration of jet properties, such as, brightness asymmetry and separation ratios between the jet and counter–jets. The brightness asymmetry is used to constrain the flow speed of the jet emitting matter, which may be different from the pattern speed estimated from separation ratio[28]. For powerful sources, Mackay[29] obtained flow speeds $\sim$ 0.08 while Banhatti[30] gave speeds of $\sim$ 0.15 which is within the limits of $\beta_{\max} \sim 0.3$ set by Macklin[31]. But the absence of any clear consistency between the asymmetries in jet structure and the expectations of relativistic effects suggests that observed asymmetries may be due to other factors, such as, the influence of the external environment. This is supported by recent observations of correlations between the spatial distribution of line–emitting gas and jet asymmetry[32].

A powerful tool in getting to grips with the physics of jet motion is computer modelling[33,34]. Such studies seem to give indications that the jets in powerful objects (FRII radio galaxies and quasars) are light compared to the surrounding gas and possibly highly supersonic with Mach number $\sim$ 3—5. It is, however, believed that all jets are initially light relative to the surrounding medium. FRIIs are supersonic, while FRIs are subsonic; they easily slow down in order to conserve momentum as they entrain more matter and flow more turbulently[28].

3.2 Superluminal motion

In the mid sixties the standard hypothesis for the radiation from AGN's was that the radio emission was synchrotron radiation emanating from relativistic electrons in a weak magnetic field. The model explained the spectrum of the observed radio emission but had severe problems explaining the rapid flux variations observed in several quasars.

The angular extension can be expressed as a function of the variability timescale, t_ν, luminosity distance, $D_{\rm L}$ (equation 4), redshift, z, as[35]:

$$\phi = ct_\nu \frac{(1+z)}{D_{\rm L}} \tag{2}$$

The expected self–Compton produced X–ray flux density $S^{\rm c}_\nu$ can be written as[36]:

$$S^{\rm c}_\nu \approx d(\alpha)\phi^{-2(2\alpha+3)}\nu_m^{(-3\alpha+5)}S_m^{2(\alpha+2)}(h\nu)^{-\alpha}_{\rm keV}\ln\frac{\nu_2}{\nu_{\rm m}}(\frac{\delta}{1+z})^{2(\alpha+2)} \tag{3}$$

where α is the spectral index, ν_m is the turnover frequency, where the spectrum reaches its peak. At frequencies lower than ν_m the flux density decreases rapidly due to synchrotron self–absorption. S_m is the observed flux at the turnover frequency; $(h\nu)_{\rm keV}$ is the energy of the X–ray photon; ϕ is the angular size of the source; ν_2 in GHz is the upper cutoff frequency assumed to be $\sim 10^{15}$ Hz. $\delta^{-2(\alpha+2)}$ corrects the flux emitted in the source frame for doppler beaming effects.

With a non–moving source, the doppler factor, $\delta = 1$. Using equation 2 to determine the angular extensions of the source, and solving equation 3 for the X–ray give a much higher X–ray flux than observed.

A model that alleviated this problem was proposed by Rees[37]. This model consisted of a varying synchrotron source expanding with relativistic velocities. Relativistic time dilation effects would allow apparently short time scales of variations. At the same time an emitting plasma moving with relativistic speed towards the observers would result in a Doppler boosting of the intensity, which would decrease the self–Compton flux density by a factor $\delta^{2(\alpha+2)}$. The model also predicted apparent expansion of components with velocities exceeding that of light. Direct observations of this phenomena were impossible at that time due to inability to resolve the compact radio sources.

The first tentative evidence was produced by a VLBI experiment between USA and Australia[39,73]. Gubbay *et al.*[38,39] concluded that the observed change in the source visibilities for 3C279 indicated that the source was expanding with a velocity larger than twice that of light. Observations made by others confirmed the apparent superluminal expansion in 3C279[40,41].

Since what we observe is the angular proper motion, μ, we need to transform from angular separation to linear separation in the plane of the sky. This transformation is simple if we can determine the actual distance to the source.

Assuming that the observed redshift is cosmological in origin with $H_0 = 100h\mathrm{km{\cdot}s^{-1}{\cdot}Mpc^{-1}}$, $q_0 = 0.5$, and h is a constant assumed to be in the range $0 \le h \le 1$. Using the standard Friedmann–Robertson–Walker metric, the luminosity distance can be expressed as:

$$D_{\mathrm{L}} = \frac{c}{H_0 q_0^2}(q_0 z + (q_0 - 1)(\sqrt{1 + 2q_0 z} - 1) \tag{4}$$

where c is the speed of light and z is the measured redshift. The angular size distance of the source can be expressed as:

$$D_\theta = \frac{D_{\mathrm{L}}}{(1+z)^2} \tag{5}$$

To obtain proper motion distance we need to take into consideration time dilation effects between the source frame and the observers frame into account:

$$D_{\mathrm{pm}} = \frac{D_{\mathrm{L}}}{(1+z)} \tag{6}$$

Combining equations 4, 5 and 6, the transverse velocity $\beta_{\mathrm{app}} = \mu D_{\mathrm{pm}}/\mathrm{c}$ can be expressed as:

$$\beta_{\mathrm{app}} = \frac{\mu z}{H_0(1+z)} \frac{1 + \sqrt{1 + 2\, q_0\, z} + z}{1 + \sqrt{1 + 2\, q_0\, z} + q_0\, z} \tag{7}$$

It is clear from equation 7 that large μ results in transverse velocities larger than c. A model explaining this follows almost directly from the "unified model of AGN's". In this model, a core is ejecting relativistic plasma in a collimated beam. The plasma jet is inclined with an arbitrary angle θ to the line of sight.

Assuming that a disturbance in the smooth flow of the plasma in the jet is travelling down the jet (whether this disturbance is real shocks or just an interference pattern is not important for this model), it is straightforward to show that the apparent expansion velocity can be expressed as:

$$\beta_{\mathrm{app}} = \frac{\beta \sin\theta}{1 - \beta\cos\theta} \tag{8}$$

where $\beta = \frac{v}{c}$ is the pattern speed in the frame of the emitter. The observed intensity of a relativistically moving emitter can be written as[42]:

$$I_{\mathrm{app}} \propto \frac{I_{\mathrm{com}} D^a}{\sin\theta} \tag{9}$$

where I_{com} is the comoving intensity, D is the Doppler boosting factor, and I_{app} is the apparent intensity. From equations (8) and (9) it is clear that a very small change in the viewing angle, θ, can cause very large changes in the apparent flux and in the apparent motion of the emitter.

Results from VLBI also show that jets originate as a continuous fluid flow rather than a succession of projectiles or particles moving ballistically. In many sources blobs emerging from the nucleus do not appear to move in straight lines as would be expected if they were merely being shot out as projectiles. In the powerful quasars 3C345, for example, recent VLBI results show blobs emerging from the core at different angles and with different superluminal speeds.

However, there are grave difficulties in devising a mechanism for drawing energy from a black hole to accelerate meterial up to the relativistic speeds now revealed by superluminal motion. *It is also not clear whether all powerful sources, including those with weak cores, will show superluminal expansion.* VLBI observations had until recently been confined to bright cores since the narrow bandwidth of the data recorders used only yield adequate signal–to–noise signal on strong sources, and the structures had to be compact because unfilled apertures of the conventional arrays could not detect extended features. However as many more telescopes and wide band recorders become a regular feature of VLBI some of these questions are bound to have answers.

3.3 Confinement and collimation

A central problem of understanding jets is the one of "confinement". How do they remain jet–like over distances up to hundreds of kiloparsecs and for anything up to a million years? If they contain energetic particles, why don't they splay out as soon they leave the nucleus, or do they and are later recollimated?

Jet collimation is a complex phenomenon and not quite understood. It is generally agreed that it is related to the initial jet speed and the properties of the gas within the jet as well as in the surrounding ambient medium. Jets that are light compared with a uniform IGM propagate stably and are easily confined by the ambient pressure. Internally there could be significant structure caused by Kelvin–Helmholtz (K–H) instabilities, but these could in general not build up sufficient strength to 'break up' the jet. If such a jet continues to converge supersonnically then it can in principle avoid internal disruption and dissipation by maintaining considerable symmetry over a long scale.

Heavy jets or jets of comparable density as their surrounding are more susceptible to internal shocks and instabilities such as K–H and could easily be disrupted. A collimated jet, on entering a region of considerable lower pressure is likely to expand freely. An 'undisturbed' jet may not exist as all jets suffer to some degree various fluid instabilities. If the external medium is clumpy then even light supersonic jets can be prone to deflections and disruptions giving rise to some of the bends and knots seen in jets. Jet collimation can also be enhanced by radiative cooling of the the non–relativistic component of the gas in the jet due to energy losses via free–free emission.

Until recently it was thought that the pressure of the intergalactic medium, though very low, was enough to confine the jets. Estimates of the pressures within the jets were comparable to those outside. But it now seems that this explanation would not apply to all jets. The observations of the jets in Cygnus A[20] and Virgo A[43] show that their internal pressure is actually well above that of their surroundings.

Alternatively, jets could be confined magnetically, but magnetic confinement hypothesis is problematic since both the jet current and its path will have to be sustained. That such support can come from a dynamo and other inertial effects makes magnetic confinement attractive to 'dynamo theorists'.

4 Jet asymmetries and unified models

Many powerful radio sources do not have two jets, as the twin–beam model would predict but one. Partly this could be a selection effect. Early radio images had a narrow dynamic range, and a faint jet is easily swamped by emission from a brighter jet, from the core and from other bright feature in the structure. If the twin–beam model is correct the question of why one jet should be brighter than its companion has a simple answer. But suppose the jets are intrinsically one–sided? One important benefit of understanding the structure of jets is to know the defining relationships between the various classes of external galaxies — this is the kernel of the unified scheme.

4.1 One–sided jets

If a radio source is viewed by an observer at some inclination angle θ and the jets are flowing at speeds close to the velocity of light, relativistic beaming will concentrate their emission in the forward direction. The Doppler factors for the approaching and receding jets respectively are:

$$d_1 = \frac{1}{\gamma(1-\beta\cos\theta)} \tag{10}$$

and

$$d_2 = \frac{1}{\gamma(1+\beta\cos\theta)} \tag{11}$$

where $\beta = v/c$. The relative surface brightness of the approaching and receding jet will be given as (for a steady jet flow):

$$D = (\frac{1+\beta\cos\theta}{1-\beta\cos\theta})^{2+\alpha} \tag{12}$$

So a jet coming towards an observer will appear much brighter than an identical jet going away. This means that for speeds $v \sim$ c and moderate orientation angles of, say, 45^0, D could be quite large ~ 20[44].

A significant step in the quantification of the boosting expected in relativistic beaming[42] model has been made by Orr & Browne[45] who show that the observed boosting is related to the observed core strength, R:

$$R = \frac{1}{2R_{\rm T}\left[(1-\beta\cos\theta)^{-2}+(1+\beta\cos\theta)^{-2}\right]} \tag{13}$$

where R is defined as the ratio of core to extended flux density, $R_{\rm T} = R(90^0)$, β and θ are the jet velocity at the core and angle to the line of sight of the beam at the core. Orr & Browne[46] found (statistically) that a typical value of R_T for lobe–dominated quasars was 0.024 at 5 GHz and could explain the properties of core–domonated sources if $\beta \sim 0.98(\gamma \sim 5)$. It attributes the major difference between core–dominated sources and lobe–dominated sources to the effects of projection and the relativistic amplification of the core emission when the source is viewed end–on. Murphy[46] has recently shown that the Orr & Browne scheme can better accommodate the range of observed structures of core–dominated sources if there is a range of $\gamma \sim 5$—7.

Strong support for this explanation comes from recent studies of "depolarization". Multi–wavelength polarization measurements have shown that at longer wavelengths the counter–jet side (or the jetless side) of powerful double radio sources is usually less polarised. This is thought to be due to the fact that the counter–jet is on the far side of the core and the radio waves have had to travel through more intergalactic gas or greater 'Faraday depth'.

However, there are still difficulties with the simple beaming models. For example, Schilizzi & de Bryun[47] show that the deprojected sizes of the superluminal radio sources are too large compared with the parent population. But Barthel[48] has shown that we can overcome some of these difficulties by 'unifying' quasars and galaxies. That is, all quasars may be beamed and their unbeamed counterparts could be radio galaxies. Nonetheless, even when these effects are taken into account, there remain sources which seem to have one jet only and no sign of a counter–jet even at levels we would expect one. Some astronomers argue that this one–sidedness is intrinsic.

Another model of one–sided jets is the "flip–flop" model. In the "flip–flop" model, the outflow alternates between one side of the nucleus and the other, such that it is intrinsically one–sided at a given time. Support for this view comes from observations which tend to show that structures are rarely seen at the same distance on either side of the core, implying that the two jets have never been active at the same time. The flip–flop model predicts that a small, new jet should occasionally be seen on the opposite side of the core from a large, presumably defunct jet, but none has been observed. Other explanations include one in which the jet is two–sided but the counter–jet is less dissipative and hence intrinsically faint although it might be carrying similar energy as the main jet.

But do two–sided jets exist? Detection of the counter–jet is a good evidence of unbeaming. VLA observations have shown that two–sided jets are common in FRI sources where relativistic beaming is thought not to be very important. However, in FRIIs two–sided jets are rare but do actually exist. Bridle have searched for counter–jets in high luminosity sources and found kpc–scale counter–jets, or at least 'pieces' of them in 3C218, 3C219, 3C228, 3C341, 3C348, 3C405 (Cygnus A) and 3C438. VLBI measurements detected counter–jet in NGC1275[49], Cygnus A[50] and 3C338[51]. Figure 4 shows the images of Cygnus A at different scales. Both the jet and the counter–jet are clear on the map. But we should be conservative. Those sources may not be typical objects. NGC1275 is a core–dominated radio source and has very low polarization. It is possible the low polarization quasar is not a simple blazar (a double source seen end–on)[52]. The counter–jet in Cygnus A remains elusive[50]. 3C338 has very complicated morphology at large scale[51]

4.2 The unified model

The twin–beam model, or variants of it, offer a natural explanation for the diversity of jet sources. The "unified scheme" holds that all active galaxies are essentially similar, and what makes them look different is chiefly the orientation of the jets with respect to the observer. It thus attributes the observed differences between the flat spectrum core–dominated sources and the steep spectrum lobe–dominated quasars, and possibly between quasars and galaxies to different orientations of the source axis to the line of sight[42,45,48,53].

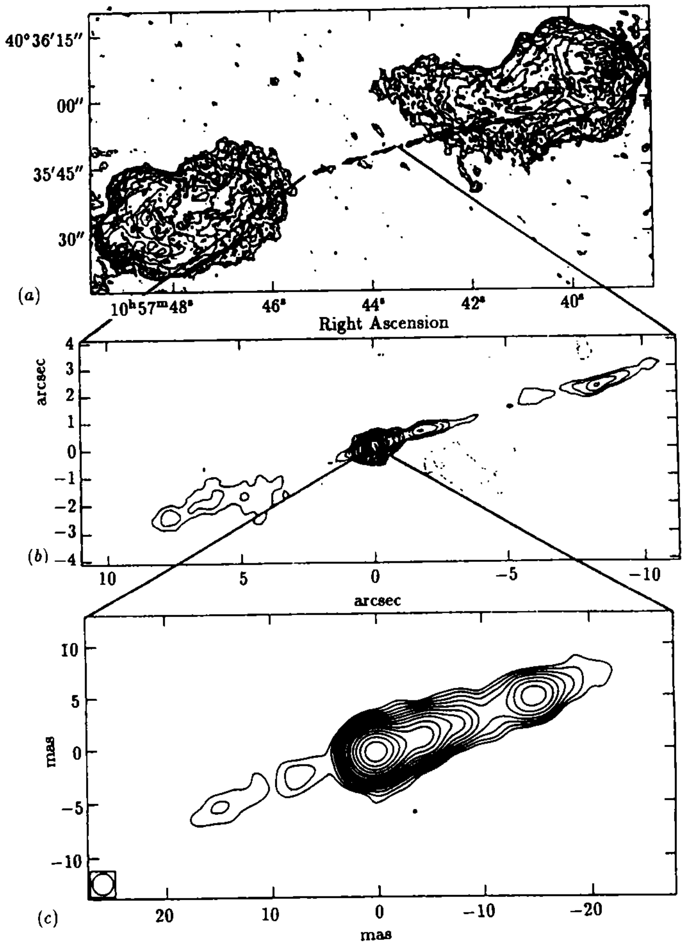

Figure 4 Nuclear jet in Cygnus A[50].

The radio cores of FRIIs are stronger, probably reflecting more powerful central engines. This is independently supported by optical emission lines which are stronger in FRIIs than FRIs. In wide–angle tail sources the inner part of the jet has parallel magnetic fields similar to those of FRIIs and well collimated. Thus the transition to perpendicular magnetic fields in the outer parts of the jet may correspond to a transition from supersonic to subsonic flow.

One strongly contentious issue in the ‘unification’ debate is the relationship between BL Lacs and other types of radio sources. A consensus is emerging, however, that BL Lacs have the FRI sources as a parent population and are dominated by non–thermal continuum of bulk relativistic motion of a beam oriented close to the line of sight[54]. But observation of superluminal motion in radio cores suggest that observed apparent speeds in BL Lacs, although higher than those of FRIs is generally lower than those seen in OVVs and FRIIs. If BL Lacs are indeed related more to FRIs then this has a natural explanation in orientation at progressively larger angles than in OVVs and FRIIs rather than on low values of γ. Indeed models of the best studied cases of BL Lacs favor relatively large angles $\sim 34^0$ in Mkn 421[55,56], $\sim 30^0$ in BL Lac itself[57,58], and $\sim 20^0$ in 0735+178[59]. But some argue that BL Lacs have their relativistic jet axis so close to the line of sight that the apparent speed is reduced relative to the maximum value of $\theta = 1/\gamma$.

4.3 Whither compact steep–spectrum radio sources

One of the nagging questions of the unification debate is the relationship between compact steep–spectrum sources (CSS) and other types of extragalactic radio sources. An understanding of the nature of CSSs and their (radio) jets can possibly give an insight into extragalactic jet phenomena. In general, they are radio sources found in active nuclei of galaxies with $\alpha \geq -0.5$ ($S \propto \nu^{\alpha}$) and linear sizes $\leq$ 10kpc, that is, of galactic dimension[60,61]. CSS account for about 30 percent of all sources in samples selected at 2.7 GHz and occur in a wide variety of hosts, from distant powerful quasars (e.g. 4C43 and 3C380) and galaxies (e.g. 3C241 and 3C295) to the nearby low luminosity Seyferts[62].

The questions are whether they are intrinsically small because they are young and still evolving, made small by the confining influence of dense surrounding gas, or appear small due to the effects of projection. In the last few years a lot of observational data have been accrued that we are beginning to distinguish between these effects. Most simply it is now believed that the number of CSSs appears to be too many for projection to explain them all. Also Wilkinson[64] and Fanti *et al.*[65] have shown that there is a clear–cut morphological separation between CSS quasars and galaxies, while quasars usually have complex and distorted structures, galaxies are simple doubles and triples.

Because of their compactness most of our knowledge of the detailed structure of CSSs come from high resolution MERLIN and VLBI observations. While jets are detected in many quasars they are very rare in CSS galaxies[63]. One significant observation is that jets in CSSs seem to show more distorted structures and show sharper bends (e.g. 3C43)[64] than seen in other powerful radio sources, and in some cases appear to be disrupted. A typical example of a disrupted jet is that of 3C48[65]. 3C48 is a powerful quasar whose jet lies well within the body of the gas–rich host galaxy; the disruption of its jet is ascribed to collision with a dense clump of gas in the interstellar medium (ISM) of the host galaxy. In other powerful CSS quasars distortions in structure are characterised by sharp bends which in all cases occur within a few parsecs of the nuclei suggesting also strong interaction with the ISM of the host galaxy.

But could such structures also be explained by projection on a relativistically beamed source? Large apparent bends can be seen either if the intrinsic bends are large or if rather small bends are amplified by projection. In the context of the relativistic beaming model[45] the boosting observed depends on the angle to observer's line of sight and γ in the core. In the powerful quasars like 3C147, 3C216, 3C309.1 and 3C380 one could do with a combination a range of γ, say, $\sim$ 5—7, moderate angles, $\theta \sim$ 10—30 and moderate intrinsic bends. The detection of superluminal motion in these powerful sources seems to support this view[66]. But in others like 3C43, 3C119 and 3C48 with weak core strengths comparable to those seen galaxies where beaming is thought to be unimportant, it is difficult to deny that we are witnessing really large bends and distortions. However, the pressure in these jets appears to be comparable to those expected in typical thermal gas associated with dense narrow–line region, which may be responsible for the bends.

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