J. Astrophys. Astr. (2011) **32,** 497–500

Seyfert Galaxies: Radio Continuum Emission Properties and the Unification Scheme

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Abstract. Seyfert galaxies are classified mainly into type 1 and type 2 depending on the presence and absence of broad permitted emission lines in their optical spectra, respectively. Unification scheme hypothesizes that the observed similarities and differences between the two Seyfert subtypes can be understood as due to the differing orientations of anisotropically distributed obscuring material having a torus-like geometry around the AGN. We investigate the radio continuum emission properties of a sample of Seyfert galaxies in the framework of the unification scheme.

Key words. Galaxies: Seyfert—galaxies: active—radio continuum: galaxies.

1. Introduction

Seyfert galaxies are a subclass of Active Galactic Nuclei (AGN) and are categorized as low-luminosity ($M_{\rm B\text{-}band} > -23$; Schmidt & Green 1983), radio-quiet AGN ($\frac{F_{5\ \rm GHz}}{F_{\rm B\text{-}Band}} < 10$; Kellermann *et al.* 1989), hosted in spiral or lenticular galaxies (Weedman 1977). Seyfert galaxies are broadly classified into type 1 and type 2 depending on the presence and absence of broad permitted emission lines in their optical spectra, respectively. Unification scheme of Seyfert galaxies hypothesizes that Seyfert type 1s and type 2s constitute the same parent population and appear different solely due to the differing orientations of dusty molecular obscuring material having a torus-like geometry around the AGN. In Seyfert type 2s, molecular dusty torus intercepts the observer's line-of-sight and blocks the direct view of the nuclear region, however, in type 1s, observer's line-of-sight is away from the plane of the torus and the central region is visible (Antonucci & Miller 1985; Antonucci 1993). There have been several studies to test the predictions of Seyfert unification scheme at radio regime (Wilson & Ulvestad 1982; Thean *et al.* 2000), although, certain subtle selection effects are inherent in most of the samples (Ho & Ulvestad 2001). Furthermore, most of the Seyfert samples in the literature have been studied at higher frequencies ($\geq$ 1.4 GHz) with high resolution ($\sim$sub-arcsec) observations (e.g., Kukula *et al.* 1995; Thean *et al.* 2001), which effectively filter out the extended low-surface-brightness radio emission component. We attempt to investigate the low-frequency radio emission properties at 240 MHz and 610 MHz of a sample of Seyfert galaxies in the framework of the unification scheme.

2. The Sample

Sample selection is one of the most important issues in testing the unification scheme. We acquire a sample of 20 Seyfert galaxies (10 type 1s and 10 type 2s) in which the two Seyfert subtypes have matched distributions in isotropic properties (i.e., cosmological redshift, [OIII] λ5007 Å line luminosity, Hubble type of the host galaxy, total absolute stellar luminosity of the host galaxy and absolute bulge magnitude) that are independent to the orientation of the obscuring torus, AGN and the host galaxy. Our selection criteria mitigate biases and ensure that we are not comparing entirely intrinsically different sources selected from different parts of the (luminosity, bulge mass, Hubble type, redshift) evolution function. All our sample sources satisfy the GMRT observing feasibility.

3. Observations and data reduction

We carried out full array GMRT snapshot observations of all our sample sources at 610/240 MHz dual frequency using bandwidth of 32 MHz and 4 second integration time. The data were reduced in a standard way using NRAO 'AIPS' package. Absolute flux and bandpass calibration were done by observing standard flux calibrators 3C 147 and 3C 286, at the start and end of the observing run. The phase calibration was done by observing a nearby phase calibrator source before and after every scan of the target sources. For each run, bad visibility points were edited out, after which the data were calibrated. The edited and calibrated visibilities were Fourier transformed into radio maps using 'IMAGR' task in AIPS with uniform weightage. Primary beam size of full array GMRT at 610/240 MHz is rather large $\sim 43'/81'$ and therefore we performed wide field imaging by dividing whole field-of-view in $\sim$ 25/49 sub-fields. Self-calibration is used iteratively to improve the image quality.

4. Results and conclusions: Comparison of radio properties of the two Seyfert subtypes

The unification scheme hypothesizes that the two Seyfert subtypes are intrinsically similar and therefore both the subtypes are expected to show similar level of nuclear activity as well as star-formation. The observed radio emission at cm wavelengths in Seyfert galaxies is independent to the orientation of obscuring torus and AGN as it is optically thin to the obscuring torus and there is no relativistic beaming in Seyfert galaxies (Ulvestad *et al.* 2005). Therefore both the Seyfert subtypes are expected to show statistically similar radio luminosities and radio spectra. We compare the radio luminosity distributions of the two Seyfert subtypes of our sample at 240 MHz, 610 MHz, 1.4 GHz and 5.0 GHz and find that the two Seyfert subtypes have similar radio luminosity distributions with similar median values at respective frequencies. The radio luminosities at 240 MHz, 610 MHz, 1.4 GHz and 5.0 GHz are in the range of $\sim 10^{28}$–10^{31} erg s^{-1} for both the Seyfert types. Figure 1 shows the distributions of

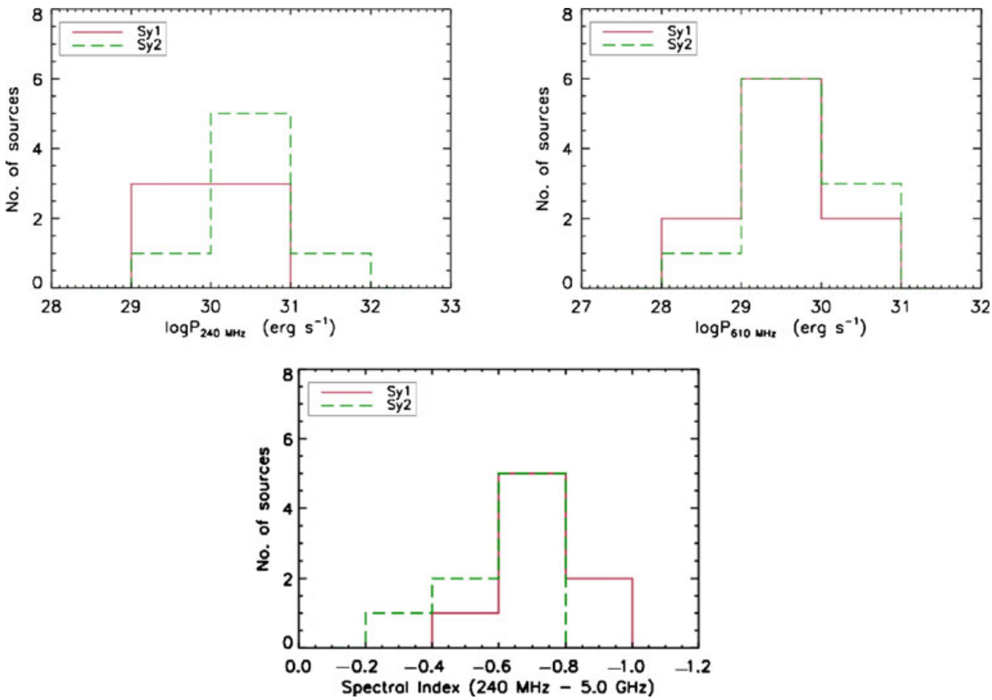

Figure 1. Distributions of radio luminosities at 240 MHz, 610 MHz (*left and right panel*) and multi-frequency integrated spectral index (*bottom panel*) for the two Seyfert subtypes.

radio luminosities at 240 MHz and 610 MHz for the two Seyfert subtypes. We also obtain multi-frequency (240 MHz, 610 MHz, 1.4 GHz, 5.0 GHz) integrated radio spectra of our sample sources using 240 MHz, 610 MHz flux densities from our GMRT observations, 1.4 GHz flux densities from NVSS (Condon *et al.* 1998) and 5.0 GHz flux densities from the literature (e.g., Gallimore *et al.* 2006). Figure 1 shows that the distributions of average spectral index in 240 MHz–5 GHz regime are similar for the two Seyfert subtypes. Since GMRT observations at 240 MHz, 610 MHz and NVSS observations at 1.4 GHz are of low resolution, we considered 5 GHz flux density measured with low resolution observations, e.g., VLA in 'D' configuration or observations with single dish Green Bank, and Parkes radio telescopes. We note that the average spectral index in 240 MHz–5.0 GHz radio regime is fairly steep ($\alpha \sim -0.7$, $S_\nu \propto \nu^\alpha$) for most of our sample sources and both the Seyfert subtypes have similar spectral indicies. The steep radio spectral index (~ -0.7) is consistent with the synchrotron radio emission from optically thin plasma. A few sample sources show inverted or flat spectrum which may be due to significant contamination from starburst or self-absorption of synchrotron emission. According to the unification scheme, if radio emission is primarily from AGN jet, Seyfert type 1s are expected to show smaller radio source sizes than 2s, since type 1s have nearly face-on tori and their radio jets would be expected to lie along the line-of-sight of the observer, and hence to be foreshortened. In our 240 MHz and 610 MHz GMRT observations, radio emission in Seyferts is primarily dominated by the central nuclear component.

Several of both the Seyfert subtypes of our sample sources show the signature of kpc-scale extended emission at 610 MHz, while at 240 MHz, most of the sources are unresolved due to rather large synthesized beam and high rms. The extended kpc-scale emission may have contribution from AGN as well as star formation. Also, there is a possibility of distortion of radio jet due to its interaction with dense interstellar medium of the host galaxy, therefore, kpc-scale jet-related emission may not necessarily align with the pc-scale jet emission (Kharb *et al.* 2006). We do not compare the radio sizes of the two subtypes since many of our sample sources are either unresolved or marginally resolved at 240 MHz and 610 MHz due to coarser resolution and lower sensitivity. Using our sample of Seyfert galaxies we conclude that low-frequency radio properties, i.e., radio spectra, radio luminosities are similar for Seyfert type 1s and type 2s, consistent with the orientation and obscuration based Seyfert unification scheme.

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