Active Galactic Nuclei and Related Phenomena
IAU Symposium, Vol. 194, 1999
Yervant Terzian, Daniel Weedman, Edward Khachikian, eds.

HST Observations of Active Galactic Nuclei

F. Duccio Macchetto

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; E-mail: macchetto@stsci.edu

On assignment from the Space Science Department of ESA

Abstract. The *HST* has made many contributions to all areas of research in the field of AGN, and I have selected three topics where major progress in our understanding has been made over the last two years. The study of the NLR is key to understanding to what extent the unified model for AGN is applicable. In particular, understanding how the NLR is ionized and how its morphology is defined makes an important contribution to clarify the differences between Seyfert 1 and Seyfert 2. Work by Macchetto et al., Capetti et al., Axon et al., and Wilson et al. has helped clarify the picture. Our work on NGC 1068, Mrk 3, Mrk 7, Mrk 348, Mrk 6, and Mrk 573 has shown the following important properties: a) all AGN with a linear radio jet show emission-line morphology ([O III], [O II], Hα) which is aligned along the jet in a surrounding cocoon; b) those AGN with radio lobes show emission-line morphology which is filamentary and coincident with the position of the lobes; and c) in NGC 1068 and in Mrk 3 we have measured transverse velocities to the radio-jet as large as 1700 km s^{-1}. These velocities measured at different positions across the radio-jet show an almost perfect velocity ellipsoid, indicating that the cocoon around the jet is expanding, compresses the ISM and shocks and ionizes the region.

The main conclusion in this field is that the radio-jet is responsible for defining the morphology, both through the expanding cocoon and at the working surface of the radio lobe, and is largely responsible for the observed ionization. The ionization parameter Q in these sources is either constant or actually increases with distance from the nucleus; therefore, nuclear ionization alone cannot explain the observations, whereas local ionization by shocks is fully capable of providing the required flux of ionizing photons.

Many *HST* observations (Ford et al., Ferrarese et al., van der Marel et al.) have shown the presence of extended accretion disks ($\sim$ 200–300 pc). For the first time however, we have been able to show that in the case of M87 we are dealing with a true Keplerian disk. We carried out long-slit spectroscopy with the FOC and measured in particular the [O II] emission line, developed a sophisticated model which took into account the impact parameter, the shape of the PSF, the unknown SED of the nucleus in the 0.06″ inner region, and built a set of models which best fitted the data and were fully self-consistent. We derived an inclination of the disk to our line-of-sight of 51° and a black-hole mass of $3(\pm0.5)\times$

https://doi.org/10.1017/S0074180900161674 Published online by Cambridge University Press

10^9 $M_\odot$. We showed that this mass is concentrated within the inner 3 pc and cannot be uniformly distributed; therefore, it must be a black hole.

We have investigated the optical counterparts of all the 3C radio jets and discovered a number of new optical jets. (Sparks et al.). By comparing the radio and optical data we conclude that beaming is responsible for the optical visibility of these objects. We have also measured the proper motions of the jet in M87 over a 3-year period, and we find apparent velocities of features which vary from $1.5c$ to $6c$ for different knots. This is a very important observation which shows among other things that the bulk and pattern velocities differ.

1. Introduction

The investigation of the physical properties of the nuclear regions of active galaxies has been the subject of many *HST* observing programs. In the now standard paradigm for AGN, the basic differences between the different classes of objects are simply explained as a result of different orientations to the line-of-sight. In the unified picture, a central energy source, generally assumed to be a massive black-hole, is surrounded by two spatially and kinematically distinct regions. The Broad Line Region (BLR) has scales of the order of a parsec in diameter and emits broad permitted emission lines with widths up to 10000 km s^{-1}. The Narrow Line Region (NLR) emits narrow (a few hundred km s^{-1}) permitted and forbidden lines and has sizes of up to a kiloparsec in diameter. The orientation effects and, therefore, the classes of AGN, are determined by an optically thick torus composed of dense molecular clouds, whose inner diameter is comparable to the size of the BLR and can extend for tens of parsecs. The symmetry axis of the torus determines the direction of the kiloparsec scale radio jet and is independent of the orientation of the galactic disc. In the standard model if the torus is seen face on, we can see the continuum source and BLR directly and the galaxy is classified as a Seyfert 1. If, instead, the torus obscures the central regions, the galaxy is classifed as a Seyfert 2.

While *HST* observations to date seem to confirm the broad validity of this picture, high spatial resolution observations as well as the important new imaging polarimetry results have shed new light on the fundamental physical phenomona that are at play in the nuclear regions of active galaxies.

Another important field of research has been the study of the optical counterparts to the radio jets. We know that these jets play a fundamental role in transporting energy from the central source to the extended radio lobes. Observations at optical and ultraviolet wavelengths with the *HST* are essential to obtain spatial resolutions similar to, or better than, those achieved in the radio band and, thus, provide the possibility of directly comparing the sites and mechanisms responsible for the emission at these different wavelengths.

In all cases to date, the emission has been attributed to the synchrontron mechanism, and since the electron lifetime is a strong function of the observed frequency, observations at optical and ultraviolet wavelengths offer the possibility to determine the precise location where particle acceleration occurs. Comparison of the radio and optical morphologies further allows the study of the confinement mechanisms and diffusion processes within the jet. A number of important discoveries and observations that place the theoretical models on firmer observational grounds have been published based on the *HST* data.

In this review, I will discuss in detail examples for the two main categories of Seyfert galaxies. I will show the significant progress made in our understanding of the NLR, and I will highlight *HST* discoveries related to the optical counterparts to radio jets.

2. The Seyfert 1.5 Prototype: NGC 4151

NGC 4151 is the nearest (13.3 Mpc; $0.1'' = 6.4$ pc) example of a (sometime) type 1 Seyfert galaxy although it is rather a low-luminosity example of the class. The broad emission component of $H\beta$, which is a characteristic of Seyfert 1 galaxies, varies dramatically and, in a low state, can almost disappear. This led to NGC 4151 being reclassified as Seyfert 1.5. Both the permitted and the continuum emission show variations on time scales as short as days. FOC observations in [0 III] and nearby continuum have shown that the NLR is resolved into a number of emission-line clouds (sizes ~ 10 pc) with elongated morphology. These are distributed in a biconical structure with apices coincident with the central point source and a cone opening-angle projected on the sky of $\sim 75^\circ \pm 10^\circ$. The cone position angle of $60^\circ/240^\circ \pm 5^\circ$ is aligned with the extension of the nuclear VLBI radio source, suggesting that the same mechanism may align both the optical ionizing radiation field and the parsec scale radio structure.

Long-slit spectroscopic observations were carried out with the (uncorrected) FOC (Boksenberg et al. 1995). They found a high and a low radial velocity component within the narrow emission lines and identify the low-velocity component with the bright, extended, knotty structure within the cones, and the high velocity component with more confined diffuse emission. Also present are strong continuum emission and broad Balmer emission-line components, which are attributed to the extended point spread function arising from the intense nuclear emission.

Winge et al. (1997) have carried out Faint Object Camera long-slit spectroscopy of the inner $8''$ of the Narrow Line Region of NGC 4151 at a spatial resolution of $0.029''$. The emission gas is characterized by an underlying general orderly behaviour consistent with galactic rotation over which are superposed kinematically distinct and strongly localized emission structures. High velocity components shifted up to ~ 1500 km s^{-1} from the systemic velocity are seen, associated with individual clouds located preferentially along the edges of the radio knots. Off-nuclear blue continuum emission is also observed associated with the brightest emission-line clouds. Emission line ratios of key diagnostic lines vary substantially between individual clouds. The high spatial resolution long-slit spectroscopy of the nuclear region of NGC 4151 by Winge et al. (1997), shows that the popular picture of anisotropic illumination by the nuclear source is overly simplistic to explain the complex morphology and kinematics observed in the NLR. Comparison of the radio and optical data shows that the line emission is enhanced along the edges of the radio knots, as would be expected from the interaction between the jet and the surrounding medium. This clear association implies that the interaction with the radio jet plasma, and not illumination effects, is the dominant mechanism in determining the morphology, as well as the physical conditions in the individual clouds.

3. The Seyfert 2 Prototype: NGC 1068

A number of observations of the prototypical Seyfert 2 galaxy NGC 1068 ($D \sim$ 22.7 Mpc, $0.1'' = 11$ pc) have been carried with the FOC and WFPC2 (Macchetto et al. 1994, Capetti et al. 1995b, 1996a, Bower et al. 1995, Capetti, Axon and Macchetto, 1997b). These include visible and UV continuum and emission-line observations, as well as FOC imaging polarimetry (F253M, F372M & F501N). These observations show that the inner morphology is very complex. In first approximation, it appears as a "bi-cone," with the axis of symmetry changing with distance from the nucleus. This may be due to the different location of the gas as it streams around the inner bar. Alternately, the ionization and scattering cone is rather narrow and tracks the radio jet more closely. The brightest feature in the continuum and line emission images is "Cloud-B" which is highly polarized (65%) and contrary to previous claims is not the location of the nucleus. The polarization data show that the true nucleus is located some $0.6''$ South of Cloud B and is obscured. This is very consistent with the unified scheme of AGNs. A strange feature, the "twin crescent" is also highly polarized (45%). The distance from the active nucleus $\sim 0.1''$ makes it unlikely that it has any physical relations to it and thus, it remains a mystery. The high-degree of polarization in the circumnuclear region implies that most, if not all, of the observed UV light is scattered light from the nucleus, with either dust or electrons providing the scattering medium.

High precision ground-based and *HST* astrometry (Capetti, Macchetto & Lattanzi, 1997) has allowed the alignment of the optical and radio data to be carried-out. The maps have been registered with a precision of better than $\pm 0.030''$. With this determination the position of the obscured nucleus, as derived from the polarization measurements, falls within the S1 and S2 peaks of the radio data, but is not coincident with any of these two peaks, whereas it is within 1 σ of the position of the H_20 maser source.

Capetti et al. (1997b) have used *HST*/WFPC2 imaging to investigate the emission-line structure of the NLR of NGC 1068 and its relationship to the extended radio emission. Previous works showed that the brightest knots of the NLR lie along the opposite edges of the radio-jet. These WFPC2 images indicate that a similar association also holds on a larger scale. In NGC 1068 both radio-jets and lobes are present and the NLR also displays a quasi-linear emission feature associated with the radio-jet and emission-line filaments around the radio lobe. Outside the radio lobe, the emission-line surface brightness drops dramatically. This NLR structure is, therefore, strongly reminiscent of that which has been seen in most Seyfert galaxies studied to date with *HST*. We conclude (Axon et al. 1998) that in NGC 1068, the morphologhy of the NLR is determined by the presence of a radio-outflow which is sweeping and compressing the surrounding interstellar gas causing the line-emission to be highly enhanced in the region where this interaction occurs.

Furthermore, it appears that the role of the radio jet is not just limited to determining the morphology of the NLR but is physically involved in its ion-

https://doi.org/10.1017/S0074180900161674 Published online by Cambridge University Press

ization structure. The brightest knots of the NLR, located along the radio jet, show a much higher ionization state than the surrounding gas. The density measurements of individual knots derived from archival FOS/*HST* spectra and compared with ground based data indicate that they are high density condensations within the NLR. Their higher ionization and their higher density imply that these knots are illuminated by an incident ionizing flux greater by at least one order of magnitude than the rest of the NLR. Shocks can produce large ionizing flux as soon as their velocities exceed a few hundreds km s^{-1}. This source of ionizing photons can prevail locally over the nuclear radiation field and dominates the ionization conditions in these regions of the NLR. While there are hints of such complex NLR ionization structure changes in the *HST* observations of other more distant Seyferts, only in NGC 1068 can we really resolve it.

At a distance of $\sim 4''$ ($\sim$ 300 pc) from the nucleus, the ionization structure of the NLR shows a sharp and well-defined boundary between an inner low-ionization zone and an outer higher zone in correspondence to the transition in the radio structure from jet-like to lobe-like. This ionization change can best be explained with a density drop where the jet enters the lobe which we interpret as evidence for backflowing jet material.

4. Radio Outflow and NLR Structure

For many years, it was generally accepted that in the NLR of Seyfert galaxies, the gas is photoionized by nuclear radiation. The discovery of the NLR with "conductive" morphology on initial *HST* observations of some nearby Seyfert galaxies (NGC 1068, Evans et al. 1991; NGC 4151, Evans et al. 1993; NGC 5728, Wilson et al. 1993) seemed to give further support to that view. However, ground-based studies have shown that the NLR is cospatial with the radio emission and its kinematics clearly shows signs of the effect of interactions with the ejected radio-plasma. This association, now clearly confirmed by the observations of NGC 4151 and NGC 1068 described in the previous sections has been given even stronger support by the observations of several other Seyfert galaxies with *HST*. (Bower et al. 1994, 1995, Capetti et al. 1995c, 1996a,b).

These and other *HST* observations of the nuclear regions of Seyfert 2 have been discussed in a seminal paper by Capetti et al. (1996b). They show that in all cases the physical structure of the NLR in Seyfert 2s is closely related to the radio-emission. The optical morphology is dominated by the interaction with the radio ejecta. The NLR appears to take a different form depending on the structure of the radio emission. Where there are radio lobes, there are shell-like emission-line structures. For Mrk 573, Mrk 78 and Mrk 348, the emission-line structures are bow-shocks. Where a collimated radio jet is present, the morphology is different. In Mrk 3, the NLR follows the jet morphology. Capetti et al. (1996b) show that this dichotomy implies that bow-shock emission-line structures are produced by the sweeping-up of gas at the advancing working surface of the ejected radio plasma. The corrugated structure indicates that instabilities have developed in the compressed gas. Where a jet is apparent, it is surrounded by a halo of hot gas which expands radially from the jet axis and the emission line region forms a cylindrical cocoon on the outer cooling surface. In all cases, the ionization conditions, as determined for example from

https://doi.org/10.1017/S0074180900161674 Published online by Cambridge University Press

the emission-line ratios, are such that the ionization parameter increases with distance from the nucleus. This requires a source of ionization in addition to the nuclear ionizing flux.

Capetti et al. (1996b) show that shock mechanisms are the best candidates to produce the relatively small amount of locally produced excess radiation. They are fully consistent with both the measured ionization conditions and the observed filamentary morphology.

5. Black Hole Masses

The presence of massive black holes at the center of galaxies is widely believed to be the common origin of the AGN phenomena. The black hole model is very appealing because it provides an efficient mechanism that converts gravitational energy, via accretion, into radiation within a very small volume as required by the rapid variability of the large energy output of AGNs (e.g., Blanford 1991).

The standard model comprises a central black hole with mass in the range $\simeq 10^6$–10^9 $M_\odot$ surrounded by an accretion disk that releases gravitational energy. The radiation is emitted thermally at the local black body temperature and is identified with the "blue bump," which accounts for the majority of the bolometric luminosity in the AGNs. The disk posesses an active corona, where infrared synchrotron radiation is emitted along with thermal bremsstrahlung X-rays. The host galaxy supplies this disk with gas at a rate that reflects its star formation history and, possibly, its overall mass (Magorrian et al. 1996), thereby accounting for the observed luminosity evolution. Broad emission lines originate homogeneously in small gas clouds of density $\geq 10^9$ cm^{-3} and size $\simeq 1$ AU in random virial orbits about the central continuumn source. Plasma jets are emitted perpendicular to the disk. At large radii, the material forms an obscuring torus of cold molecular gas. Orientation effects of this torus to the line of sight naturally account for the differences between some of the different classes of AGNs (see Antonucci 1993). While this picture has been supported and improved by a number of observations, direct evidence for the existence of accretion disks around supermassive black holes is sparse and detailed measurements of their physical characteristics are conspicuous by their absence.

Ground-based observations of the giant elliptical galaxy M87 first revealed the presence of a cusplike region in its radial light profile accompanied by a rapid rise in the stellar velocity dispersion and led to the suggestion that it contained a massive black hole (Young et al. 1978; Sargent et al. 1978). Stellar dynamical models of elliptical galaxies showed, however, that these velocity dispersion rises did not necessarily imply the presence of a black hole but could instead be a consequence of an anisotropic velocity disperion tensor in the central 100 pc of a triaxial elliptical potential.

Considerable controversy has surrounded this and numerous other attempts to verify the existence of the black hole in M87 and other nearby giant ellipticals using ground-based stellar dynamical studies (e.g., Dressler & Richstone 1990; van der Marel 1994). To date, the best available data remain ambiguous largely because of the difficulty of detecting the high-velocity wings on the absorption lines that are the hallmark of the black hole.

One of the major goals of *HST* has been to establish or refute the existence of black holes in active galaxies by probing the dynamics of AGNs at much smaller radii than can be achieved from the ground.

HST emission line imagery (Crane et al. 1993b; Ford et al. 1994) of M87 has led to the discovery of a small-scale disk of ionized gas surrounding its nucleus which is oriented approximately perpendicularly to the synchrotron jet. This disk is also observed in both the optical and UV continuum (Macchetto 1996a, 1996b). Similar gaseous disks have also been found in the nuclei of a number of other massive galaxies (Ferrarese et al. 1994; Jaffe et al. 1993).

Because of surface brightness limitations on stellar dynamical studies at *HST* resolutions, the kinematics of such disks are in practice likely to be the only way to determine if a central black hole exists in all the very nearest galaxies. In the case of M87 FOS observations at two locations on opposite sides of the nucleus separated by $0.5''$ showed a velocity difference of $\simeq 1000$ km s^{-1}, a clear indication of rapid motions close to the nucleus (Harms et al. 1994). By *assuming* that the gas kinematics determined at these and two additional locations arise in a thin rotating Keplerian disk, Ford et al. (1996) estimated the central mass of M87 to be $\simeq 2 \times 20^9$ $M_\odot$ with a range of variation between 1 and 3.5×10^9 $M_\odot$.

HST FOC f/48 high spatial resolution long-slit spectroscopy of the ionized circumnuclear gas disk of M87, at three spatially separated locations $0.2''$ apart, was carried out by Macchetto et al. 1997, who analyzed the emission lines and derived rotation curves that extend to a distance of $\sim 1''$ from the nucleus. Within the uncertainties, these data are insensitive to density variations over a broad range of values that are larger than the constraints on density derived from the FOS archive data (Ford et al. 1994). The rotation curve is compatible with that obtained from the archival FOS archive data, given their substantially larger intrinsic errors.

To analyze the data Macchetto et al. first constructed a simple analytical model for a thin Keplerian disk around a central mass condensation, and fitted the model function to the observed rotation curve. Since the number of free parameters is large they carried out trial minimization of the residual errors by using different estimates for the values of the key parameters. Using this simple model they derived two extreme sets of self-consistent solutions that provide good fits to the observational data.

They then conducted a more realistic analysis incorporating the finite slit width, the spatial PSF and the intrinsic luminosity distribution of the gas. This analysis showed that the thin Keplerian disk with a central hole in the luminosity function provides an excellent match to the data, and the resulting parameters of the disk are $i = 51°$, $\theta = -9°$, $V_{sys} = 1290$ km s^{-1} and a corresponding mass of $(3.2 \pm 0.9) \times 10^9$ $M_\odot$, where the error in the mass allows for the uncertainty of each parameter. They showed that this mass must be concentrated within a sphere of less than 3.5 pc and concluded that the most likely explanation is a supermassive black hole.

Another major result has come from high-spatial resolution long-slit observations of the nuclear region of NGC 4151 (Winge et al. 1999). They carried out a detailed study of the kinematics of the gas in both the extended and inner NLR of NGC 4151 using ground-based and *HST* data with high spatial resolution that allow them to separate the underlying velocity field of the emission gas in the NLR from the effects of the radio jet, and to probe its connection with the large scale rotation of the ENLR in the galactic disk.

They decomposed the [O III] $\lambda5007$ line profile in multiple Gaussian components and traced the main kinematic component of the ENLR across the nuclear region, connecting smoothly the emission gas system with the large scale rotation defined by H I observations. The individual clouds in the NLR ($R < 4''$) are kinematically disturbed by the interaction with the radio jet, but underlying these perturbations the cloud system is moving in a pattern best described by disk rotation. High velocity components (up to ±1000 km s^{-1}, relative to systemic) and broad (FWHM up to 1800 km s^{-1}) bases are detected in the [O III]$\lambda5007$ profile of the brightest clouds. Such regions are invariably at the edge of the radio knots, and this association, together with the overall morphology of the velocity field, show that the main kinematic system in the inner region of NGC 4151 is still rotation in the plane of the disk, disturbed but not defined by the interaction with the radio jet and the AGN emission.

They fitted the data with a planar rotation and showed that the ENLR gas ($R > 4''$) has a kinematic behaviour well represented by rotation in the galactic disk, with characteristics similar to other normal spiral systems. They obtain $i = 21°$, and $\Psi_o = 34°–43°$ for the inclination to the line of sight and position angle of the line of nodes of the disk, respectively. The velocity field of external knots at $R \sim 6''$ and $20''$ transverse to the radial direction presents evidence of non-planar or non-circular movements, probably associated with gas turbulence and streaming motions along the bar. The NLR emission component believed to represent the continuation of the disk velocity field was also found to be consistent with planar rotation, although disturbed by the jet, as expected. However, while the velocity field of the extended ENLR gas is dominated by the potential of the galactic bulge, they find that the behaviour of the gas in the inner NLR is best represented by a Keplerian-like potential, with the kinematics of the gas up to $4''$ dominated by the $\sim 10^9$ $M_\odot$ mass concentration located within the 0.54 turn-over radius of the rotation curve.

Thus in NGC 4151 they were able to directly measure, for the first time, the mass of the central black hole.

6. Optical Counterparts to Radio Jets

To date, thirteen optical synchrotron jets have been identified and most of these have been discovered with the *HST*. The jets are located in the radio galaxies M87 (Curtis 1918), 3C15 (Martel et al. 1998), 3C66B (Fraix-Burnet et al. 1989), 3C78 (Sparks et al. 1995), 3C120, 3C200 (de Koff 1996), 3C264 (Crane et al. 1993b), 3C273 (Bahcall et al. 1995), 3C346 (Sparks et al. 1995), 3C371 (Nilsson et al. 1997), PKS 0521–365, 3C212, and 3C245.

In the standard model of jet formation, material accretes on a supermassive black-hole leading to the ejection of a collimated, relativistic hot plasma. The jet becomes visible in the optical if the Doppler boosted synchrotron radiation is "beamed" towards the observer. High-resolution optical imaging with *HST* has revealed common properties among the jets and their nuclei, consistent with this hypothesis: the jets originate from a bright, compact, unresolved nucleus, characteristic of an AGN, no counter jet is observed, the jets are curved and possess a distorted morphology, and they are smaller and narrower in appearance than their radio counterparts (Sparks et al. 1995). Presently, the only known exception to this relativistic beaming picture is 3C 66B whose counterjet has been imaged in both the radio (Hardcastle et al. 1996) and the optical (Fraix-Burnet 1997), suggesting that the observed synchrotron optical emission is due to environmental effects. On the other hand, despite a superficial consistency with the relativistic beaming picture, Sparks et al. (1995) showed that qualitatively, the statistics of optical jet sizes and power favor, instead, an intrinsic difference between the optically emitting jets and those radio jets which show no optical emission.

Other important issues regarding the formation, collimation, acceleration, evolution and lifetime of optical jets still need to be addressed comprehensively. For example, the acceleration mechanism responsible for the emission of optical synchrotron radiation is still a matter of debate, especially when the radio and optical structures are broadly similar (Meisenheimer 1996). Either the particle acceleration is *in situ* to the jet through processes such as shocks or magnetic reconnection or the electrons are accelerated in the nucleus and are transported along the jet in a channel having low magnetic field and consequently low radiation losses as suggested for M 87 (Owen, Hardee, & Cornwell 1989). Eilek & Arendt (1996) have shown that the observed synchrotron spectrum can be attributed not only to power-law particle distribution functions, but also to power-law magnetic field distributions, instead of the uniform magnetic field assumed in the standard model. This has important ramifications for spectral aging studies since observed synchrotron sources can be significantly older than predicted by the standard model. Ultimately, the properties of optical jets need to be understood in the context of their host galaxies and their environment. Since so few optical jets have been identified, it is important to carefully study the few that are known to understand their physical properties and improve the theoretical models.

Although few in number, there are several common features shared by the optical jet radio sources: (i) all have relatively prominent nuclei in both radio and optical domains; (ii) the nuclei all have flat radio spectra; (iii) the jets are small compared to typical radio jet dimensions, with the arguable exception of 3C 273; (iv) there are no two-sided optical jets—they are all one-sided with a large jet to counterjet lower limit; (v) there is noticeable jet curvature; (vi) in addition, where measured, the optical emission is more localized than the radio and the optical jet is narrower than the radio jet.

An obvious candidate explanation for most of these characteristics is relativistic 'beaming', in which the jet becomes visible in the optical only when pointing towards the observer. In the beaming picture, the jet appears brightened, foreshortened and with a prominent active nucleus. Beaming is also expected to blueshift the synchrotron 'break' frequency.

As an alternative to relativistic beaming, environmental effects may be considered. If the pressure is higher in the vicinity of the optically emitting sources, then the additional confinement may act to enhance their radiative luminosity while suppressing the growth of the source, thereby giving rise to the correlation between size and power. This does not immediately suggest an explanation for the core dominance and one-sidedness; however, there may be instabilities which

https://doi.org/10.1017/S0074180900161674 Published online by Cambridge University Press

cause jet disruption and optical emission that are sufficiently rapid that only one side is visible at a given time. 'Age' may provide yet a third alternative, with the optical jet sources being young, in the process of forcing their way out through the interstellar medium, and ram pressure playing a similar role in enhancing the visibility.

There are statistical uncertainties at present, however an extensive analysis of many more optical jets should provide results that will be essential in elucidating the nature of extragalactic synchrotron jets.

7. M87: The Best Studied Optical Jet

The giant elliptical galaxy M87 contains the closest extragalactic jet, which makes it a prime target for studies of jet structure and kinematics. Optical and ultraviolet observations of M87 have been carried out with *HST* and have been extensively reported (Macchetto 1991, Boksenberg et al. 1992; Macchetto, Biretta & Sparks 1992).

While the radio and optical images present a remarkable degree of similaity, there are nevertheless significant differences. The optical/UV images show intrinsically higher contrast than the radio, with compact regions of emission localized within the knots. The jet is narrower in the optical/UV, and more concentrated to the jet center in the optical/UV than in the radio. The radio-to-optical spectral index of the inter-knot regions is steeper than that of the knots themselves. There are also differences in the detailed knot structure of the optical emission compared to the radio, and there is a weak overall spectral steepening with distance from the nucleus beyond knot A.

Capetti et al. (1997c) have analyzed polarization observation of the M87 jet taken with the FOC in the ultraviolet and with the WFPC1 in the visual. The degree of polarization is typically 30% over most of the jet. At the edges of the jet the polarization is as high as 60%, requiring a highly ordered magnetic field. In the center of the jet the small scale structure of the magnetic field produces significant cancellation reducing the polarization to $\sim 10\%$. The degree of polarization and the polarization pattern are very similar at radio and optical wavelengths. No significant depolarization or Faraday rotation have been detected, in agreement with previous radio determinations. However, the morphology of knot D is considerably different in the VLA observations by Owen et al. (1989) and these *HST* observations. Knot D1 appears to be relatively brighter and closer to the nucleus in the optical than in the radio images. Capetti et al. (1997c) conclude that this component is associated with a shock front. At the location of a shock front acceleration of relativistic electrons occurs, enhancing the synchrotron emission at shorter wavelengths, and the transverse component of the magnetic field is amplified by the compression produced by the shock.

As part of a long-term ongoing study, Biretta, Sparks and Macchetto (1999) have measured proper motions for twelve features within the first $6''$ (500 pc) of the M87 jet. Of these, ten appear to be superluminal with eight having apparent speeds in the range $4c$ to $6c$. The two sub-luminal features, knot L and HST-1 EAST, have speeds of $0.63 \pm 0.27c$ and $0.84c \pm 0.11c$, respectively, and coincidentally, are the two features nearest the nucleus.

https://doi.org/10.1017/S0074180900161674 Published online by Cambridge University Press

The most natural explanation for the observed superluminal speeds is that they are due to bulk relativistic flow in the context of the relativistic jet model (Blandford and Königl 1979a). The predominance of speeds in the range $4c$ to $6c$ suggests these are closely linked to an underlying bulk flow. Several regions have much lower speeds, but they attribute this to obstruction or standing shocks within the jet (e.g., Blandford and Königl 1979b). Alternative models which invoke phase effects to produce superluminal motion seem unlikely to work in M87. The consistency of the large speeds in different regions of the M87 jet, as well as the lack of large negative speeds, argues against phase effects as the source of motion.

The observed speeds provide strong constraints on the bulk flow speed and line-of-sight angle for the jet; the strongest constraints result from the largest apparent speeds, of $6c$. Assuming that the jet's velocity is parallel to the jet axis, the relativistic jet model requires a bulk flow with Lorentz factor $\gamma \geq 6$ and a jet orientation within $\theta \sim 19^{\circ}$ of the line-of-sight.

All solutions imply very large jet to counter-jet brightness ratios owing to strong dimming of the receding counter-jet. Ratios are 4×10^4 or larger, which are entirely consistent with the lack of a detected counter-jet.

These results strongly confirm "unified models" which propose that FR-I radio galaxies like M87 are the parent population of BL Lac objects (Browne 1983). Urry, Padovani, and Stickel (1991) predict that FR-I radio galaxies should have jets with bulk flow speeds in the range $\gamma \sim 5$ to ~ 35, with most near $\gamma \sim 7$, which is in good agreement with speeds $\gamma \geq 6$ implied by the observed $6c$. Furthermore, they derive a critical angle $\theta_{crit} \sim 10^{\circ}$ for the FR-I/BL Lac division, which is consistent with the angle $\theta \sim 10^{\circ}$ to 19° found for M87. These speeds of $6c$ are in fact the fastest yet seen for an FR-I radio source.

References

Antonucci, R. 1993, Ann. Rev. Astron. Astrophys., 31, 473

Axon, D. J., Marconi, A., Capetti, A., Macchetto, F. D., Schreier, E., & Robinson, A. 1998, ApJL, 496, L78

Bahcall, J. N., Kirhakos, S., Schneider, D. P., Davis,R. J., Muxlow, T. W. B., Garrington, S. T., Conway, R. G., & Unwin, S. C., 1995, ApJL, 452, L91

Biretta, J. A., Sparks, W. B., & Macchetto, F. D. 1999, ApJ, in press

Blandford, R. D. 1991, Proc. Heidelberg Conf., Physics of AGN, ed. W. J. Duschl & S. J. Wagner (Berlin: Springer), 3

Blandford, R. D. and Königl, A. 1979a, ApJ, 232, 34

Blandford, R. D. and Königl, A. 1979b, ApJL, 20, 15

Boksenberg, A., et al. 1992, A&A, 261, 393

Bower, G. A., Wilson, A. S., Morse, J. A., Gelderman, R., Whittle, M., & Mulchaey, J. 1995, ApJ, 454, 106

Bower, G. A., Wilson, A. S., Mulchaey, J. S., Miley, G. K., Heckman, T. M. & Krolik, J. H., 1994, AJ, 107, 1686

Browne, I. W. A. 1983, MNRAS, 204, p23

Capetti, A., Axon, D. J., Kukula, M., Macchetto, F., Pedlar, A., Sparks, W. B., & Boksenberg, A. 1995a, ApJ, 454, 185

Capetti, A., Axon, D. J., Macchetto, F., Sparks, W. B., & Boksenberg, A. 1995b, ApJ, 446, 155

Capetti, A., Macchetto, F., Sparks, W. B., & Boksenberg, A. 1995c, ApJ, 448, 600

Capetti, A., Macchetto, F., Axon, D. J., Sparks, W. B., & Boksenberg, A. 1996a, ApJ, 466, 169

Capetti, A., Axon, D. J., Macchetto, F., Sparks, W. B., & Boksenberg, A. 1996b, ApJ, 469, 554

Capetti, A., Macchetto, F., & Lattanzi, M. G. 1997a, ApJ, 476, 67

Capetti, A., Axon, D. J., & Macchetto, F. D., 1997b, ApJ, 487, 560

Capetti, A., Macchetto, F., Sparks, W. B., & Biretta, J. A. 1997c, A&A, 317, 637

Crane, P., et al. 1993, ApJL, 402, L37

Crane, P., et al. 1993, AJ, 106, 1371

Curtis, H. D. 1918, Publ. Lick Obs., 13, 11

de Koff, S., Baum, S. A., Sparks, W. B., et al. 1996, ApJS, 107, 621

Dressler, A. & Richstone, D. O. 1990, ApJ, 348, 120

Eilek, J. A., & Arendt, P. N., 1996, ApJ, 457, 150

Evans, I. N., Ford, H. C., Kinney, A. L., Antonucci, R. R. J., Armus, L. & Caganott, S, 1991, ApJL, 369, L27

Evans, I. N., Tsvetanov, Z., Kriss, G. A., Ford, H. C., Caganott, S., & Koratkar, A. P., 1993, ApJ, 417, 82

Ferrarese, L., van den Bosch, F. C., Ford, H. C., Jaffe, W., & O'Connell, R. W. 1994, AJ, 108, 1598

Ford, H. C., et al. 1994, ApJ, 435, L27

Ford, H. C., Tsvetanov, Z. I., Hartig, G. F., Kriss, G. A., Harms, R. J., Dressel, L. L. 1996, in Science with the *HST* II, ed. P. Benvenuti, F. Macchetto, & E. Schreier (Washington: GPO), 192

Fraix-Burnet, D., 1997, MNRAS, 284,911

Fraix-Burnet,D., Nieto, J. L., Leliévre, G., Macchetto, F., Perryman, M. A. C., & di Serego Alighieri, S. 1989, ApJ, 336, 121

Hardcastle, M. J., Alexander, P., Pooley, G. G., & Riley, J. M., 1996, MNRAS, 278, 273

Harms, R. J., et al. 1994, ApJ, 435, L35

Jaffe, W., Ford, H. C., Ferrarese, L., van den Bosch, F. C., & O'Connell, R. W. 1993, Nature, 364, 213

Macchetto, F. 1991, Proceedings, Physics of AGN, ed. S. J. Wagner, W. J. Duschl, Springer-Verlag: Berlin, 325

Macchetto, F. 1996a, in IAU Symp. 175, Extragalactic Radio Sources, ed. R. Ekers et al. (Dordrecht: Reidel), 195

Macchetto, F. 1996b, in Science with the *HST* II, ed. P. Benvenuti, F. Macchetto, & E. Schreier (Washington: GPO), 394

Macchetto, F., Biretta, J. A., & Sparks, W. B. 1992, Proceedings 182nd AAS Meeting, 24, 1183

Macchetto, F., Capetti, A., Sparks, W. B., Axon, D. J. & Boksenberg, A. 1994, ApJL, 435, L15

Macchetto, F. D., Marconi, A., Axon, D. J., Capetti, A., Sparks, W. B., & Crane, P., 1997, ApJ, 489, 579

Magorrian, J., Tremaine, S., Gebhardt, K., Richstone, D., & Faber, S. 1996, BAAS, 189,111

Marconi, A., Axon, D. J., Macchetto, F. D., Capetti, A., Sparks, W. B., & Crane, P., 1997, MNRAS, 2891, 21M

Martel, A. R., Sparks, W. B., Macchetto, F. D., Biretta, J. B., Baum, S. A., Golombek, D., McCarthy, P. J., de Koff, S., & Miley, G. K., 1998, ApJ, 496, 203

Meisenheimer, K., 1996, in Jets from Stars and Galactic Nuclei, ed. W. Kundt (New York: Springer)

Nelson, C. H., Mackenty, J. W., Simkin, S. A., & Griffiths, R. E. 1996, ApJ, 466, 713

Nilsson, K., Keidt, J., Pursimo, T., Sillanpää, A., Takalo, L. O., & Jaäger, A. 1997, ApJ, 484, L107

Owen, F. N., Hardee, P. E. & Cornwell, T. J. 1989, ApJ, 340, 698

Sargent, W. L. W., Young, P. J., Boksenberg, A., Shortridge, K., Lynds, C. R., & Hartwick, F. D. A. 1978, ApJ, 221, 731

Sparks, W. B., Golombek, D., Baum, S. A., Biretta, J., de Koff, S., Macchetto, F. D., McCarthy, P., & Miley, G. K., 1995, ApJ, 450, L95

Urry, C. M., Padovani, P., & Stickel, M. 1991, ApJ, 382, 501

van der Marel, R. P. 1994, MNRAS, 270, 271

Wilson, A. S., Braatz, J. A., Heckman, T. M., Krolik, J. H., & Miley, G. K., 1993, ApJ, 419, L61

Winge, C., Axon, D. J., Macchetto, F. D. & Capetti, A., 1997, ApJL, 487, L121

Winge, C., Axon, D. J., Macchetto, F. D., Capetti, A., & Marconi, A., 1999, ApJ, in press

Young, P. J., Westphal, J. A., Kristian, J., Wilson, C. P., & Landauer, F. T. 1978, ApJ, 221, 721

https://doi.org/10.1017/S0074180900161674 Published online by Cambridge University Press