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High Frequency Cluster Radio Galaxies: Luminosity Functions and Implications for SZE Selected Cluster Samples

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We study the overdensity of point sources in the direction of X-ray-selected galaxy clusters from the Meta-Catalog of X-ray detected Clusters of galaxies (MCXC; $\langle z \rangle = 0.14$) at South Pole Telescope (SPT) and Sydney University Molonglo Sky Survey (SUMSS) frequencies. Flux densities at 95, 150 and 220~GHz are extracted from the 2500~deg^2 SPT-SZ survey maps at the locations of SUMSS sources, producing a multi-frequency catalog of radio galaxies.
In the direction of massive galaxy clusters, the radio galaxy flux densities at 95 and 150~GHz are biased low by the cluster Sunyaev-Zel'dovich Effect (SZE) signal, which is negative at these frequencies. We employ a cluster SZE model to remove the expected flux bias and then study these corrected source catalogs. We find that the high frequency radio galaxies are centrally concentrated within the clusters and that their luminosity functions (LFs) exhibit amplitudes that are characteristically an order of magnitude lower than the cluster LF at 843~MHz. We use the 150~GHz LF to estimate the impact of cluster radio galaxies on an SPT-SZ like survey. The radio galaxy flux typically produces a small bias on the SZE signal and has negligible impact on the observed scatter in the SZE mass-observable relation. If we assume there is no redshift evolution in the radio galaxy LF then 1.8 ± 0.7~percent of the clusters with detection significance $\xi \geq 4.5$ would be lost from the sample. Allowing for redshift evolution of the form $(1+z)^{2.5}$ increases the incompleteness to 5.6 ± 1.0~percent. Improved constraints on the evolution of the cluster radio galaxy LF require a larger cluster sample extending to higher redshift.

Summary

We use the MCXC catalog of galaxy clusters, the SUMSS catalog of radio galaxies, and the SPT-SZ survey maps to measure the overdensity of radio galaxies associated with clusters. We construct radio galaxy LFs and radial profiles at 843~MHz, 95~GHz, 150~GHz and 220~GHz. The MCXC systems in the SPT-SZ and SUMSS regions have a median redshift $z \sim 0.1$, and the highest redshift system is at $z = 0.686$. There are 139 MCXC objects in the SPT-SZ region and 333 in the SUMSS region; they span the mass range from groups to clusters with a median mass $M_{500} = 1.5 \times 10^{14} \mathrm{M}_\odot$ and $M_{500} = 1.7 \times 10^{14} \mathrm{M}_\odot$ in the SPT-SZ and SUMSS regions, respectively.

To construct LFs at high frequencies, we examine SPT maps at the locations of SUMSS sources, extracting the high frequency fluxes and correcting for the cluster SZE flux at 95 and 150~GHz. We compare this sample with the 150~GHz sample with uncorrected fluxes to examine the impact of SZE flux biases, showing that they are significant – especially for high redshift clusters that are more compact on the sky and for higher mass clusters that have stronger SZE signatures. In essence, it is more challenging to find cluster radio galaxies at high frequency in high redshift and high mass clusters, because the SZE signature is biasing their fluxes low.

We use the SUMSS selected sources with fluxes measured at SPT frequencies and correct for SZE flux bias (at 95 and 150~GHz) to construct the cluster radio galaxy sample for further analysis. We find that the radial profile is centrally concentrated, consistent with an NFW model with concentration $c = 108^{+107}_{-48}$. We examine the spectral indices of the radio galaxy population, finding that the spectral index α measured between 95 and 150~GHz is steeper than that measured between 843~MHz and these high frequencies. We construct the LFs and find best fit parametrizations within the context of \citet{condon02} models. In doing so, we assume the overdensity of radio galaxies toward a cluster is at the redshift of the cluster, and we apply a k-correction using the spectral indices extracted from the sample. The amplitude of the 843~MHz LF is approximately one order of magnitude higher than the amplitude of the high frequency LFs. Our high frequency radio galaxy sample is not large enough to constrain redshift or mass trends in the radio galaxy LF.

We use the measured high frequency cluster radio galaxy LFs to examine the effect of the contaminating flux on the SZE signatures of galaxy clusters. To do that, we use the LF for a given cluster mass and redshift to obtain the number and flux of cluster radio galaxies, sampling 10^6 times to recover the full range of behavior of the cluster radio galaxies within the clusters. We define a quantity called the contamination s, which is the absolute value of the ratio of the total cluster radio galaxy flux from all the radio galaxies with power $> 10^{21}$~W~Hz^{-1} to the total SZE flux of that cluster within r_{200}. With this information we calculate the fraction of clusters with $s \simeq 1$, where the total cluster radio galaxy flux in a cluster is equivalent to the negative SZE flux. We find that 0.5 and 1.4~percent of clusters meet this criterion for cluster mass $M_{500} = 3 \times 10^{14} \mathrm{M}_{\odot}$ and redshift $z = 0.25$ at 150 and 95~GHz, respectively.

To estimate the impact of cluster radio galaxies on the cluster sample from the SPT-SZ 2500~deg^2 survey at 150~GHz, we use the theoretically predicted mass function to produce 100 mock cluster samples. We then compare the $\xi > 4.5$ cluster samples with and without cluster radio galaxies. We find that around 1.8 ± 0.7~percent of clusters would be lost from the sample in a redshift range of 0.25 to 1.55 in the 2500~deg^2 SPT-SZ survey.

We evaluate the bias in the parameters of the $\zeta-$mass relation caused by radio galaxy contamination and find a small shift in the mean parameter values which is well within the current 1-σ parameter constraints. We also calculate the contribution of the cluster radio galaxy contamination to the intrinsic scatter in the $\zeta-$mass relation for the observed clusters, finding that cluster radio galaxies contribute a scatter of 2.8 ± 0.4~percent out of a total empirically calibrated $\sim$22~percent scatter.

Finally, we note that with the MCXC sample we cannot place strong constraints on the redshift evolution of the high frequency radio galaxy LF. We review previous findings at 1.4~GHz, none of which provide evidence for strong redshift evolution of the cluster radio galaxy LF. We attempt to bracket the impact of possible redshift evolution by adopting a radio galaxy LF evolution in the number of point sources of the form $(1 + z)^{2.5}$, showing that at 150~GHz there could be a 5.6 ± 1~percent incompleteness in a $\xi > 4.5$ SPT-SZ like SZE selected cluster sample.

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