CIRCUMNUCLEAR DISKS IN RADIO-QUIET ACTIVE GALAXIES

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Abstract. In this paper, I review some of the evidence for gaseous circumnuclear disks in radio-quiet active galaxies (Seyfert galaxies and LINER's). Results from observations of Fe Kα lines, H_2O megamasers, extended structures seen in near infrared observations and ionization cones are discussed.

1. Introduction

The paradigm for active galactic nuclei (AGN) comprises a massive black hole and an accretion disk. In radio-loud objects, the paradigm is strongly supported by the existence of powerful relativistic jets. The evidence for disks in radio-quiet objects is also strong and in this paper I should like to discuss selected recent developments in this area.

2. Evidence for Gaseous Disks

2.1. FE Kα LINES – DISKS AT SEVERAL SCHWARZSCHILD RADII

Tanaka et al. (1995) have recently shown that the Fe Kα emission line in the Seyfert 1 galaxy MCG–6–30–15 is extremely broad, with a full width at zero intensity of 100,000 km s^{-1}. The line is also asymmetric, with a relatively narrow core around 6.4 keV and a broad red wing. Tanaka et al. show that the profile can be modelled in terms of emission from an accretion disk between 3 and 10 Schwarzschild radii from a Schwarzschild or Kerr black hole. This observation is probably the strongest piece of evidence that radio-quiet AGN are powered by massive, relativistic compact objects.

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2.2. H_2O MEGAMASERS – DISKS AT $\simeq 0.1 - 10$ PC

2.2.1. *NGC 4258*

Recent VLBI observations (Greenhill et al. 1995a; Miyoshi et al. 1995) of the LINER galaxy NGC 4258 have shown that the water vapor megamasers in this galaxy arise in a thin, edge-on gaseous annulus at a galactocentric radius of 0.13 – 0.26 pc. Maser emission is observed both near systemic velocity, arising from clouds at the near side of the disk and along our line of sight to a central opaque core (hypothesised to be a source of continuum radiation at 22 GHz), and from "satellite lines" with velocities of $\pm$ 900 km s^{-1} w.r.t. systemic (Nakai, Inoue & Miyoshi 1993), arising from gas at the tangent points with rotational velocities directed towards and away from Earth. The satellite lines show an accurately Keplerian rotation curve. The recessional velocities of the near-systemic features are observed to be increasing at a rate of about 9 km s^{-1} yr^{-1} (Haschick, Baan & Peng 1994; Greenhill et al. 1995b). This increase of velocity is believed to result from the centripetal acceleration of clumps of gas in the annulus as they move across our line of sight to the central core (Watson & Wallin 1994; Haschick, Baan & Peng 1994; Greenhill et al. 1995b).

The most important information obtainable from these observations can be summarised in the following simplified way. Suppose that the masers arise in a thin, circular annulus viewed edge-on. Let θ be the observed angular dimension along the projected edge-on disk, V the observed recession velocity of the masers and V_{gal} the systemic velocity. Intrinsic properties of interest include the distance to the galaxy, D, the rotational velocity of the annulus, U, and the radius of the annulus, r. We can relate the information from the various observations to the intrinsic properties as follows.

a) VLBI mapping of the systemic features: $(dV/d\theta)_{syst} = UD/r$.

b) Monitoring of the time dependence of the velocity of individual clumps of gas in the systemic features: $(dV/dt)_{syst} = U^2/r$.

c) VLBI measurement of the angular radius of the satellite lines: $\theta_{sat} = r/D$.

d) Measurement of the velocity of the satellite lines: $V_{sat} - V_{gal} = U$.

e) VLBI mapping of the systemic features at more than one epoch: $(d\theta/dt)_{syst} = U/D$ (this measurement has not yet been made).

Combination of measurements a) through d) gives $D = 6.4$ Mpc, $r = 0.13 - 0.25$ pc, $U = 800 - 1,100$ km s^{-1}, and a central mass $M = rU^2/G = 3.6 \times 10^7$ $M_\odot$ (Greenhill et al. 1995a, b; Miyoshi et al. 1995). What is impressive here is the high degree of internal self-consistency in the model. If instead of obtaining D from the maser observations we assume it is known, measurements a) through d) give four equations for two unknowns. For example, measurement of the angular radius (c) and velocity (d) of the satellite lines allows the angular change in velocity (a) and the acceleration (b) of the systemic components to be correctly predicted. This self-consistency gives confidence in the model and argues strongly against alternative theories in which the masering gas is moving radially.

2.2.2. *NGC 1068*

Using VLA observations, Gallimore et al. (1995) have recently found that the brightest H_2O masers in NGC 1068 trace a 5 pc long structure which is almost at right angles to the local axis of the radio jet. They find that the kinematics may be described by an edge-on disk around a central mass concentration. The inner radius of the disk is 1.3 ± 0.2 pc and the mass within the inner radius $(4.4 \pm 0.8) \times 10^7$ $M_\odot$. Higher resolution observations with the VLBA are desirable to confirm these results and check whether the rotation curve is Keplerian.

2.2.3. *The Population of H_2O Megamasers*

In 1992, five galaxies, all of which are Seyferts or LINER's, were known to contain H_2O megamasers. Surveys of non-active spirals, starbursts and luminous infrared galaxies over the last decade have failed to provide new detections (e.g. Greenhill et al. 1995b). We therefore decided to perform a new survey for H_2O megamasers, targeting exclusively AGN. The results of this survey at present are as follows (Braatz, Wilson & Henkel 1994, 1996):

1) With $\simeq$ 350 galaxies observed, nine new detections have been obtained. For a distance-limited sample (all Seyferts and LINER's listed in the Huchra or Véron-Cetty & Véron catalogs with cz < 7,000 km s^{-1}), the detection rate is 5.2%. This fraction is 12% for those sources with cz < 2,000 km s^{-1}.

2) All the H_2O detections are either LINER's or Seyfert 2's; none are Seyfert 1's. This result is consistent with the model proposed by Miyoshi et al. (1995) for NGC 4258, in which the molecular disk is viewed edge-on.

3) When measured, the column densities to the nuclei of the detected galaxies (from soft X-ray photoelectric absorption) are high – 10^{22-25} cm^{-2}.

4) The line profiles are mostly narrow ($\approx$ km s^{-1} wide) spikes, with some broad features. NGC 1052, the only elliptical detected, shows only a single, broad (FWHM $\simeq$ 90 km s^{-1}) line.

5) An ongoing VLA project confirms that all masers observed so far are confined to the nucleus of the galaxy.

6) Monitoring of the brightest maser spike in NGC 2639 reveals a redward velocity drift of 6.6 ± 0.4 km s^{-1} yr^{-1} over a period of 1.4 yrs (Wilson, Braatz & Henkel 1995). If this acceleration represents the centripetal acceleration of the near side of an edge-on Keplerian disk, as is the case in NGC 4258, the mass of the central object is 1.5×10^7 $(r/0.1\ pc)^2$ $M_\odot$ (cf. observation b for NGC 4258). Further observations (i.e. a, c, or d in the NGC 4258 list) are needed to determine r or v, and hence M, uniquely.

Unfortunately, no satellite lines have been detected so far and the maser is too weak for VLBI observations.
7) There is a possible trend for the detections to be highly inclined galaxies. If confirmed, this result would suggest that some of the maser amplification occurs in gas disks coplanar with the galaxy stellar disk.
8) VLBI observations of two of the new detections are planned.

2.3. DUST EMISSION – DISKS AT $\simeq 10^2 - 10^3$ PC

Mkn 348 is a type 2 Seyfert galaxy with broad Hα emission visible in polarized light (Miller & Goodrich 1990). There is a bi-polar (bi-conical?) nebulosity of high excitation gas in p.a. $\simeq 170°$ (Mulchaey, Wilson & Tsvetanov 1995), which aligns well with the radio axis in p.a. $\simeq 168°$ (Neff & de Bruyn 1983). These directions are perpendicular to that of the optical polarization in p.a. $\simeq 84°$ (Miller & Goodrich 1990), as is usually the case in Seyfert 2's. Simpson et al. (1995) have recently discovered a red 'bar-like' feature in a J–K color map; this 'bar' aligns in p.a. $\simeq 90°$ and extends about 1 kpc. There is excess emission (after subtracting a model of the galaxy starlight) at K band associated with the 'bar'. This infrared 'bar' is perhaps best interpreted as emission from hot ($\approx$ 700K) dust in a torus or disk viewed edge-on. Simpson et al. (1995) speculate that this torus may represent the outer parts of the 'obscuring torus' invoked to hide the broad line region (Miller & Goodrich 1990). These authors also infer that the obscuration to the nucleus is $A_V \approx 60$ mag and that the total mass in the torus is $M \approx 3 \times 10^6$ (h/1 pc)(r/500 pc) $M_\odot$, where h is the height of the torus and r its outer radius.

2.4. IONIZATION CONES - SHADOWING BY A DUSTY DISK?

An ionization cone is a region of high excitation, ionized gas within a triangular envelope on the sky (presumably conical or wedge-shaped in three dimensions), with one apex at the active nucleus. They are usually interpreted in terms of illumination of ambient or narrow line gas by a collimated beam of ionizing radiation from the nucleus. Dopita & Sutherland (1995) suggest instead that the emission-line region is excited by local shocks, with the cones resulting from entrainment and pressurisation of cool gas at the boundaries of an outflow driven by a relativistic jet. The first explanation is most convincing when the 'cone' has *sharp and straight* edges. Only in such cases can we be reasonably sure that the nebulosity is radiation-, rather than matter-, bounded. Strong evidence that the ionization cone in NGC 5252 is radiation-bounded comes from HI 21 cm mapping by Prieto & Freudling (1993). They find that the neutral hydrogen tends to avoid the ionization cones and there is good evidence for velocity continuity from

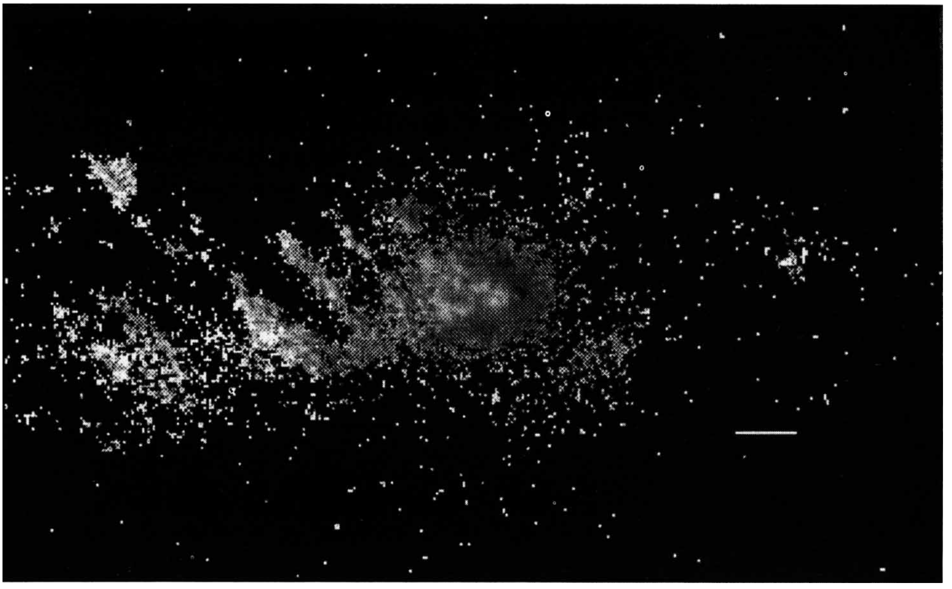

Figure 1. The ratio of the [OIII]λ5007 to the Hα+[NII]$\lambda\lambda$6548, 6583 image of the Seyfert 2 galaxy NGC 5643. High excitation gas is white, low excitation dark. The white bar indicates 1 arc sec ($\simeq$ 78 pc). The triangular envelope of the high excitation gas is notable. The data were obtained with HST by ASW, C. Simpson, G. A. Bower, T. M. Heckman, J. H. Krolik and G. K. Miley.

the neutral to ionized gases. These results provide strong support to the interpretation (Tadhunter & Tsvetanov 1989) that the ionized arcs within the triangular envelope in this galaxy represent pre-existing ring structures which have been ionized by a collimated, nuclear, radiation field. Still, many nebulosities in Seyfert galaxies are best described as bi-polar, and show strong evidence for interaction with radio jets and lobes (e.g. Wilson 1982; Whittle et al. 1988). In these cases, the morphologies by themselves do not indicate collimated nuclear ionizing radiation. An ionization cone, recently discovered by HST observations, is shown in Fig. 1. The morphological properties of ionization cones are as follows (cf. Wilson & Tsvetanov 1994):

1) Both bi-cones and single cones are seen. Single cones generally project against the far side of the galaxy disk, suggesting the counter-cone is hidden behind the disk's near side. Thus all cases may be intrinsically bi-conical.

2) Observed cone opening angles range between $\simeq 40°$ and $100°$. Projection effects can cause the observed opening angle of the ionized gas and the true opening angle of the photon cone to differ (see Mulchaey, Wilson & Tsvetanov 1996 for simulations of this effect).

3) Cone extents range between $\approx$ 100 pc and 2 kpc.

4) Clearly defined cones have, so far, been seen in only radio-quiet AGN.

The current lack of detections in radio-loud objects (especially Fanaroff-Riley class II radio galaxies) may reflect observational limitations occasioned by their greater distances than Seyfert galaxies, the lower mean interstellar gas density, and the possibility that the interstellar gas in these ellipticals may be mostly hot and any cool gas patchy.

5) Overall there is no relation between the cone and galaxy disk axes. However, a very strong alignment is found between the cone and radio axes. Thus the radio plasma and ionizing photons must be collimated by the same, or coplanar, disks. These disks are not coplanar with, and may be randomly oriented with respect to, the host galaxy disks (Ulvestad & Wilson 1984). NGC 4258 is an excellent example of this phenomenon: the plane of the disk mapped out in H_2O maser emission (Miyoshi et al. 1995) is almost perpendicular to that of the host galaxy disk. Consequently, the radio, optical and emission-line jet in this galaxy lies close to the galaxy disk (e.g. Cecil, Wilson & De Pree 1995).

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