EVIDENCE FOR JET DOMINATION OF THE NUCLEAR RADIO EMISSION IN LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI

NEIL M. NAGAR, ANDREW S. WILSON, AND HEINO FALCKE

Received 2001 June 28; accepted 2001 August 21; published 2001 September 7

ABSTRACT

We present simultaneous, subarcsecond (≤50 pc) resolution 5, 8.4, and 15 GHz Very Large Array observations of a well-defined sample of 16 low-luminosity active galactic nuclei. The radio emission in most of these nuclei does not show the rising spectrum (0.2 ≤ s ≤ 1.3, L ∝ ν^s) expected from thermal electrons in an advection-dominated accretion flow (ADAF) with or without weak to moderately strong outflows. Rather, the flat radio spectra are indicative of either synchrotron self-absorbed emission from jets, convection-dominated accretion flows (CDAFs) with L ∝ 10^{-2}L_{Edd}, or ADAFs with strong (p ≳ 0.6) outflows. The jet interpretation is favored by three factors: (1) the detection of parsec-scale radio extensions, morphologically reminiscent of jets, in the five nuclei with the highest peak radio flux density, (2) the domination of parsec-scale jet radio emission over unresolved “core” emission in the three best-studied nuclei, and (3) the lack of any clear correlation between radio spectral shape and black hole mass as would be expected from the dependence of the radio turnover frequency on black hole mass in ADAF and CDAF models. A jet domination of nuclear radio emission implies significantly lower accretion rates in ADAF-type models than earlier estimated from core radio luminosities.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: jets — galaxies: nuclei — radio continuum: galaxies — surveys

1. INTRODUCTION

The detection of optical broad emission lines (Ho et al. 1997b) and high brightness temperature (≥10^8 K) radio cores (Bietenholz, Bartel, & Rupen 2000; Junor & Biretta 1995; Falcke et al. 2000; N. M. Nagar, A. S. Wilson, H. Falcke, & J. S. Ulvestad 2001, in preparation) in the nuclei of a well-defined sample of nearby bright galaxies (Ho, Filippenko, & Sargent 1997a) indicates that at least 20% of all nearby bright galaxies have an accreting massive black hole. These nearby nuclei have been christened low-luminosity active galactic nuclei (LLAGNs). Their low nuclear luminosities require either very low accretion rates (∼10^{-4}L_{Edd}; e.g., Falcke & Biermann 1999) or radiative efficiencies (the ratio of radiated energy to accreted mass) much lower than the typical value of ∼10% (e.g., Frank, King, & Raine 1995) assumed for powerful AGNs. This has led to renewed interest in spherical accretion models that produce low radiated luminosities, e.g., advection-dominated accretion flows (ADAFs; Narayan, Mahadevan, & Quataert 1998b), which may have associated outflows (Blandford & Begelman 1999), and convection-dominated accretion flows (CDAFs; Stone, Pringle, & Begelman 1999; Narayan, Igumenshchev, & Abramowicz 2000; Quataert & Gruzinov 2000).

The subarcsecond radio emission in LLAGNs may originate in an ADAF or CDAF inflow, and the predictions of these models are discussed in § 2. The subarcsecond radio emission may alternatively originate in synchrotron radiation from discrete plasma components or from the base of a continuous jet ejected from the central engine. In the former case, the presence of different self-absorption frequencies for individual components results in a flat spectral shape (s ∼ 0; L ∝ ν^s) for the overall system (e.g., Marscher 1988). In the latter case, i.e., for relativistic electrons at the base of a continuous, freely expanding jet (Blandford & Königl 1979), the variation of the electron density (n ∝ d^{-2}), electron temperature (T_e ∝ d^{1/2}), and magnetic field (B ∝ d^{-2}), where d is the distance along the jet axis), results in a flat overall radio spectrum. Slightly inverted spectra (up to s ∼ 0.2) may result from the bulk acceleration of the jet plasma (Falcke 1996), and even higher (temporary) values of s may be measured during radio outbursts (e.g., Ho et al. 1999).

On larger scales, the synchrotron emission from the ejecta or jet becomes optically thin (s ∼ −0.7). Thus, the spectral index of the overall synchrotron emission from a “jet” is expected to be between 0.2 and −0.7, depending on the relative contributions of the base and extended components.

2. RADIO SPECTRAL PREDICTIONS OF ADAFS AND CDAFS

In their simplest form, ADAF and CDAF self-similar spherical models invoke standard α-viscosity, a two-temperature thermal plasma, and a fixed ratio (β) of magnetic to gas pressure. Let us first use the analytic scaling law approximations of Mahadevan (1997, hereafter M97) to estimate the expected radio spectral index in a self-similar flow. If we follow the derivation in § 4.1 of M97 using magnetic field B ≃ r^{−3/2}, electron temperature T_e ≃ r^{−1/2}, and synchrotron emission factor x_{syn} ≃ r^{−2}, then the radio emission is self-absorbed, with spectral index s ∼ (5a + 2c + 2d - 2) / (2a + c + d) at frequencies below a critical frequency ν_c. Here r is the radius in units of the Schwarzschild radius and c is 5/4 in an ADAF (Narayan & Yi 1995) and 3/4 in a CDAF (Narayan et al. 2000). When L ∼ 10^{-2}L_{Edd} the dominance of synchrotron cooling forces a to 0 over the radio-emitting region (≤10 r) in an ADAF or CDAF (see Narayan & Yi 1995). However, when L ∼ 10^{-3}L_{Edd} the electrons are adiabatically compressed so that a ∼ 0.5 in an ADAF (Narayan et al. 1998a) and a ∼ 1 (i.e., virial) in a CDAF (Narayan et al. 2000). The value of d is more difficult to estimate. M97 find d ≃ 1/15 in ADAFs with

1 Arcetri Observatory, Largo E. Fermi 5, Florence 50125, Italy; neil@arcetri.astro.it.
2 Department of Astronomy, University of Maryland, College Park, MD 20742; wilson@astro.umd.edu; Adjunct Astronomer, Space Telescope Science Institute.
3 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany; hfalcke@mpifr-bonn.mpg.de.
4 The VLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
the accretion flow corresponds to the ADAF case for
established work dealing explicitly with numerical modeling of the
analytical method, the above results should be considered only
when . Given the many approximations in this
M97 with typical values of \( K \) and \( 0.2 \)

Thus, for an ADAF one expects , and for a CDAF

ADAFs are considered separate from “outflows” as their convective eddies
are not unbound (Narayan et al. 2000).

\[ L \approx 10^{-4}L_{\text{Edd}} \text{ (their Appendix B). Solving equation (B1) of } \]

M97 with typical values of \( T_{\nu}(r = 1) = 10^{4} - 10^{10} \) K and

\[ m_{n} = 10^{3} \text{ to } 10^{9} \text{ shows that for an ADAF } d \approx -0.15 \text{ when } \]

\( a = 0 \) and \( d = -0.6 \) when \( a = 0.5 \). Here \( m \) is the black hole

mass in solar masses and is the accretion rate in units of the

Eddington rate (assuming 10% radiative efficiency). If we simply

modify the form of \( \rho \) and \( B \) in an ADAF (eq. [5] of M97) only in the power-law dependence of \( r \) to

convert them to the equivalent expressions for a CDAF (see

Narayan et al. 2000 for some justification of this), then we can

solve the equivalent of M97’s equation (B1) to find that for a

CDAF \( d \approx -0.2 \) when \( a = 0 \) and \( d \approx -1.6 \) when \( a = 1 \).

Thus, for an ADAF one expects \( 0.2 \leq s \leq 1.1 \), and for a CDAF

one may expect \( s = 1.8 \) when \( L \approx 10^{-4}L_{\text{Edd}} \) and \( s = 1.1 \)

when \( L \approx 10^{-2}L_{\text{Edd}} \). Given the many approximations in this

analytical method, the above results should be considered only

roughly indicative. ADAFs with outflows have density profile

\[ \rho \propto r^{-2/5+\gamma} \] (Blandford & Begelman 1999), with \( \gamma \) varying from

0 (no outflow) to 1 (strong outflow). The radio emission from the

accretion flow corresponds to the ADAF case for \( \rho = 0 \)

and to the CDAF case for \( \rho = 1 \); radio emission from the outflow has not been modeled and is not considered in this Letter.

More accurate numerical modeling of the radio emission from an ADAF gives \( s = 0.4 \) when \( L = 10^{-4}L_{\text{Edd}} \) (M97) and

\( s \approx 1 \) when \( L \approx 10^{-2}L_{\text{Edd}} \), with \( s \) decreasing but still positive as \( p \) increases from 0 to 0.6 (Narayan et al. 1998a; Quataert & Narayan 1999). To our knowledge, there has been no pub-
lished work dealing explicitly with numerical modeling of the

radio emission from a CDAF. In summary, the radio emission below \( \nu_{c} \) from the accretion inflow of an ADAF or CDAF is

expected to have a moderately to highly inverted spectrum except for (1) CDAFs in systems with \( L \approx 10^{-2}L_{\text{Edd}} \) and (2) ADAFs with strong \((\rho \approx 0.6)\) outflows.

The inflow is optically thin at frequencies greater than

\[ \nu_{c} = 1.3 \times 10^{-4} \alpha^{-1/2} (1 - \beta)^{1/2} \frac{m_{n}^{-1/2} m_{e}^{1/2} T_{e}^{-1/2}}{\rho_{\text{min}}} \] (1)

so the radio emission falls off exponentially above \( \nu_{c} \) (M97).

For ADAFs without outflows, \( T_{e} \) and \( m_{n} \) are relatively independent of \( m \) for \( m = 10^{-1} - 10^{3} \) (Fig. 2 of M97). Thus, for typical values of \( \alpha (0.3), \beta (0.5), \) and \( m (10^{-4} \text{ to } 10^{10}), \) one has \( \nu_{c} \approx (5 \times 10^{-15} - 10^{5}) m^{-1/2} \) i.e., the turnover frequency is greater than 15 GHz for all black holes considered here. In

ADAFs with outflows and in CDAFs, the flatter density profile

results in a decrease in the values of \( T_{e} \) and \( B \) near \( r \approx 1 \), and consequently a decrease in \( \nu_{c} \) and \( L_{c} \); the introduction of a moderately strong \((\rho \approx 0.6)\) outflow to an ADAF can lower the value of \( \nu_{c} \) by almost 2 orders of magnitude (Quataert & Narayan 1999).

3. OBSERVATIONS AND DATA REDUCTION

Sixteen of the 96 nearest \((D \leq 19 \text{ Mpc})\) LLAGNs from the Palomar sample (Ho et al. 1997a) have a highly compact \((\leq 2 \text{ mas})\), high brightness temperature \((\leq 10^{5} \text{ K})\) radio core (see Falcke et al. 2000; N. M. Nagar et al. 2001, in preparation). These sixteen LLAGNs, listed in Table 1, were observed with the Very Large Array (VLA) at 5 GHz (6 cm), 8.4 GHz (3.6 cm), and 15 GHz (2 cm). The observations were made on 1999 September 5 and September 10, while the VLA was in A configuration (see Thompson et al. 1980). Each LLAGN observation was sandwiched between two observations of a nearby phase calibrator with typical cycle times, in minutes, of 1-7-1, 1-6-1, and 2-7-2, at 5, 8.4, and 15 GHz, respectively. The ob-

| Galaxy Name | Activity Type | \( T \) | Full Resolution | 0\(^{5}\) Resolution |
|-------------|---------------|-----|----------------|----------------|
| NGC 2787    | L1.9          | -1  | 15.7           | 15.6           |
| NGC 3031    | S1.5          | 2   | 208.7          | 278.6          |
| NGC 3718    | L1.9          | 1.6 | 6.6            | 6.6            |
| NGC 4143    | L1.9          | -2  | 8.3            | 7.8            |
| NGC 4168    | S1.9          | -5  | 4.7            | 3.9            |
| NGC 4203    | L1.9          | 10.8| 10.6           | 10.7           |
| NGC 4258    | S1.9          | 4   | 1.6            | 1.5            |
| NGC 4278    | L1.9          | -5  | 143.9          | 105.9          |
| NGC 4374    | L2            | -5  | 168.7          | 163.1          |
| NGC 4477    | S2            | -5  | 4.8            | 4.7            |
| NGC 4486    | L2            | -4  | 2875.1         | 2368.6         |
| NGC 4552    | T2            | -5  | 131.1          | 104.0          |
| NGC 4565    | S1.9          | 3   | 2.5            | 2.4            |
| NGC 4579    | S1.9          | 3   | 26.1           | 25.6           |
| NGC 4772    | L1            | 1   | 1.8            | 2.9            |
| NGC 5866    | T2            | -1  | 12.4           | 11.2           |

Note.—Col. (1): Galaxy name. Col. (2): Nuclear activity type as derived by Ho et al. 1997a. “L” represents LINER, “S” represents Seyfert, “H” represents an H II region–type spectrum, and “T” represents objects with transitional L + H spectra. “2” implies that no broad Hα is detected, “1.0” implies that broad Hα is present but not broad Hβ, and “1.5” implies that broad Hα and broad Hβ are detected. Col. (3): Morphological type of the host galaxy as listed in Ho et al. 1997a. Cols. (4) and (5): Peak flux density and total flux of the core at 5 GHz in the highest (~0.5 resolution) VLA maps. Cols. (6) and (7): Peak flux density and total flux of the core at 8.4 GHz in the highest (~0.5 resolution) VLA maps. Cols. (8) and (9): Peak flux density and total flux of the core at 15 GHz, in maps tapered to 0.5 resolution. Cols. (10) and (11): Peak flux density and total flux of the core at 15 GHz, in maps tapered to 0.5 resolution. Col. (14): Ratio of the peak 5 GHz VLA flux (0.5 resolution) to the total 5 GHz flux in the inner ~20 mas of (nonsimultaneous) VLBA maps, for nuclei observed with the VLBA by Falcke et al. 2000 and N. M. Nagar et al. 2001, in preparation.
observations at the three frequencies are simultaneous to ≤30 minutes for each LLAGN.

Data were calibrated and mapped using the AIPS software, following the standard procedures outlined in the AIPS cookbook. Observations of 3C 147 and 3C 286 were used to set the 5 GHz flux density scale, and observations of 3C 286 were used to set the 8.4 and 15 GHz flux density scales. The 15 GHz observation of 3C 286 was made at a single (1.4) air mass, and all 15 GHz observations were made at air masses of 1.06–1.4, so the 15 GHz flux calibration error from elevation effects is expected to be less than 0.2% (R. A. Perley 2000). For this reason, we did not make elevation-dependent gain corrections to the 15 GHz data. The VLA documentation suggests that the flux calibration at 5 and 8.4 GHz should be accurate to 1%–2% and that at 15 GHz should be accurate to 3%–5%; we conservatively use the higher numbers as the respective 2 σ errors. For sources with flux greater than 3 mJy, we were able to iteratively self-calibrate (both phase-only and amplitude and phase) and image the data so as to increase the signal-to-noise ratio in the final map. The rms noise in the final uniformly weighted maps was typically 100, 60, and 170 μJy at 5, 8.4, and 15 GHz, respectively. The resolution at these three wavelengths was typically 0.5, 0.27, and 0.15, respectively. We also made 15 and 8.4 GHz maps with the same resolution (0.5) as the 5 GHz maps, by appropriately tapering the (u, v)-data.

4. RESULTS

All sources except NGC 4168 at 15 GHz were clearly detected in initial (non–self-calibrated) maps. The 15 GHz observation of NGC 4168 was made during very bad weather, and we were able to make a noisy map only after self-calibration with a point-source model. The newly measured flux densities are listed in Table 1. The 15 GHz data are noisy because of bad weather and high humidity. Therefore, the three nuclei for which we could not self-calibrate the 15 GHz data have true 15 GHz fluxes somewhere between the measured values and 3 mJy. For all but three of the objects, the radio emission at all three frequencies is compact; a Gaussian fit to the source does not give a deconvolved size more than half a beam size. The three sources with detected extended structure are all previously known to have such structure: NGC 4278 (Wilkinson et al. 1998), NGC 4472 (Ekers & Kotanyi 1978), and NGC 4486 (M87; e.g., Junor & Biretta 1995). The unresolved emission dominates the extended emission in our maps of these three sources except in NGC 4472, which has a very weak core. Most nuclei have roughly similar fluxes in the full-resolution 15 GHz maps and the 0.5 resolution tapered maps (Table 1); the same is true at 8.4 GHz. The peak flux density in the 0.5 resolution, 5 GHz VLA maps is ∼0.8–2.1 times the total (but not necessarily core) flux in the central ≤20 mas of the 5 GHz (nonsimultaneous) Very Long Baseline Array (VLBA) maps for all sources that were observed in our 1997 June and 1999 April VLBA runs (col. [14] of Table 1).

The variation of the core spectral index (from the peak fluxes in matched resolution maps) with black hole mass is shown in Figure 1a. We have distinguished between black hole masses derived directly from stellar, gas-, and maser dynamics (Gebhardt et al. 2000; Richstone et al. 1998) from those inferred from central velocity dispersions (using the relationship derived by Gebhardt et al. 2000) and galaxy bulge masses (using the relationship derived by Richstone et al. 1998). Only NGC 3031 (M81) and NGC 4772 consistently show the highly inverted radio spectrum expected in ADAF models with or without weak to moderately strong outflows. The core radio emission from the latter galaxy is probably dominated by extended emission (see above), and as discussed below the radio emission from the former is probably from a jet. Apart from NGC 4472, the elliptical galaxies have a similar spectral shape above and below 8.4 GHz. Most of the nonelliptical galaxies have a spectrum

---

**Fig. 1.** (a) Spectral index and (b) change in the spectral index, between 5 and 15 GHz, as a function of black hole mass. Nuclei with positive y-axis values in (b) have spectra that fall off more steeply above 8.4 GHz than below. Filled circles are used for reliable black hole estimates, and open circles and open diamonds are used for black hole masses inferred from the relationships of Gebhardt et al. (2000) and Richstone et al. (1998), respectively (see text). The 2σ error bars in y are shown.

---

6 In VLA Observational Status Summary, available on-line at http://www.nrao.edu.
that falls more rapidly at frequencies above 8.4 GHz than below (Fig. 1b), with NGC 3718 and NGC 4258 being the exceptions. When high- ($\leq 2^\circ$) resolution 2–10 keV X-ray luminosities are available (e.g., Ho et al. 2001), the ratio of $L_x$ between X-ray and radio is $\sim 10^{-3} - 10^{-4}$, suggestive of strong outflows in an ADAF scenario (Di Matteo, Carilli, & Fabian 2001). Interestingly, this ratio is $\geq 100$ for the Seyfert 1 galaxies and $\leq 100$ for the other nuclei.

5. DISCUSSION

Very low accretion rates (perhaps due to convection or strong outflows) may cause $p_\nu$ to fall close to 5–15 GHz for the objects in the sample. Such a scenario is supported by the evidence for turnover frequencies in the 10–30 GHz range for a few elliptical galaxies (Di Matteo et al. 2001). If this is the case, then equation (1) implies lower values of $p_\nu$ for more massive black holes. That is, within our sample we would expect nuclei with less massive black holes to have more inverted spectra than nuclei with more massive black holes. However, even though we sample more than 2 orders of magnitude in $m$, Figure 1 does not support such a trend. Therefore, unless non-elliptical galaxies have different microphysical parameters, or higher accretion rates, or a different accretion mechanism, as compared to elliptical galaxies, it is unlikely that a turnover frequency in the 5–15 GHz range is the cause of the observed flat radio spectrum in most of the sample. If $p_\nu > 15$ GHz for most nuclei in the sample, then any inverted spectrum radio component must be dominated by other sources at 5 and 8.4 GHz (and perhaps even at 15 GHz). One potential source is nonthermal electrons within the ADAF (Özel, Psaltis, & Narayan 2000). Significant emission from star formation–related processes can be ruled out as the radio core has a high brightness temperature at 5 GHz, and at this wavelength most of the flux within the central 0.5 is also detected on milliarcsecond scales (Table 1). On the other hand, the observed distribution of spectral indices is consistent with the 5–15 GHz radio emission originating in synchrotron-emitting jets.

Whether or not an accretion flow contributes to the nuclear radio emission, the detections of what appear to be collimated parsec-scale jets in the five LLAGNs of Table 1 with the highest core flux—NGC 3031 (M81; Bietenholz et al. 2000), NGC 4278 (Jones, Wrobel, & Shaffer 1984; Falcke et al. 2000), NGC 4486 (M87; Junor & Biretta 1995), NGC 4374 (M84; Wrobel, Walker, & Bridle 1996; N. M. Nagar et al. 2001, in preparation), and NGC 4552 (M89; N. M. Nagar et al. 2001, in preparation)—do indicate that synchrotron emission from jets is a significant contributor to the subarcsecond radio emission. In fact, in all three sample nuclei that have been comprehensively studied at high resolution in the radio, the radio flux from the jet dominates that from the unresolved core. In NGC 4486, the jet component within 30 mas (2.5 pc) of the nucleus contributes 3 times the radio flux of the unresolved (1 x 0.2 mas) core (Junor & Biretta 1995). Given that this core continues to be further resolved at higher resolutions (Junor, Biretta, & Livio 1999), and that the jet is a strong radio emitter on scales from 30 mas to 1", the jet is certainly the dominant subarcsecond radio emitter. In NGC 3031, which has a spectral shape consistent with an ADAF model, submilliarcsecond multiepoch observations reveal that the subparsec jet contributes at least 3 times the radio flux of the unresolved core (Bietenholz et al. 2000). Deep radio observations of NGC 4258 not only reveal a subparsec jet but also indicate an absence of continuum emission from the putative location (as traced by the water vapor maser disk) of the nucleus (Herrnstein et al. 1997).

In the context of any low-luminosity spherical accretion model, the presence of outflows and the smaller radio luminosities attributable to the inflow both point to accretion rates at least an order of magnitude lower than earlier predicted using ADAF models (e.g., $10^{-2} L_{Edd}$ to $10^{-4} L_{Edd}$; Chang, Choi, & Yi 2000; Yi & Boughn 1999). A jet can also cause considerable disruption of the high-frequency radio-emitting region ($\sim 1 r_{\text{g}} - 100 r_{\text{g}}$). Junor et al. (1999) find a wide ($\sim 60^\circ$) initial opening angle for the (potentially relativistic) radio jet in NGC 4486, with collimation only occurring at $\sim 100 r_{\text{g}}$. For a moderately strong outflow (e.g., $p = 0.6$), about 25% of the material accreted at 100 $r_{\text{g}}$ is lost to the outflow by 2$r_{\text{g}}$. Thus, it may not be accurate to model the radio-emitting region as a spherical self-similar flow in which the only effect of the outflow is a modification of the accretion rate and central density.

REFERENCES

Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2000, ApJ, 532, 895
Blandford, R. D., & Begelman, M. C. 1999, MNRAS, 303, L1
Blandford, R. D., & Königl, A. 1979, ApJ, 232, 34
Chang, H., Choi, C., & Yi, I. 2001, ApJ, submitted (astro/0009267)
Di Matteo, T., Carilli, C. L., & Fabian, A. C. 2001, ApJ, 547, 731
Ekers, R. D., & Kotanyi, C. G. 1978, A&A, 67, 47
Falcke, H. 1996, ApJ, 464, L67
Falcke, H., & Biermann, P. L. 1999, A&A, 342, 49
Falcke, H., Nagar, N. M., Wilson, A. S., & Ulvestad, J. S. 2000, ApJ, 542, 197
Frank, J., King, A., & Raine, D. 1995, Accretion Power in Astrophysics (2d ed.; Cambridge: Cambridge Univ. Press), chap. 7.8
Gebhardt, K., et al. 2000, ApJ, 539, L13
Herrnstein, J. R., Moran, J. M., Greenhill, L. J., Diamond, P. J., Miyoshi, M., Nakai, N., & Inoue, M. 1997, ApJ, 475, L17
Ho, L. C., et al. 2001, ApJ, 549, L51
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997a, ApJS, 112, 315
Ho, L. C., Filippenko, A. V., Sargent, W. L. W., & Peng, C. Y. 1997b, ApJS, 112, 391
Ho, L. C., van Dyk, S. D., Pooley, G. G., Sramek, R. A., & Weiler, K. W. 1999, AJ, 118, 843
Jones, D. L., Wrobel, J. M., & Shaffer, D. B. 1984, ApJ, 276, 480
Junor, W., & Biretta, J. A. 1995, AJ, 109, 500
Junor, W., Biretta, J. A., & Livio, M. 1999, Nature, 401, 891
Mahadevan, R. 1997, ApJ, 477, 585 (M97)
Marscher, A. P. 1988, ApJ, 334, 552
Narayan, R., Igmenshtein, I. V., & Abramowicz, M. A. 2000, ApJ, 539, 798
Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R. G., & Gammie, C. 1998a, ApJ, 492, 554
Narayan, R., Mahadevan, R., & Quataert, E. 1998b, in The Theory of Black Hole Accretion Disks, ed. M. A. Abramowicz, G. Björnsson, & J. E. Pringle (Cambridge: Cambridge Univ. Press), 148
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Özel, F., Psaltis, D., & Narayan, R. 2000, ApJ, 541, 234
Quataert, E., & Gruzinov, A. 2000, ApJ, 539, 509
Quataert, E., & Narayan, R. 1999, ApJ, 520, 298
Richstone, D., et al. 1998, Nature, 395A, 14
Stone, J. M., Pringle, J. E., & Begelman, M. C. 1999, MNRAS, 310, 1002
Thompson, A. R., Clark, B. G., Wade, C. M., & Napier, P. J. 1980, ApJS, 44, 151
Wilkinson, P. N., Browne, I. W. A., Patnaik, A. R., Wrobel, J. M., & Sorathia, B. 1998, MNRAS, 300, 790
Wrobel, J. M., Walker, R. C., & Bridle, A. H. 1996, in IAU Symp. 175, Extragalactic Radio Sources, ed. R. D. Ekers, C. Fanti, & L. Padrielli (Dordrecht: Kluwer), 131
Yi, I., & Boughn, S. P. 1999, ApJ, 515, 576