

Fig. 8. Multi-resolution MGCLS view of Abell 85. *Top*: full-resolution ($7.7'' \times 7.1''$; yellow, log scale between 0.006 and 2 mJy beam^{-1}) and filtered $25''$ resolution (blue, log scale between 0.06 and 3 mJy beam^{-1}) Stokes- I intensity image of Abell 85, with the bright BCG and tailed radio galaxy emission filtered out. Smoothed archival *Chandra* $0.5\text{--}7 \text{ keV}$ X-ray contours (levels: $1.0, 1.7, 3.4, 6.8, 13.6 \times 10^{-7} \text{ counts cm}^{-2} \text{ s}^{-1}$) are overlaid in white. The respective synthesised MGCLS beams are shown on the lower left. The physical scale at the cluster redshift is indicated on the upper left, and the red \times marks the NED cluster position. A newly detected elongated mini-halo (largest linear size $\sim 370 \text{ kpc}$) is seen around the cluster BCG. Filamentary structures are seen in the known phoenix/revived fossil plasma source SW of the cluster. *Bottom*: Pan-STARRS r -band images of the boxed regions from the top panel, with MGCLS $15''$ resolution contours overlaid. Contour levels start at $3\sigma = 30 \mu\text{Jy beam}^{-1}$ and increase by factors of 3.

the MGCLS contains discoveries of several other examples of elongated diffuse halos with embedded central radio-loud BCGs (indicated by \dagger) in Table 4 at the end of the paper), some of which are on megaparsec scales. We may be observing a new type of diffuse structure, bridging both halo and mini-halo classifications. A handful of cool-core clusters have been found to host larger scale radio halos (Bonafede et al. 2014; Sommer et al. 2017), and in each case the cluster shows signs of merger activity in addition to the cool X-ray core, as is the case for Abell 85 (Yu et al. 2016).

The phoenix source has been studied at multiple frequencies (Slee & Reynolds 1984; Slee et al. 1994, 2001; Giovannini & Feretti 2000; Duchesne et al. 2021a), variously

classified as a revived fossil plasma source, a phoenix, and a relic. At full resolution (yellow in Fig. 8), MeerKAT images this source in unprecedented detail, resolving a large number of filamentary structures extending from a brighter complex core region. At the filtered $25''$ resolution (blue in Fig. 8) we recover the full angular extent of the source as seen at lower frequencies (Duchesne et al. 2021a). The diffuse emission extends far from the filaments, suggesting that some form of distributed re-acceleration is necessary.

The source’s complex morphology could result from recurrent episodes of AGN activity, although determining the host galaxy(ies) for these structures is not trivial. Several potential hosts can be seen in the Pan-STARRS r -band image in Fig. 8. Sub-arcsecond resolution imaging is needed to identify the radio core(s), if present, in order to cross-match with optical counterpart(s). The toroidal structure in the western region of the source may indicate late stage radio-mode feedback in a non-central cluster galaxy source (such as in M 87, Nakamura & Asada 2013; Walker et al. 2018), possibly caused by an evolved radio lobe that has been transformed into a ‘smoke-ring’-like feature (Enßlin & Brüggen 2002). Such vortex structures can travel much further than amorphous plasma structures can, as shown by hydrodynamical simulations (Turner & Taylor 1957), and the radio features here could therefore be at a more advanced stage than the radio emission in M 87. The buoyancy produced by this off-centre bubble is sufficiently powerful to uplift the ICM, visible in the *Chandra* X-ray contours in Fig. 8. Filamentary wings of radio emission trail the bubble for about 200 kpc (at the cluster redshift). The filaments are quite narrow ($10\text{--}20 \text{ kpc}$), which constrains transport parameters for the enclosed cosmic-ray electrons, as well as ambient turbulent motions that would disrupt such structures (de Gasperin et al. 2017). Such filaments can survive in turbulent motions provided that there are Reynolds stresses of magnetic fields that thread the wings (Banda-Barragán et al. 2018). Determining the Alfvén scale – the physical scale at which the magnetic tension starts to play a role in turbulent dynamics – may assist in clarifying their role.

Spectral information can help constrain the history of the cosmic-ray population in the phoenix source. From the full source volume, we measure a flux density of $S_{1283 \text{ MHz}} = 242.4 \pm 12.1 \text{ mJy}$. Comparing to a flux density of $S_{148 \text{ MHz}} = 9.82 \pm 0.98 \text{ mJy}$ within the same solid angle from TGSS (Intema et al. 2017), we obtain a steep integrated spectrum of $\alpha_{148}^{1283} = -1.7 \pm 0.3$ for the full source. This latter value is in agreement with the $148\text{--}300 \text{ MHz}$ spectral index of -1.85 ± 0.03 derived by Duchesne et al. (2021a). The brightest regions of the complex structure have sufficient S/N across the MeerKAT bandwidth to determine in-band spectral indices, and we find values¹¹ ranging from -2.9 to -3.5 . The steep spectra of the diffuse and filamentary structures indicate old electron populations; however, the cause of the extreme steep spectrum in the central regions is unclear. There may be an artificial steepening effect from the frequency-dependent uv -coverage; although this should not be important in the brightest fine scale structures, this requires further investigation.

6.1.2. RXC J0520.7–1328: Revealing a diffuse multiplex

The MGCLS reveals complex structures in the previously studied cluster RXC J0520.7–1328 (also known as

¹¹ Statistical uncertainties on the in-band spectral index are less than 0.05 in these regions.

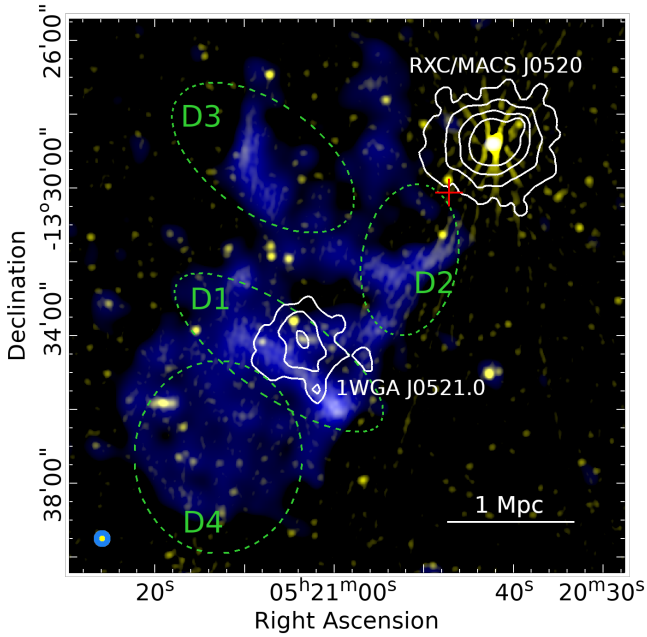


Fig. 9. MGCLS full-resolution (8.6''; yellow) and diffuse emission filtered 25'' resolution (blue) Stokes- I intensity image of a portion of the RXC J0520.7–1328 field, showing complex extended emission within the region. The corresponding synthesised beams are shown on the lower left by the filled yellow and blue ellipses, respectively. The colour scales are in square root scaling between 10–500 $\mu\text{Jy beam}^{-1}$ (yellow) and 20–500 $\mu\text{Jy beam}^{-1}$ (blue). The physical scale at the cluster redshift is indicated on the lower right, and the cross marks the NED cluster position. Smoothed archival *Chandra* 0.5–7 keV X-ray contours (levels: 3, 6, 12, 24×10^{-8} counts $\text{cm}^{-2} \text{s}^{-1}$) are overlaid in white, with RXC J0520.7–1328 and its companion cluster 1WGA J0521.0–1333 labelled. Dashed green ellipses indicate the regions of diffuse emission, D1 to D4, identified in Macario et al. (2014). The full-resolution MGCLS image contains artefacts that radiate from the bright compact source in RXC J0520.7–1328.

MACS J0520.7–1328, Ebeling et al. 2001) that do not obviously fit any of the existing paradigms. RXC J0520.7–1328, at $z = 0.336$, is part of a possible cluster pair, with its companion, 1WGA J0521.0–1333, lying to the south-east at a redshift of $z = 0.34$ (Macario et al. 2014). Multi-resolution MGCLS images of this pair, presented in Fig. 9, show a large, complex, diffuse source south-east of RXC J0520.7–1328, coincident in part with 1WGA J0521.0–1333. The brightest portion of the radio emission is a bar-like feature seen at both full (8.6''; yellow) and 25'' (blue) resolution, at the south-east edge of 1WGA J0521.0–1333's X-ray emission. This feature was observed with the GMRT at 323 MHz (Macario et al. 2014), along with three other distinct regions of faint diffuse emission (labels D2 to D4 in Fig. 9, taken from Macario et al. 2014). Although characterised as a relic by Macario et al. (2014), the bar's south-west end is significantly brighter in the full-resolution MeerKAT image than the rest of the feature, and could instead be a head-tail galaxy. Although no MeerKAT polarisation maps are available for this system, spatial spectral index studies may be able to disentangle these two possibilities.

The filtered 25'' resolution MGCLS image shows that the bar-like feature is connected to two other low-surface-brightness structures: a filled circular 'bubble' overlapping the south-east region of 1WGA J0521.0–1333, coincident with the 323 MHz D4 source, and a partial ring or arc of radio emission lying

between the two clusters (incorporating sources D2 and D3). MeerKAT reveals much more detail and extent to the complex emission seen at lower frequency. It also reveals a new faint structure ($\sim 0.8 \mu\text{Jy arcsec}^{-2}$ surface brightness) to the east of RXC J0520.7–1328. Despite the improved sensitivity, due to the location and morphology of the structures, it remains difficult to classify the majority of the emission in terms of typical cluster-related nomenclature. A more detailed analysis, including deeper X-ray data, polarimetry, and spectral index studies, will be required to resolve the nature of this emission.

6.1.3. Abell 3667: Polarisation with MGCLS

Radio relics are among the most polarised radio sources known, reaching 70% polarisation levels in localised regions (van Weeren et al. 2010; Loi et al. 2017). Here we showcase the MGCLS dataset's ability to probe polarisation structure in diffuse sources on $\sim 10''$ scales by presenting initial results from polarised observations of the north-west radio relic in the Abell 3667 galaxy cluster ($z = 0.056$). This relic is one of the most impressive examples of radio emission generated by a merger shock wave (Rottgering et al. 1997; Johnston-Hollitt 2003). The shock wave propagates in the ICM with a speed of 1200 km s^{-1} , at roughly two times the sound speed (Finoguenov et al. 2010). The polarisation is maximal close to the shock front, as well as in other regions of the radio relic where the magnetic field is likely compressed and aligned by the action of the shock wave (Ensslin et al. 1998).

In Fig. 10 we see that the magnetic field appears aligned with the NW edge of the radio relic at the location of the shock; this is seen in other radio relics as well (see e.g. van Weeren et al. 2010; Ozawa et al. 2015). We also observe a patchy, disordered structure to the magnetic field away from the edge; this is seen in other relics, and is expected as turbulence develops post-shock (Kang 2017). In Abell 3667, we can rule out disorder due to Faraday rotation in the ICM since we removed these effects using the RMs shown in panel C of Fig. 1. At the same time, the RM is seen to increase from the north towards the central regions of the relic; this could be due to the sub-cluster identified in that region with X-ray observations (Finoguenov et al. 2010), if it is located in front of the radio emitting plasma.

6.2. New clusters with diffuse emission

There are 34 MGCLS clusters in which we detect cluster diffuse emission for the first time. Here we present three examples that raise interesting science issues and showcase the capabilities of the MGCLS.

6.2.1. J0352.4–7401: Multiple relics in a massive merger

The MGCLS has detected several new relics, many with large-scale filamentary structure. One such example is the newly detected SE relic in MCXC J0352.4–7401 (Abell 3186, $z = 0.1270$) shown in Fig. 11. The relic, located approximately 1.2 Mpc SE of the cluster centre, is very large, 2 Mpc long and 340 kpc wide. The brightest region of the SE relic is a straight bar, aligned N–S and spatially connected to a 3 mJy compact source (marked by the black cross). No optical counterpart is visible in the Digitized Sky Survey (DSS). The in-band spectral index map of the SE relic, also in Fig. 11, shows this compact source to have a significantly flatter spectrum ($\alpha \sim -0.4$) than that of the bar ($\alpha \sim -1.0$ to -1.2). The overall shape of the relic is curved, with the southern part consisting of two parallel

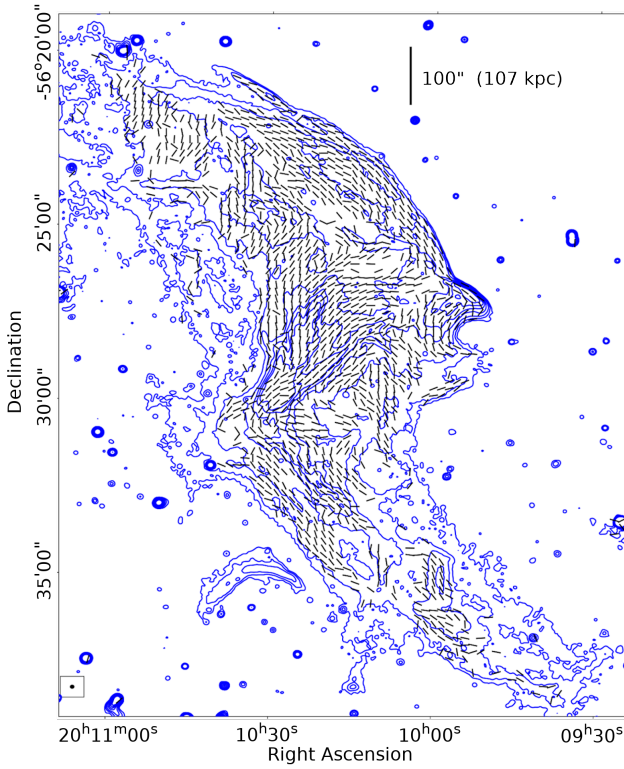


Fig. 10. Inferred magnetic field angles for the north-west relic in Abell 3667, after correction for Faraday rotation (which is shown in Fig. 1). Blue contours show the full-resolution ($7.5'' \times 7.4''$) Stokes- I MGCLS intensity, with the synthesised beam shown in the boxed region on the lower left. Contour levels are 10, 20, 40, 60, 80, $100 \times 1\sigma$, where $\sigma = 6.7 \mu\text{Jy beam}^{-1}$. Magnetic field vectors (angles only) are shown where the linearly polarised intensity is $>8\sigma$. The magnetic field is highly ordered along the NW edge of the relic.

filaments with complex structure. The filaments have steeper spectra than the northern bar, with in-band spectral indices of -1.5 at the centre of the filaments, steepening to -2.5 at the edges. The trailing edge of the relic is much wider in $25''$ resolution imaging of the field (shown in blue in the top panel of Fig. 11), with a maximum width of ~ 580 kpc. The SE relic has a measured 1.28 GHz flux density of ~ 65 mJy, which corresponds to a total radio power of $P_{1.28\text{GHz}} \sim 2.8 \times 10^{24} \text{ W Hz}^{-1}$.

This system also hosts a smaller 1.1 Mpc relic north of the cluster, as well as a large radio halo that fills the X-ray emitting region. The N relic has two components in the full-resolution image and its morphology is strikingly linear, reminiscent of revived radio galaxies, although no obvious optical counterpart is seen in DSS images. Both the SE and N relics lie far beyond the observed thermal ICM (shown by white *Chandra* contours in Fig. 11). The large-scale radio halo, with a 1.28 GHz flux density of ~ 20 mJy, lies at the centre of the cluster, and its SE–NW elongated morphology closely follows that of the X-ray emission. This giant radio halo, with a largest linear size of 1.5 Mpc, has a faint ($\sim 0.2 \mu\text{Jy arcsec}^{-2}$) diffuse arc-like protrusion off its NW edge, mirroring the SE relic. As the shape and position of the arc-like structure may hint at the presence of another shock front, we classify it as a candidate relic.

The presence of the multiple relics, and their location with respect to the asymmetric X-ray emission, are indicative of a major cluster merger. Recent numerical simulations of galaxy cluster mergers suggest that a merger shock may

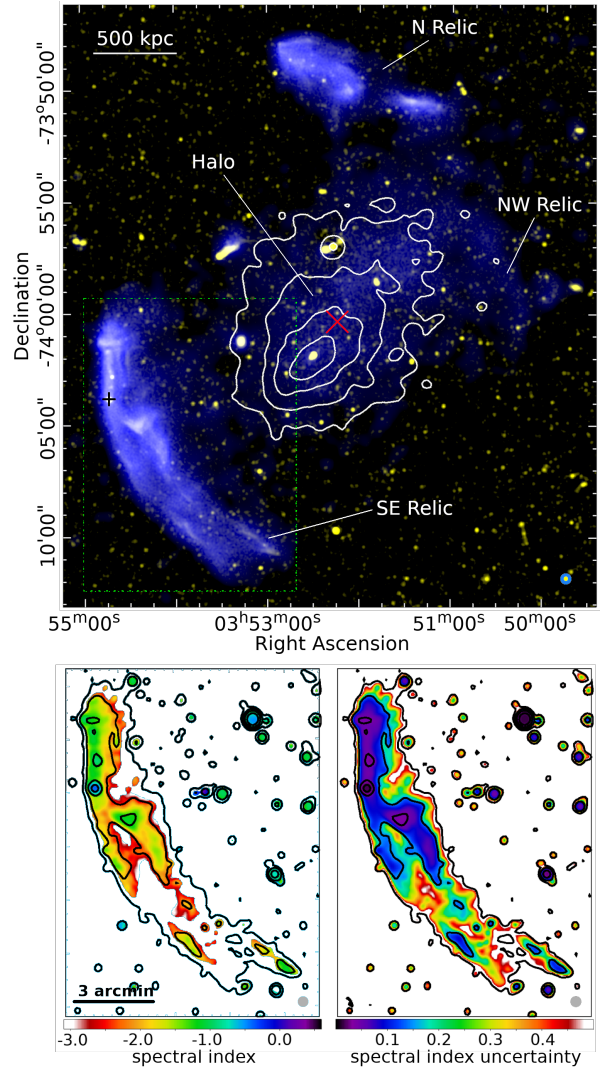


Fig. 11. MGCLS view of the newly detected multiple-relic and radio halo system in MCXC J0352.4–7401. *Top:* MGCLS full-resolution ($7.0'' \times 6.8''$; yellow) and filtered $25''$ resolution (blue) Stokes- I intensity images. The colour scales are in square root scaling between 50 – $500 \mu\text{Jy beam}^{-1}$ (yellow) and 5 – $300 \mu\text{Jy beam}^{-1}$ (blue). Synthesised MGCLS beams are shown on the lower right, and the physical scale at the cluster redshift is shown on the upper left. The red \times marks the NED cluster position, and the black cross indicates the position of a 3 mJy compact source coincident with the SE relic. Smoothed archival *Chandra* 0.5–7 keV contours (levels: 4, 8, 16, $30 \times 10^{-7} \text{ counts cm}^{-2} \text{ s}^{-1}$) are overlaid in white. *Bottom:* in-band spectral index (*left*) and spectral index uncertainty (*right*) maps of the dashed region from the top panel, with $15''$ resolution MGCLS intensity contours overlaid. Contours start at $5\sigma = 40 \mu\text{Jy beam}^{-1}$ and increase in factors of 4. The synthesised beam is indicated by the filled grey circle on the lower right of each panel.

gradually detach from the dense merging clumps (Zhang et al. 2020), and propagate to the cluster outskirts. There is observational radio evidence for the presence of such merger shocks in the periphery of clusters, for example in the Coma cluster (Giovannini et al. 1991; Brown & Rudnick 2011) and in Abell 2744 (Pearce et al. 2017; Venturi et al. 2013). Given that the N and SE relics lie far beyond the detectable X-ray emitting region, MCXC J0352.4–7401 may be in an advanced merger state, with the merger-induced shocks having propagated into the