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The Discovery of a Remnant Radio Galaxy in A2065 Using GMRT

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Abstract

The upgraded Giant Metrewave Radio Telescope (GMRT) has been used to map the cluster A2065 at \( z = 0.0726 \). We report the discovery of a remnant radio galaxy at the peripheral cluster region. The spatially resolved radio emission from the remnant radio galaxy shows an elongated, bar-shaped structure, whose size is \( \approx 52'' \times 110'' \) (\( \approx 72 \times 152 \text{ kpc}^2 \)). Our study with multiwavelength GMRT data and Chandra data shows that across the remnant radio galaxy there is a hint of a surface-brightness edge in the hot X-ray gas. We detect tentative flattening of the radio spectral index as the old plasma at the near end of the surface-brightness edge is reinvigorated by the passage of a possible shock front and shows the expected change in radio emission characteristics. We suggest that the remnant radio galaxy has been seeded by the lobes of the active galactic nucleus (AGN) hosted by the WISEA J152228.01+274141.3 source, demonstrating the connection between AGNs and remnant radio sources. Although the number of known remnant radio sources is beginning to increase, we emphasize the need for better data to understand the physics and nature of poorly understood remnant radio sources.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Extragalactic radio sources (508); Fanaroff-Riley radio galaxies (526); Galaxy structure (622); Radio continuum emission (1340); Galaxy clusters (584)

1. Introduction

The hierarchical structure formation scenario suggests that cluster mergers are the mechanisms by which galaxy clusters form and these mergers are the most energetic phenomena in the universe since the Big Bang. A large number of clusters of galaxies are known to contain large-scale, low-surface-brightness diffuse radio emission whose origin is not often related to the active galactic nuclei (AGNs) but to the intracluster medium (ICM). According to the location with respect to the cluster center, these sources are of two key types, radio halos and relics. Radio halos show a regular, amorphous emission around the cluster center of a size from a few hundred kiloparsecs (minihalo) to megaparsecs (halo), whereas radio relics show an irregular emission located in peripheral cluster regions of a size from several hundreds of kiloparsecs to megaparsecs. Another third broad type of sources comprises revived fossil plasma sources and phoenixes. These do not have any preferred location in the ICM are of a size from several tens to a few hundred kiloparsecs and trace AGN radio plasma that has somehow been reenergized through the processes in the ICM (Giovannini & Feretti 2002; Kemper et al. 2004; van Weeren et al. 2019).

The radio jets emanating from an AGN arise from the accretion onto a supermassive black hole. These form synchrotron-emitting radio lobes in a radio-loud AGN in the environments of their host galaxies. The active phase of an AGN can last several tens of megayears, following this the radio jets stop and their features, namely an unresolved radio core, radio jets, hotspots, and radio lobes, all start to fade away due to synchrotron cooling. This phase once the jets have switched off is called as the remnant phase of a radio galaxy, or merely the remnant radio galaxy. The remnant radio galaxy falls into the third broad type of sources in the ICM, which is poorly understood and presently very few sources are known (Parma et al. 2007; Brienza et al. 2017; Quici et al. 2021).

The high spatial resolution of the Chandra and upgraded Giant Metrewave Radio Telescope (GMRT) allow us to study the interplay between X-ray-emitting hot gas and nonthermal radio emission. We have obtained new upgraded GMRT data, and have used archive GMRT and Chandra data of the nearby \( z = 0.0726 \) (Struble & Rood 1999) richness class 2 cluster, A2065, which is one of the 10 galaxy clusters that make up the Corona Borealis supercluster. Postman et al. (1988) noted that two cD galaxies dominate the cluster center in the optical and their radial velocities differ by \( \approx 600 \text{ km s}^{-1} \).

Previous radio study using the 100 m Green Bank Telescope at 1.4 GHz (Farnsworth et al. 2013) detected a smooth diffuse structure \( \approx 1 \text{ Mpc} \) in extent, a giant radio halo, whereas a recent study showed a slightly smaller extent for the radio halo using the Low-Frequency Array (LOFAR) at 153 MHz (in Drabent et al. 2017). Similarly, previous X-ray studies led to detections of two surface-brightness peaks coincident with the two cD galaxies observed in the cluster’s center. The data indicated that the cluster is an unequal-mass merger and only one of the two cooling cores has survived the merger. The northern cluster seems to have fallen into the more massive southern cluster from the southeast, and having lost its gas content it has now moved to its present location to the northwest. Evidence of shock with \( M \approx 1.7 \) at \( \approx 140 \text{ kpc} \) from the southern cD galaxy too is noted and the cooling flow is displaced to the southeast of the southern cD galaxy (Markevitch et al. 1999; Chatzikos et al. 2006). In this study, we report the discovery of a remnant radio galaxy in cluster A2065 using the GMRT. We also present an X-ray analysis of archive Chandra data, which enhances the interpretation of the current discovery.

We define spectral index, \( \alpha \), as \( S_\nu \propto \nu^{-\alpha} \), where \( S_\nu \) is the flux density at frequency, \( \nu \). To estimate the intrinsic parameters, we use a \( \Lambda \)CDM cosmology with \( \Omega_m = 0.27 \), \( \Omega_\Lambda = 0.73 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). At the redshift of the cluster, \( 1'' \) corresponds to 1.384 kpc. All uncertainties are at 1σ error bars unless otherwise stated. The position angles (P.A.s) are measured from north to east. Throughout, positions are given in J2000 coordinates.

The organization of the paper is as follows. We present the X-ray and radio observations and their data analyses in...
Section 2. Our results, i.e., radio morphology, spectral structure, and X-ray gas properties are presented in Section 3. In Section 4, we discuss our observational results, source diagnostics, and dynamical interpretation of the remnant radio galaxy. Section 5 summarizes our conclusions.

2. Observations

2.1. Chandra Data

A2065 was observed by Chandra with the ACIS-I detector on 2002 August 18 and November 24 for 28 and 22 ks (Obs_ID 3182) respectively, and on 2007 September 13 for 5 ks (Obs_ID 7689). The data reduction of these three archival data sets has been performed independently. We used the calibration databases CALDB v4.7.6 and CIAO v4.9. After the initial calibration, i.e., standard filtering and removal of bad pixels, the event list of the three observations were projected to a common reference point and then merged to create a Gaussian-smoothed, background-subtracted, exposure-corrected image in the broadband 0.5–7.0 keV energy range.

We excised the central AGN and background point sources. Using the CIAO tool SPECEXTRACT, we extracted the source, background spectra, and the response files of selected regions in the Chandra images separately for the three data sets. The spectra for each data set were grouped so that each bin contained at least 20 counts. We restricted our spectral extraction to the energy range 0.5–7.5 keV, and fitted for the thermal gas emission with XSPEC (v12.10.1, Arnaud 1996) using the isothermal APEC model. The abundance was fixed to 0.3 × solar (Chatzikos et al. 2006) and all spectral fits include absorption by the Galactic column (N_{H} = 2.9 × 10^{20} cm^{-2}; Dickey & Lockman 1990).

2.2. GMRT Data

A summary of the radio observations is presented in Table 1. We inspected the data for bad antennas, bad time stamps, and data impacted by radio frequency interference. The data were analyzed using the standard reduction methodologies (see also Lal 2020). After the initial steps of flux density and bandpass calibration, all corrupted data were removed using standard routines. The bandpass calibrated data for wide-bandwidth GMRT data, i.e., the 250–500 and 1050–1450 MHz band data, were split into five 40 MHz (from 300–500 MHz) and eight 50 MHz (from 1050–1450 MHz) subbands, respectively. Subsequently, each subband data was analyzed separately, similar to narrowband “classic” GMRT data. Several cycles of phase-only self-calibration and imaging were performed and the calibration solutions were applied to the target data to correct for residual phase errors. To take care of the wide-field imaging at low GMRT frequencies, we performed faceting imaging. Problematic bright sources in the field of view whose side lobes affected the area of the target were subtracted, a.k.a. peeled; this (direction-dependent) calibration step improved the dynamic range of images. The calibrated data for five 40 MHz 250–500 MHz band data and eight 50 MHz 1050–1450 MHz band data were joined to form full 200 MHz and 400 MHz wide-bandwidth-calibrated visibility data sets, respectively. The combined wide-bandwidth-calibrated data (and similarly the narrowband-calibrated “classic” GMRT data) were imaged using the CASA task TCLEAN. We used 3D imaging (gridder = “widefield”), two Taylor coefficients (nterms = 2, tt0 and tt1) and Briggs weighting (robust = 0.5) in task TCLEAN. A final amplitude-and-phase self-calibration with a solution interval equal to the length of observation was then carried out using the GAINCAL and APPLYCAL tasks in CASA. The two Stokes polarizations, RR and LL, were combined to obtain the final total intensity Stokes I image, and corrected for the GMRT primary beam response. This provides images at center frequencies (tt0) and the corresponding in-band spectral index maps (tt1/tt0). The amplitude errors are estimated to be within 5% or less for archival narrow-bandwidth and wide-bandwidth GMRT data. Table 1 also provides image properties, including the restoring beams and rms noise levels at half-power points of the final images. The uncertainty in the flux density measurements are estimated as

\[(S_{\nu} \times f)^{2} + (\text{rms})^{2} \times N_{\text{beams}}^{-0.5},\]

where \(S_{\nu}\) is the flux density, \(f\) is an absolute flux density calibration uncertainty, rms is the noise, and \(N_{\text{beams}}\) is the number of synthesized beams. We use these error estimates for the flux density measurements when computing the error estimates for spectral index measurements.

3. Results

The exposure-corrected background-subtracted X-ray-hinned (bin = 16) and Gaussian-smoothed (10’’ kernel) image in the 0.5–7.0 keV band is shown in Figure 1. Figure 2 shows Chandra X-ray contours from Figure 1 and 250–500 MHz band radio

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Table 1

| Obs. Band  | Obs_ID  | Obs. Date      | Flux Cal. | Phase Cal. | ν (MHz) | Δν (MHz) | t_{ex} (hr) | FWHM, P.A. (″ × ″) | rms (mJy beam^{-1}) |
|------------|---------|----------------|-----------|------------|---------|-----------|-------------|-------------------|---------------------|
| 150 MHz    | 12RKA02 | 2007 Aug 10    | 3C 286    | 1459+716   | 152     | 6         | 0.9         | 26.90 × 15.19    | 136.15              | 4.98                |
| 240 MHz    | 14RMD01 | 2008 Jul 26    | 3C 286    | 1513+236   | 240     | 8         | 5.4         | 13.95 × 10.94    | 98.89               | 0.56                |
| 610 MHz    | 14RMD02 | 2008 Jul 26    | 3C 286    | 1513+236   | 606     | 16        | 5.4         | 4.93 × 3.97      | 65.80               | 0.06                |
| Upgraded GMRT 250–500 MHz | 32_084 | 2017 Jun 27    | 3C 147    | 3C 286     | 400     | 200       | 1.3         | 9.48 × 6.38      | 69.18               | 0.06                |
| 1050–1450 MHz | 32_084 | 2017 Jun 28    | 3C 147    | 1609+266   | 1274    | 400       | 0.9         | 11.13 × 5.90     | 95.45               | 0.03                |

Note. Each column, in ascending order, details the observing band (Column 1), project code (Column 2), the date observations were conducted (Column 3), the primary flux density calibration source observed (Column 4), the secondary phase calibration source observed (Column 5), the central frequency of the receiver band (Column 6), the bandwidth available within each band (Column 7), the approximate time spent in each observing run (Column 8), the shape of the restoring beam (Column 9), and the rms noise at the half-power point (Column 10).
Figure 1 shows a diffuse X-ray tail extending to the north at the center and that the cluster emission is elongated along a northwest–southeast direction. The hot gas emission (i) shows a compact, bright region and a diffuse tail extending to the north at the center, and (ii) is extended along the northwest–southeast direction showing evidence for surface-brightness edges. Though the X-ray peak emission and peak of the radio emission register well (see Figure 2, left), the position of the optical host of the southern cD galaxy (R.A.: 15:22:29.17, decl.: +27:42:27.5) is displaced by ~2″/4 from the compact, bright, X-ray peak emission at the cluster center (see Figure 2, right, and also Figure 3). A low-surface-brightness diffuse tail, both in X-ray as well as in radio images, extending to the north at the center of the image, reaches out to the second cD galaxy (R.A.: 15:22:28.92, decl.: +27:42:44.1; Figures 3 and 4, top-right panels). The X-ray peak corresponding to the second northern cD galaxy and the peak of the second weaker component of radio emission at this location also register well. The southern cD galaxy seems to have retained a cool core residing at the center of its subcluster and there is no evidence for a cool core corresponding to the northern cD galaxy (Markevitch et al. 1999; Chatzikos et al. 2006). The closely associated radio and X-ray morphology at the center and its connection with the southern cD galaxy suggest that both X-ray and radio emissions are due to ram pressure stripping as the southern cD galaxy moves relative to the ICM.

The two blue plus signs in the 250–500 MHz band image marked in Figure 4 (top-right panel) correspond to the hosts of the brighter southern cD galaxy, 2MASS J152229.17 +274222.75, at z = 0.074875 and the fainter northern cD galaxy, 2MASX J152228.92+274244.1, at z = 0.072854 (see also Figure 3). The northern cD galaxy is only detected in our 250–500 MHz band image. However, we not only detected the southern cD galaxy in our long observations, we also detected the peak radio emissions at the location of the southern cD galaxy at R.A.: 15:22:29.17, decl.: +27:42:27.5 in our short, 150 MHz band, and 1050–1450 MHz band data sets. The two cD galaxies are barely resolved using LOFAR at 153 MHz (Drabent et al. 2017). The southern cD galaxy also had a 2.8σ (upper limit) detection at 74 MHz (VLA Low-Frequency Sky Survey, VLSS; Cohen et al. 2007). It seems that around the southern cD radio galaxy there is some extended radio emission, which is more clearly seen in our 250–500 MHz band image (Figure 4, top-right panel). Since several cluster-member galaxies also show radio emission, it is unclear if this extended radio emission is indeed associated with the southern cD radio galaxy or with the two adjacent cluster-member galaxies southeast of it (see Figure 3).

3.2. Remnant Radio Galaxy

Figures 3 and 4 also suggest that the remnant radio galaxy is hosted by the 19.19 magnitude WISEA J152228.01+274141.3 source that is 7″/8 away from the optical galaxy V1CG 136 (R.A.: 15:22:28.5, decl.: +27:41:46) at redshift z = 0.072 (Griffin et al. 2014). The cluster contains gas not only with an extremely wide range of temperatures and complex structure but that also shows a cold front at 30″′ (~41.5 kpc) and a shock-like bow-shaped feature beyond ~100″′ (~140 kpc) on the southeast of the southern cD (Chatzikos et al. 2006). Figure 2 shows that the northeastern boundary of the remnant radio

counters overlaid on the exposure-corrected, background-subtracted broadband (0.5–7.0 keV) Chandra image of A2065. The image was binned (bin = 16) and smoothed using a Gaussian kernel of 10″. The color bar shows the surface brightness, in 10^-3 counts s^-1 arcsec^-2 per 8 × 8 pixel binning. The X-ray peak is located at R.A.: 15:22:29.18, decl.: 27:42:21.05. The peak surface brightness and the faintest regions transitioning between blue and green have a surface brightness of 6.0 × 10^-3 counts s^-1 arcsec^-2 and 1.6 × 10^-3 counts s^-1 arcsec^-2, respectively. The surface brightness is displayed in logarithmic scales to emphasize low-surface-brightness emission.

Figure 1. Exposure-corrected, background-subtracted, broadband (0.5–7.0 keV) Chandra image of A2065. The image was binned (bin = 16) and smoothed using a Gaussian kernel of 10″. The color bar shows the surface brightness, in 10^-3 counts s^-1 arcsec^-2 per 8 × 8 pixel binning. The X-ray peak is located at R.A.: 15:22:29.18, decl.: 27:42:21.05. The peak surface brightness and the faintest regions transitioning between blue and green have a surface brightness of 6.0 × 10^-3 counts s^-1 arcsec^-2 and 1.6 × 10^-3 counts s^-1 arcsec^-2, respectively. The surface brightness is displayed in logarithmic scales to emphasize low-surface-brightness emission.
The remnant radio galaxy coincides with the 1.3 × 10^{-7} counts s^{-1} arcsec^{-2} surface-brightness contour level; gas in false color transitioning from the green region to the blue region at a distance of ∼33″ (≈45.7 kpc) from the southern cD galaxy. All four panels of Figure 4 suggest that the radio emission from the remnant radio galaxy has an elongated, bar-shaped structure. The remnant radio galaxy, buried in the radio halo emission that is barely detectable using LOFAR at 153 MHz seems to possess an elongated, bar-shaped structure (Drabent et al. 2017), consistent with our results. This suggests that the remnant radio galaxy has a steep spectrum, and its consistency in radio morphology gives us additional confidence in our image fidelity, imaging calibration, and data reduction processes. The best sensitivity image for the low surface brightness was obtained from the 250–500 MHz band data and we now discuss the morphology of the remnant radio galaxy.

The remnant radio galaxy broadly consists of a high-surface-brightness southeastern part and a fainter low-surface-brightness extended northwestern part. The two oppositely directed radio jets emanating from the apex of the WISEA J152228.01+274141.3 source initially traverse toward the southeast and northwest directions. As the galaxy plows through the dense intracluster gas, these jets traversing in opposite directions form a trail, after sharp bends in the jets, behind the WISEA J152228.01+274141.3 source due to interaction with the ICM. The width of the remnant radio galaxy increases from ∼17″ (≈23.5 kpc) at the southeastern end to ∼27″ (≈37.4 kpc) and reduces again before flaring to reach a maximum width of ∼35″ (≈48.4 kpc) and finally fading completely. The average width of the narrower southeastern part is a factor of ∼2.3 smaller than the broader northwestern part. It seems that a pinch is present at ∼35″ (≈48.4 kpc) of the ∼16″2 (∼22.4 kpc) width from the southeastern end, i.e., between the two narrower and the broader parts. The northeastern boundary toward the two cD galaxies of the remnant radio galaxy is sharp, while the emission fades more slowly at the southwestern boundary. The overall source size, assuming elongation, of the bar-shaped structure is ≈52″ × 110″, corresponding to 72 × 152 kpc^2 at the assumed distance.

### 3.2.1. Radio Spectra

The total flux densities were determined from integration in polygons measured in areas encompassing the remnant radio galaxy, i.e., we determined the surface brightness and divided it by the number of pixels in the polygon at each frequency. These results are presented in Table 2 along with the total intensity spectra of the remnant radio galaxy, and the southern cD galaxy is shown in Figure 5. A 2.8σ upper limit at the 74 MHz (VLSS at 80′′ angular resolution; Cohen et al. 2007) and the peak flux density from our 150 MHz band data for the southern cD galaxy are also reported. We see that all these radio measurements, within the error bars, fall nearly along with a “straight” power law, α = −1.2 ± 0.2, with some hints of energy losses by synchrotron cooling for the dominant southern cD galaxy. This provides confidence in our data calibration and its reduction methodologies.
The remnant radio galaxy is not detected in our 150 MHz band short observation, and is barely detected using LOFAR at 153 MHz (see also Section 3.2). However in the 1050–1450 MHz band short observation, we see hints of radio emission from the remnant radio galaxy. We made a low-resolution, 15″ image at the 1050–1450 MHz band and report peak flux density for the radio emission from the remnant radio galaxy in Figure 5. Since this 1050–1450 MHz band measurement comes from a short ≤0.9 hr duration observation, has relatively high rms noise (see also Section 3), and the observation does not sample similar (u, v) spacings as the rest of our low-frequency observations, we henceforth no longer include it in our spectral index analysis. It appears that the integrated spectrum for the remnant radio galaxy cannot be represented by a single power law. The segment of the spectrum with the best data is <1250 MHz, and the low-frequency spectral index \( \alpha (240–610 \text{ MHz}) = -1.4 \pm 0.2 \). Our data cannot rule out the possibility of spectral shape to be due to two populations of the relativistic electrons: a low-frequency component characterized by \( \alpha (240–610 \text{ MHz}) \approx -1.4 \) and a second component having \( \alpha (>610 \text{ MHz}) < -1.4 \) with a cutoff or a spectral break between 400 and 1250 MHz.

The spectral index measurements between the 240 MHz band and 250–500 MHz band data sets, and between the 250–500 MHz band and 610 band MHz band data sets show that the radio spectrum steepens with distance from the head, from \(-1.2 \pm 0.1\) to \(-1.4 \pm 0.2\), and from \(-1.3 \pm 0.1\) to \(-1.6 \pm 0.2\), respectively, due to synchrotron and inverse Compton losses (Figure 6). The location after the pinch, where the radio plasma from the AGN connects to the remnant radio galaxy, the spectrum, between the 240 MHz band and 250–500 MHz band data, remains flattened, \( \alpha = -1.3 \pm 0.1 \).

The wide-bandwidth data sets were imaged to make multiscale multifrequency synthesis images, which provide images at center frequencies and the corresponding in-band spectral index maps (see also Section 2.2). The in-band spectral index map averaged over a region of interest, to increase signal-to-noise ratio, for the 250–500 MHz band data is shown in Figure 7. We divided the remnant radio galaxy into three distinct regions: (1) the high-surface-brightness narrower southeastern part ahead of the pinch (in cyan), the latter low-surface-brightness broader northeastern part is divided into two; (2) the northeastern region (in yellow), and (3) the southwestern far-end region (in magenta). The size of the regions is chosen such that the signal in the total intensity image is (approximately) more than five times the rms noise. The southern cD galaxy has an in-band spectral index of \(-0.9 \pm 0.2\). Similarly, the spectra of three regions of the remnant radio galaxy are \(-1.2 \pm 0.2\), \(-1.3 \pm 0.2\), and \(-1.4 \pm 0.2\) for regions (1), (2), and (3), respectively. This is consistent with the averaged in-band spectral index of \(-1.3 \pm 0.2\) within the error bars for the remnant radio galaxy. It is also consistent with the crude estimates of two 50 MHz subband images, 300–350 MHz and 450–500 MHz, at two extreme ends of the 250–500 MHz band data. The region ahead of the pinch (in cyan) and the northeastern region close to two cD galaxies (in yellow) have comparable spectral indices. It appears that the high-surface-brightness narrower region (in cyan) ahead of the pinch is flatter than the two regions, together forming a low-surface-brightness broader northeastern region (in yellow and magenta) after the pinch, consistent with our result discussed above. Furthermore, the area between the two regions of the broader northeastern part of the source, i.e., the southwestern far-end region (in magenta) has a significantly steeper spectrum than the northeastern region close to two cD galaxies (in yellow).

3.3. ICM Gas Properties

Chatzikos et al. (2006) reported that the cluster contains gas with an extremely wide range of temperatures and a wealth of structure. They also reported a discontinuity at \( \approx 30° \) (\( \approx 41.5 \text{ kpc} \)) in the southeast region from the southern cD galaxy. It is at nearly this same distance where we report an enhancement of radio surface brightness, toward the two cD galaxies, showing a sharp feature. We aim to search an X-ray surface-brightness edge, i.e., the shock front that is coincident with the northeastern sharp edge toward two cD galaxies of the remnant radio galaxy. In order to understand the gas physics at this region of the cluster, we have extracted the surface-brightness profile from two box-shaped regions, one encompassing the remnant radio galaxy (called “outside” here) and the other adjacent to it toward cD galaxies (called “inside” here) as shown in Figure 8 (in magenta). We extracted the surface brightnesses and the spectra from these regions, which are displayed in Figure 9. A single temperature model with Galactic absorption and the abundance fixed provided a good fit to the spectrum.

We noticed the X-ray surface-brightness edge where the surface brightness drops (see Figures 8 and 9) and therefore implies a
discontinuity, or jump, in the gas density. The surface brightnesses are $S_{\text{inside}} \approx (8.2 \pm 0.3) \times 10^{-6}$ counts s$^{-1}$ arcsec$^{-2}$ and $(3.7 \pm 0.3) \times 10^{-6}$ counts s$^{-1}$ arcsec$^{-2}$, respectively. Consequently, our modeled densities in the two regions, $\rho_{\text{inside}}$ and $\rho_{\text{outside}}$, are approximately $2.9^{+0.2}_{-0.2} \times 10^{-3}$ cm$^{-3}$ and $1.9^{+0.2}_{-0.2} \times 10^{-3}$ cm$^{-3}$, respectively. Our corresponding derived temperatures for the two regions, $kT_{\text{inside}}$ and $kT_{\text{outside}}$, are approximately $6.1^{+0.9}_{-0.8}$ keV ($\chi^2 = 0.93$ for 221 degrees of freedom) and $5.5^{+0.5}_{-0.4}$ keV ($\chi^2 = 1.08$ for 462 degrees of freedom), respectively. We also repeated this exercise for a pie-circular aperture (shown in blue in Figure 8) centered on the southern cD galaxy and lying toward the radio emission from the remnant radio galaxy with two regions containing the radio emission from the remnant radio galaxy and the smaller adjacent region toward the cD galaxy. The quantitative estimates from this are nearly identical and the fit statistics are at 90% confidence intervals. Although with large error bars, these density and temperature measurements are hinting that the surface-brightness edge toward the two cD galaxies is possibly a shock front. Consequently, the observed density jump and the temperature jump across the edge, $\rho_{\text{inside}} / \rho_{\text{outside}} = 1.5^{+0.2}_{-0.2}$ and $kT_{\text{inside}} / kT_{\text{outside}} = 1.1^{+0.7}_{-0.5}$, suggest the Mach numbers, $M = 1.3^{+0.2}_{-0.2}$ and $1.1^{+0.4}_{-0.3}$, respectively, under the Rankine–Hugoniot shock conditions for the intracluster gas, $\gamma = 5/3$, which are all obviously in agreement, are within the error bars of Chatzikos et al. (2006). We also believe that a smaller measure for the temperature jump is due to the contribution of cool
thermal emission from the core to the adjacent region toward two cD galaxies, $kT_{\text{inside}}$. Note, it is equally possible that the surface-brightness edge is a cold front. Here, we assume it to be a shock front because of consistencies between our measurements and those of Chatzikos et al. (2006) and Markevitch et al. (1999).

### 4. Discussion

In passing, we note that we do not detect the radio halo of A2065 in our current ≈8$''$ resolution 250–500 MHz band image. This is likely to be due to the fairly short duration of our observing run (just ≈1.3 hr), which results in poor ($u$, $v$) coverage at the short spacings that are critical to detect ≈10$'$-sized structures like the radio halo (e.g., Farnsworth et al. 2013). However, the large fractional bandwidth at the 250–500 MHz band implies that it has excellent ($u$, $v$) coverage at the intermediate and long baselines that are needed to accurately map the arcminute-sized structures like our target, the remnant radio galaxy (angular size ≈1$''$ × 2$'$). In addition, we have performed deep CLEAN, where we have used the multiscale multifrequency synthesis process of combining data from multiple spectral channels onto the same spatial-frequency grid during imaging to take advantage of the increased ($u$, $v$) coverage and imaging sensitivity, and hence we do not foresee any loss of flux density that could be linked to the remnant radio galaxy in the data presented above. Below we discuss the nature of this newly discovered remnant radio galaxy in A2065.

As the remnant radio galaxy ages, its electrons will lose so much energy that their spectra will eventually steepen. This steepening would reach a point where they do not emit significant radiation at high frequencies, instead, the radio emission may only be observable at low frequencies. However, Brienza et al. (2017) argues that in addition to the aged population of remnant radio galaxies, there should be younger population as well in which lobes have not had time to steepen over the observed frequency range (e.g., 3C 28 and MIDAS J230304–323228 in Feretti et al. 1984 and Quici et al. 2021, respectively). It is possible that the remnant phase of a radio galaxy is governed by a Sedov-like expansion, which will cause the dimming of radio emission due to a decrease in the magnetic field strength and a decrease in particle energies due to adiabatic expansion losses. Unfortunately, the models of the spectra of remnant radio galaxy are highly degenerate, and the modeling of an individual remnant radio

### Table 2

Radio Flux Densities for the Remnant Radio Galaxy and the Southern cD Galaxy

|          | $S_{\text{74 MHz}}$ | $S_{\text{150 MHz}}$ | $S_{\text{240 MHz}}$ | $S_{\text{400 MHz}}$ | $S_{\text{610 MHz}}$ | $S_{\text{1250 MHz}}$ | $S_{\text{1400 MHz}}$ |
|----------|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
|          | (mJy)               | (mJy)                | (mJy)                | (mJy)                | (mJy)                | (mJy)                | (mJy)                |
| Remnant radio galaxy | 46.52 ± 0.90      | 26.76 ± 0.08         | 2.60 ± 0.22          | 0.73 ± 0.15          |                     |                     |                     |
| Southern cD galaxy   | 395.2 ± 141.1     | 46.52 ± 0.90         | 36.26 ± 0.90         | 21.97 ± 0.08         | 11.12 ± 0.22        | 3.83 ± 0.09          | 3.09 ± 0.15          |

Note. The total flux densities for the remnant radio galaxy were determined from integration in polygons measured in areas encompassing the remnant radio galaxy, whereas the peak flux density for the remnant radio galaxy is reported from our low-resolution, 15$''$ image at the 1050–1450 MHz band (Column 7) shown in Figure 4 (bottom-right panel) (see also Section 3.2.1 for a discussion). The 2.8$\sigma$ upper limit at 74 MHz (Column 2), peak flux density at 150 MHz band (Column 3), measurements at 240 MHz (Column 4), 400 MHz (Column 5), 610 MHz (Column 6) and 1250 MHz (column 7), and the data at 1400 MHz (column 8) for the southern cD galaxy, are from the VLSS at 80$''$ angular resolution (Cohen et al. 2007), GMRT 150 MHz band, GMRT 240 MHz band, upgraded GMRT 250–500 MHz band, GMRT 610 MHz band, upgraded GMRT 1050–1450 MHz band data, and Chatzikos et al. (2006), respectively.

Figure 5. Integrated radio spectrum of the remnant radio galaxy using the data in Table 2. Peak flux density is reported from our low-resolution 15$''$ image at the 1050–1450 MHz band for the remnant radio galaxy (see also Section 3.2.1 for a discussion). We also show the spectra of the southern cD galaxy for comparison; note that the (nearly) straight spectra of it provides a good check of our calibration. A 2.8$\sigma$ limit is reported at 74 MHz (VLSS; Cohen et al. 2007), peak flux densities at the 150 MHz band, and the 1050–1450 MHz band are our measurements; the 1400 MHz data is from the VLA FIRST survey (Chatzikos et al. 2006) for the southern cD galaxy.

Figure 6. The plot shows the radio spectra between the 240 MHz and 250–500 MHz band data sets (red upper triangles) and between the 250–500 MHz band and 610 MHz band data sets (blue lower triangles) as a function of distance from the head. The location of the pinch is shown as a vertical line.
across the remnant radio galaxy in our in-band spectral index measurements, from $\alpha = -1.3 \pm 0.2$ to $\alpha = -1.4 \pm 0.2$ (Figure 7), in the direction away from the two cD galaxies. Our X-ray measurements show a surface-brightness edge that is coincident with the northeastern boundary of the remnant radio galaxy and its nature (shock or cold front) is not clear from the data. If it is a shock front, it is rather weak, with $M$ being between 1.1 and 1.3; however it is unclear if an (inward?) traveling shock is responsible for spectral steepening across the remnant radio galaxy. Below we discuss the possible progenitor of the remnant radio galaxy in A2065.

### 4.1. Remnant Source Diagnostic

Remnant radio sources are old, and are bound by model-dependent physical parameters because of the required assumptions of volume-filling factors, etc. We use the parameter $N$, which is the number of relativistic electrons found by integrating the energy spectrum of radiating electrons between Lorentz factors of 1000 and 10,000 for a typical equipartition magnetic field of $5 \mu G$ in the 2–200 MHz band for the remnant radio galaxy. The number distribution of relativistic electrons drops rapidly with energy for a steep spectrum remnant radio galaxy. Hence the number of low-energy electrons is a good measure of the total acceleration of relativistic electrons during the lifetime of $\sim 10^8$ yr for the small redshift of the source, and indicates the entire history of the source.

We thus determine $N \approx 2.1 \times 10^{60}$ and the total energy stored in the magnetic field $\approx 1.1 \times 10^{57}$ erg assuming cylindrical geometry for the size of the remnant radio galaxy (Pacholczyk 1970; Miley 1980). Here, we have assumed the volume-filling factor is unity, and hence the volume and the number of relativistic electrons $N$ are thus the upper limits. The emitting plasma will most likely occupy a smaller volume, leading to larger energy densities and therefore larger values of the magnetic field strength and will require a smaller number of electrons to produce the observed luminosity. These basic energetics are similar to the Coma radio relic source 1253 + 275 (Giovannini et al. 1991). Moreover, the number of relativistic electrons, $N$, is similar to that of the typical FR I radio galaxy 3C 31 but two orders of magnitude smaller than the FR II radio galaxy Cygnus A (Harris et al. 1993). This suggests that the FR I radio galaxy is possibly the progenitor of the remnant radio galaxy in A2065.

Thus, our high-resolution, high-sensitivity radio image at the 250–500 MHz band along with the presence of the WISEA J152228.01+274141.3 source suggest that the source is a wide-angle-tailed radio source (see also Section 3.2). Furthermore, the position of the WISEA J152228.01+274141.3 source exactly coincides with the likely radio core position of the wide-angle-tailed radio source. The source diagnostic based on the number of low-energy relativistic electrons also suggests that the remnant radio galaxy is fed by the small radio tail of the wide-angle-tailed FR I radio galaxy. If this proposition is correct, the two oppositely directed radio jets emanating from the apex of the WISEA J152228.01+274141.3 source initially traverse toward the northwest and southeast. As the galaxy plows through the dense ICM, these jets traversing in opposite directions form a trail after a sharp bend in the southeastern jet due to interaction with the ICM. The jets probably overlap and twist forming a pinch and then expand, and the jet becomes weaker (e.g., NGC 4869; Lal 2020). The sharpness in surface brightness toward the northeast, i.e., the side facing two cD galaxy cannot constrain the remnant phase of radio galaxy (Kaiser & Cotter 2002). Therefore, a possible way to constrain the remnant phase is via a statistical approach, and sadly, due to their small number, the physics of remnant radio galaxies remains poorly understood. Of course, there must exist a significant population of remnant radio galaxies, which show the absence of detectable radio emission in many clusters associated with merger activity (see also Godfrey et al. 2017). Thus, searching for low-surface-brightness profiles, say $\leq 50$ mJy arcmin$^{-2}$, with an absence of radio cores and hotspots, and with no well-defined radio morphologies, is a possible way to identify remnant radio sources in large survey images.

Radio morphology of the remnant radio galaxy in A2065 shows that it is an elongated, bar-shaped structure ($52'' \times 110'' \approx 72 \times 152$ kpc$^2$), which is buried within a radio halo emission of $\leq 1$ Mpc in size (Drabent et al. 2017; Farnsworth et al. 2013). The remnant radio galaxy is located near the southern cD galaxy; the northeastern boundary of the remnant radio galaxy is at a distance of $\sim 33''$ ($\approx 45.7$ kpc) from the southern cD galaxy. The possible radio core of the remnant radio galaxy is coincident with the WISEA J152228.01+274141.3 source that is $77''$ away from the optical galaxy V1CG 136. Our spectral index measurements show that the radio spectrum steepens with distance from the possible radio core from $\alpha = -1.2 \pm 0.1$ to $\alpha = -1.4 \pm 0.2$ in our low-frequency (between the 240 MHz band and the 250–500 MHz band) spectra, and from $\alpha = -1.3 \pm 0.1$ to $\alpha = -1.6 \pm 0.2$ in our high-frequency (between the 250–500 MHz band and the 610 MHz band) spectra (Figure 6), as is expected for synchrotron and inverse Compton losses. We also find evidence for spectral steepening across the remnant radio galaxy in our in-band spectral index A2065.
galaxies and diffuse extensions toward the far southwest side, along with corresponding spectral gradients, suggests the passage of an inward traveling shock front.

5. Summary and Conclusions

The remnant radio source seems to trace AGN radio plasma that has somehow been reenergised through processes in the ICM. It is possible that, similar to radio relic sources, remnant radio sources are also believed to be tracers of merger shocks, unfortunately, only a few clusters have shown to possess corresponding features in hot X-ray gas. The remnant radio galaxy in A2065 may belong to this rare class possessing an X-ray surface-brightness edge across the remnant radio galaxy, indicating a possible connection with the shock front. Using our deep high-resolution low-frequency observations, we discovered a bar-shaped remnant radio galaxy, whose size is \( \approx 52'' \times 110'' \) \(( = 72 \times 152 \text{ kpc}^2 \)) in the massive unequal-mass-merger galaxy cluster A2065 at \( z = 0.072 \). It has a steep spectral index \( \alpha(240-610 \text{ MHz}) = -1.4 \pm 0.2 \) and \( \alpha(>610 \text{ MHz}) < -1.4 \pm 0.2 \), corresponding to the line representing the best-fitting regression to the radio data. The Chandra data, and the upgraded and “classic” GMRT data, show (i) the presence of an X-ray surface-brightness edge attributed to a shock front, though a possibility of cold front cannot be ruled out, at the remnant radio galaxy’s edge toward the two cD galaxies, (ii) the tentative flattening of the radio spectral index, in our 250–500 MHz in-band data, of the remnant radio galaxy at the near end of the X-ray surface-brightness edge, and (iii)
that possibly a wide-angle-tailed FR I radio galaxy is the progenitor of the remnant radio galaxy. Thus, the remnant radio galaxy has possibly been reinvigorated by the passage of the shock front and adiabatic compression, and shows the expected change in radio emission. We also suggest that the remnant radio galaxy was seeded by the AGN during its past active phase, and has been hosted by the WISEA J152228.01 +274141.3 source, demonstrating the connection between AGNs and remnant radio galaxies, similar to the connection between AGNs and radio relic sources (e.g., A3411–3412; van Weeren et al. 2017).

Although low-frequency observations are starting to reveal more and more of these type of sources, there are presently very few known remnant radio systems; clearly an outstanding difficulty is the small sample size. Although the number of known remnant radio sources is increasing, better data are necessary for several of them to allow a detailed study. Fortunately, forthcoming radio surveys using the LOFAR, MeerKAT, Square Kilometre Array, etc., will greatly increase the sample size, along with deep multifrequency radio data, e.g., using the upgraded GMRT, which will constrain the physics and nature of poorly understood remnant radio sources. We are undertaking an upgraded GMRT study at the 125–250, 250–500, and 550–850 MHz bands of several clusters in order to detect such ultra-steep-spectrum sources, map radio halo emission, and provide exact flux density estimates, models, and statistics.

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Facilities: Chandra, GMRT.

Data Availability

The GMRT and Chandra data underlying this article are available via the GMRT Online Archive, naps.ncra.tifr.res.in/goa and the Chandra Data Archive, cxc.harvard.edu/cda. All data analysis packages used in this work are publicly available.

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