Disks, Tori, and Cocoons: Emission and Absorption Diagnostics of AGN Environments

R. Morganti [a], L. J. Greenhill* [b], A. B. Peck[c], D. L. Jones[d], C. Henkel[e]

[a]Netherlands Foundation for Research in Astronomy,
Postbus 2, NL-7990 AA, Dwingeloo, NL; morganti@astron.nl

[b]Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, MA 02138 USA; greenhill@cfa.harvard.edu

[c]Harvard-Smithsonian Center for Astrophysics, SMA Project, 645 N. A'ohoku Pl., Hilo, HI 96720, USA; apeck@cfa.harvard.edu

[d]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109 USA; dj@sgra.jpl.nasa.gov

[e]MPIfR, Auf dem Huegel 69, D-53121 Bonn, Germany; p220hen@mpifr-bonn.mpg.de

One of the most important problems in the study of active galaxies is understanding the detailed geometry, physics, and evolution of the central engines and their environments. The leading models involve an accretion disk and torus structure around a central dense object, thought to be a supermassive black hole. Gas found in the environment of AGN is associated with different structures: molecular accretion disks, larger scale atomic tori, ionized and neutral "cocoons" in which the nuclear regions can be embedded. All of them can be studied at radio wavelengths by various means. Here, we summarize the work that has been done to date in the radio band to characterize these structures. Much has been learned about the central few parsecs of AGN in the last few decades with contemporary instruments but the picture remains incomplete. In order to be able to define a more accurate model of this region, significant advances in sensitivity, spectral and angular resolution, and bandpass stability are required. The necessary advances will only be provided by the Square Kilometer Array and we discuss the possibilities that these dramatic improvements will open for the study of the gas in the central region of AGN.

1. Introduction

The physical conditions in active galactic nuclei (AGN) are unique in the cosmos. Stellar and gas densities are very large, and enormous amounts of angular momentum and energy are released as material accretes onto massive black holes. Stellar and interstellar gas constitute reservoirs of accreting material. Study of the structure, kinematics, and excitation of this material is the sole means available to directly study massive compact objects, which are not otherwise directly visible. While stars close to massive black holes are difficult to detect because of obscuration and crowding, emission and absorption by the neutral atomic, ionized, and molecular components of the interstellar medium (ISM) may be readily studied at radio wavelengths.

The role of the ISM in active nuclei is an important one because it feeds the central engines, thus determining their masses and angular momenta. In addition, material directly affects the overall appearance of AGN in two ways. First, it affects the degree of shielding of the central engines from various viewing angles, recognition of which motivated formulation of the AGN unification paradigm. Second, the accreting gas emits intense electromagnetic radiation from radio to X-ray bands, which affects the ISM structure and energetics in parts of the parent galaxies and pro-

*Current address: Visiting physicist, Kavli Institute for Particle Astrophysics and Cosmology, Stanford University.

vides a handle for the study of matter under truly extreme conditions.

Gas structures (from disks to tori to "cocoons") in AGN have been extensively studied at radio wavelengths, providing a wealth of important results that have been crucial to building our present picture of AGN. However, the picture remains incomplete because the studies haved been limited by the sensitivity, spectral resolution, instantaneous bandwidth, and bandpass stability of present and past instruments. We discuss in detail the substantially deeper studies of AGN that will be possible through the dramatic improvements that can be obtained with observers with the SKA.

2. Accretion disks and tori

The AGN unification paradigm (Antonucci 1993) posits that central engines are surrounded by a parsec-scale toroidal (or disk-like) distribution of atomic or molecular gas that obscures lines of sight for which the radio axis is close to the plane of the sky. Some fraction of the gas accretes to the central engine and is responsible for observed high luminosities. Tori can exist where energetic processes can provide vertical support, e.g. as in heating or magnetic turbulence at subparsec radii. In cases where infalling material can cool, it forms a thin accretion disk (Shakura & Sunyaev 1973), which may be warped by radiative, magnetic, gravitational, and relativistic effects (Pringle 1996, Neufeld & Maloney 1995). For example, radiative warping can be driven by X-ray heating of a disk and anisotropic reradiation of the energy by disk material. As is true for tori, warps shadow material at larger radii and similarly affect the appearance of the AGN for different observers.

The most challenging AGN to study are those whose radio axes are close to the plane of the sky, because of high obscuration (at optical and infrared wavelengths) and a superposition of structures along the line of sight. At radio wavelengths, signatures of emission and absorption by molecular gas, absorption by atomic gas, and free-free absorption of continuum emission are the most commonly used probes.

In the radio, there are three methods by which it is possible to detect circumnuclear structure in objects whose jet axis lie close to the plane of the sky: molecular gas seen either masing or in absorption, atomic gas seen in absorption, and ionized gas revealed through free-free absorption.

2.1. Mapping H_2O masers < 1pc from massive black holes

Over 50 type-2 active galactic nuclei contain known sources of H_2O maser emission ($\nu_{\rm rest} \sim$ 22 GHz), a large fraction discovered since 2000 (see Figure 3, Greenhill this Volume). Radio interferometric studies of these "nuclear masers" are the only means by which structures < 1 pc surrounding supermassive black holes can be mapped directly, which is particularly important for type-2 nuclei because edge-on orientation and obscuration complicate the study by other means. Investigations of several sources have demonstrated that H_2O maser emission traces warped accretion disks 0.1 to 1 pc from central engines with masses of order 10^6-10^8 $M_\odot$. Though not yet mapped, almost half the known nuclear masers share spectral characteristics consistent with emission from edge-on accretion disks. Their mapping and the discovery of new nuclear masers are high priorities. Instrument requirements include sensitivity to sub-mJy lines, instantaneous GHz bandwidths, spectral resolutions on the order of tens of kHz, and sub-milliarcsecond resolution for imaging. Built to current specifications, the SKA will provide a *two* order of magnitude increase in spectroscopic sensitivity for surveys intended to detect new maser sources in AGN. This should permit discovery of new sources at cosmological redshifts. The Array will enable a *one* order of magnitude improvement in sensitivity for (follow-up) high angular resolution imaging, where the SKA must be combined with an array of outrigger antennas operating on intercontinental (and ground-space) baselines (see Section 4.1).

2.1.1. What are nuclear H_2O masers?

Water maser emission from galactic nuclei is a beacon of accretion onto supermassive black holes. Recent general reviews may be found in

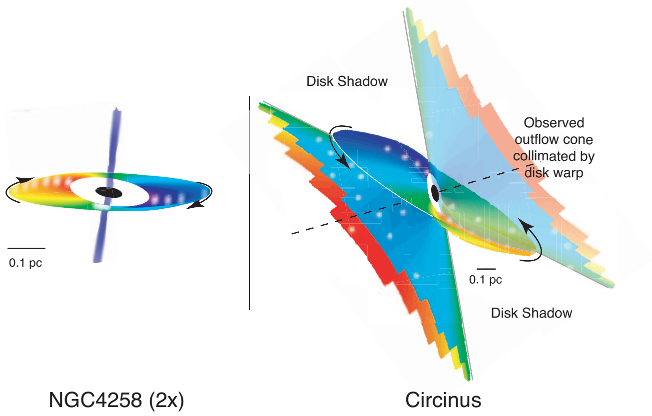

Figure 1. Representations of warped disk models for two AGN. Color codes mark the Doppler shift. Light smudges indicate the mapped positions of maser emitting regions. In NGC 4258, the continuum emission from a narrowly collimated jet has been observed in line-free interferometer channels and registered precisely with respect to the dynamical centre of the disk (Herrnstein et al. 1997). Circinus is not known to have a jet, but the edges of a well known kiloparsec-scale outflow and ionization cone correspond well to the edges of the shadow created by the disk warp. "Off-disk" masers are also seen in the unshadowed region but at sub-parsec radii, where they likely trace a clumpy, high density flow that arises possibly < 0.1 pc from the central engine.

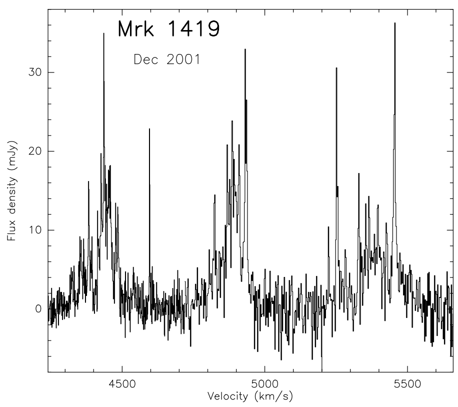

Figure 2. 22 GHz H_2O spectrum of Mrk 1419 (NGC 2960), showing the characteristic systemic (center), red- and blue-shifted groups of maser features that are hinting at an edge-on accretion disk.

Maloney (2002), Greenhill (2002, 2004), Watson (2002) and Henkel et al. (2004). On the order of 10^3 galaxies ($cz < 2 \times 10^4$ km s^{-1}) have been observed in searches for new maser sources, with a variety of sensitivities and bandwidths. Somewhat more than 50 have been detected (see Figure 3 in Greenhill, this Volume). The phenomenon is associated generally with Seyfert-2 galaxies and LINERS (Braatz et al. 1996), though there are examples in narrow line Seyfert-1 systems (Hagiwara et al. 2003), transition objects between Seyfert 1 and 2 classes (e.g., Braatz et al. 1996), and FR-II radio galaxies (Tarchi et al. 2003). The spectra of almost half the known masers exhibit emission over a broad range of velocity that (more or less) symmetrically brackets the systemic velocities of the host galaxies. The emission is distributed in plateaus from one velocity extreme to the other or in distinct line complexes, at large offset velocities and near the systemic velocities of the host galaxies.

Long baseline interferometers have resolved the angular and velocity structure of several maser sources each with emission spread over up to $\sim$ 2200 km s^{-1} ($\sim$ 160 MHz). This has demonstrated that the emission originates in nearly edge-on accretion disks. In addition to position and Doppler velocity, proper motions and secular drifts in line-of-sight velocities have also been measured for material near systemic, which correspond to the rotation and centripetal acceleration of the disk orbits, respectively. The best established cases are NGC 4258 (Humphreys et al. 2004, in prep; Herrnstein et al. 1999; Moran, Greenhill, & Herrnstein 1999, and references therein), NGC 1068 (Greenhill & Gwinn 1997), and the Circinus galaxy (Greenhill et al. 2003). In NGC 4258, Herrnstein et al (1997) have used the VLBA to determine the size and shape of the warped molecular disk as traced by maser spots. In this source, the masing disk extends from 0.13 pc to 0.25 pc from the central engine (see Fig. 1). Maps of maser emission in NGC 3079 (Trotter et al. 1998; Kondratko, Greenhill, & Moran 2004), are also suggestive of emission from a disk, while evidence for NGC 4945 (Greenhill et al. 1997), IC 2560 (Ishihara et al. 2001), NGC 5793 (Hagiwara et al. 1997), IRAS F22265-1826 (Ball et al. in prep.), and NGC 1386 (Greenhill & Braatz, unpublished), is less complete.

In the firmly established cases, NGC 4258, NGC 1068, and Circinus, maser emission traces well ordered disk material at radii of 0.1-1 pc and rotation speeds up to $\sim$ 1100 km s^{-1} around central engines of 10^6-10^8 M$_\odot$. Disk shape, orientation with respect to the line of sight, velocity shear, and background amplification largely determine where favoured maser gain paths are found within the disks (i.e., chiefly where the orbital motion is nearly parallel or perpendicular to the line of sight). To first order, the high perceived brightness of nuclear masers, compared to masers in star forming regions, can be accounted for by the long amplification paths made possible by the large-scale orderly dynamics of accretion disks, which (anisotropically) beam maser radiation in planes tangent to disk surfaces. However, pumping considerations are also important. The most broadly applicable mechanism is probably heating of disk gas via oblique irradiation by a central X-ray power-law source (Neufeld & Maloney 1995). It is disk shape (e.g., warping) that determines which surfaces and regions are irradiated and which are not (i.e., shadowed). In addition to the three established cases, masers in NGC 1386 also probably trace a warped accretion disk $\sim$ 1 pc across around a central mass on the order of 10^6 M$_\odot$. The inferred central mass for disks in NGC 3079 (Trotter et al. 1998, Kondratko et al. 2004) and IRAS F22265-1826 (Ball et al. 2004) are similar, but these disks are relatively large, 1-3 pc in radius, and not well ordered kinematically, probably because they are gravitationally unstable to fragmentation and star formation (e.g., Goodman 2003; Levin & Beloborodov 2003; Milosavljević & Loeb 2004). In the cases of IC 2560 (Ishihara et al. 2001) and Mrk 1419 (Henkel et al. 2002; see Fig. 2), full disk models are not yet available, but central masses of 3×10^6 and $\sim 10^7$ M$_\odot$, respectively, have been obtained using reported accelerations and estimates of orbital velocity.

2.1.2. Key science with nuclear H_2O masers

As already mentioned, interferometric observation of masers is presently the only means by which structures < 1 pc from supermassive black holes can be mapped. This is especially important for type-2 systems because in them, the central parsec is viewed close to edge-on, such that obscuration is heavy. Reverberation mapping of broad line emission is impractical and modeling of spectroscopic data (e.g., X-ray) must account for the superposition of multiple emission and absorption components along the line of sight. Examples of key science unique to maser studies follow.

Sub-parsec dynamical masses for central engines— Mass estimates enable calculation of Eddington luminosities and accretion efficiencies. For disks whose rotation curves can be resolved and a simple geometric model fit, the fractional uncertainty in central mass is dominated by the fractional uncertainty in distance to the host galaxy. Ultimately, maser dynamical masses for a large sample of galaxies will establish independently the slope of the $M_\bullet - \sigma$ relation (e.g., Ferrarese & Merritt 2000) and intrinsic scatter therein, limited chiefly by uncertainties in the stellar velocity dispersions in nuclei.

The 3-D shapes of accretion disks— Disks that have been mapped provide strong evidence that accretion disks can be warped by 0.1-1 radian on 0.1-1 pc scales. However, the warping mechanism is not certain. Though radiative torques have been suggested (Neufeld & Maloney 1995, Pringle 1996), stability is a concern. Testing of warp models requires characterisation of warps for a sample of AGN that contain masers and exhibit a range of luminosities and accretion rates.

Accretion disk thickness— Estimates of thickness are critical to calculations of accretion rate and identifications of accretion modes (e.g., advective, convective, viscous). No thicknesses have been measured directly, but high angular resolution observations of masers provide perhaps the best chance. Limits established for NGC 4258 are the tightest so far, and they are consistent with hydrostatic equilibrium (Moran et al. 1999). However, because NGC 4258 is underluminous, this disk thickness may not be typical.

Heterogeneity among type 2 AGN— Because of the high gas density required to support maser action, disks that cross the lines of sight to central engines are ready substitutes for the obscuring tori featured in the AGN unification paradigm. These tori have been difficult to observe directly and in large numbers. In contrast, warped accretion disks (at least in nuclei that host masers) appear to be common and their shapes suggestive. Outflows close to central engines may also provide the observed absorption columns (e.g., Fig. 1).

2.2. Gas in the circumnuclear tori

2.2.1. The neutral hydrogen component

Evidence of circumnuclear H I is detectable in absorption in radio sources whose jet axes lie close to the plane of the sky (Conway 1997), particularly in young compact sources ($\sim 10^4$ yr, Readhead et al 1996, Vermeulen et al. 2003). Evidence of a circumnuclear torus of atomic gas has been seen in Cygnus A (Conway 1999), NGC 4151 (Mundell et al 1995) and 1946+708 (Peck et al. 1999). In Cygnus A, H I absorption measurements with the VLBA indicate a torus with a radius of ~ 50 pc. In NGC 4151, H I absorption measurements using MERLIN indicate a torus ~ 70 pc in radius and ~ 50 pc in height. One of the best examples of this type of torus is the Compact Symmetric Object (CSO) 1946+708. The H I absorption in 1946+708 consists of a very broad line and a lower velocity narrow line which are visible toward the entire ~ 100 pc of the continuum source (see Fig. 3 (left), Peck et al. 1999). The broad line has low optical depth and peaks in column density near the core of the source. This is consistent with a thick torus scenario in which gas closer to the central engine is much hotter, both in terms of kinetic temperature and spin temperature, so a longer path-length through the torus toward the core would not necessarily result in a higher optical depth. Figure 3 (right) shows a cartoon of what this structure might look like. The high velocity dispersion toward the core of 1946+708 is indicative of fast moving circumnuclear gas, perhaps in a rotating toroidal structure. Further evidence for this region of high kinetic energy and column density is found in the spectral

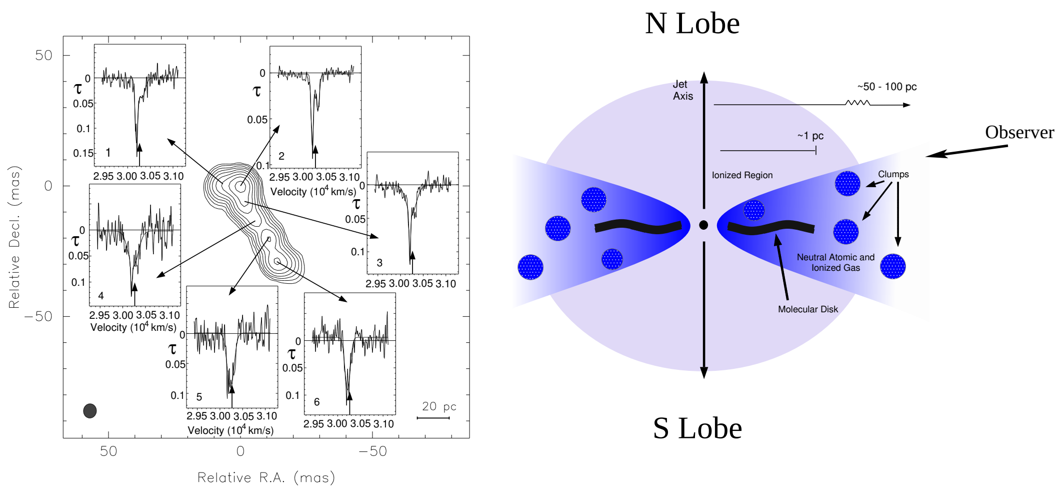

Figure 3. *(Left)* The absorption profiles toward each of the 6 resolved continuum components across 1946+708. The systemic velocity is indicated by an arrow in each profile. The velocity resolution is 16 $\mathrm{km\,s^{-1}}$. The beam, shown in the lower left corner, is 4.3×4.9 mas. The linear scale shown in the lower right assumes H_0=75 $\mathrm{km\,s^{-1}}$ $\mathrm{Mpc^{-1}}$. *(Right)* A cartoon of how a circumnuclear torus might look. Some notable simplifications have been made. For example, it is not necessary for the toroidal structure to be perpendicular to the jet axis, the "clumps" of denser gas are unlikely to be uniform in size, and the degree of warp in the disk can vary greatly. Also, the relative scale heights and radii of the various regions are not yet well constrained. This model represents only the central $\lesssim$100 pc of the source, and does not address the possibility of an extended H I or molecular disk or torus associated with the host galaxy, although this could conceivably be part of the same continuous structure. The extent of the inner molecular disk is likely to be on the order of a parsec, and the region of atomic gas beyond that probably extends some 50-100 pc from the central engine. This outer region, although predominantly atomic, probably contains clumps or clouds of denser gas which could harbour molecular gas.

index distribution which indicates a region of free-free absorption along the line of sight toward the core and inner receding jet. The H I optical depth increases gradually toward the receding jet. The most likely scenario to explain these phenomena consists of an ionized region around the central engine, as well as an accretion disk or torus, with a scale height of $\leq$10 pc at the inner radius and at least 80 pc at the outer radius, which is comprised primarily of atomic gas (Peck & Taylor 2001).

Due to the weakness of the radio core in many sources, the study of the H I associated with circumnuclear tori can be done only for a limited number of cases, namely those with compact jets. The extension of this study to radio sources of different power and ages is crucial. For example, in low luminosity radio galaxies the situation could be different. In these sources, the standard pc-scale geometrically thick torus is perhaps not present (as obtained from optical and X-ray studies). Indeed, the presence of a thin disk has been determined from H I observations in the case of NGC 4261 (van Langevelde et al. 2000). For this object, the VLBI data suggest that the H I absorption is due to a disk $\sim$1.3 pc thick seen in projection against the counter-jet. Differences in the nuclear torus/disk system (and corresponding difference in the accretion processes) is key to understanding the observed variations in radio power, radio morphology, optical ionisation, and other parameters.

The sensitivity of the SKA will allow radio counterjets to be detected in a much larger sample of sources spanning a wide range of luminosities and orientations. Thus, the SKA will reduce the observational bias in future studies of source symmetry and absorption probes of the circumnuclear region. As a result, correlations between the gas properties and geometry in the inner parsecs of active nuclei and other properties of the sources will be easier to measure and understand.

2.2.2. Maser emission and the circumnuclear tori

Once evidence for a torus has been found in H I, these sources are prime candidates to search for molecular absorption, maser emission and ionized gas in the central parsecs. Observations of NGC 1068, for example, suggest evidence of all three components, consisting of OH and H_2O masers, H I absorption, and a compact source of free-free emission (Gallimore et al 1996). As mentioned above, in this source, the maser emission indicates that the molecular disk makes a large angle with the radio axis (Greenhill & Gwinn 1997) and so might be more strongly warped than that of NGC4258. IRAS F22265-1826 contains the most luminous known H_2O megamaser, with a luminosity in the 1.3 cm line of 6100 $L_\odot$; (Koekemoer et al. 1995). Although the 420 km s^{-1} absorption probably results from neutral material associated with the atomic and molecular torus thought to feed the active nucleus, the deeper 125 km s^{-1} line in TXS 2226-184 could be indicative of an interaction between the radio jet and surrounding material (Taylor et al. 2002). The main component of the water maser emission is also fairly broad (almost $100\,\mathrm{km\,s^{-1}}$) in TXS 2226-184 and could likewise originate from the central torus or from a jet-cloud interaction.

To date, however, too few sources have been found which exhibit both H I absorption and H_2O maser emission to confirm this scenario. Of the 19 H_2O megamaser galaxies presented in Taylor el al. (2002), 7 are known to have associated H I absorption. Likewise, 4 H I torus systems (1946+708: Peck, Taylor, & Conway 1999; PKS 2322-123: Taylor et al. 1999; Hydra A: Taylor 1996, NGC 3894: Peck & Taylor 1998) have been searched for maser emission with no detections. A fifth H I torus source (NGC 4151: Mundell et al. 1995) has recently been found to exhibit very weak maser lines (Braatz et al. in prep). Part of the reason for this may be orientation effects, insofar as the maser emission is more heavily dependent on the line of sight through, and the degree of warp in, the accretion disk itself. Much of the difficulty, however, might simply stem from a lack of sensitivity. Many megamaser sources have very little 21cm continuum emission toward which to detect the HI absorption. In addition, increasingly faint masers are being detected with every improvement to the 22 GHz receiver systems at existing telescopes, to the point that detections of extragalactic megamasers with peak flux densities of 10-20 mJy are becoming fairly common

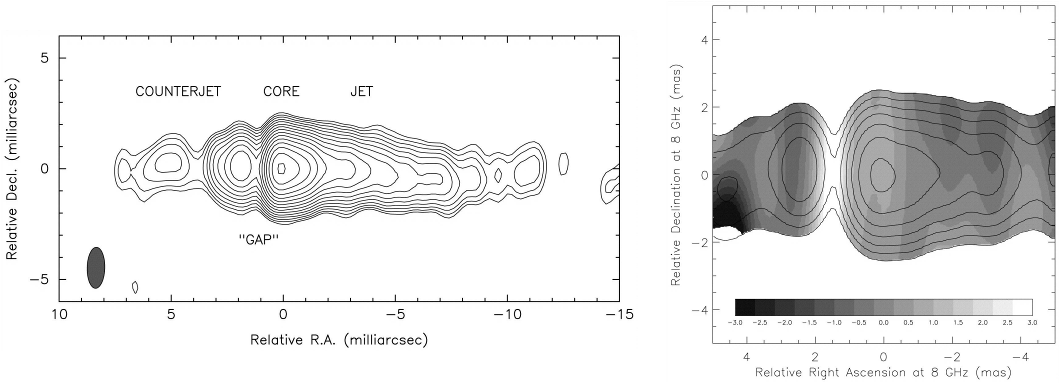

Figure 4. *(Left)* VLBA image at 4.9 GHz of the nucleus of NGC 4261 (Jones et al. 2001), showing a radio jet and counterjet and a deep and narrow gap in emission just on the counterjet side of the core. *(Right)* The distribution of radio spectral index (between 4.9 and 8.4 GHz) across the central few parsecs of NGC 4261 (Jones et al. 2001). Note that the region of minimum emission just east of the brightest peak has a strongly inverted (absorbed) spectrum, while the peak (core) has a less inverted spectrum and the jet and counterjet have flat to steep spectra.

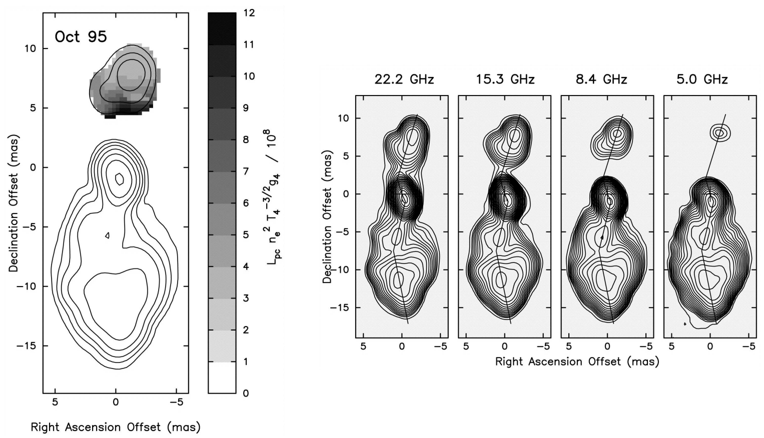

Figure 5. *(Left)* Two-dimensional distribution of the free-free absorption in 3C 84 over the region of the counterfeature (from Walker et al. 2000). There is no detected absorption over the brighter southern feature. The overlaid contours are from the 8.4 GHz image while the spectral index is determined from a fit to data at four frequencies (5.0, 8.4, 15.4, and 22 GHz). The strong radial gradient away from the core is apparent. *(Right)* Montage of the VLBA images of 3C 84 (from Walker et al. 2000). These displays are based on the CLEAN components convolved with a common Gaussian beam of 1.6 × 1.2 mas, elongated north-south. The contour levels start with 5, 10, 14, 20 mJy beam^{-1} and increase from there by factors of $\sqrt{2}$. The north-south segmented line shows the location of the slice along which some of the analysis was done. Note that, for $H_0 = 75$ km s^{-1} Mpc^{-1}, the scale is about 3 mas pc^{-1}.

(Peck et al. in prep.). In both cases, building a statistical sample relies solely on increased sensitivity and moderate angular resolution, such as would be achieved with the SKA.

2.2.3. Free-Free absorption by accretion disks

Parsec-scale radio counterjets are important for studying the intrinsic symmetry of the jet-formation process, and as probes of the structure of ionized gas in the central pc of accretion disks surrounding the central black holes in AGN. In this latter case, the counterjet serves as a source of radiation which can be absorbed by thermal electrons in the disk. If geometrically thin, the disk will cover the inner part of the counterjet but not the approaching jet. If geometrically thick, the core and perhaps the base of the approaching jet may also be absorbed, but with lower total optical depth than the base of the counterjet.

Multi-frequency observations can detect the highly inverted spectrum created by free-free absorption from flat or steep spectrum synchrotron emission from the radio core and jet. Two well studied cases are shown in Figs. 4 and 5. Even in cases where the radio core has an inverted spectrum because of synchrotron self-absorption, it is possible to use the differing angular size of free-free absorbing regions as a function of frequency to distinguish this process from synchrotron self-absorption.

The SKA will allow such studies of disks in a much larger sample of objects, covering a wider range of jet and disk orientations, and will detect absorption over a larger range of disk radii. By measuring the free-free optical depth as a function of projected disk radius, and knowing the disk orientation from the radio jet observations (comparisons of jet and counterjet brightness and proper motions), we can solve for the radial distribution of plasma density in the disk.

In addition, the SKA will be able to routinely add Faraday rotation and depolarisation constraints (from multi-frequency polarisation measurements) to models of the electron density and magnetic field distributions with the accretion disks. The radial distribution of free electrons in the disk can be used to estimate the mass accretion rate dm/dt (Kungic & Bicknell, in prep.); this in turn can be compared with the observed jet energetics to provide critical input parameters for all models of the central engine.

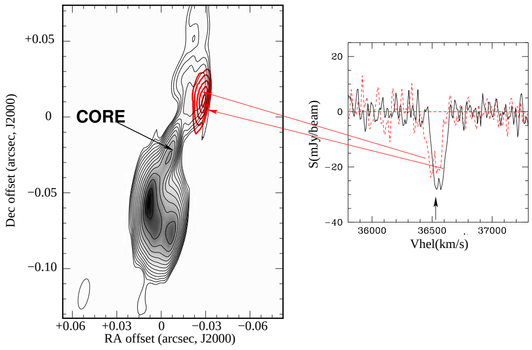

Figure 6. Continuum image (grey scale and thin contours) of 4C 12.50 (from Morganti et al. 2004a) superimposed onto the total intensity of the H I absorption (thick contours). The position of the radio core is also indicated. The contour levels for the continuum image are: 5 mJy beam^{-1} to 800 mJy beam^{-1} in steps of factor 1.5.

Accretion disks are a fundamental component of the central engines that produce relativistic jets in objects from galactic microquasars containing stellar mass black holes to powerful AGN containing billion solar mass black holes. It is very likely that relativistic jets cannot form without an accretion disk. Consequently the study of the basic physics of central engines requires knowledge of the physical properties of these disks. The SKA will revolutionise our ability to determine many of the relevant physical parameters.

3. Rich ISM and the evolution of the radio sources

The origin of activity in galaxies is often explained as having been triggered by merger and/or interaction processes. Torques and shocks during the merger can remove angular momentum from the gas in the merging galaxies and this provides injection of substantial amounts of gas/dust into the central nuclear regions (see e.g. Mihos & Hernquist 1996). It is, therefore, likely that in the initial phase of an AGN, this gas still surrounds (and possibly obscures) the central regions. AGN-driven outflows have major effects on this dense ISM. This feedback process can also play an important part in the evolution of the host galaxy as it may limit the growth of the supermassive black holes (BHs) and regulate the correlation between BH and bulge properties (see e.g. Silk & Rees 1998).

H I absorption can be used to trace such a rich medium. One example is the radio galaxy 4C 12.50 (see Fig. 6, Morganti et al. 2004a), a galaxy that has often been suggested to be a prime candidate for the link between ultraluminous infrared galaxies and young radio galaxies. In this object, deep and relatively narrow H I absorption (observed at the systemic velocity) is associated with an off-nuclear cloud ($\sim$ 50 to 100 pc from the radio core) with a column density of $\sim 10^{22}\ T_{\rm spin}/(100\ {\rm K})\ {\rm cm}^{-2}$ and an H I mass of a few times 10^5 to $10^6\ M_\odot$. There are more examples of objects where the H I traces the rich medium surrounding the active nucleus. Examples of off-nuclear H I absorption are found in 3C 236 (Conway & Schilizzi 2000) and, more recently, in the CSO 4C 37.11 (Maness et al. 2004) where a broad ($\sim$ 500 km s^{-1}) absorption line was found in the region of the southern hot-spot.

The relevance of this is that it may have important implications for the evolution of the radio jets. Although this gas will not be able to confine the radio source, it may be able to momentarily destroy the path of the jet as shown also by numerical simulations (Bicknell et al. 2003). Thus, this interaction can influence the growth of the radio source until the radio plasma clears its way out.

3.1. Outflows of neutral hydrogen

The scenario described above, where the central region could be still surrounded by a rich cocoon of ISM, implies that gas outflows can be generated by the nuclear engine interacting with such a medium. The discovery of a number of radio galaxies where the presence of fast ($>$ 1000 km s^{-1}) outflows is associated with *neutral hydrogen* is thus extremely intriguing. This finding gives new and important insights into the physical conditions of the gaseous medium around an AGN. The best examples so far are the radio galaxies 3C 293 (Morganti et al. 2003a) and 4C 12.50 (see Fig.) and the Seyfert galaxy IC 5063 (Oosterloo et al. 2000). Observations carried out recently (using the WSRT) have revealed fast H I outflows in a few more objects with line widths ranging from 800 up to 2000 km/s. The optical depths of the broad, shallow absorption lines are low, typically around 0.001. The detection of these broad shallow absorption features represents a significant challenge for present-day radio telescopes. Broad bandwidths and a very stable bandpass are needed. Furthermore, we can currently only hope to detect such weak features in very strong radio sources. Thus, the improvement that the SKA will bring will be crucial to really understanding how common these phenomena are, in which kind of sources they are observed, and what, indeed, is their origin.

A number of possible hypotheses can be already made about the origin of the gas outflow (e.g., starburst winds, radiation pressure from the AGN adiabatically expanded broad emission line clouds, interaction of the radio jet with the ISM). However, to understand which of these physical process drives the outflows we need to identify their exact location with high enough resolution and sensitive observations, something quite difficult to carry out with the available instruments.

3.2. Jet masers

The rich ISM in the central parsecs of AGN can also be detected via the so-called "jet masers". Although H_2O megamasers are best known as a means to probe the accretion disks, there is now evidence for a distinct class of H_2O megamasers. In these sources, the amplified emission is the result of an interaction between the radio jet and the encroaching molecular clouds. The only known sources in this class are NGC 1068 (Gallimore et al. 1996) and the Circinus galaxy (Greenhill et al. 2001) which appear to have both circumnuclear disk masers and maser emission arising along the edges of an ionisation cone or outflow, and NGC 1052, in which the masers appear to arise along the jet (Claussen et al. 1998).

One further example of this is Mrk 348, where the amplified emission is found in VLBA studies to arise along the line of sight to a jet component and has a very high linewidth (130 km s^{-1}), occurring on small spatial scales (0.25 pc) and varies on scales of days or months (Peck et al. 2003). The combination of these points suggest that the H_2O emission is more likely to arise from a shocked region at the interface between the energetic jet material and the molecular gas in the cloud where the jet is boring through, than simply as the result of amplification by molecular clouds along the line of sight to the continuum jet. The orientation of the radio jets close to the plane of the sky also results in shocks with the preferred orientation for strong masers from our vantage point. This hypothesis is supported by the spectral evolution of the continuum source, which showed an inverted radio spectrum with a peak at 22 GHz, later shifting to lower frequencies. The maser emission in this source allows us to determine the physical and chemical conditions in the pre-shock gas very accurately.

A stronger "jet maser" has been found in NGC 1052 (Claussen et al 1998), but in general, these sources tend to be orders of magnitude weaker than the better known "accretion disk" megamasers. Recent surveys have found that masers with peak flux densities of tens of mJy have been found in 29% of galaxies which have either some evidence of interaction between the NLR and the jet, or have their radio jet axis oriented close to the plane of the host galaxy (Peck et al 2004). Even this high detection rate is probably limited only by the sensitivity of current survey instruments, there may be many more such sources. This class of masers is distinguished by the broad shallow shape of the line, rather than by the physical location, since these very broad lines from very compact sources must be occurring in a region as energetic as the central few pc of an AGN. Thus, high angular resolution is less of an imperative than high sensitivity, broad bandwidth and bandpass stability, so the SKA would be able to detect and monitor these sources where current instruments cannot.

4. The impact of SKA

4.1. H_2O maser emission

The SKA will contribute substantively to the detection and mapping of H_2O maser sources in AGN, and perhaps to the detection of obscured and distant low luminosity AGN through detection of their maser emission (which can be strong even in "weak" AGN). The typical line strength of new detections has dropped by about an order of magnitude per decade, to 0.01-0.05 Jy today, with a maximum distance of ~ 230 Mpc (see Figure 3, Greenhill this Volume). The rapid increase in source counts over the last few years is attributable to the advent of observing systems with higher sensitivity *and* instantaneous bandwidth at Effelsberg, Green Bank, and Tidbinbilla. Though the sensitivity of some existing assets can be improved somewhat, order of magnitude improvements will require use of the SKA or prototypes. For line detection experiments, the SKA will be on the order of $100\times$ more sensitive than the best observing systems today. Instantaneous bandwidths on the order of 500 MHz per polarisation and baseline will accommodate even the broadest maser source known today (200 MHz) and provide a margin for detection of broader systems. Observed line widths can be on the order of 1 $\mathrm{km\,s^{-1}}$. Hence, the SKA backend channel spacing must be < 30 kHz to properly sample the spectra (i.e., 16 K channels per baseline per polarisation). The use of an interferometer for line detection experiments promises better (flatter) spectral baselines than can be achieved consistently over very broad bandwidths and in the presence of background continuum emission with most single dish instruments. Perhaps more importantly, deep, high frequency continuum mapping programs could be conducted in parallel with maser surveys. The simplest survey mode would entail use of the SKA core so that the beam width is at least as large as the galactic nuclei. However, if real-time imaging pipelines are available, the full array could be used to search spectra constructed from image cubes.

The two most important ramifications of high SKA sensitivity for AGN surveys will be completeness for nearby targets and extension to dis-

Table 1
Approximate Array Sensitivities

Array[a]	Relative Sensitivity	Self-cal $F_\nu^{peak\,(b)}$ (mJy)	Self-cal Synthesis[c] (mJy $\mathrm{hr}^{\frac{1}{2}}$)	Posn-Swtch Synthesis[c] (mJy $\mathrm{hr}^{\frac{1}{2}}$)
VLBA	1	~ 1	33	59
VLBA+G	3.1	~ 0.2	11	20
VLBA+G+Y	6.4	~ 0.2	5.1	9.1
VLBA+G+Y+E+2×D	10	~ 0.2	3.2	5.7
G+Y+E+2×D	9.0	~ 0.06	3.7	6.6
SKA core + 10 × 25m	44	~ 0.02	0.74	1.3
SKA core + 400 × 12m	100	~ 0.05	0.33	0.59

[a] G: GBT; Y: VLA; E: Effelsberg; D: DSN 70-m (Spain and US); SKA core: proposed 5 km core of the Square Kilometer Array, corresponding to 50% of the total collecting area and treated as a phased aperture. Because of required high angular resolution, *proposed 12-m and 25-m supplements to the SKA core must be external to the SKA* in light of a planned 3000 km maximum extent.
[b] Minimum peak line strength for which self-calibration is possible. The adopted minimum requirement is a 3σ detection of a reference Doppler component on individual baselines, assuming a 1 $\mathrm{km\,s^{-1}}$ spectral channel, dual polarisation, 30 second coherence time, and 10% processing loss. Nominal system equivalent flux densities (SEFD) are 1100 Jy (VLBA), 30 Jy (GBT), 40 Jy (VLA), 100 Jy (Effelsberg), 80 Jy (DSN-Spain), 90 Jy (DSN-US), and 0.56 Jy (SKA core) for elevations of $\sim 40°$. The SKA SEFD corresponds to a high-frequency array specification of $A_e/T = 10^4$, where A_e is effective collecting area and T is system temperature. For arrays of large and small apertures, self-calibration requires the 3σ detection to be achieved on baselines that link the large and small apertures.
[c] Detection limit (5σ) for a 1 hour synthesis, 1 $\mathrm{km\,s^{-1}}$ spectral channel, dual polarisation, 10% processing loss, and 80% duty cycle on source for self-calibration or 25% duty cycle for position-switching with a nearby calibrator. In arrays that include the VLBA, antennas outside the continental US are assumed to have half-tracks because of source visibility.

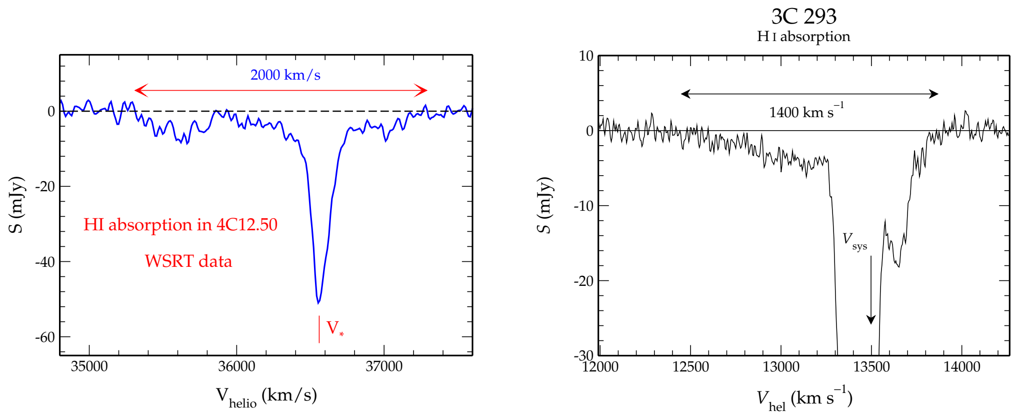

Figure 7. The H I absorption profile detected in 4C 12.50 (left) and 3C 293 (right) from the WSRT observations (Morganti et al. 2003a,b). The spectra are plotted in flux (mJy) against optical heliocentric velocity in $\mathrm{km\,s^{-1}}$.

tances 10× greater than can be attempted with existing instruments. It is difficult to predict how many sources will be detected because statistics for present-day surveys remain poorly understood. However, in principal, the source sample will increase three orders of magnitude, contingent in part on spectroscopic identification of AGN at X-ray, optical, and near-infrared wavebands. If the generic detection rate obtained in past surveys is applied, and if the H_2O luminosity function is taken into account, 10^5-10^6 maser sources could be detected.

Interferometric mapping of sources that exhibit broadband emission will continue to be a high scientific priority. Self-calibration is the most robust supporting technique, where a single Doppler component is used to solve for complex station gains, which are subsequently applied to other components. This approach is feasible if there is a line strong enough to be detected on individual baselines in an atmospheric coherence time, or ~ 30 seconds at 22 GHz (conservatively). The phasing sub-arrays (or stations) within the SKA would be critical for self-calibration to be practicable. Weak maser sources can be mapped with high fidelity if they lie close on the sky to continuum calibration sources ($< 1°$) and rapid position switching of the array is possible. (Most maser sources do not lie in nuclei that are also strong continuum emitters and would permit continuum self-calibration at 22 GHz or below.) For many maser sources, the greatest limitations are presented by the absence of a nearby, detectable calibrator with a well known position. This reinforces the importance of broad continuum observing bandwidths and the inclusion of astrometry (i.e., enrichment of the celestial reference frame) in the SKA mission. Sensitivity limits for self-calibration and position-switched observations are presented in Table 1.

Although the SKA will substantially increase the number of known maser sources, most key science (e.g., apart from statistical studies of detection rates for different samples) will require high angular resolution imaging. For a nominal maximum baseline of 3000 km, a ~ 1 pc radius disk inner edge (e.g., NGC 1068) will subtend the synthesised beam at a distance of only ~ 500 Mpc, and detection of smaller disks (e.g., NGC 4258) at such large distances would be problematic. If masers detected in each back-end spectral channel are modelled as point sources, angular resolution limitations may be offset via centroid fitting, which amounts to subdividing the beam in proportion to the signal-to-noise ratio (the higher the S/N, the smaller the uncertainties in the centroid position). However, reliance on this technique at a greater level than today, when intercontinental baselines are used for mapping, forecloses the possibility of unambiguously detecting fine-scale substructure (e.g., disk thickness, spiral waves) as well as robust measurement of proper motions.

The simplest solution, contingent on geography, will be operation of outrigger stations in combination with the core of the SKA, which itself would be best operated as a phased element. This could provide an order of magnitude increase in sensitivity over present day interferometers (Table 1), depending on the size of the outrigger array. In gross terms, this would increase the distance at which imaging is possible by half an order of magnitude and the sample of targets by on the order of 30×, to a few hundred. However, even with intercontinental baselines, resolution of accretion disks such as the one in NGC 4258 will be difficult beyond on the order of 100 Mpc. In that sense, the SKA is a critical instrument, but it is just half of what is needed for future robust investigation of accretion onto supermassive black holes. The other half is space interferometry (i.e. the iARISE and VSOP2 missions operating in conjunction with the SKA).

4.2. H I 21cm absorption studies and SKA

The study of neutral hydrogen in the surroundings of active nuclei is limited, at present, to AGN with a relatively strong radio core. This limit is even stronger if we are looking for weak and broad features, associated with H I with extreme kinematics. These limitations will be completely overcome by the SKA and this has a number of interesting implications. The most obvious is that for an improvement in sensitivity of two orders of magnitude (combined with higher image fidelity), we will be able to expand the study to radio-loud AGN with weak cores, like most of the classical powerful radio galaxies. In this way, we will expand our knowledge base on the occurrence of H I associated with circumnuclear tori and their structure. H I absorption with optical depths of the order of $\tau \sim 0.01$, typical for the absorption that we consider is associated with the tori, will then be detectable in sources as weak as a few mJy.

From this improvement, we will not only obtain a complete picture of the presence of H I in the nuclei of radio loud AGN, but we will also explore the uncharted region of low luminosity AGN. The comparison of the structure of the circumnuclear tori (as derived from the H I) in low and high (radio) luminosity AGN will tell us whether the differences in radio properties are related to the way the accretion (low *vs* high rate/efficiency) occurs.

The new possibilities offered by the SKA will be even more crucial for the detection and study of the shallow, broad ($\sim$ 1000 km s^{-1}) H I absorption. The typical optical depth found so far for these components is $\tau \sim 0.001 - 0.0005$. These values imply that, at present, we can only search for such H I with extreme kinematics in very strong radio sources (around 1 Jy or more). Reaching this result has already required an effort in terms of bandpass stability of present day telescopes and this issue will have to be considered for the SKA as well. However, even for spectral dynamic range of the order of what can be reached today ($\sim 10^{-4}$), the SKA will allow us to explore the presence of extreme kinematics in radio sources as weak as 10 mJy. Moreover, depending on the lower frequency reachable by SKA, we will be able to investigate the presence of low opacity, broad H I absorption and in particular the occurrence of outflows of neutral hydrogen, in high-z sources, i.e. sources that are believed to be surrounded by a denser and richer ISM.

Interestingly, for very strong radio sources the sensitivity of the SKA will permit the study of gas at extremely low optical depth (of the order of $\tau \sim 0.00001$). Thus, we will be able to explore the presence of gas in different physical conditions (gas with very low column density or gas in regions with high temperature) and extend the parameter space for exploring the condition of the gas in the nuclear regions. All these studies will also require high spatial resolution (sub-arcsec, but possibly milliarcsec) that will be essential for localising the absorption and understand its origin.

However, the SKA will go much further. It will also allow us to carry out blind searches, a technique that we are just beginning to explore with the present-day telescopes. The spectral-line mode, in which continuum observations will be carried out as well, with its large instantaneous bandwidth and large number of channels, facilitates the serendipitous detection of H I (in emission or absorption) from galaxies in any observed field and in the redshift range of the observed band. This can be already done to some extent using WSRT standard continuum observations but the SKA will allow us to investigate an unexplored region of parameter space. In the case of the WSRT deep survey of the Spitzer Space Telescope First-Look Deep region (Morganti et al. 2004b), H I emission was detected in four galaxies in the central region of the field. The sensitivity of these observations (and the limited band), however, do not allow the detection of H I in absorption (except with extremely high optical depths). All this will be routinely possible with the SKA and, with the sensitivity expected, we could search for H I absorption at $\tau \sim 0.01$ level (the typical absorption found in cases of circumnuclear tori) on every source in the observed field stronger than only a few mJy. It will be like searching every source of the NVSS catalogue for H I absorption. The large instantaneous bandwidth will ensure that a large range in redshift is covered to detect this absorption.

5. Conclusions

The dramatic improvement in spectral line sensitivity made possible by the large collecting area of the SKA will benefit all types of emission and absorption studies. A much larger sample of host and background sources will be available, and consequently we will be able to compare the nuclear environments, as determined by these observations, over a wide range of AGN luminosities, orientations, and evolutionary stages. This is essential to allow the effects of orientation, for example, to be disentangled from other source properties.

The critical SKA parameters for these studies are high angular resolution at moderately low frequencies (1-2 GHz) for imaging of HI absorption, OH masers, and free-free absorption in AGN, and high angular resolution at high frequencies (up to 22 GHz) for water masers. In all cases, of course, collecting area is the key to sensitivity. However, very wide bandwidths and high spectral dynamic range will also be important parameters of the SKA. All this will contribute to a significant and necessary step forward in the understanding of the environment of AGNs.

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