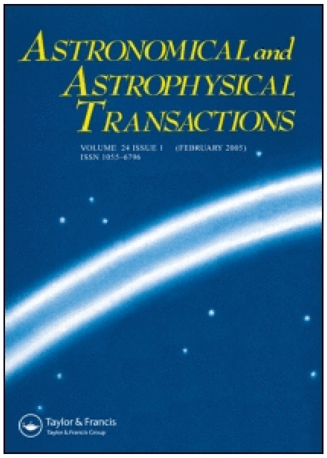

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P. Shastri [a]
[a] Indian Institute of Astrophysics, Bangalore, India

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SEYFERTS AND THEIR RADIO MORPHOLOGY

P. SHASTRI

Indian Institute of Astrophysics, Bangalore, India

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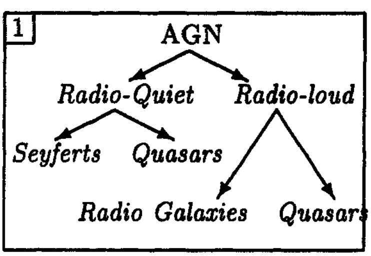
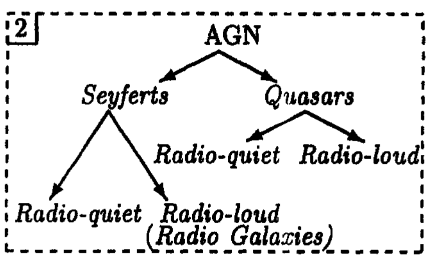
In this short review, current knowledge of the radio structure of Seyfert Galaxies is briefly outlined and its application in addressing 3 key debates, viz.,the validity of the Unified Scheme, the validity of the starburst model, and the source of ionization of the Narrow Line Region, is discussed.

KEY WORDS Seyfert galaxies, active galactic nuclei, radio structure

1 INTRODUCTION

In this review of the radio morphology of Seyfert galaxies and the related debates, Seyferts are defined to be Active Galactic Nuclei (AGN) that are optically *weak* ($M_B \geq -23$), in hosts of galaxy-type S0 or later, and radio-*quiet* ($S^{5\ \mathrm{GHz}}/S^B < 10$). Effectively, the taxonomy subscribed to is *1* below, as against *2* (e.g., Veron-Cetty and Veron, 2000). The choice is not merely semantic: the radio-quiet/radio-loud dichotomy is clearly more fundamental than the Seyfert-quasar dichotomy.





Further, Seyferts are customarily categorized into types 1 and 2 (Sy 1 and Sy 2), according to whether or not they have spectrophotometrically observable 'Broad' optical Emission Lines (BELs), i.e., lines with inferred Doppler-broadening >1000 km s^{-1} (for details of Seyfert anatomy, see Robson 1996, p. 334). Seyfert radio morphology can address the following debates:

- Are Sy 1s and 2s intrinsically similar, appearing different solely due to different orientations (the Unified Scheme) ?
- Can starbursts alone power Seyferts or is a more 'monstrous' engine, e.g., a supermassive black hole required to explain their observed power?
- Are the Narrow-Line clouds in Seyferts photoionized by the central continuum or shock-excited by the jets?

2 RADIO MORPHOLOGY OF SEYFERTS

One of the first radio images of a Seyfert was of Mrk 3 (Wilson *et al.* 1980), which showed two lobes straddling the optical nucleus. Subsequent higher fidelity images (e.g., Kukula *et al.*, 1993; Morganti *et al.*, 1999; Nagar *et al.*, 1999) show this and other Seyferts to have 'double' structures which resolve into elongations reminiscent of the jets of much higher power in radio galaxies, albeit confined to within the host galaxy. Some show radio emission coincident with the optical nucleus. Diffuse, ring-like or otherwise complex morphology is also sometimes seen. The inferred high brightness temperatures point to non-thermal emission being the dominant mechanism, and the spectra are consistent with it being synchrotron radiation.

3 SEYFERTS AND THE UNIFIED SCHEME

The Unified Scheme (US) for Seyfert galaxies (e.g., Antonucci, 1993) hypothesizes that Sy 1s and 2s constitute the same parent population and appear different *solely* due to their differing orientations. The US requires the presence of optically thick material around the central region in the form of a torus. When the torus is face-on, the BELs from the central clouds are directly visible, as in Sy 1s, whereas when the torus is edge-on, these clouds are obscured from view, resulting in Sy 2s. The US found particularly strong support in the discovery of BELs in *polarized light* from Sy 2s (Antonucci and Miller, 1985; Moran *et al.*, 2000), which is interpreted as originating from the hidden clouds and scattered periscopically into our line of sight. Other observations consistent with the predictions of the US include (i) the detection in Sy 2s of BELs of Paschen-β, to which the torus is expected to be transparent (Veilleux *et al.*, 1997), (ii) the paucity of measured ionizing photons in Sy 2s, expected to be due to the torus attenuating the *visible* ionizing continuum (e.g., Kinney *et al.*, 1991), (iii) the 'double-cone' morphology of the narrow emission line structures, interpreted as due to the torus shadowing the central ionizing photons (Wilson 1996). Results inconsistent with the US include (i) Sy 1 host galaxies being of earlier Hubble-type than Sy 2s (Malkan *et al.*, 1998), (ii) the galaxy densities around Sy 1s and 2s being dissimilar (Dultzin-Hacyan *et al.*, 1999) (iii) the polarization of the (scattered) nuclear continuum not matching with that of the BELs (Tran, 1995).

Radio studies in individual cases have yielded direct evidence supporting the existence of a molecular torus/disc around Seyfert nuclei as, e.g., in the discovery of ionized gas with elongated structure perpendicular to the kpc-scale radio jet in NGC 1068 (Gallimore *et al.*, 1997). In addition, the US has definite predictions for the radio morphology of Seyferts: the total radio luminosities of Sy 1s and 2s are expected to be similar and the radio structures are expected to differ only by projection effects. Indeed, Sy 1s and 2s have been shown to have similar luminosities on different spatial scales (Ulvestad and Wilson, 1989; Lal *et al.* these proceedings). Also, the radio linear sizes of Sy 1s are systematically smaller than those of Sy 2s (Morganti *et al.*, 1999). The result of Roy *et al.* (1994), however, contradicts the US, in that they reported that Sy 2s were more likely to show compact radio structures on pc-scales than Sy 1s. But rigorous tests of the US require Sy 1s and 2s that are *intrinsically similar.* When such a sample is constructed (by matching Sy 1s and 2s in orientation-independent parameters) and the pc-scales probed with VLBI, the 2 subclasses show a similar propensity for compact radio structures, and the contradiction with the US no longer exists (Lal *et al.*, these proceedings).

4 CAN SEYFERTS BE POWERED BY STARBURSTS ALONE?

Mrk 3, as imaged by Wilson *et al.* (1980), was then termed a 'double source', with the loaded meaning that a monstrous central engine (viz.,supermassive blackhole) produces collimated beams of plasma that power these lobes, like 'classical double' radio galaxies. An alternate model (Cid Fernandes, 1997 and refs. therein) tries to explain Seyferts by nuclear starbursts alone, where the radio emission is due to supernova remnants (SNRs). There is, however, strong radio morphological evidence against this model. Firstly, the derived brightness temperatures of the radio components in Seyferts at kpc-scales are often too high to be explained by clusters of SNRs. Secondly, and more conclusively, VLBI shows both types of Seyferts to have compact features on pc-scales with high brightness temperatures (e.g., Lal *et al.*, these proceedings), as against e.g., the distributed faint sources (clusters of SNRs!) seen in the nucleus of the known starburst galaxy Arp 220 (Smith *et al.*, 1998). Note that the low resolution images of Arp 220 (Norris, 1988) and Mrk 3 (Wilson *et al.*, 1980) on kpc-scales look similar. Thirdly, and most decisively, multi-epoch VLBI images have shown proper motion of the compact components (Ulvestad and Wrobel, 1999). One must add, however, that circumnuclear starbursts do *accompany* many a Seyfert activity (e.g., Heckman *et al.*, 1997), and a *few* of the radio components could well be due to SNRs.

5 IONIZATION OF THE NARROW-LINE REGIONS

The Narrow-Line Regions (NLRs) of Seyfert galaxies (e.g., Wilson, 1996) are clouds that emit high-excitation forbidden lines Doppler-broadened to $\sim$300–1000 km s^{-1}.

The NLRs of Seyferts often show 'double-cone' shapes with their apex close to the nucleus. The standard paradigm to explain the NLRs invokes photoionization by the nuclear continuum. The structures are explained, especially in the presence of the obscuring torus, since shadowing of the central ionizing continuum by the torus can account for the straight sharp edges of the 'cones' seen. The alternative, viz.,ionization by the jet, spurred by early correlations between the radio and [OIII] luminosities for Seyferts (de Bruyn and Wilson, 1978) was called into question by the argument that the radio powers of the jets are too low to ionize the NLRs (Wilson, 1997). Detailed optical and radio imaging of Seyferts has shown a very detailed spatial correspondence between the ionized structures and the radio components (e.g., Falcke *et al.*, 1998). Clearly, the two are directly physically connected, but this could also be via the compression of the ISM gas by the jets to densities inferred in the NLR (e.g., Taylor *et al.*, 1992). Bicknell *et al.* (1998) argue, on the other hand, for shock-excitation by the jets, and conclude therefore that if the jets are not thermal when produced, they must be mildly relativistic near the centre. There is, however, no decisive evidence yet for relativistic ejection. Proper motions measured so far obtain subluminal speeds (Ulvestad and Wrobel, 1999). The fraction of compact (pc-scale) radio emission would be a statistical measure of relativistic beaming if the the compact components are nuclear, and Lal *et al.* (these proceedings) show that, in their sample of Seyferts, this fraction is not systematically different for the face-on (beamed?) Sy 1s relative to the edge-on (unbeamed?) Sy 2s. This result may have to be reexamined, however, in the light of the fact that pc-scale radio components in Seyferts may, in some cases, be the 'hotspots' rather than the nuclei as, e.g., in Mrk 463E (Kukula *et al.*, 1999).

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