AGN FEEDBACK IN GALAXY GROUPS: A DETAILED STUDY OF X-RAY FEATURES AND DIFFUSE RADIO EMISSION IN IC1262

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ABSTRACT

This paper reports a systematic search of X-ray cavities, density jumps and shocks in the inter-galactic environment of the galaxy group IC 1262 using Chandra, GMRT and VLA archival observations. The X-ray imaging analysis reveals a pair of X-ray cavities on the north and south of the X-ray peak, at projected distances of 6.48 kpc and 6.30 kpc respectively. Total mechanical power contained in both these cavities is found to be $\sim 12.37 \times 10^{42}$ erg s$^{-1}$, and compares well with the X-ray luminosity, within the cooling radius, measured to be $\sim 3.29 \times 10^{42}$ erg s$^{-1}$, suggesting that the mechanical power injected by the central AGN efficiently balances the radiative loss. We detect a previously unknown X-ray cavity at the position of southern radio lobe in the intra-group medium and find a loop of excess X-ray emission extending $\sim 100$ kpc southwest from the central galaxy. The X-ray cavity at the position of southern radio lobe probably represents a first generation X-ray cavity. Two surface brightness edges are evident to the west and east–north of the center of this group. The radio galaxy at the core of the IC 1262 group is a rare low-redshift ultra-steep radio galaxy, its spectral index being $\alpha \sim -1.73$ (including the central AGN) and $\alpha \sim -2.08$ (excluding the central AGN). We detect a radio phoenix embedded within the southern radio lobe, for the first time in a poor group, with a spectral index ($\alpha \leq -1.92$). The spectral index distribution across the phoenix steepens with increasing distance from its intensity peak.

Keywords: galaxies:active—galaxies:general—galaxies:group:individual:—IC 1262
1. INTRODUCTION

High resolution X-ray images from the new generation X-ray telescopes, \textit{Chandra} and \textit{XMM-Newton}, have provided us with mounting evidence of various modes of interaction between the hot intergalactic gas, and the active galactic nucleus at the core of the clusters (e.g. Perseus), groups (e.g. NGC 5044) and ellipticals (e.g. Cygnus A). This interaction may also result in the formation of the substructures or cavities apparent in the surface brightness distribution of the X-ray emission (Rafferty et al. 2006; Birzan et al. 2008; David et al. 2009; Dunn et al. 2010; O’Sullivan et al. 2011; Birzan et al. 2012; Chon et al. 2012). Radio observations indicate that many of these cavities are associated with enhanced level synchrotron emitting cosmic-ray particles of either charge. As the cosmic rays provide enough pressure without appreciable increase in the mass density, these cavities or bubbles are found to rise buoyantly in the hot gaseous environment. These cavities can be as small as \( \sim 5 \) kpc in diameter, and as large as \( \sim 200 \) kpc located in the central \( \sim 20 \) kpc of a cluster, or in its outskirts. They are seen in giant elliptical galaxies (Jones et al. 2002), groups (Machacek et al. 2006; Jetha et al. 2008; Giacintucci et al. 2011, 2012), as well as in galaxy clusters (McNamara et al. 2000; Birzan et al. 2004; Dunn & Fabian 2006; Rafferty et al. 2006). The mechanical power required for “inflating” these cavities matches well with the radiative cooling loss in many of the cluster cores, suggesting that these bubbles, and perhaps the cosmic rays that fill them, are involved in the feedback process.

Most studies of AGN feedback seem to concern massive clusters (e.g., the analysis of cluster samples by Birzan et al. (2008); Dunn & Fabian (2006); Mittal et al. (2009), yet most of the galaxies in the universe are found in smaller systems, such as poor clusters and groups (Eke et al. 2004). Complete volume-limited studies of galaxy groups are rare (e.g. O’Sullivan et al. 2017), but these reveal the diversity of physical phenomena that exist in the intergalactic medium of groups due to close interactions in the sluggish environment of groups. A systematic study of nearby galaxy groups with AGN-ICM interactions is important to understand the AGN feedback in relatively smaller dark matter halos. Due to their shallower gravitational potentials, the AGN outbursts in such systems are believed to produce a larger impact on the intra-group medium (IGM).

This study is also important because the relationship between the AGNs and intergalactic hot gas (e.g. Giacintucci et al. 2011) and the atomic and molecular gas (e.g. O’Sullivan et al. 2018) can significantly influence galaxy evolution in the group environment. Nearby groups are also useful to probe regions closer to the central black hole, in the brightest galaxy in the core, in greater detail, due to proximity and better signal. We have thus chosen to perform a systematic study of the impact of AGN feedback on the IGM in the nearby galaxy group IC 1262, which has the eponymous dominant early-type galaxy, and 31 members within \((20' \times 20')^2\) (Smith et al. 2004).

Trinchieri & Pietsch (2000) reported a bright arc in close proximity of the cD galaxy, which may have resulted from the dynamic evolution of the central galaxy due to a merger event in this poor group. (Hudson & Henriksen 2003; Hudson et al. 2003) studied this group using BeppoSAX and Chandra in the X-ray and the NRAO VLA Sky Survey and the Westerbork Northern Sky Survey measurements in the radio, to claim the detection of diffuse non—thermal emission to the South of IC1262, likely associated with a radio mini-halo, produced by an earlier merger event. These authors also detected a diffuse radio structure of spectral index \( \sim 1.8 \), slightly more extended than the central cD galaxy. Further, Trinchieri et al. (2007) identified and confirmed certain signatures of merging, such as surface brightness discontinuities, with disturbed structures in the core and the sharp and narrow filamentary structures east of the central galaxy, using high resolution X-ray images from \textit{Chandra} and \textit{XMM-Newton}. The above studies have in general concluded that high resolution, deeper radio observations are needed for IC1262 in order to understand the radio properties in more detail. This group is located at a relatively low redshift of \( z = 0.0326 \), and its central galaxy hosts the radio source 4C+43.46, whose radio power is given by \( \log P_{1.4 \text{ GHz}} \leq 22.56 \text{ W Hz}^{-1} \) (Trinchieri et al. 2007; Dong et al. 2010). A single X-ray cavity was detected by Dong et al. (2010) towards the north of the center of the group. It is interesting to note that the central galaxy IC 1262 shows very little star formation (\( \sim 4.35 \times 10^{-2} M_{\odot} \text{yr}^{-1} \)) (Vaddi et al. 2016). In this work, we have tried to assemble available multi-wavelength data from different archives such as \textit{Chandra}, SDSS, GMRT and VLA in order to understand the nature of this group, in particular to understand the relation between its merger history and the various X-ray and radio features that are detected, and to understand the AGN feedback process operating in this group. In addition, we use high resolution radio images to understand the origin of more complex radio structure detected in southern radio lobe (Hudson et al. 2003). The structure of the paper is as follows: in Section 2 we present the data analysis, while the detection of the X-ray cavity is outlined discussed in Section 3. Section 4 describes the
X-ray spectral analysis. Finally, we present the results from the radio analysis in Section 5. Throughout this paper we assume ΛCDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$ & $\Omega_\Lambda = 0.73$, translating to a scale of 0.639 kpc arcsec$^{-1}$ at the redshift $z=0.032$ of IC 1262. All spectral analysis errors are at 90% confidence, while all other errors are at 68% confidence.

2. DATA ANALYSIS

2.1. X-ray observations

The field of IC 1262 was observed three times in X-rays by the Chandra X-ray Observatory between 17–22 April, 2006, for an effective exposure of 120 ks (ObsID and other details in Table 1). The observations were reprocessed using CHANDRA_REPRO task available within CIAO 4.8 and employing the latest calibration files CALDB 4.7.2 provided by Chandra X-ray center (CXC). We followed the standard Chandra data-reduction threads for the analysis. Periods of high background flares were identified using the lc_sigma_clip algorithm, with the threshold set at 3σ. These periods were removed from the further analysis. The CIAO REPROJECT_OBS script was used to reproject the event files, and exposure maps in the energy band 0.7–7.0 keV were extracted using the FLUX_OBS script. CIAO scripts blanksky and blanksky_image were used to identify suitable blank sky background fields, corresponding to each of the event file, and were used for removing the particle background contamination. Point sources were identified using the WAVDETECT algorithm within CIAO and were removed from the image. Spectra and corresponding Redistribution Matrix Files (RMF),

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1 http://cxc.harvard.edu/ciao
2 http://cxc.harvard.edu/ciao/threads/index.html
Ancillary Response Files (ARF) were generated using the SPECEXTRACT task within CIAO 4.8.

2.2. Radio observations

Archival high frequency VLA and low frequency GMRT data for IC1262 used, whose observational details are summarized in Table 2.

2.2.1. VLA

We used VLA archival radio data for the field IC 1262, using L-band continuum (1400 MHz) observations in the B (max baseline 11.1 km) and D (max baseline 1.03 km) configurations. These observations were analyzed following the standard routine and using the Common Astronomy Software Applications (CASA) package of version 4.6.0. The data were inspected for RFI (radio frequency interference), non-working antennas, bad baselines, channels and time period. Corrupted data were excised from the $u-v$ dataset. The flux density of each primary or flux calibrator was set according to Perley & Butler (2017). The list of both primary and secondary calibrators is given in Table 2. The same flux calibrator was used for the bandpass calibration followed by determining the flux density of the secondary or phase calibrator(s) using the antenna complex gain solutions. Calibrated visibilities were then used to create the images by the standard Fourier transform deconvolution. A few rounds of self-calibration (2 phase + 1 amplitude) were applied to reduce the effects of residual phase errors in the data and to improve the quality of the final images. We produced images with the robust ‘0’ parameter in the ‘clean’ task of CASA.

2.2.2. GMRT

GMRT archival (Project code 07MHA01) P band data of 16 MHz bandwidth centered at 325 MHz frequency and TGSS 150 MHz (TIFR-GMRT SKY SURVEY) data (Intema et al. 2017) was used for low frequency study of IC1262. The 325 MHz P band data was processed using SPAM (Source Peeling and Atmospheric Modeling; Intema 2014), an AIPS-based semi-automated pipeline radio data reduction package that performs flagging, initial-calibration and imaging with direction dependent calibration in an iterative way. The complete working of SPAM can be seen in Intema et al. (2017). Same package was used for processing the entire TGSS data by Intema et al. (2017).

3. X-RAY IMAGING ANALYSIS

The background subtracted, exposure-corrected, adaptively smoothed 0.7–2.0 keV Chandra image of this group is shown in Figure 1 (left panel). For comparison, we also show its optical counterpart R-band image taken from the Sloan Digital Sky Survey (right panel, SDSS) on the same scale, which confirms the extended nature of the X-ray emission from this system. This figure reveals interesting structures in the X-ray image such as surface brightness edges, and a narrow X-ray ridge in the central region of this group. These structures are consistent with those reported by Trinchieri et al. (2007).

To understand the broad spectral properties of the X-ray map, we generated a tricolor image in the energy range 0.7–8.0 keV, where, from the Chandra observation, X-ray photons were extracted in three different energy bands, namely, soft (0.7–1.0keV), medium (1–2.0keV) and hard (2–8.0keV). These were smoothed, setting the parameters $sigmin = 3$ and $sigmax = 5$, and were combined to generate the tricolor image for this system (Figure 2). The red color in these image represents the soft component of the X-ray emitting gas, while the medium and hard components are represented in green and blue respectively. This broadband spectral image highlights the presence of several substructures in this system.

3.1. Detection of X-ray Cavities

A visual inspection of the 0.7–2keV Chandra image (Figure 1) of IC 1262 reveals structures like depressions or cavities in the surface brightness distribution of the hot ICM, of the kind reported in Dong et al. (2010), where the existence of cavities were discussed, but their position and size were not measured. Here we identify

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Table 1. Chandra Observation log

| ObsID | Observing Mode | CCDs on | Starting Date | Total Time (ks) | Clean Time (ks) |
|-------|----------------|---------|---------------|----------------|----------------|
| 6949  | VFAINT         | 0,1,2,3,6 | 2006-04-17   | 40             | 37.54          |
| 7321  | VFAINT         | 0,1,2,3,6 | 2006-04-19   | 40             | 35.97          |
| 7322  | VFAINT         | 0,1,2,3,6 | 2006-04-22   | 40             | 37.47          |

3 http://tgssadr.strw.leidenuniv.nl/doku.php
4 http://www.sdss.org/
Figure 3. The 0.7–2.0 keV, unsharp-masked (left panel) and 2-d model-subtracted, residual (right panel) images of IC 1262. The unsharp-masked image was derived by subtracting a 10σ wide Gaussian kernel-smoothed image from that smoothed with a 2σ wide Gaussian, while the smooth 2-d model generated from the ellipse fitting was subtracted from the original image to derive its residual map. The VLA 1.4 GHz (green) contours are overlaid on the residual image. The contours are at (2.5σ, 3.0σ, 3.5σ) levels where σ is 6 μJy beam⁻¹ for the VLA B-configuration. The annular regions used to extract the surface brightness profiles (A) (30° – 110°) and (B) (120° – 270°) are shown by yellow color.

Table 2. IC 1262 radio data.

| Telescope | Project code | Frequency (MHz) | Telescope configuration | Date of obs   | Total obs time (min) |
|-----------|--------------|----------------|-------------------------|---------------|----------------------|
| VLA       | S7601        | 1400           | B                       | 27-Jul-2006   | 38                   |
| VLA       | S7601        | 1400           | B                       | 28-Jul-2006   | 18                   |
| VLA       | S7601        | 1400           | D                       | 13-May-2007   | 120                  |
| VLA       | S7601        | 350            | C                       | 11-Jan-2007   | 120                  |
| GMRT      | 07MHA01      | 325            | -                       | 4-March-2005  | 400                  |
| GMRT      | 16_279       | 150            | -                       | 17-June-2011  | 10                   |

the cavities and quantify them using two different techniques.

3.1.1. Unsharp masked image

The 0.7–2 keV Chandra image of the IC 1262 group, after exposure correction and subtraction of background, was subjected to a procedure of unsharp masking, a procedure often used to reveal underlying structures. The image was first smoothed with a 2σ wide Gaussian kernel, using the task aconvolve within CIAO. This suppresses the pixel-to-pixel variations of the X-ray brightness, while preserving small-scale uncorrelated structures. A similar image was also generated by smoothing it with 10σ wider Gaussian kernel, which erases small-scale features, while preserving the overall morphology of the hot gas distribution in this group. The unsharp masked image was then generated by subtracting the image smoothed with 10σ from that smoothed with 2σ wide Gaussian kernel. The resulting unsharp masked image is shown in Figure 3 (left panel). A careful inspection of this figure confirms the presence of X-ray depressions or cavities in the surface brightness distribution of the hot gas from IC 1262. In addition to the obvious depressions or cavities, there are some regions delineating excess emission, as compared to the average surface brightness.

3.1.2. β-model subtracted residual maps

Further confirmation of the X-ray cavities and excess emission evident in the unsharp masked image, a 2-D β-model-subtracted residual image of IC 1262 was generated. For this, we first generated the 2-dimensional smooth model by fitting ellipses to the isophotes in the clean background-subtracted, point-source-removed X-ray image, using the fitting package Sherpa available within CIAO. The model parameters i.e., ellipticity, po-
Figure 4. Projected radial surface brightness profile, in the energy range of 0.7–4.0 keV, extracted from the northwest wedge shaped sector with opening angles (30° – 110°) (left panel) and from the east region with angle (120° – 270°) (right panel). The surface brightness profiles are extracted from the annuli A and B, shown in yellow, in Figure 3 (A, B). In each panel we show the corresponding 3D gas density model, while the bottom panels show the residuals from the best-fit surface brightness profiles.

The best fit 2-D model was then subtracted from the background-subtracted, exposure-corrected Chandra image of IC 1262 to produce its residual map, which is shown in Figure 3 (right panel). This confirms all the major features evident in the unsharp masked image. The 1.4 GHz (green) contours (from the VLA observation) are overlaid on the unsharp-masked image. The contours are at levels 2.5σ, 3.0σ, 3.5σ, where σ is 6 μJy beam$^{-1}$ for the VLA-B configuration.

Both these images confirm the presence of a loop-like structure or an arc (see Figure 3 left panel) directed ∼38′′ north-west of IC 1262. In comparable groups or clusters (e.g. Gitti et al. 2010; David et al. 2011) dark cavities normally are seen in pairs, on either side of the central excess emission, and are believed to be the result of the interaction of radio jets from central dominant system with the surrounding IGM, in the form of buoyantly rising bubbles. In this system, we detect two X-ray cavities towards the north (hereafter Ncavity) and south (hereafter Scavity) from the center: these are highlighted by white arrows in both the images. The detected X-ray cavities and their morphological parameters are tabulated in Table 3. In this Table, columns 3 & 4 show the semi-major and semi-minor axes of the cavities, while column 5 gives their projected distance from the center of the group.

### Table 3. X-ray cavity parameters

| Group  | Cavity | a   | b   | R   |
|--------|--------|-----|-----|-----|
| IC 1262 | Ncavity | 2.22 | 1.52 | 6.48 |
|        | Scavity | 4.01 | 2.00 | 6.13 |

3.2. Surface Brightness Edges

In Figure (1, 2, 3), we find clear hints of surface brightness edges (hereafter SBEs) along the east and north-west directions, at ∼38′′ and 45′′ respectively, from the center of IC 1262. In order to investigate the origin of these SBEs, we extract surface brightness profiles of the X-ray emission in the energy range 0.7–4.0 keV, using PROFFIT-V1.4 (Eckert et al. 2011), in the annular regions (A) (30°–110°) and (B) (120°–270°) 5(shown in yellow in Figure 3). The extracted profiles along the east and north-west edges are shown in Figure 4. These figures indicate that the apparent sharp changes in the surface brightness are due the existence of edges along the respective directions.

The extracted surface brightness profiles across these edges A and B were fitted with a broken power-law density model. In both cases, clear density compressions, at levels of over 90% confidence, are evident. The broken
The derived temperatures from regions A and B (120° - 260°) are inconsistent with each other and indicate that the edge B is also a cold front and is consistent with the cold front reported by (Panagoulia et al. 2014).

Cooling time is an important parameter to understand thermal evolution of the hot baryonic matter, in an individual galaxy, or in a group or cluster of galaxies. We derived the cooling time of the X-ray surface brightness distribution in this group by performing a projected spectral analysis. The cooling time was then determined for each of the annular regions, in a projected sense, using the derived values of the projected electron densities and temperatures. The cooling time profile was then derived using Sarazin (1988):

$$t_{\text{cool}} = 8.5 \times 10^{10} \text{yr} \left(\frac{n_e}{10^{-3} \text{cm}^{-3}}\right)^{-1} \left(\frac{T_{\text{gas}}}{10^8 \text{K}}\right)^{1/2}.$$  

where $n_e$ represents the electron density and $T_{\text{gas}}$ gas temperature. The resultant cooling time profile is shown in Figure 5, which reveals that the cooling time of the gas in the core of this group is much shorter than the Hubble time; in perfect agreement with those seen in many other groups (Peterson & Fabian 2006; McDonald et al. 2010; Giacintucci et al. 2008; Panagoulia et al. 2014). This strongly supports the argument that heating by the central AGN occurs at least over a timescale of $10^8$ yr.

### 4. RESULTS AND DISCUSSION

#### 4.1. Cooling parameters

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#### 4.2. X-ray properties within the cooling radius

To investigate the global properties of the X-ray emitting gas, we extracted a combined spectrum, from within

| Regions       | $\alpha_1$ | $\alpha_2$ | $r_{sh}$ (arcmin) | $n_0$ (10$^{-4}$) | C     | $\chi^2$/dof |
|---------------|------------|------------|-------------------|------------------|-------|--------------|
| A (30° - 110°) | 0.18 ± 0.11| 1.43 ± 0.20| 1.02 ± 0.02       | 3.20 ± 0.40      | 1.81 ± 0.17| 18.93/18    |
| B (120° - 260°)| 0.23 ± 0.08| 1.30 ± 0.02| 0.41 ± 0.03       | 6.60 ± 0.03      | 1.52 ± 0.02| 48.96/48    |

The best fit parameters of the broken power-law density model are summarized in Table 4. In order to determine the nature of the detected edges at A, B (i.e., shocks or cold fronts), we need to measure temperatures on their either sides. First, we extract the spectrum from two regions (A1 and A2) on either sides of edge A and fit them with a single temperature APEC (Smith et al. 2001) model by keeping redshift fixed at 0.032. The best fit temperature values for A1 and A2 are 2.39 ± 0.40 keV and 1.68 ± 0.05 keV, respectively. The A2 region contains cool, dense gas and a sharp boundary. The derived temperatures from regions A1 and A2 are inconsistent with each other and indicate that the edge A is due to the presence of a cold front and is consistent with the cold front reported by (Trinchieri et al. 2007).

We also extract the spectra on either side of the edge B and fit them in the same way, yielding best-fit temperatures of 2.36 ± 0.23 keV and 1.66 ± 0.04 keV, respectively. These derived temperature values seem to indicate that the edge B is also a cold front and consistent with the cold front reported by (Trinchieri et al. 2007).

#### Figure 5

Cooling time profile of IC1262. The horizontal solid line corresponds to the cooling time of 7.7 Gyr. The vertical solid line (black) represents cooling radius at 50 kpc, while vertical dashed line (red) represents cooling radius of IC 1262 group where $R_{\text{cool}}$=80 kpc at 7.7 Gyr.

The best-fit broken power-law density model parameters are summarized in Table 4. In order to determine the nature of the detected edges at A, B (i.e., shocks or cold fronts), we need to measure temperatures on their either sides. First, we extract the spectrum from two regions (A1 and A2) on either sides of edge A and fit them with a single temperature APEC (Smith et al. 2001) model by keeping redshift fixed at 0.032. The best fit temperature values for A1 and A2 are 2.39 ± 0.40 keV and 1.68 ± 0.05 keV, respectively. The A2 region contains cool, dense gas and a sharp boundary. The derived temperatures from regions A1 and A2 are inconsistent with each other and indicate that the edge A is due to the presence of a cold front and is consistent with the cold front reported by (Trinchieri et al. 2007).

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the cooling radius ($\leq r_{\text{cool}}$ 80 kpc), in the energy range 0.7–8.0 keV for this group. The cooling radius is the radius within which gas cools faster than $7.7 \times 10^9$ yr, the time in which the cluster/group is believed to relax and establish a cooling flow.

The spectrum was extracted using the CIAO tool SPEXEXT and grouped to have a minimum of 25 counts per spectral bin. This was done after removing compact point-like sources, including the central $\sim 2''$ region. The count-weighted response matrices were generated for each of the extraction. The extracted spectrum was then exported to the fitting package XSPEC and fitted with the model ($\text{wabs} \times \text{apec}$). The gas temperature $kT$ and APEC normalization $N$ were allowed to vary during the fit. We repeated the fitting exercise by freeing and fixing the values of the Galactic hydrogen column $N_H$ and the gas abundance $Z$. The fit in which $N_H$ and $Z$ were allowed to vary returned the best-fit results. Using these best-fit parameters, we derive the 0.7–10.0 keV X-ray luminosity, from within the cooling radius ($L_{\text{cool}}$) for the IC 1262 group, to be equal to $3.29^{+0.2}_{-0.3} \times 10^{42}$ erg s$^{-1}$.

4.3. X-ray and Radio morphology

In order to map the diffuse radio emission and its extent in this group, we generate a tri-color map, using GMRT radio, VLA radio and Chandra X-ray observations, shown in Figure 6. In this figure, red denotes GMRT 325 MHz radio emission, green denotes the high resolution VLA radio 1.4 GHz emission map and blue denotes the soft X-ray (0.7–2.0) keV emission detected by Chandra. From this figure it is evident that radio lobes are more extended than that of the X-ray emission. The detailed spectral properties of multi-frequency radio emission are discussed in Section 4.7.

4.4. Cavity Energetics

In the present study we assume the X-ray cavities to be bubbles devoid of gas, moving outward due to buoyant force at the local ambient temperature. Volumes of the individual cavities were calculated assuming that they are symmetric about the plane of the sky, with their centers lying in the plane perpendicular to the line-of-sight passing through the central AGN. For this, we assumed the cavities of prolate ellipsoidal shape, with semi-major axis $a$ and semi-minor axis $b$. The volume of each cavity was estimated as $V = 4\pi abR/3$, where $R$ is the line-of-sight distance between the nuclear source and the center of the cavity.

Following the method proposed by Birzan et al. (2004), we estimate the age of the cavities as given in column 7 of Table 5. This analysis has enabled us to investigate two clear cavities with their projected distance from the center of group equal to $\sim 6.48$ kpc and $\sim 6.13$ kpc. Generally, the age derived using the approach of sound crossing provides lower estimates, while that derived from time required to refill the cavities lead to estimates on the higher side. The estimates of the total mechanical power content of the cavities for the IC 1262 group are given in column 8 of Table 5. The total mechanical power contained in these two cavities is about $12.37 \times 10^{42}$ erg s$^{-1}$.

4.5. Quenching of the cooling flow

To cross check whether the apparent AGN feedback can efficiently work to quench the cooling flow in IC 1262, we compare the balance between the total AGN output power ($P_{\text{agg}}$), derived from the gas luminosity within the cooling radius $L_{\text{ICM}}(r_{\text{cool}})$. This is shown in the heating versus cooling diagram (Figure 7 left panel). Here, $P_{\text{agg}}$ gives the measure of the energy injected by the AGN into the hot gas, while $L_{\text{ICM}}(r_{\text{cool}})$ represents the energy lost by the hot gas from within cooling radius in the form of X-ray emission. This comparison reveals that the radio source hosted by the central dominant galaxy IC 1262 is capable enough to deposit sufficient energy into the IGM to offset the cooling flow.

The equality between the heating and cooling at the heat input rates of $pV$, $4pV$ and $16pV$ per cavity are
Figure 7. left panel: Cavity power versus X-ray luminosity within the cooling radius of groups and clusters (from Rafferty et al. (2006)), represented as filled circles (black). The cavity power and X-ray luminosity for IC 1262 is shown by the “+” symbol (magenta). The diagonal lines represent samples where $P_{\text{cav}} = L_{\text{ICM}}$, assuming pV, 4pV, 16pV as the total enthalpy of the cavities. Right panel: Cavity power plotted against radio power, with filled circles representing galaxy clusters and groups from Cavagnolo et al. (2010). The magenta “+” represents the IC 1262 group.

Table 5. Cavity parameters from the X-ray observations

| Group  | Cavity | $E_{\text{bubble}} = pV$ | $t_{\text{ca}}$ | $t_{\text{buoy}}$ | $t_{\text{refill}}$ | $t_{\text{avg}}$ | $P_{\text{cav}}$ |
|--------|--------|-------------------------|----------------|-----------------|-----------------|----------------|----------------|
|        |        | $10^{56}$ erg           | $10^7$ yrs     | $10^7$ yrs      | $10^7$ yrs      | $10^7$ yrs      | $10^{42}$ erg s$^{-1}$ |
| IC 1262 | Ncavity | 58.0                    | 1.7            | 2.4             | 5.2             | 3.1             | 6.0             |
|        | Scavity | 50.1                    | 1.2            | 2.1             | 4.2             | 2.5             | 6.3             |

Column 3: total energy stored in each of the cavity.
Column 4, 5 and 6: cavity ages estimated by three different ways (see text).
Column 7: average age of cavities.
Column 8: power stored in each cavity.

shown by the diagonal lines in this figure. In the same figure we also plot the similar results derived by other authors (Rafferty et al. 2006; O'Sullivan et al. 2011; Pandge et al. 2013; Vagshette et al. 2016, 2017). The position of the IC 1262 group in this plot, with respect to the others from the literature, is shown by a magenta “+”, and is found to lie near the 4pV enthalpy line. This in turn confirms that the total power available within the cavities is sufficient to offset the cooling flow within the cooling radius.

We also compared the $P_{1.4}$ GHz radio power with total cavity power ($P_{\text{cav}}$) (Figure 7, right panel). In this figure, filled circles represent the sample studied by Cavagnolo et al. (2010), and IC 1262 is marked by a magenta “+” symbol. This plot also indicates that the radio source associated with IC 1262 is capable of quenching the cooling flow in this group.

4.6. Association of X-ray cavities with radio emission

It is well established that the X-ray surface brightness depressions seen in a majority of the cool-core systems are produced due to the interaction between the radio lobes, originating from the active nucleus, and the surrounding ICM, even in galaxy groups (Jetha et al.
Figure 8. color & contour maps of IC 1262 made, using the task “viewer” in CASA with relative contour levels at [0.2, 0.4, 0.6, 0.8] mJy/beam. Image (A) shows the GMRT 325 MHz data with a beam size of $16.40'' \times 7.39''$, where we can see the entire radio source at rms of $\sim 0.25$ mJy/beam. On the right-hand side of the image, we see the zoomed-in version of the various components of the source. Images (B) and (C) are higher resolution images from JVLA (B-array) at 1.4 GHz with a beam size of $3.62'' \times 3.48''$ and rms of 0.02 mJy/beam. Image B shows the inner core and jet structure. Image C shows the southern lobe of unusual structure.

Table 6. Radio parameters.

| Region         | Frequency | Flux density | Angular size (deconvolved) | Linear size | $P_{1.4GHz}$ |
|----------------|-----------|--------------|-----------------------------|-------------|--------------|
|                | MHz       | mJy          | $'' \times ''$              | kpc x kpc   | 10$^{23}$ (W Hz$^{-1}$) |
| North Lobe (NL)| 150       | 1135$\pm$4.6 | 113x90                      | 68x54       |              |
|                | 325       | 341.2$\pm$0.25 | 97x86                      | 58x22       |              |
|                | 1400      | 13.04$\pm$0.06 | 97x67                      | 58x40       | 0.3          |
| Central Source (CS)| 150       | 418.3$\pm$4.5 | 86x37                      | 51x22       |              |
|                | 325       | 112.1$\pm$0.25 | 78x24                      | 47x14       |              |
|                | 1400      | 16.40$\pm$0.06 | 28x18                      | 17x10       | 0.3          |
| South Lobe (SL)| 150       | 2140$\pm$4.6 | 92x75                      | 55x45       |              |
|                | 325       | 855.1$\pm$0.25 | 76x71                      | 46x43       |              |
|                | 1400      | 50.01$\pm$0.06 | 53x44                      | 32x27       | 1.0          |
Figure 9. *left panel:* The *Chandra* image of IC1262, corrected for exposure and background, in the energy range 0.7-7.0 keV. This X-ray image is smoothed by a 6σ-wide Gaussian kernel (σ = 1 pixel). The location of a first generation X-ray depression is shown by white arrows, while the position of the shock is shown by a white dotted arc. *Right panel:* Same figure as left panel, on which GMRT 325 MHz radio contours are overlaid. The excess X-ray emission seen southwest of the central source is highlighted by white arrows.
The radio jets emanating from the cores of the groups or clusters displaces the surrounding hot gas and leaves depressions or cavities in their surface brightness. These X-ray cavities are often found to be filled with radio emission in many of the systems.

We have attempted to examine whether the X-ray cavities in this group also have a similar association with the radio emission from the central source. For this we have made use of the multi-frequency radio data available in the VLA and GMRT archives. Results from the analysis of the radio data on this system are shown in Figure 8, where Panel A shows the GMRT extended radio emission map at 325 MHz, and its contours from the central source, while Panels B and C are higher resolution images from the VLA (B array) at 1.4 GHz with a beam size of $3.62'' \times 3.48''$ and rms of 0.02 mJy/beam. Image B shows the inner core and jet structure whereas image C shows the possible southern lobe that has highly unusual structure.

The morphology of the radio emission varies greatly over the images and appears to be quite complicated. Radio emission from IC 1262 appears to be widespread, extending over more than $5'' (\sim 200$ kpc). The radio source in IC 1262 is found to be associated with the cavities detected in X-ray image of this group and appears to coincide with the X-ray center of this group (Figure 3, right panel). It implies the presence of two radio sources, one relatively weaker object associated with the obvious X-ray bright source, while the other appearing $14.62'' (\sim 9.7$ kpc) to the east of the former at about. This radio image shows a clear jet-like structure in this system (see Figure 8 B).

We have also detected another X-ray depression at the position of the southern radio lobe, which could be the first generation X-ray cavity and is shown by white arrows in Figure 9 (left panel). GMRT 325 MHz contours (green color) overlaid on this image are shown in Figure 9 (right panel). An excess X-ray emission on the west to the center highlighted by white arrows is also shown in this figure. A weak shock to the south of the central source at a projected distance of 200 kpc has been detected and is shown by a (white) dotted arc in the Figure 9 (left panel). A weak shock (of Mach number 1.5) has been reported at this location by Sun et al. (2009). We could not detect a first generation cavity at the position of the northern lobe.

We measured flux densities for three different regions of IC 1262 - (1) the North Lobe (NL), (2) the Central Source (CS), and (3) the South Lobe (SL) using observations from the 150 MHz TIFR-GMRT-Sky Survey (TGSS), VLA P (325 MHz) and L (1400 MHz) bands.

In the L-band, D-configuration image, we see two separate radio sources on the south of the central radio source, which are blended in both the lower resolution P (VLA) and TGSS images. In the flux density calculation, we separate out this southern source (RA:17$^h$32$^m$58, Dec:43$^\circ$41 45$''$) from that in the South lobe (RA:17$^h$32$^m$59, Dec:43$^\circ$43 44$''$). We have listed our measurements (deconvolved sizes and integrated flux densities) in Table 6.

To calculate the flux densities of these sources, we convolved the L-band (resolution of 41$''$ x 37$''$) and TGSS (resolution of 20$''$ x 20$''$) images to P (VLA) band image of beam size of 57$''$ x 41$''$. The rms in the L-band, P-band and TGSS images are 0.15 mJy beam$^{-1}$, 1.5 mJy beam$^{-1}$ and 20 mJy beam$^{-1}$, respectively. We scaled TGSS, P and L bands flux densities values to the recent (Perley & Butler 2017) flux density scale. This new flux density scale provides accurate measurements over 50 MHz to 50 GHz using current observations with the Janesky VLA. We plotted the integrated spectra of IC 1262 in Figure 10, where both the lobes exhibit steep spectrum radio sources (we follow the convention $S \propto \nu^\alpha$, where $\alpha$ is the spectral index and $S$ is the flux density at frequency $\nu$). We find that the radio luminosity of the south lobe exceeds that of the north lobe at all these frequencies. This is also in agreement with the spectral index of the north lobe ($\alpha_1 = -2.23$) is steeper than the south lobe ($\alpha_3 = -1.94$). Moreover, we find that average spectral index values for IC1262 radio galaxy, including and excluding the central AGN, are 1.73 and 2.08, respectively.

The error estimation in the flux density measurements were carried out using the following procedure. There are two primary sources of errors in the flux density measurements: (1) one due to the uncertainties in the flux densities of the unresolved source(s) used for the calibration of the data. We assumed this error to be $\sim 10\%$ at 325 and 1400 MHz, while that at 150 MHz to be $20\%$; (2) since these radio sources (the north and the south radio lobes) are extended sources, the errors in their flux density estimations will be the rms in the image multiplied by the square root of the ratio of the solid angle of the source to that of the synthesized beam. Since these two sources of errors are unrelated, we added them in quadrature to estimate the final error on the flux.

4.7. Spectral index of IC 1262

4.7.1. Spectral Plot
Figure 10. The integrated radio spectrum of IC 1262.

Figure 11. A: Spectral index map between 150 MHz (TGSS) and 325 MHz (GMRT) frequencies. B: Spectral index map between 325 MHz (GMRT) and 1400 MHz (JVLA) frequencies very clearly depicting the steep regions.
Figure 12. A: The spectral index map of the radio phoenix, measured between 325 MHz (GMRT) and 1400 MHz (VLA) frequencies. B: Spectral index along the radio phoenix, which is embedded in southern radio lobe of IC 1262, computed using the regions shown in the inset.
densities of the extended sources, using
\[\Delta S = [(\sigma_{\text{amp}}S)^2 + (\sigma_{\text{rms}}\sqrt{n_{\text{beams}}})^2)]^{1/2},\]
where \(S\) is the flux density, \(\sigma_{\text{rms}}\) the image rms noise, and \(n_{\text{beams}}\) the number of beams within the extent of the source.

### 4.7.2. Spectral Index Maps

Three spectral index maps were made, combining data from VLA, GMRT, and TGSS, as shown in Figure 11. The maps at various frequencies were convolved appropriately according to the requirements as described below:

1. The higher resolution (16.40″ × 42.13″) GMRT 325 MHz map was convolved to the beam size of the TGSS map (25″ × 25″). This is shown in Figure 11 (A).

2. The GMRT 325 MHz map was convolved to the beam size of the VLA L-band (D-configuration) map (40.96″ × 37.00″), as shown in Figure 11 (B).

3. The high resolution (3.63″ × 3.28″) VLA L-band (B-configuration) map was convolved to the resolution of GMRT 325 MHz map, as shown in Figure 12 (A).

After the above procedure, the routine tasks in AIPS (OHGEO and COMB) were used to make the spectral index maps. Pixels below 3σ rms were blanked in images A & B were blanked before computing the spectral index maps. For Figure 12 (A), a higher cut off of 5σ rms was observed for higher precision. In Figure 12 (A), the contours of the VLA L-band (B configuration) are overlaid with its beam size represented in bottom left corner of the image. From these figures it is evident that the average spectral index obtained for the northern lobe is \(\sim -2.23\), and that of the southern lobe is \(\sim -1.94\) (see Figure 10). Figures (10 and 11) clearly show that the average spectral index obtained for the northern lobe is steeper than that of the southern lobe. The average spectral index of both the lobes is extremely steep relative to that found in typical low redshift radio galaxies, namely \(\sim 0.7\) (Blundell et al. 1999).

### 4.7.3. Radio Phoenix in the southern radio lobe

Extended radio sources found in galaxy clusters and groups are interpreted in a variety of ways, in terms of their inferred age and origin, from observed parameters such as extent, shape, flux and spectral index. A taxonomy of such sources has been summarised in Kempner et al. (2004), in which a radio phoenix appears as an extended filamentary steep spectrum (spectral index \(\sim -1.5\)) radio source. These are found in the cores of groups and clusters, and are interpreted as an indication of a recent merger. Accretion shocks in mergers of groups and clusters can be found over regions as large as hundreds of kpc. These appear extended more frequently at lower than at GHz frequencies. Radio phoenixes are start their life as relics resulting from an earlier merger, having a population of charged particles that have significantly aged such that synchrotron radiation from them are too faint to detect at high frequencies (e.g. Enßlin & Gopal-Krishna 2001). The accretion shock due to a recent merger then rejuvenates this faded relic, by compressing the plasma and re-accelerating the particles to energies such that they would again be detectable at radio frequencies. The analogy is thus to a phoenix rising from its embers. The classic example of a radio phoenix is the cluster Abell 85 (Young et al. 2005).

The complex feature detected in southern radio lobe (Figure 8 C) is not associated with any X-ray or optical emission, but is found to be embedded within the southern radio lobe, suggesting that it is related to the central radio AGN. The radio emission is complex and largely filamentary in morphology, which usually indicates interaction with the surrounding ICM, and is characteristic of a phoenix. The average value of the radio spectral index of this feature within the southern radio lobe (Figure 8 C, obtained by combining fluxes from TGSS, GMRT 325 MHz, and VLA L-band in the B-configuration) is equal to \(\sim -1.92\). As noted above, this is consistent with that of a phoenix, where the aged plasma would have been compressed adiabatically by merger shock waves boosting the radio emission (Enßlin & Gopal-Krishna 2001; Kempner et al. 2004; Ogrean et al. 2011; van Weeren et al. 2012).

Several radio phoenixes with these characteristic features have been so far identified, but they have all been discovered in rich clusters with high mass or X-ray temperature. Prominent examples are Abell 85 (radial velocity dispersion = 692 km s\(^{-1}\)) and Abell 1033 (radial velocity dispersion = 677 km s\(^{-1}\), both values taken from Rines et al. 2016). However, IC 1262 is considered to be a poor group, its radial velocity dispersion being about \(= 300\) km s\(^{-1}\) (Wegner et al. 1999), and thus we find that this is the first case where such an object has been found in a group-scale dark halo, showing that merger shocks can revive relic plasma in group-scale mergers as well.

We also checked the variation of the spectral index along this complex structure, computed using the regions shown in the inset (Figure 12 B). This shows that the spectrum of the diffuse emission steepens with in-
creasing distance from the peak of the radio emission, which indicates that plasma overall has aged and lost its energy via synchrotron or inverse Compton (IC) radiation as it has moved away from its source. However, the feature in question, appears to have been revived by the passing of a weak merger shock with a Mach number $M \sim 1.2$ (Sun et al. 2009), sufficient for compressing the aged radio plasma.

To find the possible merger signature in the X-ray image described above, we postulate that the complex filamentary structure within the southern radio lobe originates from an aged radio lobe due from the central radio AGN, which has been ‘revived’ by a weak merger shock passing through this galaxy group. Thus, we classify this complex feature as a radio phoenix (Ogrean et al. 2011).

5. CONCLUSIONS

We present results based on the analysis of 120 ks Chandra X-ray, SDSS optical, VLA 350/1400 GHz and GMRT 235/610 MHz radio observations of the galaxy group IC 1262. The objectives of this study were to identify and confirm the positions of the X-ray cavities and surface brightness edges present in the hot intra-group medium (IGM) of IC 1262. We summarize the important results derived from the present analysis:

1. In the unsharp masked as well as the 2-d $\beta$-model-subtracted residual images of the hot intra-group medium, we find two X-ray cavities ($N_{\text{cavity}}$ and $S_{\text{cavity}}$) and a ridge around the center of the group IC 1262.

2. The X-ray cavities are located at projected distances of $\sim 6.48$ kpc and $\sim 6.13$ kpc from the center of IC 1262.

3. Two surface brightness edges are evident to the east and north-west of the center of this group and confirmed as cold fronts.

4. The total mechanical power of both X-ray cavities $L_{\text{cavity}}$ and the X-ray luminosity within the cooling radius $L_{\text{cool}}$ indicate that the total mechanical power emitted by central radio source is sufficient to balance the cooling loss in this group.

5. The radio emission from the Jansky VLA 1400 MHz observation appears to coincide with the location of detected X-ray cavities.

6. The analysis of the X-ray cavity images and the estimated cooling time enabled us to calculate the mechanical power for the cavities to be $P_{\text{cavity}} \sim 12.37 \times 10^{42}$ erg s$^{-1}$ and $L_{\text{cool}} \sim 3.29 \times 10^{42}$ erg s$^{-1}$, respectively. The comparison of these values implied that the radio jet-mode feedback is sufficient to quench the cooling losses occurring in this group within the cooling radius.

7. From the radio imaging analysis, and the spectral index plot and maps, it is evident that the radio sources hosted by IC 1262 have a flatter spectrum at the core, while that at the lobes appears steeper.

8. The radio galaxy belonging to the IC 1262 group is the low-redshift ultra-steep radio galaxy detected with a spectral index $\alpha \sim -1.73$ and $\alpha \sim -2.08$ with and without the central AGN, respectively.

9. The X-ray depression at the position of southern radio lobe has been detected in the present analysis. It is likely that it represents a first generation X-ray cavity.

10. We detect a radio phoenix embedded within the southern radio lobe, for the first time in a poor group, having a spectral index ($\alpha \leq -1.92$). Its spectral index steepens with increasing distance from its peak.

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Facilities: SDSS, CHANDRA (CIAO), GMRT, VLA, CXO

Software: SPAM (Intema 2014), PROFFIT (Eckert et al. 2011)

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