VLBI Imaging of Seyfert Galaxies

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Abstract. The advent of the Very Long Baseline Array and its phase-referencing capability have enabled milliarcsecond-scale imaging of radio sources at sub-millijansky sensitivity, opening the door to high-resolution imaging of Seyfert galaxies. Over the last few years, this has led to a number of interesting new results that shed light on the characteristics of the inner cores of Seyfert galaxies. These include the following: (1) classical Seyfert galaxies with steep radio spectra have a strong tendency to exhibit radio jets at milliarcsecond scales, sometimes with considerable curvature in the jets; (2) apparent speeds of jets imaged at multiple epochs generally are considerably less than \(c\), often in the vicinity of \(0.1c\) or less, although there sometimes are faster motions seen after strong outbursts; and (3) lower luminosity Seyfert galaxies have a much stronger tendency to show flat or somewhat inverted radio spectra, usually are unresolved on milliarcsecond scales, and probably are dominated by a combination of low-radiative-efficiency accretion flows and very compact radio jets. This paper discusses some examples that illustrate these properties, and summarizes some of what we have learned about weak active galaxies on milliarcsecond scales.

1. Introduction

Seyfert galaxies were first identified as a class by Seyfert (1943), now 60 years ago. They are cousins of the more luminous quasars, having the advantage of being much more numerous, so that they include many nearby objects that can be studied at high linear resolution. Seyfert galaxies exhibit forbidden optical emission lines of moderate width (a few hundred km s\(^{-1}\)), while their permitted emission lines may be very broad (Seyfert 1 galaxies, with line widths of a few thousand km s\(^{-1}\)) or of widths similar to the forbidden lines (Seyfert 2 galaxies). This has been explained generally by a unified scheme in which Seyfert galaxies contain an obscuring nuclear torus or disk that is seen pole-on in Seyfert 1 galaxies or edge-on in Seyfert 2 galaxies (e.g., Antonucci 1993). Most of the observational manifestations of Seyfert galaxies, certainly in the inner few milliarcseconds, are thought to be powered by central supermassive black holes that typically have masses in the range of \(\sim 10^7 M_\odot\) to \(\sim 10^8 M_\odot\) (e.g., Wandel, Peterson, & Malkan 1999).
2. **Scientific Goals and Context**

There are a number of scientific problems that can be addressed by imaging Seyfert galaxies on milliarcsecond scales, a realm that is just beginning to be explored in these objects. Among the key questions are the following:

1. Why is there such a wide range of spectral properties in active galactic nuclei (AGNs), with radio/optical luminosity ratios spanning many orders of magnitude?

2. What do Seyfert galaxies reveal about the formation and fueling of supermassive black holes and radio jets?

3. What are the observational manifestations of supermassive black holes in nearby galaxies?

The above questions can be asked in the context of several currently unsolved problems in AGN physics. Specifically, one current question of interest is the assessment of the differences between radio-quiet and radio-loud AGNs. Are there two populations or a continuous distribution, and what are the parameters that control the relative strengths in different spectral regimes? Another question is that of the general nature and physics of the low-luminosity AGNs (LLAGNs). Here, we would like to know how LLAGN accretion and jet-formation processes differ from radio galaxies and quasars.

The general areas of interest lead to a few specific observations of Seyfert galaxies that may be made with VLBI arrays such as the Very Long Baseline Array (VLBA):

1. *Jet properties and speeds:* Are Seyfert and LLAGN jets intrinsically weak and slow, or quenched by gas in their nuclei? Do VLA and VLBI-scale jets have the same symmetry axes?

2. *Compact radio-source spectra and luminosities:* Are these quantities consistent with various flavors of accretion models, or jet models, or is a combination required?

3. *Radio core sizes:* For nearby galaxies at distances of tens of megaparsecs, classical models of advection-dominated accretion flows, or ADAFs (e.g., Narayan, Mahadevan, & Quataert 1998) predict sizes of tens of microarcseconds. Models in which the radio emission is dominated by compact jets (e.g., Falcke 1999) predict sizes of hundreds to thousands of microarcseconds. Can the two be distinguished by means of VLBI imaging?

4. *Location of gas relative to the AGNs:* The location of various parcels of gas can be studied by imaging H$_2$O megamaser emission (Greenhill et al. 2003), free-free absorption (Walker et al. 2000), or HI absorption (Mundell et al. 2003). Discussion of this issue is beyond the scope of the current contribution, and the reader is referred to the cited references instead.
Figure 1. Two-epoch VLBI images of the Seyfert galaxies Mrk 231 (left) and Mrk 348 (right) are shown, taken from Ulvestad et al. (1999). The apparent speeds corresponding to the small relative motions of the two components are $\sim 0.1c$ within the central parsec of each galaxy.

3. Jet Properties and Speeds

A few Seyfert galaxy jets have been imaged at multiple epochs, so that their jet speeds can be measured on parsec scales. Examples are shown in Figure 1, taken from Ulvestad et al. (1999). Here, the cores of the Seyfert galaxies Mrk 231 and Mrk 348 are shown at two epochs from early VLBA imaging; the respective relative component speeds are $\beta_{\text{app}} = 0.14 \pm 0.052$ and $0.074 \pm 0.035$, where $\beta_{\text{app}} = v_{\text{app}}/c$. These values appear fairly typical of most Seyfert galaxies measured to date, although objects in outburst, such as III Zw 2 (Brunthaler et al. 2000) and Mrk 348 (Peck et al. 2003) may display apparent speeds on sub-parsec scales that are (at least) a substantial fraction of the speed of light.

A summary of published measurements of Seyfert jet speeds is given in Table 1. In contrast to the Seyfert galaxies, radio galaxies and radio-loud quasars generally have highly relativistic jets on scales of a few parsecs to hundreds of parsecs. Since the properties of nuclear gas in Seyfert galaxies and the more powerful objects are fairly similar (as indicated by emission-line measurements), it seems likely that Seyfert galaxy jets initially are much less powerful relative to the nuclear environment, and may even have different acceleration mechanisms.

At present, there is no obvious systematic difference between objects of different Seyfert classes in the few objects studied. In a large sample, we might expect that Seyfert 2 galaxies would have larger apparent jet speeds as a class; their more edge-on tori should translate into jets that have a larger projection in the plane of the sky than for Seyfert 1 galaxies. However, this would be true only if the small-scale jet axes truly indicate the orientation of the nuclear torus.

Recently, it has been shown conclusively that VLA-scale jets in Seyfert galaxies essentially are randomly oriented with respect to their host galaxy ma-
Table 1. Published jet speeds in Seyfert galaxies

| Galaxy     | $\beta_{app}$ | Scale  | Comment            | Reference          |
|------------|---------------|--------|--------------------|--------------------|
| III Zw 2   | < 0.04        | 0.2 pc | Quiescent          | Brunthaler et al. (2000) |
|            | > 1.25        | 0.4 pc | Outburst           | Brunthaler et al. (2000) |
| Mrk 348    | 0.07          | 0.5 pc | Start of outburst  | Ulvestad et al. (1999) |
|            | ~ 0.4         | 0.5 pc | Outburst           | Peck et al. (2003)  |
| NGC 1068   | < 0.08        | 21 pc  | Quiescent          | Roy et al. (2000)   |
| NGC 4151   | < 0.14        | 7 pc   | Quiescent          | Ulvestad et al. (1998) |
| Mrk 231    | < 0.05        | 7 pc   | Quiescent          | Ulvestad et al., in prep. |
| NGC 5506   | 0.14          | 1 pc   | Moderate outburst  | Ulvestad et al. (1999) |
|            | < 0.25        | 3.4 pc | Quiescent?         | Roy et al. (2001)   |

Major axes (Kinney et al. 2000). This generally is thought to indicate that the central tori are misaligned with respect to the galaxy disks, and therefore had a different origin. However, it is not necessarily the case that the VLA-scale jet must indicate the direction of the torus axis, since there often is significant curvature between milliarcsecond and arcsecond scales. For example, Mrk 231 shows a position angle difference of 65° between scales of 1 pc and tens of parsecs (Ulvestad, Wrobel, & Carilli 1999) and NGC 5506 has a jet bend of 90° at a few parsecs from the nucleus (Roy et al. 2001). The beautiful 1.4-GHz continuum image of NGC 4151 by Mundell et al. (2003) demonstrates that a jet which looks straight in VLA and MERLIN images (e.g., Mundell et al. 1994) actually contains a number of remarkable changes in jet direction when viewed with milliarcsecond resolution, possibly due to interactions with narrow-line gas clouds. Given that nuclear tori can be strongly warped by radiation on sub-parsec scales (Pringle 1997), we must be wary of inferring the directions of the central tori even from milliarcsecond-scale jet directions.

4. Compact Radio-source Spectra and Luminosities

Significant samples of LLAGNs, including both Seyfert and LINER galaxies, have been imaged with the VLBA in order to determine whether they contain milliarcsecond-scale cores that must be powered by supermassive black holes (Falcke et al. 2000; Nagar et al. 2002). In virtually all objects that have unresolved cores on arcsecond scales, a compact radio source with a brightness temperature $T_B \geq 10^8$ K has been detected, a sure indicator of a nucleus powered by a massive black hole.

Classical Seyfert galaxies typically have steep radio spectra, indicative of optically thin synchrotron radiation; no more than $\sim 10\%$ of such objects appear to have flat or inverted spectra (Ulvestad & Wilson 1989). In the classical Seyfert galaxy NGC 1068, a weak flat-spectrum radio core has been resolved by the VLBA. This core has multiple components with brightness temperatures of $\sim 10^6$ K, interpreted as direct or reflected emission from the nuclear torus itself (Gallimore, Baum, & O’Dea 1997). However, efforts to find similar objects by VLBA imaging of flat-spectrum cores in other classical Seyfert galaxies have failed thus far (Wilson et al. 1998; Mundell et al. 2000), indicating that most of these objects are likely to have flat spectra due to synchrotron self-absorption.
In the classical Seyfert NGC 4151, a high-sensitivity VLBI observation in 2002, using the VLBA together with several 100-m class telescopes, has revealed a flat-spectrum 2-mJy radio core at 15 GHz. That core is shown here in Figure 2; it appears to be the AGN and the origin of the two-sided jet seen on larger scales, but shows no evidence of emission from a nuclear torus (Ulvestad et al. 2003, in preparation). Comparison of this image with an 8.4 GHz image made from data taken in 1998 is under way, in order to measure the apparent speed on a 0.1-pc scale.

Surprisingly, within the lower-luminosity Palomar Seyfert sample (Ho, Filippenko, & Sargent 1997), it appears that roughly half of the objects in an optically selected sample have flat or inverted radio spectra (Ulvestad & Ho 2001a). In these objects, which appear to be radiating far below their Eddington luminosities, the accretion flows almost certainly have low enough densities
so that they have low radiative efficiencies. Then, synchrotron radiation from hot electrons in the accreting gas can be self-absorbed, yielding a slightly inverted spectrum at radio frequencies in the gigahertz range (Narayan et al. 1998). Ulvestad & Ho (2001b) used the VLBA to image three of the stronger LLAGNs with inverted spectra at radio frequencies ranging from 1.6 GHz to 8.4 GHz. In all three cases, they found unresolved sources with radio spectra that increase gradually with frequency, similar to the spectrum of the radio source Sgr A* at the center of our own galaxy.

One of the well-known problems of classical ADAF models is that the radio emission in LLAGNs and Sgr A* is observed to be far stronger relative to the X-ray emission than is predicted by the models. This problem can be “fixed” if a large fraction of the observed radio emission comes from a compact radio jet rather than from the accretion flow itself (Falcke & Markoff 2000; Falcke 2001). The jet models seem to predict that the radio emission should become optically thin and turn over above a few gigahertz. However, Anderson & Ulvestad (2003, in preparation) have used the VLBA to image the LLAGNs from Ulvestad & Ho (2001b) at frequencies up to 43 GHz, and found that the radio spectra continue to be flat or rising with frequency, in contradiction to the current jet models.

Ho & Peng (2001) and Terashima & Wilson (2003) have used high-resolution optical and X-ray imaging to attempt to isolate the active nuclei of Seyfert galaxies and LLAGNs, and to divide them into radio-quiet and radio-loud objects. Terashima & Wilson studied the radio/X-ray ratio using the quantity $R_X \equiv \nu L_\nu(5 \text{ GHz})/L_X(2 - 10 \text{ keV})$, useful even for heavily obscured nuclei. They found that $\log R_X = -4.5$ is the rough dividing line between radio-quiet and radio-loud objects. When compact radio flux is used, most of their Seyfert galaxies have $\log R_X \sim -5$ and are in the radio-quiet category, whereas using the total radio flux would make more of these objects radio loud. The general trend found by Terashima & Wilson (2003), using the VLBI core powers from some of the references cited above, is that most LLAGNs are radio loud. These LLAGNs almost certainly have accretion flows with low radiative efficiency. Therefore, the implication is that the central power sources in such objects put a significantly larger fraction of their total energy output into radio emission than in galaxies with classical accretion flows.

5. Radio Core Sizes

Radio emission from low-efficiency accretion flows is thought to originate very close to the central black holes, perhaps within a few to a few tens of Schwarzschild radii (Mahadevan 1997). In contrast, emission from compact jets connected to these flows is thought to come from scales a factor of $\sim 30 - 40$ times larger, up to as much as 1000 Schwarzschild radii (Falcke & Biermann 1999). Ulvestad & Ho (2001b) found upper limits of $10^3 - 10^4$ Schwarzschild radii from their VLBA imaging of three LLAGNs, and these limits have been extended downward by factors of $\sim 5$ by 43-GHz VLBA imaging of the same objects (Anderson & Ulvestad 2003, in preparation). The upper limits now are getting uncomfortably small for the compact jet models. Putting this together with the problem mentioned above, that the radio spectra do not turn over above $\sim 10$ GHz, it is
VLBI Imaging of Seyfert Galaxies

becoming clear that the accretion/jet models used to date may need more work in order to account for the compact radio emission from LLAGNs.

Since the Earth is not going to get any bigger, what can we do in order to attempt to measure true sizes of the radio sources in low-luminosity Seyferts and AGNs? Space VLBI is one option, but the relative weakness of the radio cores in most Seyfert galaxies makes this only a fond hope for the relatively distant future. But a more promising technique may be to use the interstellar medium in our Galaxy to “image” the radio cores. It recently has become clear that intraday variability in strong extragalactic radio sources is caused by scintillation in the interstellar medium (Rickett et al. 2001; Jauncey & Macquart 2001; Dennett-Thorpe & de Bruyn 2002), providing a means of estimating radio core sizes in the vicinity of a few microarcseconds. Although measuring intraday variability in millijansky-strength sources will be a real challenge to modern instrumentation, it may be possible with the current VLA, and certainly is well within the reach of the more sensitive Expanded VLA.

Acknowledgments. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. I thank the many collaborators whose work has been summarized in this contribution.

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