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Seyfert galaxies : Nuclear radio structure and unification

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Abstract. We have observed a sample of Seyfert (Sy) galaxies with global Very Long Baseline Interferometry (VLBI) to test predictions of the unification scheme which hypothesizes that Sys of Type 1 and of Type 2 constitute a single population of objects. If Sy 1 and Sy 2 galaxies differ only in the orientation of the axisymmetric active nucleus with respect to the observer, then, the parsec-scale radio structures of the two types should be similar. We chose a sample of 10 Sy 1s and 10 Sy 2s such that the two subsamples were intrinsically similar within the framework of the unified scheme. This was done by matching them as far as possible in orientation-independent parameters viz., host galaxy properties and measures of intrinsic power of the active nucleus. We present the results obtained from these observations and their implications for the unification scheme. We also discuss the results obtained from the measurements at all IRAS and 2–10 keV X-ray wavebands for our Sy galaxy sample using data from the literature.

Keywords : galaxies: active, jets, nuclei, Seyfert, radio continuum

1. Introduction

Sy galaxies are nearby, low luminosity Active Galacti Nuclei (AGN)s which occur mostly in spiral hosts and are usually taken to be "radio-quiet" objects. There are two kinds of Sy galaxies, types 1 and 2, distinguished by the widths of their spectrophotometrically observable emission lines; the implied kinematic Doppler widths are > 1000 km s^{-1} and < 1000 km s^{-1} for the two types, respectively. We define a Sy galaxy as a low-luminosity ($M_B > -23.0$), radio-quiet (ratio of 5 GHz to *B*–band flux density < 10) AGN whose host galaxy is a spiral. In order to ensure that the selected Seyferts are *bona fide* AGN we require that the Sy 1 galaxies have $H\beta_{FWHM}$ (or $H\alpha_{FWHM}$) nuclear line widths exceeding 1,000 km s^{-1} (Khachikian & Weedman 1974), and that the Sy 2 galaxies have the ratio of the [O III] λ5007 to Hβ line intensities exceeding 3 (Dahari & De Robertis 1988).

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The unified scheme for Sys hypothesizes that Sy of type 1 and 2 comprise a single population and appear different due to the orientation of the axisymmetric active nucleus with respect to the observer. According to the unification scheme, the torus of obscuring material is present outside the broad line region in all Sys. The Sy 1s are those where we have a direct view of the central engine and the Sy 2s are those where our line-of-sight to the central engine is blocked by the torus. Broad emission lines (i.e. with implied Doppler widths > 1000 km s^{-1}) have been detected in a few Sy 2s in *polarized* light (Antonucci & Miller 1985). This result strongly supports the unification scheme hypothesis.

1.1 Outline of the thesis

Chapter 1 of the thesis introduces the term 'Active galaxy' and the various types of active galactic nuclei that are generally recognised. We then focus on Sy galaxies, and develop the unification model for Sy 1 and Sy 2 galaxies. We also present several pieces of evidence in support and against this model. In Chapter 2, the result that poses a çhallenge to the unified scheme which we aim to address, is discussed. We introduce aperture synthesis and Very Long Baseline Interferometry (VLBI) which is the key to achieve parsec-scale resolution. We then outline our rationale for the selection of our sample and describe its construction. In Chapter 3, we first give the description of the observing procedure, data reductions and analysis. We give the description of the images for our sample sources supplemented by data from the literature wheresoever necessary. Chapter 4 uses results from Chapter 3 within the formalism in which our sample was constructed to test the unified scheme. We address the starburst *versus* accretion powered central engine debate as well as the unified scheme hypothesis and relativistic beaming. Chapter 5 compares the radio data with the data collated at IR and X-ray wavelengths that are published in the literature. The final chapter (Chapter 6) summarizes the main results obtained in the thesis and brings together the conclusions from this work, highlighting our contribution to the understanding of Sy galaxy phenomenology. We also critically assess the strengths and weaknesses of our work and highlight opportunities for further study.

2. Aim of the research

Sy galaxies have low luminosity radio emission, but they do show radio emitting jet-like structures on small scales which appear to be the low-power analogues of jets seen in radio powerful AGNs (e.g. Nagar et al. 1999). The unified scheme predicts that the radio emission should be similar in the two classes of Sys (since it is unattenuated by the obscuring torus), and their radio structures should differ only due to projection effects. However, this issue is controversial; e.g. Roy et al. (1994), using the 275-km long single baseline Parkes-Tidbinbilla interferometer at 2.3 GHz, reported that Sy 2s were more likely to show compact radio emission than Sy 1s. This result is inconsistent with the predictions of the unification scheme hypothesis. The inconsistency remains even if mild relativistic beaming is invoked, because in this case, the face-on AGNs, viz., Sy 1s, would be more likely to show compact structures. *Our goal was to test predictions of the unified scheme, by investigating the parsec scale radio morphology of Sys using a matched sample of Sy 1 and Sy 2 galaxies.*

3. The sample

Our sample selection criteria were as follows: (i) the object should be a *bona fide* Sy galaxy (cf. our definition), (ii) it must be in a host galaxy that is a confirmed spiral, (iii) it must be detected with ~ 1 arcsecond resolution at 5–8 GHz and have a detected compact component brighter than 8 mJy at these frequencies and on these scales (i.e. as observed by VLA *A* or *B* array; this criterion was required to make our experiment feasible), and (iv) the host galaxy must have the observed ratio of minor and major isophotal diameter axes > 0.5; we thereby exclude edge-on host galaxies so as to minimize selection effects due to obscuration. We note that Pringle et al. (1998) and Nagar & Wilson (1999) have shown that there is no correlation between the host galaxy axis and the direction of the radio jet.

From all Sys with available radio images at ~ 1 arcsecond resolution in the literature (i.e. all VLA *A*, & *B* array observations of Sys) we chose 10 Sy 1s and 10 Sy 2s meeting the above criteria, such that the two sub-samples had similar distributions of heliocentric redshift, luminosity of the host galaxy (i.e. minus the AGN) in the optical *B*–band, [O III] λ5007 luminosity, and galaxy bulge luminosity. Thereby we ensured that the sub-samples of Sy 1s and Sy 2s are *matched*, as far as possible, with respect to their intrinsic AGN power and host galaxy properties which are *orientation-independent* parameters.

4. Observations

Aperture synthesis is a method where two or more antennas are arranged so that their relative positions may be altered to occupy successively the whole area of a much larger equivalent antenna. By combining mathematically the information derived from these different positions, it is possible to obtain high resolution maps equivalent to that of a single large antenna.

VLBI achieves high angular resolution by using two or more widely (> 1,000 km) separated radio telescopes. It is a special case of aperture synthesis and is an extension of interferometric techniques to the largest obtainable baselines. With telescopes separated by intercontinental distances and operating at cm wavelengths, a resolution of about 1 milliarcsec can be achieved.

We observed 15 objects from our sample in Feb 1998 at 5 GHz using a 14–station global VLBI array, consisting of the phased VLA, 10 telescopes of the Very Long Baseline Array, and three telescopes of the European VLBI Network, *viz.*, Effelsberg., Noto and Torun. We thus have simultaneous VLA data also (angular resolution ~ 1″.0) for these 15 objects. Of the remaining 5 sample objects, 4 have VLBI data in the literature which we add to our own data and use in inferring our results below.

5. Results

We detected all 15 objects that we observed on both arcsecond and milliarcses scales. Some examples are shown in Figure 1 (NGC 2639, a Sy 1 and Mrk 533, a Sy 2) and Figure 2 (MCG 8-11-11, a Sy 1 and Mrk 78, a Sy 2). The Figures also show that we detect multiple components on parsec scales in a few objects. We find that :

(i) Sy 1 and Sy 2 galaxies have equal tendency to show compact radio structures and our results do not agree with those obtained by Roy et al. (1994) (based on the significantly different detection rates of Sy 1 and Sy 2 galaxies, Roy et al. (1994) concluded that compact radio structures are much more common in Sy 2 than in Sy 1 galaxies).

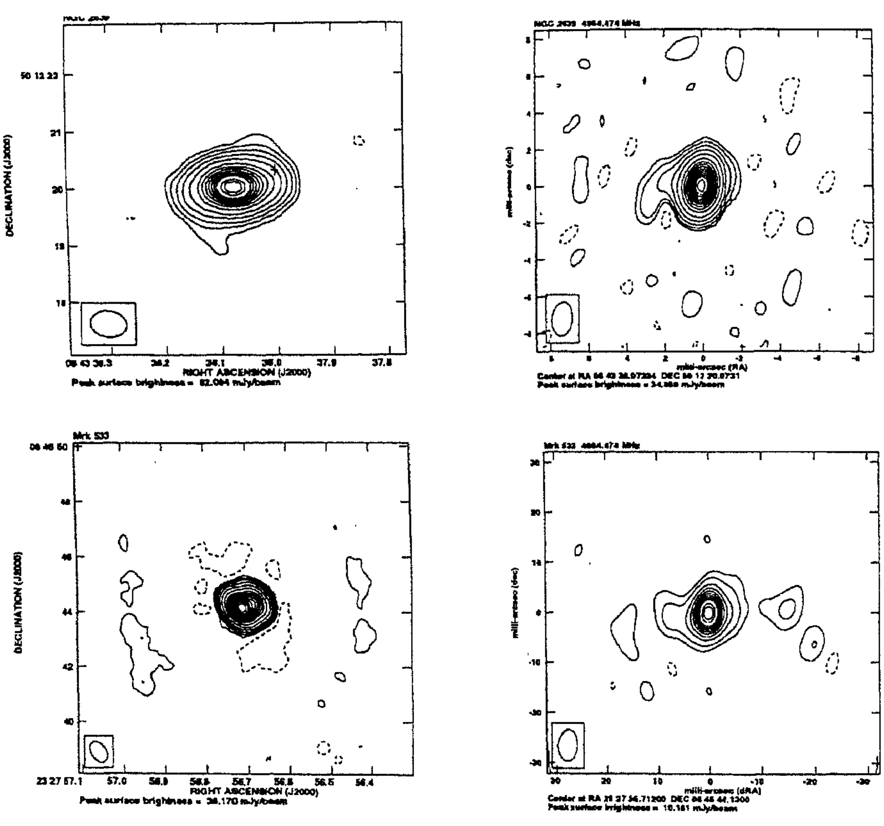

Figure 1. 6 cm VLA (*Upper, left panel*; the contour levels are at –0.4, 0.4, 1, 2, 4, 8, 16, 24, 32, 40, 48, 56, 64, 80 & 90% of the peak surface brightness) & VLBI (*Upper, right panel*; the contour levels are at –0.5, 0.5 1, 2, 4, 8, 16, 24, 32, 40, 48, 56, 64, 80 & 90% of the peak surface brightness) images of NGC 2639 and 6 cm VLA (*Lower, left panel*; the contour levels are at –0.4, 0.4, 1, 2, 4, 8, 15, 24, 32, 40, 48, 56, 64, 72, 80 & 90% of the peak of the peak surface brightness) & VLBI (*Lower, right panel*; the contour levels are at –4, 4, 8, 16, 24, 32, 40, 48, 56, 64, 80 & 90% of the peak surface brightness) image of Mrk 533. The ellipse in the bottom left corner of the image gives the size (FWHM) of the beam.

(ii) a starburst alone cannot power these radio sources because they have high brightness temperatures, and the core radio luminosities at 5 GHz are ~ 10^{28} ergs s^{-1} Hz^{-1}, arising from a region smaller than a few cubic parsec.

(iii) the distributions of radio luminosities on parsec-scales for the two classes of Sy galaxies show no statistically significant difference at a significance level of 0.05 (Mann-Whitney U test; Siegel & Castellan, 1988).

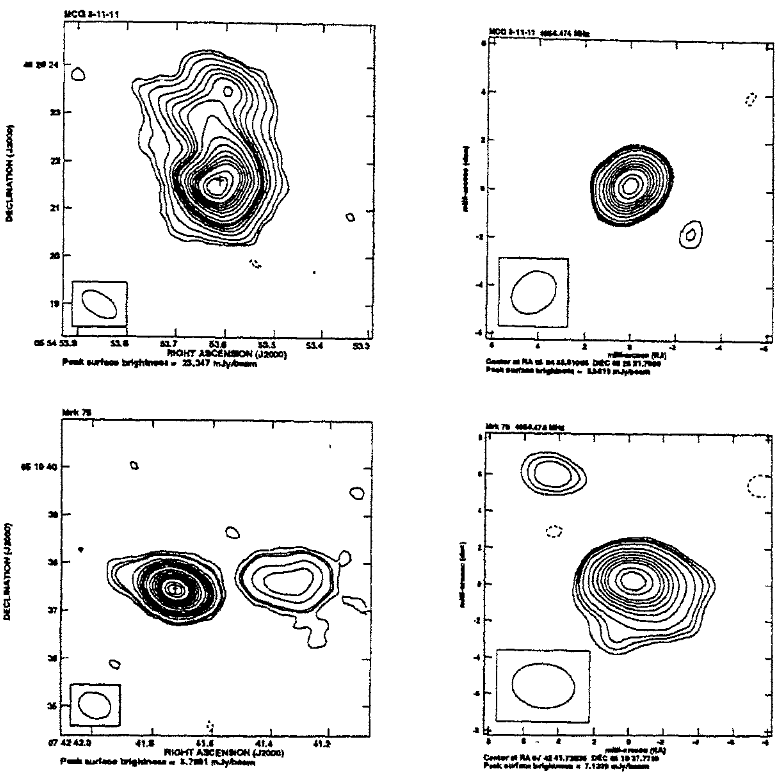

Figure 2. 6 cm VLA (*Upper, left panel*; the contour levels are at –0.6, 0.6, 1, 2, 4, 8, 10, 12, 16, 24, 32, 40, 48, 56, 64, 80 & 90% of the peak surface brightness) & VLBI (*Upper, right panel*; the contour levels are at –8, 8, 10, 12, 16, 24, 32, 40, 48, 56, 64, 80 & 90% of the peak surface brightness) images of MCG 8-11-11 and 6 cm VLA (*Lower, left panel*; the contour levels are at –1, 1, 1.6, 2, 4, 6, 8, 10, 12, 16, 24, 32, 40, 48, 56, 64, 80 & 90% of the peak surface brightness) & VLBI (*Lower, right panel*; the contour levels are at –8, 8, 10, 12, 16, 24, 32, 40, 48, 56, 64, 80 & 90% of the peak surface brightness) image of Mrk 78. The ellipse in the bottom left corner of the image gives the size (FWHM) of the beam.

(iv) the fraction of radio emission detected on milliarcsec scales (i.e. total radio emission detected with VLBI) to the emission detected on kiloparsec scales (i.e. total VLA radio emission) is not significantly different for the two Sy sub-classes at a significance level of 0.10 (Mann-Whitney U test). If the jets were significantly relativistically beamed, we would expect Sy 1s to show systematically more prominent compact radio emission than Sy 2s.

(v) the ratio of compact radio emission (i.e. emission detected with VLBI) to the extended radio emission detected on kiloparsec scales (i.e. total VLA-scale radio emission minus the total VLBI-scale radio emission) is also not significantly different for the two Sy subclasses.

(vi) Using the 12μ, 25μ, 60μ and 100μ flux density measurements from IRAS which are available for 17/20 objects in our Sy sample, we find that the two Sy subclasses have similar distribution of infrared power at all these wavebands. Further, while the infrared flux densities correlate with the kiloparsec-scale radio flux densities, they do not correlate with the parsec-scale flux densities. It thus seems likely that a significant fraction of the IR emission comes from dust on kpc-scales.

(vii) A few of the sample objects have X-ray luminosities (7 Sy 1s and 6 Sy 2s) and photon indices (8 Sy 1s and 5 Sy 2s) in the 2-10 keV band in the literature. The X-ray luminosities of the Sy 1s appear systematically higher than those of the Sy 2s, not inconsistent with the predictions of the unified scheme, although the small-number statistics should be kept in mind. Within the limitations of these small numbers, the photon indices of the two subclasses do not show any systematic difference, however.

6. Conclusions

In the thesis we have presented radio images of 15 Sys that were observed by us with VLBI and 4 Sys that had VLBI images in the literature. The maps presented in the Chapter 3 of the thesis reveal, for the first time, the milliarcsec scale radio structures of a large carefully selected sample of Sy galaxies. These measurements provide a useful database for investigating the generic properties of compact radio cores in the nuclei of Sy galaxies.

From our results we conclude that Sy 1 and Sy 2 galaxies have equal tendency to show compact radio structures, in contrast to the result of Roy et al. (1994), who concluded that compact radio structures were much more common in Sy 1s than in Sy 2s. Our results so far appear to be consistent with the unification scheme hypothesis, and there is no evidence for significant relativistic beaming in their nuclei. The IR luminosisties appear similar for the two Sy subclasses. X-ray luminosities and photon indices (2-10keV) which are available for a few objects of the sample do not show inconsistencies with the unified scheme.

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