PART 13.

Large And Small Scale Disks In AGN

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Parameters of Disks from VLBI Observations

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Abstract. VLBI provides the only direct imaging technique currently available that is able to resolve even the outer parts of accretion disks. Recent observations of water masers in NGC 4258 and of free-free absorption of counterjet radiation in NGC 1275 are the best examples of where VLBI has provided important data on the parameters of disks. Other observations are now being made of similar sources. In addition, recent VLBI observations of HI absorption promise to add yet more constraints on the outer disk regions.

1. Introduction

Very Long Baseline Interferometry (VLBI) provides resolutions of a milliarcsecond (mas) or better at radio wavelengths. One mas corresponds to a scale of one au at a distance of 1 kpc or one parsec at a distance of 200 Mpc. This would be adequate resolution to study spatial structure in at least the outer parts of the accretion disks in many objects. However such small regions must have very high brightness temperatures in order provide enough flux density to be detected with available VLBI instrumentation. Ordinarily the outer regions of disks do not have such high brightness temperatures so no direct images of disks have yet been made. However, high brightness temperatures are available from maser emission by water molecules in some disks. High brightness temperatures are also common in jets and other compact continuum structures. A few cases have now been found in which a counterjet or lobe is observed with VLBI and shows either free-free or HI absorption by material presumably associated with a disk. All of these types of observations provide significant constraints on the spatial structure and physical conditions of accretion regions on parsec scales in AGN.

2. The H_2O Maser Observations.

A number of galaxies show H_2O maser emission from their nuclear regions. It has proven possible to image this emission on sub-parsec scales with VLBI. As is typical with any maser observations, the results are characterized by emission concentrated in a number of spots, each with a well defined angular position

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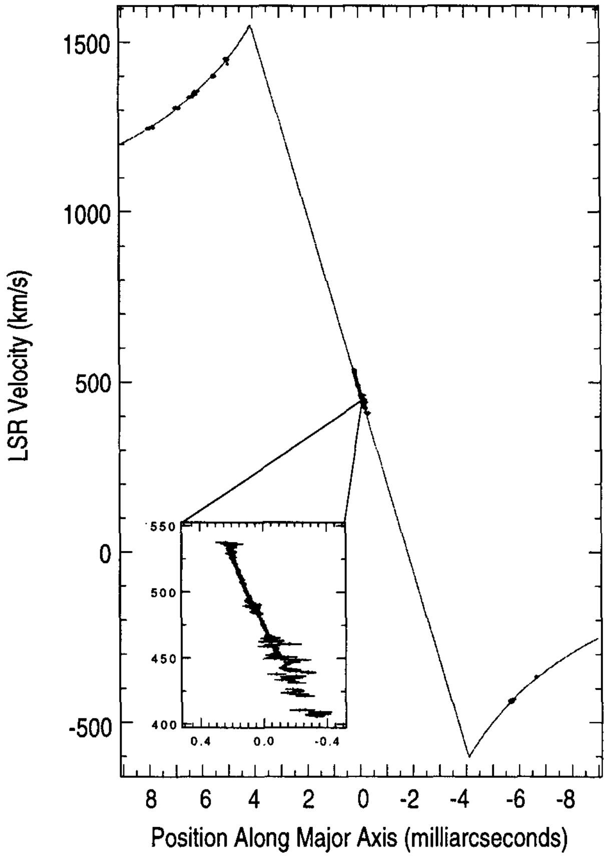

Figure 1. This figure, similar to one in Miyoshi et al. (1995), shows the line-of-sight velocities of the H_2O features in NGC 4258 plotted as a function of measured position along the major axis of the disk. The line is the prediction of the fitted Keplerian disk model. Note the remarkably good fit.

and radial velocity. These spots are locations where the density, pump conditions, and constant-velocity path lengths favor particularly strong emission in the direction toward the observer. Such spots can be monitored in time in order to determine their line-of-sight accelerations and, eventually, their transverse motions. The distribution of spots, along with their velocities and motions, can be used to constrain models of the masing region. In the best cases observed so far, this region is a disk with a scale size of less than a parsec. The observations can be used to constrain disk models, as evidenced by several contributions to this Colloquium (Maloney 1996; Begelman 1996; Maoz 1996; Kartje, Königl, and Elitzur 1996).

The H_2O maser observations are most spectacularly represented by the results on NGC 4258 by Miyoshi et al. (1995) and follow-up observations. In this source, masers are observed both radially through the disk toward the central object, and along the tangent points where the velocity along the line-of-sight is highest. The observations show a classic Keplerian disk with a $1/R$ dependence of velocity on distance from the center. The disk is thin and somewhat warped. Modeling of the disk provides good constraints on many parameters including the disk geometry, rotation velocity, orientation, central mass and mass density, and even the distance to the galaxy. Monitoring of the H_2O spectra has shown the expected accelerations (Greenhill et al. 1995) and efforts to measure their transverse motions with VLBI are continuing.

Figure 1 shows a velocity-position plot for NGC 4258 similar to that in Miyoshi et al. (1995). It shows the beautiful match to the velocities expected from a Keplerian disk that is seen in this system. On the sky, the high velocity masers don't actually lie on a straight line, indicating that the disk is warped. That warp has proven to be of significant theoretical interest. Other papers in these proceedings discuss the origin of the warp and the effects that it might have on maser pumping and maser visibility (Begelman 1996).

The masers can be used as a phase reference for VLBI, allowing the weak continuum emission from the nuclear region to be imaged. Herrnstein (1996) has done this in NGC 4258 and sees structure indicative of a radio jet beginning near, but a bit north of the dynamical center of the disk as determined by the maser model. Assuming that the jet actually starts at the dynamical center, this indicates that the radio emission is greatest some distance from the jet base or that the base region is obscured. Besides saying something about this region, this result serves as a reminder that the "core" observed in many VLBI sources may not be exactly coincident with central massive object and hence may not be as stationary as is sometimes assumed.

Other galaxies besides NGC 4258 show masers from the central regions and studies are in progress to determine their disk parameters. One good example is NGC 1068 (Greenhill et al. 1996) which has stronger emission in the high velocity lines than at the systemic velocity. Modeling of the initial VLBI observations in this source suggest a rather different geometry from that seen in NGC 4258. The masers may lie on the inner surface of a torus.

3. The Free-free Absorption Observations.

Most continuum observations done with VLBI are of core/jet systems, usually in the nuclei of AGNs. Such systems show very high brightness temperatures from regions on parsec scales. Typically such systems are one sided and, by standard models, especially of the superluminal sources, are oriented with the jet pointed more-or-less toward the observer. It is extremely rare to see the counterjet — the jet pointed away from the observer. Since the core and main jet emission are on the side of any accretion disk toward the observer, they cannot be used to probe conditions in the disk. It was only very recently, with the observation of counterjets or other symmetric structures in a few sources, that it has become possible to use absorption of counterjet radiation to study disks. Two types of absorption have been seen so far; free-free absorption, which cuts off the continuum radiation at lower frequencies, and spectral line absorption by atomic hydrogen.

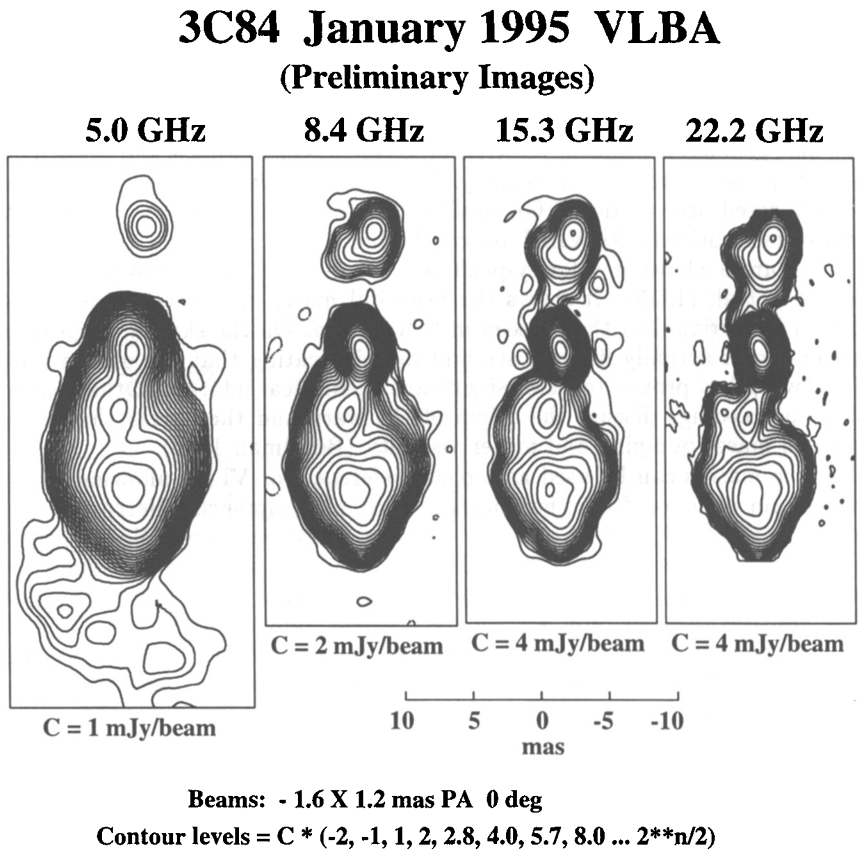

Figure 2. A montage of preliminary VLBA images of the radio source in NGC 1275 (3C 84). Note the feature to the north of the "core" (the central bright component) that is much stronger at high frequencies. This is the feature that appears to be free-free absorbed at low frequencies. It is not even visible in a 2.3 GHz high-dynamic-range image.

The free-free absorption observations are best represented by the results on NGC 1275 (3C 84, Persius A — Walker, Romney, and Benson 1994; Vermeulen, Readhead, and Backer 1994; Romney et al. 1995; Romney et al. 1996; Walker et al. 1996). A parsec scale counterjet is observed in this source at the higher radio frequencies. That counterjet is very weak or absent at lower frequencies, contrary to the situation in the main jet which is stronger at low frequencies. The lack of detectable emission at lower frequencies is ascribed to free-free absorption by material that is along the line of sight to the counterjet but not to the main jet. The natural geometry for such a situation is that the material is in, or associated with, a disk or torus. The free-free optical depth is proportional to the integral along the line-of-sight of $gN_e^2/T^{3/2}$ (where g, the Gaunt factor, is

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weakly temperature dependent). The observations constrain this combination of physical parameters in the disk region as a function of position over the the lines-of-sight to the observed counterjet.

Preliminary VLBI images of NGC 1275 at 5.0, 8.4, 15, and 22 GHz, based on observations made with the VLBA over a 2 week period in 1995 January, are shown in Figure 2. These images all show very similar structure to the south of the presumed core, with the emission getting brighter and a bit smoother with decreasing frequency. At the high frequencies, there is very similar emission, just reduced in scale and brightness, to the north of the presumed core. This emission is much weaker at the lower frequencies and, in a very-high-dynamic-range 13 cm image, that is not shown, is not seen at all. The low frequency cutoff is not likely to be due to synchrotron self-absorption because of the large size of the feature and because the spectrum is too steep. It is far more likely that the cutoff is the result of free-free absorption in an intervening medium. Since that absorption is only seen against the counterjet, it is natural to assume that the absorbing medium has a disk-like geometry.

The orientation of the system can be deduced from a simple relativistic beaming model using the jet-to-counterjet length and brightness ratios, and angular speeds measured in the southern jet with previous VLBI observations (Walker, Romney, and Benson 1995). True jet velocities of a third to half the speed-of-light and angles of 30° to 50° to the line-of-sight are obtained.

On the assumption that the counterjet is free-free absorbed, measurements can be made of the integral along the path of $gN_e^2/T^{3/2}$. These measurements can be made as a function of position over the counterjet. Profiles of the emission as a function of core distance, along a segmented slice that follows the ridge line of the jet and counterjet, are shown in Figure 3. Figure 4 shows the results of a fit to the profiles using an intrinsic spectral index ($S \propto \nu^{\alpha}$) and a free-free opacity (parameterized as $LN^2/T^{3/2}$ where L is the path length in pc). The error bars are formal errors and do not take into account calibration and imaging errors. Along the main jet, the fit gives a spectral index that gets flatter further from the core (an interesting result that will not be discussed here) and effectively no absorption. Along the counterjet, the fitted spectral index is flatter and there is strong absorption. This flatter spectral index should not be taken too seriously because, in the presence of strong absorption, it is rather sensitive to the 2 and 1 cm calibrations. The absorption results are not very sensitive to the fitted spectral index. Indeed, fits in which the spectral index is held fixed at about the average jet-side value give absorption values similar to those shown here.

The absorption measurements give strong constraints on the ionized material and its distribution at about a parsec from the nucleus. These constraints should help in the overall effort to model the nuclear regions of AGN, including accretion disks. The absorbing material must be in a geometry such that the counterjet is obscured but the jet, down to near the nucleus, is not. A disk or disk atmosphere would naturally do this. The amount of ionized material is dropping rapidly with distance from the nucleus as shown by the fitted opacity. That there is adequate ionized material at these distances at all takes some explaining. Normally, accretion disk material in this region would not be expected to be ionized. Levinson, Laor and Vermeulen (1995) discuss the implications of the observations for disk models, including suggesting possible ways to ionize

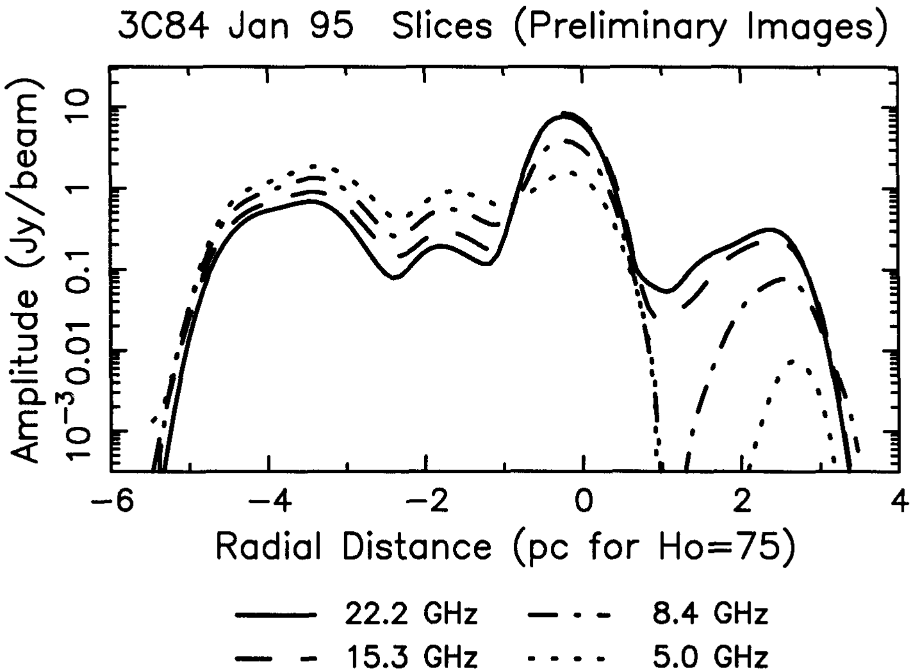

Figure 3. Profiles of the emission from 3C 84 along the ridge of the jet and counterjet as a function of projected distance from the "core". Note the logarithmic scale. This emphasizes the differences between the jet and counterjet side, especially the very steep spectral index on the counterjet side.

gas at these distances. Generally this involves exposing the gas to hard radiation from the central region through scattering or by direct illumination of a flared or warped disk.

How unique is NGC 1275? Despite decades of looking, observations of counterjets with VLBI are extremely rare. Even the counterjet in NGC 1275 remained unseen, despite many observations of the source, until the high dynamic ranges and short baselines provided by the VLBA became available. Most bright VLBI targets seem to have much higher jet speeds which will lead to much higher sidedness ratios, making counterjets close to impossible to see. Those sources with slower jets, and larger angles to the line-of-sight, are typically rather weak and have not been well observed so far. NGC 1275 is unique in being a very bright, sub-luminal source. That said, some other sources have been found recently which show the same free-free absorbed counterjet phenomenon. MRK 231 has structure that looks almost exactly like NGC 1275 (Ulvestad and Wrobel 1996). Even the position angle is the same! However the linear scale of the bright jet is about 5 times that in NGC 1275 and the absorption of the counterjet is seen mainly below about 2 GHz — indicating lesser amounts of material in the way as might be expected for the larger distances. Also, CEN A

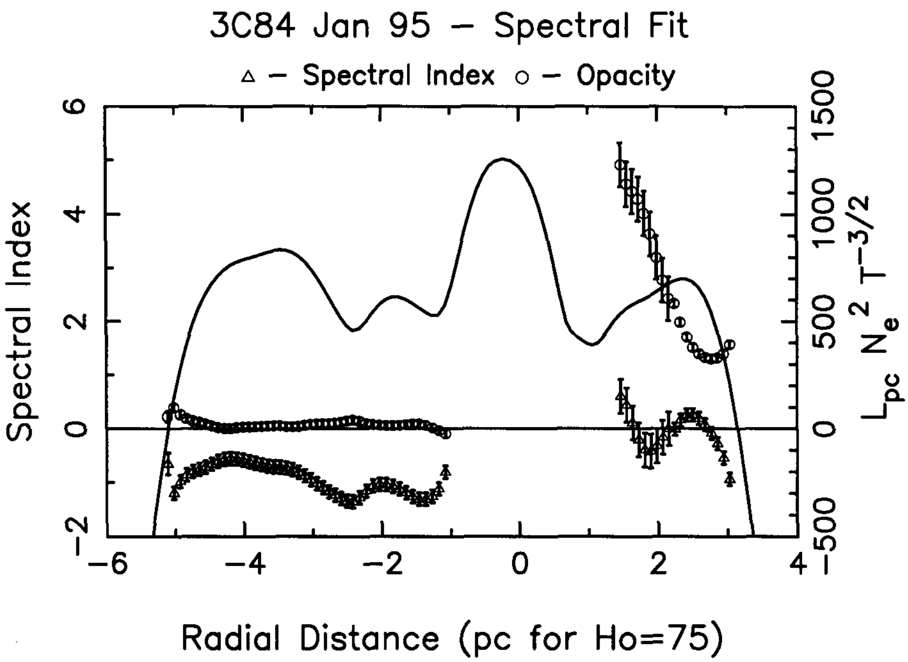

Figure 4. Results of a fit to the data shown in Figure 3 free-free opacity. Note that a similar fit, but holding the spectral index fixed at about $\alpha = -0.7$ gives rather similar results for the opacity.

shows a VLBI counterjet with evidence for absorption of the lower frequency emission, although the images are not as good as for the other sources (Jones et al. 1996).

4. The Hydrogen Absorption Observations.

Broad HI absorption lines are seen in a few radio-loud AGN. These offer the opportunity to study the absorbing gas on parsec scales with VLBI. The AGN in which such absorption has been seen are not those with typical core-dominated VLBI structures in which beaming is likely to play a major role. Rather they are in objects such as FRI radio galaxies, Compact Symmetric Objects (CSO), and Steep Spectrum Core (SSC) objects (Conway, 1996a) which are more likely to show symmetric, or at least two-sided, structure. This is understandable if the gas is in a disk-like geometry and is only seen in those sources from which some continuum emission can be seen from far side of the nucleus. Most such objects have rather weak cores and VLBI observations of them have only become possible recently.

One such object is the Seyfert galaxy NGC 4151. MERLIN observations by Mundell et al. (1995), show that the HI absorption is seen only in front of one of several compact components. VLBI observations of HI absorption in this system

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have been made but results are not yet available. However indications from the MERLIN observations are that the absorbed component is the beginning of the counterjet as might be expected with a disk geometry. The absorption provides information on the atomic hydrogen content of the disk region

Conway (1996b) has observed the HI absorption in the CSO 4C31.04 with the VLBA and finds structure indicative of a flattened geometry. One of the lobes is much more strongly absorbed than the other and the lobe with the lesser absorption shows a strong gradient with the strongest absorption closer to the nucleus. He also sees depressions in the continuum emission that might be evidence for free-free absorption by unresolved clouds. He suggests a thick disk geometry with the absorption on the near side being due to material well above the plain. He is investigating other sources including Cygnus A.

Both free-free absorption of the continuum and HI line absorption have been seen with VLBI in Hydra A (Taylor 1996). The HI absorption is stronger toward the core than the inner jets, suggesting a disk geometry. Both types of absorption suggest densities of the order of 300 cm^{-3} at projected distances of a few to a few tens of parsecs from the central object.

5. Summary

During the last few years, it has become apparent that VLBI observations can be used to investigate accretion disks and related regions in AGN on scales from tenths to tens of parsecs. This has occurred partly because of the arrival of the VLBA with its enhanced capabilities for spectral processing, multi-band observing, and high-dynamic-range imaging. Spectral line imaging of H_2O in AGN provides position and line-of-sight velocity information for spots in disks with conditions favorable for maser emission. This has provided a wealth of information on the dynamics, geometry, and physical conditions of a few disks and future work will presumably do the same for many more. Free-free and HI absorption observations are starting to provide constraints on the material in disk regions in sources that have observable continuum emission from beyond the central object. These observations are just beginning and the quality of the constraints should improve significantly as the quality of the observations and the number of sources increase.

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Discussion

K. Horne: Why do we see maser spots from the front side of the disk but not from the back side? Both places have no Doppler gradient along the line of sight, and so would seem suitable as sites for masing.

C. Walker: The back side the masing region is not back-lit by seed emission from the jet.

W. Jaffe: Why do we seldom see HI absorption in Radio galaxies with bright cores, but you show 2 cases where it is seen. What is special about these cases.

C. Walker: Parsec scale counterjets are rarely seen in VLBI images but are required to see the HI absorption. This may account for the small number of cases seen.