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Radio sources in the Massive and Distant Clusters of the WISE Survey (MaDCoWS)

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Radio sources in galaxy clusters at high redshifts ($z > 0.8$) remain less explored due to the limitations of existing radio surveys and the dearth of known clusters at those redshifts. Recently new high redshift (~ 1) clusters have been detected using the Wide-field Infra-red Survey Explorer (WISE). We present preliminary results from our radio survey of the Massive and Distant Clusters from the WISE Survey (MaDCoWS) with the Giant Metrewave Radio Telescope.

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1. Introduction

Radio surveys of clusters of galaxies are necessary to study the occurrence and evolution of AGN in the dense environments of the intra-cluster medium (ICM). All sky radio surveys with sufficient depth have already facilitated studies of nearby clusters but have limitations to study high redshift clusters due to insufficient resolution and sensitivity. For example, the widely used all sky surveys such as the NRAO VLA Sky Survey (NVSS,[1]), the Sydney University Molonglo Sky Survey (SUMSS,[2]), VLA Low Frequency Sky Survey (VLSS, [3]), the Westerbork Northern Sky Survey (WENSS, [4]) have resolutions in the range $45'' - 80''$ which at redshifts ~ 0.05 are equivalent to linear resolutions of $44 - 80$ kpc, sufficient to study individual galaxies; but at $z = 1$ imply linear resolutions of $360 - 640$ kpc that are not sufficient to identify unique optical counterparts. The Faint Images of the Radio Sky at Twenty centimeters (FIRST,[5]) survey at 1.4 GHz with a resolution of $\sim 5''$ is useful to resolve sources on linear scales of ~ 50 kpc. However, FIRST does not cover the full sky and is relatively shallow (~ 0.2 mJy beam^{-1}) to detect faint emission from galaxies and the ICM. Deep surveys sample limited regions of the sky and thus cannot be effectively used to study large samples of high redshift clusters. Thus pointed observations of a sample of galaxy clusters at high redshifts are needed in order to probe the radio sources they host.

The energy density of Cosmic Microwave Background (CMB) photons increases with redshift as $(1+z)^4$, and thus the inverse Compton (IC) losses are the main source of energy loss for the relativistic electrons responsible for the synchrotron emission at high redshifts. The equivalent IC field, $B_{IC}(\mu\mathrm{G}) \approx 3.2(1+z)^2$, is about 12.8 μG at redshift 1. Moreover due to the cosmological redshift, observations at 1.2 GHz are sampling a rest frequency of 2.4 GHz at the source. Thus to make a comparison with the spectra of nearby sources known around 1 - 1.4 GHz, observations of high redshift clusters at 0.5- 0.7 GHz are needed.

2. Massive and Distant Clusters of the WISE Survey

The MaDCoWS [6, 7] is a new IR-selected galaxy cluster survey based on the all-sky catalogues of the Wide-field Infrared Survey Explorer (WISE, [8]). The WISE infrared and Sloan Digital Sky Survey (SDSS) DR8 optical photometry [9] were combined to robustly isolate galaxy clusters at z$\sim$1 in the northern hemisphere. The selection through IR colour magnitude diagram allows to select high redshift galaxies.

High redshift clusters have been extracted earlier mainly through deep surveys of limited regions of the sky. The 10,000 deg^2 survey footprint of WISE is four times larger than the South Pole Telescope - Sunyaev Ze'ldovich (SPT-SZ) Survey [10] and 1000 times larger than the area of the IRAC Distant Cluster Survey (IDCS), in which the most massive galaxy cluster at $z > 1.5$ known to date was found [11, 12]. Given the unprecedented volume surveyed at high redshift, the MaDCoWS sample is expected to contain a large number of very massive and distant clusters [13]. There are a total of 19 spectroscopically confirmed galaxy clusters in the sample with redshifts in the range $0.7 < z < 1.3$.

The MaDCoWS clusters span a variety in their properties. Some of the MaDCoWS clusters are relaxed, with a centrally concentrated core of galaxies, a well-defined red sequence, and a few emission-line objects. But others span the range of possible combinations of these characteristics,

Cluster	RA_{J2000} hh mm ss	DEC_{J2000} dd mm ss	z	M_{500} 10^{14} $M_\odot$	ν_{obs} MHz	t_{obs} min
MOO_J0012+1602	00 12 13.0	+16 02 16	0.944	1.4 ± 0.5	610	125
					1280	100
MOO_J0133-1057	01 33 55.6	-10 57 44	0.957		610	125
					1280	175
MOO_J0212-1813	02 12 04.1	-18 14 13	1.098		610	150
MOO_J0224-0620	02 24 51.3	-06 20 17	0.816		610	175
MOO_J1155+3901	11 55 45.4	+39 01 06	1.009	2.9 ± 0.7	610	175
MOO_J1514+1346	15 14 43.8	+13 46 32	1.059	2.2 ± 0.6	610	150
					1280	150

Table 1: Basic information of MaDCoWS clusters [13] with the GMRT observing frequencies, ν_{obs} and duration t_{obs} .

some having a few emission-line objects but little spatial concentration in the core region, and others having a relatively high fraction of emission-line galaxies and a well-formed cluster core. Thus MaDCoWS is an unbiased starting point to study the properties of radio sources in high redshift galaxy clusters.

2.1 Sample

We extracted a sub-sample from the MaDCoWS based on the criterion of the occurrence of a radio source detected in the NVSS within $2'$ of the cluster position. At the resolution of the NVSS the source cannot be uniquely identified with optical/infra-red detected galaxies. Among the selected sample, masses (M_{500}) are available for 3 clusters through Combined Array for Research in Millimetre-wave Astronomy (CARMA) detections [13] and are in the range $1.4 - 3 \times 10^{14}$ $M_\odot$ (Tab. 1).

3. GMRT observations and data reduction

Observations at 610 MHz and L-band of five MaDCoWS clusters were carried out with the Giant Metrewave Radio Telescope (GMRT) in Cycle 28. The FITS data were processed with 'Yet Another Flagger' (N. Mohan, private communication) to remove radio frequency interference. The rest of the processing was carried out in AIPS. Additional manual flagging to remove bad antennas and time ranges was done. The data were then calibrated and imaged using the AIPS task 'imagr'. A few rounds of phase only self-calibration and a final round of amplitude and phase self-calibration were carried out.

4. Results

The radio images of the clusters MOO_J1155+3901, MOO_J0012+1602, MOO_J1514+1346 and MOO_J0133-1057 have been made (Tab. 2). Within 500 kpc radius from the cluster centre

Cluster	RA_{J2000} hh mm ss	DEC_{J2000} dd mm ss	ν_{obs} MHz	rms mJy b^{-1}	Beam $''\times''$, p. a.
MOO_J0012+1602	00 12 13.0	+16 02 16	1280	0.045	2.6×2.0, 63.4°
MOO_J0133-1057	01 33 55.6	-10 57 44	610	0.051	5.1×4.9, 31.5°
MOO_J1155+3901	11 55 45.4	+39 01 06	610	0.04	5.4×4.1, 43.2°
MOO_J1514+1346	15 14 43.8	+13 46 32	610	0.06	5.0×4.0, 42.7°

Table 2: GMRT images of the MaDCoWS clusters.

(MaDCoWS position), we looked for radio sources with identification in 3.6 micron WISE images. For example, the 610 MHz image of MOO_J1514+1346 is shown in Fig. 1. Two radio souces near the cluster centre can be associated with two spectroscopically identified galaxies in this cluster. The third radio source within 500 kpc radius, has a 3.6 micron counterpart but no associated spectroscopically identified galaxy.

The cluster MOO_J0012+1602 contains a double source at the centre for which no spectroscopically identified counterpart is present. In 610 MHz images of MOO_J1155+3901 and MOO_J0133-1057, single radio sources are detected within 500 kpc radius of each of the cluster centre. Analysis of the remaining data are ongoing.

5. Discussion and conclusions

Radio sources in galaxy clusters at high redshift are of interest to study the evolution of the mode of accretion of galaxies and the evolution of the cluster itself. At lower redshift clusters are known to contain radio sources associated with galaxies and also those associated with the ICM. We have presented preliminary results from our project to study radio sources in high redshift clusters ($z\sim1$) using the GMRT. Radio data analysis of three clusters at 610 MHz and one cluster at 1280 MHz have been completed. In the analysis of these four clusters, we have not detected diffuse radio sources associated with the ICM. Within 500 kpc radius from the cluster centre, we detect radio double sources or point sources. The identification of spectroscopically confirmed cluster member galaxies with radio sources is ongoing.

Relativistic electrons suffer dominant losses of energies via IC losses to CMB photons. Therefore detections of diffuse radio sources in clusters at these redshifts are a challenge. In the massive cluster 'El Gordo' at redshift of 0.87 a radio halo and relics have been detected [14]. With a mass of $M_{500}=(1.17\pm0.17)\times10^{15}$ $M_{\odot}$, 'El Gordo' is about 3 - 5 times more massive than the MaDCoWS clusters that are surveyed. According to the studies carried out in the past decade, massive and merging clusters have been found more likely to host radio halos than less massive clusters [15, 16]. However the less massive clusters at all redshifts have not been systematically surveyed and according to the predictions of the turbulent re-acceleration model [16] steep spectrum and less powerful radio halos may be present but have never been looked for. The non-detections so far of cluster-scale radio sources in MaDCoWS are thus not a surprise.

The other aspect of our study is to build the statistics of radio sources in high redshift galaxy clusters. The MaDCoWS sample is being followed up to identify cluster member galaxies using

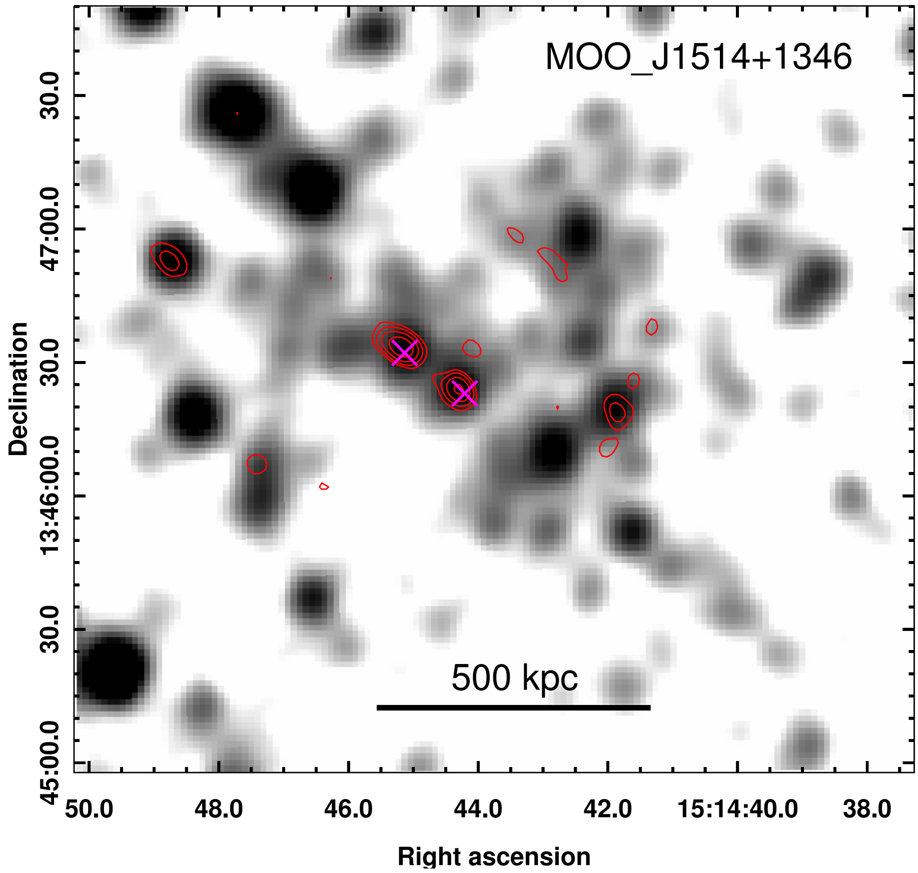

Figure 1: GMRT 610 MHz contours (red) overlaid on the WISE 3.6 micron image of MOO_J1514+1346 shown in grey-scale. The contour levels are at $3\sigma \times [\pm 1, 2, 4, ...]$ mJy b^{-1} where $\sigma = 0.06$ mJy b^{-1} and the beam is $5'' \times 4''$, p. a. 42.7°. The crosses mark the positions of two spectroscopically identified galaxies with IDs 1667 and 2668 from the left to the right [7].

spectroscopy [7]. Our study at 610 and 1280 MHz with resolutions of $5'' - 2''$ will be able to identify radio sources with the galaxies (e.g. Fig. 1). The radio sources in MaDCoWS sample will be used to build a radio luminosity function to compare with that known at lower redshifts [17]. The analysis of GMRT data on the remaining clusters and further observations of more clusters will enable to build the sample of radio sources for this study.

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