4th URSI AT-RASC, Gran Canaria, 19-24 May 2024

LOFAR Observations of Galaxy Clusters

Reinout J. van Weeren[1]

(1) Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
e-mail: rvweeren@strw.leidenuniv.nl

The vast majority of the baryonic matter in the Universe is in the form of a plasma, and most of this plasma resides in the large-scale cosmic web structure of the Universe. It is only in the densest and hottest parts of this web that the plasma can be easily observed through thermal Bremsstrahlung at X-ray wavelengths. There, massive (up to $\sim 10^{15}\ M_{\odot}$) clusters of hundreds to thousands of galaxies reside. Clusters grow via accretion of plasma and through mergers with other clusters and groups. During mergers, of the order of 10^{64} ergs of energy is dissipated into the intracluster medium (ICM) through shocks and turbulence. Radio observations have shown that cluster shocks and turbulence somehow accelerate particles to relativistic energies. In the presence of magnetic fields, these cosmic rays then emit synchrotron radiation which can be detected with radio telescopes. These extended non-thermal diffuse cluster sources are characterized by steep radio spectra ($\alpha < -1$, where $S_\nu \propto \nu^\alpha$) and large megaparsec sizes. For this reason, low-frequency observations, such as carried out with LOFAR, are a crucially important answer some of the open questions regarding these sources.

The study of diffuse radio emission in clusters has been one of the most productive areas of LOFAR science. By studying nearby clusters, and combining with higher frequency observations, important progress in our understanding of these sources has been made. Clear evidence has emerged that so-called radio relics, arc-like structures found in cluster outskirts, are related to merger-induced shock waves in the ICM. For radio halos, diffuse sources that approximately follow the ICM X-ray emission, our knowledge has also advanced. From various studies, e.g., analyzing and the statistical properties of radio halos and their connection to cluster dynamics and the detection of ultra-steep spectrum halos, it has been concluded that halos are very likely powered by turbulence. Large samples of radio halos have also been compiled to study various scaling relations and the occurrence rate at higher redshifts. Diffuse radio emission is also found in the core of relaxed, non-merging clusters in the form of mini-halos, with sizes of 100–300 kpc. LOFAR observations revealed that the radio emission in these relaxed clusters can also extend beyond the cluster core. Furthermore, a number of new phenomena were discovered. LOFAR found cluster emission that has such a steep radio spectrum that it could only be detected at low radio-frequencies. Additionally, diffuse radio emission in “bridge” regions between pre-merging clusters were discovered. Most recently, radio emission enveloping clusters was detected, showing that cosmic rays and magnetic fields extend far into the dilute cluster outskirts.