THE ASTROPHYSICAL JOURNAL, 604:L33–L36, 2004 March 20

OBSCURED BINARY QUASAR CORES IN SDSS J104807.74+005543.5?

HONGYAN ZHOU, TINGGUI WANG, XUEGUANG ZHANG, XIAOBO DONG, AND CHENG LI
Center for Astrophysics, University of Science and Technology of China, Hefei, Anhui 230026, China; mtzhou@ustc.edu.cn
Received 2003 November 29; accepted 2004 February 4; published 2004 February 26

ABSTRACT

We report the discovery of a possible close binary system of quasars in SDSS J1048+0055. The [O III] λλ4959, 5007 emission lines are clearly double-peaked, and two discrete radio sources with a projected physical separation of ∼20 pc are found in the Very Long Baseline Array milliarcsecond resolution image at 8.4 GHz. Each of the [O III] λλ4959, 5007 doublets and Hβ can be well modeled by two Gaussians, and the line ratio [O III] λ5007/H$\beta \sim 7$ is typical of Seyfert 2 galaxies. No broad component of Hβ was detected, and its [O III] λ5007 luminosity, $L_{[\mathrm{O\,III}]} \approx 9.2 \times 10^{42}$ ergs s^{-1}, is comparable to luminous quasars and is a few $\times 10$ more luminous than typical Seyfert galaxies. One natural interpretation is that SDSS J1048+0055 contains two close quasar-like nuclei, and the broad-line region around them is obscured. Other possible models are also discussed. We suggest that a double-peaked narrow emission line profile may be an effective way of selecting candidates of binary black holes with intermediate separation.

Subject headings: black hole physics — galaxies: active — galaxies: individual (SDSS J1048+0055) — quasars: emission lines — radio continuum: galaxies

1. INTRODUCTION

Black holes (BHs) are the simplest objects in the universe, and the merging of binary black holes (BBHs) can produce strong gravitational radiation. Hence, BBH systems are ideal laboratories for exploring and testing strong-field relativistic physics. There is a growing body of evidence that BHs exist on many mass scales, from stellar mass, up to ∼a few $\times 10^9 M_\odot$. Numerous clues, especially those provided by the *Hubble Space Telescope* (*HST*), suggest that almost every galaxy harbors a supermassive black hole (SMBH) in its center (e.g., Sarzi et al. 2001; Pinkney et al. 2003). According to the hierarchical merger scenario of galaxy evolution, coalescence is one of the most important processes in galaxy evolution and a typical galaxy may experience between one and several such episodes during its lifetime (Struck 1999). Merging of galaxies can bring two SMBHs together eventually to form a BBH, which can survive for about one Hubble time in spherical galaxies, axisymmetric galaxies, or certain triaxial galaxies (Yu 2002). Therefore, the presence of two SMBHs in one galaxy-forming supermassive BBH should not be a rare phenomenon.

Enormous efforts have been made in recent years to find observational evidence for the existence of supermassive BBHs. Evidence is sought in two directions: spatially resolved systems in which the BBH can be identified morphologically and unresolved systems in which the existence of the BBH can be inferred in various ways (see Komossa 2003 for an extensive review). Examples of the latter are as follows. Winged or X-shaped radio sources were suggested to be BBH merger remnants (e.g., Merritt & Ekers 2002; Wang, Zhou, & Dong 2003; Liu, Wu, & Cao 2003). Helically distorted radio jets observed in some objects were interpreted as sometimes due to the orbital motion or precession of the BH producing the jets (e.g., Sudou et al. 2003). Some BBH models predict the surface brightness of the host galaxies would decrease toward the galactic center, and such an effect has indeed been observed in a few early-type galaxies (e.g., Lauer et al. 2002). Rather, more direct evidence comes from resolved systems: several pairs of quasars with almost the same redshift and angular separations between ∼3″ and 10″ have been observed and were taken to be real binary quasars. The projected physical distance between these potential binary quasars is usually a few $\times$ 10 kpc (Mortlock, Webster, & Francis 1999). NGC 6240 is perhaps the only case in which binary active nuclei are separately identified; the high-resolution observation of *Chandra* revealed two hard X-ray nuclei in this interesting object and the projected physical separation of about 1.4 kpc (Komossa et al. 2003), which is the smallest among known binary active galactic nuclei (AGNs). As far as we know, no quasar pair with physical separation ≲1 kpc has been yet found.

Of the preceding lines of evidence for the existence of supermassive BBHs, a binary AGN is of particular interest. It must, however, be admitted that apart from NGC 6240, the evidence so far cannot be considered as conclusive, and efforts must be continued to seek out supermassive BBHs. In this Letter, we report the discovery of a new binary quasar candidate, SDSS J104807.74+005543.5 (hereafter SDSS J1048+0055). It is identified from the Sloan Digital Sky Survey[1] Data Release 1 (SDSS DR1; Abazajian et al. 2003) among ∼100 low-redshift galaxies that show double-peaked narrow emission lines, most of which are active. Apart from the presence of such lines, the other piece of evidence that sustains the BBH interpretation is that its high angular resolution Very Long Baseline Array (VLBA) image reveals two discrete radio sources, possibly corresponding to two different active nuclei. The [O III] luminosity of the two nuclei are in the range for quasars. The discovery of SDSS J1048+0055 and more than 100 double-peaked narrow-line objects in the spectral data set of the SDSS DR1 might suggest that this be an effective way of selecting candidates of BBHs with intermediate, subkiloparsec separations. We postpone detailed analysis of the whole sample of double-peaked narrow emission lines to a forthcoming paper. Throughout this Letter, an $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ cosmology is assumed.

2. DATA ANALYSIS

2.1. *Optical Spectrum*

SDSS J1048+0055 is observed by the SDSS only because it is the counterpart of a FIRST (Faint Images of the Radio Sky at Twenty cm) survey radio source and classified as "QSO"

[1] The SDSS Web site is http://www.sdss.org.

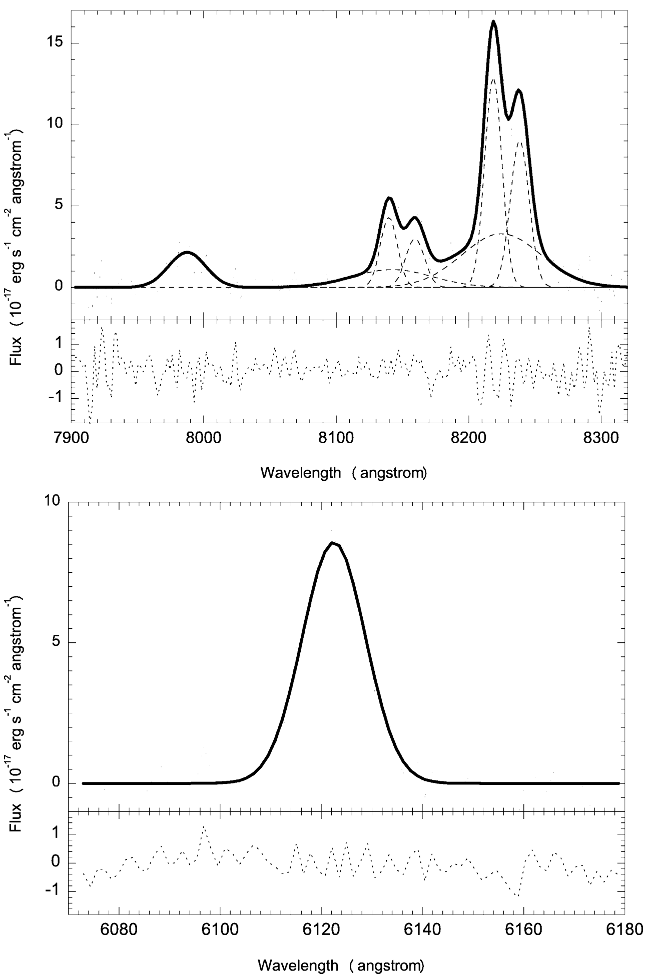

FIG. 1.—Gaussian fitting of Hβ+ [O III] regime (*upper panel*) and [O II] (*lower panel*) after continuum substraction. Dotted lines denote the fit residuals.

by the spectroscopic pipeline of the SDSS (Stoughton et al. 2002). It falls in the DR1 quasar catalog (Schneider et al. 2003) because of its high luminosity ($M_i = -22.^m63$) and seemingly broad line width.

The optical continuum of SDSS J1048+0055, which is rather noisy, is fitted with a power law. The fitted continuum is subtracted before measurement of the emission lines. Because the [O III] $\lambda\lambda$4959, 5007 doublets clearly show a double-peaked profile and a rather broad wing, the continuum-subtracted spectrum in the Hβ + [O III] $\lambda\lambda$4959, 5007 regime is fitted with $2 \times 3 + 1$ Gaussian components, i.e., two sets of three Gaussians for the two peaks and the broad wing of the [O III] $\lambda\lambda$4959, 5007 doublets and one Gaussian for Hβ. Within each set of the components for [O III], the centroids of the three Gaussians are forced to correspond to a same redshift and their widths to the same Doppler broadening; also the intensity ratio of [O III] λ5007 to [O III] λ4959 is fixed at its theoretical value. The final fit is done through minimization of χ^2 and the result is shown in the upper panel of Figure 1. The lower panel displays the [O II] λ3727 line, which is the second strongest after [O III] λ5007. However, the [O II] line is single-peaked and can be satisfactorily modeled by a single Gaussian.

We would like to point out that Hβ might also be double-peaked. When fitted with a single Gaussian, its line width FWHM(Hβ) $\approx$ 1200 km s^{-1} is much broader than [O II] and each of the [O III] peaks. The line can be comparably fitted with the template of the [O III] line profile. Other high-ionization narrow lines, such as [Ne III] λ3869 and [Ne III] λ3967, also seem to show a double-peaked profile, but higher quality spectral observation is needed to confirm this feature. We did not analyze other emission lines because the signal-to-noise ratio (S/N) is not high enough for us to draw any significant conclusion. The measured line parameters are assembled in Table 1.

2.2. *Radio Properties*

SDSS J1048+0055 was observed many times in several radio band passes, from 0.365 to 8.4 GHz. It was observed at 1.4 GHz during the NRAO VLA Sky Survey (NVSS) in 1995 February (Condon et al. 1998) and during the FIRST survey in 1998 August (White et al. 1997). There is no significant difference in the flux observed on these two occasions ($S_{\nu,\,\rm NVSS}$ = 270.9 $\pm$ 8.1 mJy and $S_{\nu,\,\rm FIRST}$ = 270.7 mJy). This flux is also marginally consistent with an early measurement in the Green Bank 1.4 GHz Northern Sky Survey, which is $S_{\nu,1.4\,\rm GHz} \approx 299$ with uncertainty of ~25–30 mJy (White & Becker 1992).

However, the 4.85 GHz flux of 340 $\pm$ 21 mJy given in the MIT–Green Bank 5 GHz Survey Catalog (MGBS; Bennett et al. 1986) is different (at ~2 σ level) from that presented by Gregory & Condon (1991) (266 $\pm$ 37 mJy), Becker, White, & Edwards (1991) (262 $\pm$ 39 mJy), and Griffith et al. (1995) (262 $\pm$ 39 mJy). The flux difference between the MGBS and the later surveys cannot be explained by the larger beam size of MGBS (FWHP = $2'.8$) because (1) the source is compact and (2) within 5′ of the source NVSS detected no other sources,

TABLE 1
LINE PARAMETERS OF SDSS J1048+0055

Line [a]	Center Wavelength[b] (Å)	Redshift	Flux (10^{-17} ergs s^{-1} cm^{-2})	FWHM (km s^{-1})
[O III] $\lambda5007_r$	8238.5 $\pm$ 0.3	0.6450	161 $\pm$ 11	553 $\pm$ 25
[O III] $\lambda5007_b$	8218.5 $\pm$ 0.5	0.6410	209 $\pm$ 13	610 $\pm$ 24
[O III] $\lambda5007_{\rm br}$	8224.7 $\pm$ 0.9	0.6423	151 $\pm$ 11	2573 $\pm$ 198
[O III] $\lambda4959_r$	8159.5	0.6450	52	553
[O III] $\lambda4959_b$	8139.7	0.6410	67	610
[O III] $\lambda4959_{\rm br}$	8142.5	0.6423	49	2573
Hβ	7987.5 $\pm$ 1.0	0.6422	76 $\pm$ 6	1238 $\pm$ 102
[O II] λ3727	6122.5 $\pm$ 0.2	0.6422	135 $\pm$ 9	721 $\pm$ 36
Mg II λ2800	4600.1 $\pm$ 1.0	0.6430	98 $\pm$ 10	1806 $\pm$ 141

[a] Subscripts "*r*," "*b*," and "br" denote the red, blue, and broad components of the [O III] $\lambda\lambda$4959, 5007 emission lines, respectively.
[b] The central wavelengths are in the observer's frame.

while FIRST only detected two with insignificant fluxes around 1 mJy. It seems likely that this variation with an amplitude of ∼39% is real. Moreover, this interpretation is consistent with its compact morphology and its flat spectrum.

The overall radio spectrum is moderately flat with a spectral slope of $\alpha_{\nu,\,0.365\text{–}8.4\,\mathrm{GHz}} = 0.13 \pm 0.03$ ($S_\nu \propto \nu^{-\alpha}$). The radio luminosity between 0.365 and 8.4 GHz, $L_{0.365\text{–}8.4\,\mathrm{GHz}} \approx 4.2 \times 10^{43}$ ergs s^{-1}, is quite high even for a radio-loud quasar. The flatness of the spectrum is consistent with the compact radio morphology. It is unresolved by FIRST at angular resolution ∼5″.4. This object is also observed by the VLBA Calibrator Survey (VCS1; Beasley et al. 2002) and remains unresolved at 2.3 GHz with resolution ellipse of ∼5 × 10 mas. However, the higher resolution 8.4 GHz radio image (∼1.5 × 3 mas) clearly shows two compact sources with the western source ∼30 times stronger than the eastern one (Fig. 2). The angular offset between the two sources is about 2.5 mas, corresponding to a projected physical distance of ∼20 pc at a redshift of 0.6422 derived from the [O II] and Hβ emission line. The large difference in the radio flux, the small angular separation, and flat spectrum conspire to indicate that we are dealing with possible two separate radio sources, rather than with two lobes of a single source. Further measurement of the radio spectrum of the weak component would be necessary to confirm this.

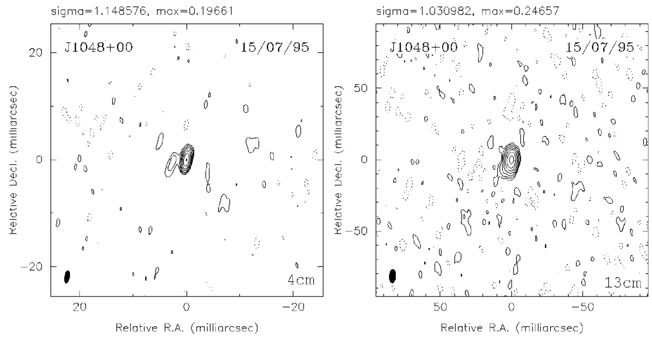

FIG. 2.—The 8.4 GHz (*left panel*) and 2.3 GHz (*right panel*) radio morphology of SDSS J1048+0055 from the VCS1. Contour levels are −1, 1, 2, 4, 8, etc., times the lowest contour level. SDSS J1048+0055 is only marginally resolved at 2.3 GHz, but higher resolution 8.4 GHz image clearly reveals two discrete radio sources.

3. DISCUSSION AND FUTURE PROSPECT

3.1. *SDSS J1048+0055 as Obscured Binary Quasars*

A straightforward interpretation of the double-peaked profile of [O III] λλ4959, 5007 is that they come from two distinct narrow-line regions (NLRs) around two active nuclei. The [O III] λ5007 luminosity of the red and blue peaks, $L_{\mathrm{[O\,III],\,red}} \approx 2.8 \times 10^{42}$ ergs s^{-1} and $L_{\mathrm{[O\,III],\,blue}} \approx 3.6 \times 10^{42}$ ergs s^{-1}, is comparable to that of luminous quasars in the BQ sample and at least 10 times more luminous than Seyfert galaxies. SDSS J1048+0055 is rather faint in the optical in comparison with the radio. The flux ratio of radio to optical or the radio loudness, $\mathrm{RL} \equiv f_r/f_o \sim (1.5\text{–}2.1) \times 10^4$, is extraordinarily large. Such a large RL implies that the nuclear emission in the optical is heavily obscured. The radio morphology also suggests that two active nuclei may be present in the center of SDSS J1048+0055, as was pointed out in the last section. If the two discrete radio sources revealed by VLBA proved to be stationary and if the weak component also shows flat spectrum by further VLBI observations, thereby thus confirming their BBH status, then we can say that the separation between the BBH should not be much larger than tens of parsecs. Then SDSS J1048+0055 would be the only galaxy harboring BBH with such a small separation, and the system may be at the last stage before the two nuclei (BHs) become a bound system (Yu 2002). The fact that [O III] λλ4959, 5007 show a double-peaked profile while [O II] λ3727 does not is understandable, because high-ionization emission line regions are often more compact than low-ionization ones. It is likely that a double-peaked [O III] emission line is mainly concentrated in the two cores of NLRs whose centers coincide with the two radio peaks, while the narrower and single-peak [O II] may be emitted by the whole NLR. Therefore, SDSS J1048+0055 would most likely be a galaxy merger with two quasar cores in its central region.[2]

[2] Readers may find other lines of evidence that support the BBH interpretation in the detailed discussion of the whole sample of double-peaked narrow emission line from SDSS DR1 (T. Wang et al. 2004, in preparation).

3.2. *The Efficiency of Finding BBH Using Double-peaked Narrow Emission Lines*

Now that most galaxies harbor an SMBH and the frequency of galaxy collisions is relatively high, closely bound BBHs in a single galaxy should not be a rare occurrence. Theoretical calculations show that the coalescence of two BHs goes through several stages. Dynamic friction causes the BHs along with their surrounding stellar cluster to approach each other. As the stars in the cluster being stripped off, the two BHs form a BBH. Some BBHs will further lose angular momentum through the scattering of passing stars, but analysis shows that some BBHs can survive for about 1 Hubble time in large, spherical galaxies, and the orbital velocities of the surviving BBHs are generally believed to be $\sim 10^2\text{–}10^4$ km s^{-1} (Yu 2002; cf. Milosavljević & Merritt 2003).

Detection of supermassive BBHs and the estimation of the frequency of such events can provide important constraints on models of galaxy formation and evolution. Now the evolution timescale of a BBH is extremely uneven. A sharp rise occurs at ∼10 pc, and the timescales for a separation of approximately less than a few parsecs are several orders of magnitude greater than for $\sim 10^1\text{–}10^4$ pc (Yu 2002). The time it takes a BBH of similar mass to evolve from a few kiloparsecs to ∼10 pc is $\sim 10^8$ yr, and this time increases with the increasing mass ratio of the BBH. Therefore, even though every galaxy experiences a major merger during its lifetime and most BBHs survive, the absolute majority would have separation approximately less than a few parsecs, which is beyond the resolution limit of most present instruments. Thus, while double nuclei with separation of several kiloparsecs or larger have been identified in some galaxies, BBH with separation $\sim 10^1\text{–}10^3$ pc have not yet been found.

It is likely that merging will trigger the activity of both BHs at intermediate separations. Gas concentration and starburst activity in the nuclei were observed in interacting galaxies at even large separation (e.g., Gao & Solomon 2004), and a pair of binary AGNs were detected in NGC 6240. The associated star cluster or bulge around each BH may survive in a fraction of such systems at this distance. Thus, each nucleus may well possess its own NLR. In this case, our calculations show that about 5%–10% of such systems will be found to be double-peaked sources under the generic assumption of virialization of the NLR. If a significant fraction of AGNs are indeed in such merging systems, a few percent of AGNs should show a double-peaked line profile. We found ∼100 objects that show this feature in at least one narrow line from the subsample of $\sim 10^4$ SDSS galaxies and quasars that either [O III] or Hα have S/N $\gtrsim 30\ \sigma$. The fraction of such objects is about 1% and increases with the level of nuclear activity. Hence, the simple model estimation is quite consistent with the results of observation. The model and the sample will be described in detail elsewhere.

3.3. *Other Possible Explanations and Future Prospect*

We would like to point out that the BBH interpretation for SDSS J1048+0055, as well as for the other objects in our double-peaked narrow-line sample, is certainly not the only one. Two other possible interpretations are bipolar outflow and a disklike emission line region. The latter seems unlikely because the compact structure and flat spectrum of SDSS J1048+0055 suggest that the system is observed face-on, while an inclined disk is required to explain the double-peaked profile in SDSS J1048+0055. On the other hand, if the bipolar outflow interpretation is correct, then we can only explain the weaker radio source as a one-sided jet like that of 2255-282, which is an optical variable radio source. For the latter, a jet is revealed by the VLBA in the 5 GHz image, and its 15 GHz images show radio structure similar to that of the former (Zensus et al. 2002 and references therein). The VLBA radio image of SDSS J1048+0055 was taken some 8 years ago; hence, another high angular resolution radio image can tell whether this is indeed the case.

About 25% of the objects in our double-peaked narrow-line sample are detected in the radio by FIRST, and $\sim$10 objects, including SDSS J1048+0055 and SDSS J094144.82+575123.7, have radio flux $\gtrsim$10 mJy. According to the estimates made in § 3.3, some of these objects should be resolved into two discrete radio sources at approximately a milliarcsecond resolution if the BBH interpretation is indeed correct. A sizable fraction of the objects in our sample may also be resolved in the optical by *HST*.

We thank T. Kiang for help with English. We are grateful to Youjun Lu & Qingjuan Yu for enlightening discussion. This work is supported by the Chinese National Science foundation (NSF 19925313 and 10233030) and the key program of Chinese ministry of science and technology. This paper has made use of data from NED, NRAO, and SDSS. Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Princeton University, the United States Naval Observatory, and the University of Washington.

REFERENCES

Abazajian, K., et al. 2003, AJ, 126, 2081
Beasley, A. J., Gordon, D., Peck, A. B., Petrov, L., MacMillan, D. S., Fomalont, E. B., & Ma, C. 2002, ApJS, 141, 13
Becker, R. H., White, R. L., & Edwards, A. L. 1991, ApJS, 75, 1
Bennett, C. L., Lawrence, C. R., Burke, B. F., Hewitt, J. N., & Mahoney, J. 1986, ApJS, 61, 1
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Gao, Y., & Solomon, P. M. 2004, ApJ, in press (astro-ph/0310339)
Gregory, P. C., & Condon, J. J. 1991, ApJS, 75, 1011
Griffith, M. R., Wright, A. E., Burke, B. F., & Ekers, R. D. 1995, ApJS, 97, 347
Komossa, S. 2003, in AIP Conf. Proc. 686, The Astrophysics of Gravitational Wave Sources, ed. J. Centrella (Melville: AIP), 161
Komossa, S., Burwitz, V., Hasinger, G., Predehl, P., Kaastra, J. S., & Ikebe, Y. 2003, ApJ, 582, L15
Lauer, T. R., et al. 2002, AJ, 124, 1975
Liu, F. K., Wu, X., & Cao, S. L. 2003, MNRAS, 340, 411
Merritt, D., & Ekers, R. D. 2002, Science, 297, 1310
Milosavljević, M., & Merritt, D. 2003, ApJ, 596, 860
Mortlock, D. J., Webster, R. L., & Francis, P. J. 1999, MNRAS, 309, 836
Pinkney, J., et al. 2003, ApJ, 596, 903
Sarzi, M., Rix, H.-W., Shields, J. C., Rudnick, G., Ho, L. C., McIntosh, D. H., Filippenko, A. V., & Sargent, W. L. W. 2001, ApJ, 550, 65
Schneider, D. P., et al. 2003, AJ, 126, 2579
Stoughton, C., et al. 2002, AJ, 123, 485
Struck, C. 1999, Phys. Rep., 321, 1
Sudou, H., Iguchi, S., Murata, Y., & Taniguchi, Y. 2003, Science, 300, 1263
Wang, T., Zhou, H., & Dong, X. 2003, AJ, 126, 113
White, R. L., & Becker, R. H. 1992, ApJS, 79, 331
White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479
Yu, Q. 2002, MNRAS, 331, 935
Zensus, J. A., Ros, E., Kellermann, K. I., Cohen, M. H., Vermeulen, R. C., & Kadler, M. 2002, AJ, 124, 662