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Date: 2025-09-28T12:32:54+00:00

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Full Text

Preamble

Research in Astronomy and Astrophysics, 25:085013 (7pp), 2025 August

https://doi.org/10.1088/1674-4527/ade384
CSTR: 32081.14.RAA.ade384

Revealing a Major Merger in the Nearby Galaxy Group IC 1262 with Chandra Observations

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Received 2025 February 6; revised 2025 May 24; accepted 2025 June 3; published 2025 July 1

Abstract

We analyze deep Chandra data of the nearby IC 1262 group and find that the bow-shaped structure located about 17 kpc (25) east of the X-ray peak is a cold front moving eastward with a Mach number of $M = 0.7 \pm 0.1$. Furthermore, the line-of-sight velocity distribution of the member galaxies is clearly divided into two subgroups. Assuming the same mass-to-light ratio, the group is undergoing a major merger. Since the cooler core of the group as a whole is not destroyed by the merger, and the high-velocity subgroup has a component of eastward movement, it can be naturally explained that the cold front appears on the east side of the group center.

Key words: galaxies: groups: individual (IC 1262 group) – ISM: kinematics and dynamics – X-rays: galaxies: clusters

1. Introduction

The merging process of galaxy groups and clusters stands as one of the most energetic events in the universe [17]. Mergers have been regarded as valuable tools for studying cosmology and galaxy formation [29], because they represent an important process for the growth of galaxy groups and clusters. Cold fronts, shocks, and radio halos are formed at different stages of merging, which are typical characteristics of the merging process [1, 18, 8]. These features often appear in X-ray and radio observations, providing valuable information about the merging process [10, 6]. They are a common subject of study in clusters, with numerous examples of shock heating of the intra-cluster medium (ICM; e.g., [19, 5, 32, 4, 31]).

However, the lower density of intra-group medium (IGM) and the lower velocities of the galaxy population have led to fewer studies of group-scale mergers. The effects of non-gravitational heating, such as AGN feedback and merger shocks, are expected to be more significant in lower mass systems as the energy input from these sources is comparable to the binding energy of the group (e.g., [22, 23, 9]). Thus, the heating effects can affect the cooling and feedback cycle, and have a considerable impact on their constituent galaxies. Only a handful of group-group mergers with high enough velocities are known (e.g., [11, 12, 25, 15, 16, 26, 20, 28, 34, 24]).

This paper presents a major merger discovered in deep Chandra observations of the nearby IC 1262 galaxy group ($z = 0.0326$; [29]), which is dominated by the cD galaxy IC 1262 (17h33m02.s0468, +43d45m34.s887, E, $M_V = -22.04$; $z = 0.03265$). X-ray imaging analyses reveal that two surface brightness edges are evident to the east and northwest in the center of this group [30, 21]. The AGN activity in the IC 1262 galaxy has led to the formation of a pair of radio lobes extending roughly northward and southward, covering a distance of over 200 kpc (5), and forming two X-ray cavities with scales of several kpc [21], respectively.

After a detailed comparison, we find that the flux centers of both the northern and southern radio lobes are located more than 22 kpc (33) west of the optical center of the IC 1262 galaxy, and the radio lobes appear as two "tails" of the galaxy. These indicate that the cD galaxy is moving to the east.

In Section 2 we describe the Chandra observations and data reductions. In Section 3 we present the X-ray image, temperature and metal abundance distributions, and confirm a cold front. In Section 4 we analyze the velocity distribution of the identified member galaxies. In Section 5 we discuss and summarize our results. Throughout the paper, we adopt the cosmological parameters $H_0 = 73$ km s^{-1} Mpc^{-1}, $\Omega_b = 0.044$, $\Omega_M = 0.27$. Unless stated otherwise, the quoted errors represent 90% confidence limits.

2. Observations and Data Reductions

The Chandra X-ray observations of the IC 1262 galaxy group were obtained on 2001 August 23 (ObsID 2018), 2006 April 17 (ObsID 6949), 2006 April 19 (ObsID 7321), and 2006 April 22 (ObsID 7322). The data were acquired using the Advanced CCD Imaging Spectrometer (ACIS) operating in VFAINT mode. According to standard data reduction procedures, we processed the data using CIAO v4.14 and CALDB v4.10.2. First, we updated the level=1 event files with the latest aspect solution files. Then, we created new bad pixel files and reprocessed the observations using the latest calibration files provided by the Chandra X-ray Center. We extracted 0.3–12.0 keV lightcurves from background regions defined on the ACIS-I chips, and found almost no strong background flares that increased the background count rate to $> 115\%$ of the mean quiescent value.

The net exposures are listed in Table 1. For spectral analyses, we used Chandra spectra in the range of 0.7–7.0 keV. The background spectrum of ObsID 2018 was taken from blank-sky observations because the diffuse emission of the IC 1262 group fills the entire CCD7. For the other three observations, local background spectra were extracted from the outer regions of the ACIS-I chips where the background is relatively clean. The results from the blank-sky background spectra and the local background spectra are consistent. During the spectral analyses, we used the SPECEXTRACT tool to create the appropriate auxiliary response files (ARF) and redistribution matrix files (RMF).

The spectra were fitted with an absorbed APEC model in XSPEC. The hydrogen column density N_H was fixed at the Galactic value of 1.58×10^{20} cm^{-2} [2], and the redshift was fixed at that of the group, while the gas temperature and metal abundance were set as free parameters.

3.1. X-ray Imaging Analyses

In Figure 1(a) we show the ACIS-I image of the IC 1262 galaxy group in the 0.3–2.0 keV band, which has been corrected for exposure but not for background. The image is obtained by merging observations ObsID 6949, 7321, and 7322. We enlarge the X-ray central region of the group, as shown in Figure 1(b). We find that the X-ray peak (R.A. = 17h33m03.s2978, decl. = +43d45m35.s717) is offset from the optical center of the IC 1262 galaxy by approximately 9.1 kpc (13.6 , where 1 = 0.668 kpc). Additionally, we see a bow-shaped structure about 17 kpc (25) to the east of the X-ray peak, extending from the center to the northeast and southeast sides, and another arc-shaped structure about 40 kpc (1) to the northwest of the X-ray peak. Both structures are consistent with those reported by [30].

In Figure 1(c) we present the optical image of the IC 1262 galaxy group overlaid with X-ray contours and LOFAR 143 MHz contours [3], the latter of which show two radio lobes extending roughly toward the northwest and southwest directions, covering a distance of over 200 kpc (5). The flux centers of the two radio lobes are located more than about 22 kpc (33) west of the optical center of the IC 1262 galaxy. These indicate that the cD galaxy is moving eastward, leaving the radio lobes previously ejected toward north and south in their original directions as "two tails." The eastward motion of the cD galaxy is possibly the reason for the formation of the eastern bow-shaped structure.

3.2. Temperature and Metal Abundance Distributions

We show the background-subtracted, exposure-corrected, and adaptively smoothed hardness ratio map in Figure 2(a), created by dividing the X-ray image in the high-energy band (2.0–5.0 keV) by that in the low-energy band (0.3–1.2 keV). The hardness ratio inside the bow-shaped structure (~ 0.36) is lower than that outside (~ 0.54). Overall, the hardness ratio is roughly lower on the north and south sides of the X-ray peak, consistent with the direction of the two radio lobes as shown in Figure 1(c), while the hardness ratio is generally higher on the east and west sides.

To obtain more accurate temperature and abundance distributions, we perform spectral analyses of the IC 1262 group using the three 2006 observations (ObsID 6949, 7321, and 7322). We fit each spectrum using the absorbed APEC model. The resulting temperature and abundance maps are shown in Figures 2(b) and 2(c), respectively. We find that the group has a cold core with a temperature of about 1.3 keV and a radius of 10 kpc, and the temperature inside the bow-shaped structure (~ 1.5 keV) is lower than the outside temperature (~ 2.2 keV). On the outside, the gas temperatures on the north and south sides of the center of the IC 1262 group are relatively low (1.3–1.7 keV), corresponding to the positions of the radio lobes in the radio map caused by AGN activity. Meanwhile, the temperatures on the east and west sides are high (~ 2.4 keV). As shown in Figure 2(c), we find no high-metallicity regions in the center, while a region with high metal abundance ($\sim 1Z_{\odot}$) is located about 37 kpc (55) southwest of the X-ray peak of the group.

3.3. A Cold Front

To quantitatively study the bow-shaped structure, we extracted the exposure-corrected X-ray surface brightness profiles (SBPs) in the 0.3–2.0 keV band from annuli restricted to an angle as shown in Figure 1(b). We present the SBPs in Figure 3(a), which exhibits a significant surface brightness discontinuity at a radius of 17.0 kpc (25.4). These results are consistent with those of [21]. Such discontinuities in surface brightness are typically caused by abrupt changes in gas density accompanied by rapid temperature variation, often indicating the presence of shocks or cold fronts (e.g., [10]).

We extract spectra from the four annuli limited in angle as shown in Figure 1(b). The gas temperature and metal abundance distributions are shown in Table 2. Across the bow-shaped edge, the gas temperature in the outer region (Region A2; 2.16 ± 0.16 keV) is significantly higher than that in the inner region (Region A1; 1.69 ± 0.06 keV) at the 90% confidence level, which confirms the existence of a temperature jump. In Figure 3(b) we present the two-dimensional fit-statistic contours between temperature and metal abundance for Regions A1 and A2, corresponding to confidence levels of 68%, 90%, and 99%, respectively.

We fit the surface brightness profiles using a truncated power-law and β model [34], parameterized as:

$$n_e(r) = n_{e,0} \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta/2} \left[1 + \left(\frac{r}{R_{\rm cut}}\right)^{\alpha}\right]^{-1}$$

where $n_{e,1}$ and $n_{e,2}$ are the electron number densities, $R_{\rm cut}$ is the truncation radius, α is the truncated power-law index, and β is the index. The best-fit values are listed in Table 3. We show the gas parameters inside and outside the bow-shaped structure in Table 4, where the density jump is a factor of 2.0 ± 0.2 across the bow-shaped edge.

Based on the one-dimensional fluid model and following the method of [33], we estimate the gas pressure at the stagnation point (P_1) using the gas temperature T_1 and electron number density $n_{e,1}$ measured in Region A1. We consider Region A2 as the free-flowing region and estimate its gas pressure (P_0) using the gas temperature T_2 and electron number density $n_{e,2}$. Thus, we obtain a pressure ratio of $P_1/P_0 = 1.5 \pm 0.2$. Using the Bernoulli equation [13], we derive a Mach number of $M = 0.7 \pm 0.1$ and a corresponding velocity of 550 ± 80 km s^{-1}. Based on these analyses—including the discontinuity in the surface brightness profile, the discontinuity in gas density and temperature distribution, as well as the Mach number and corresponding velocity—we confirm the presence of a cold front located 17.0 kpc east of the X-ray peak.

3.4. The Outer Substructures of the IC 1262 Galaxy Group

In Figure 4(a) we show the X-ray residual map of the IC 1262 group in the 0.3–3.0 keV band, obtained by subtracting an angularly averaged β-model from the exposure-corrected image. We find some diffuse emission about 390 kpc (594) northeast of the X-ray peak, which is consistent with the location of the bright galaxy CGCG 226-028 (17h33m20.s3954, +43d54m48.s604, $M_p = -20.19$; $z = 0.03622$). We extract the surface brightness profile in this direction, as shown in Figure 4(c). We find an excess over a β-model where the brightness exceeds about 6×10^{-11} photons cm^{-2} s^{-1} pixel^{-2} in the range of 364–480 kpc (545 – 719). The SBP excess is largely associated with the location of the CGCG 226-028 galaxy.

In Figure 4(b) we present the metal abundance map in a region of about 560 kpc × 560 kpc (14 × 14). We find a high-abundance region approximately 230 kpc (350) north of the X-ray peak. We extract spectra from an elliptical region and obtain a metal abundance of $0.9^{+0.9}_{-0.4} Z_\odot$ at the 68% confidence level, which is significantly higher than that of its surrounding areas ($0.3 \pm 0.03 Z_\odot$). The metal abundance in other areas that appear to show high values is consistent with that of their surrounding areas at the 68% confidence level.

4. Velocity Distribution

To investigate the merging status of the IC 1262 group, we select galaxies from NED within a radius of 22 centered on the weighted centroid of the galaxy distribution (17h33m02.s005, +43d45m35.s0, [14]). To include possible member galaxies, a velocity cut centered on the group redshift with a range of ±2000 km s^{-1} is applied. As a result, 34 galaxies are identified as belonging to the group.

We first plot the line-of-sight velocity histogram of the 34 member galaxies in the IC 1262 group in Figure 5(a). The galaxies are clearly divided into two parts: one subgroup with higher velocities of $v > 9750$ km s^{-1}, comprising 19 galaxy members (including the cD galaxy IC 1262), and another subgroup with lower velocities of $v < 9750$ km s^{-1}, comprising 15 galaxy members. We perform a fit to the histogram using a single Gaussian model, yielding a reduced χ^2/d.o.f. of 41.9/15 (> 2). Using the K-S test, we find the confidence level of the velocity distribution following a Gaussian distribution is less than 20%. Thus, the single Gaussian model is excluded. We use a double Gaussian model to fit the distribution, obtaining a reduced χ^2/d.o.f. of 5.7/12 (< 0.5). The lower-velocity part of the galaxy group is described by a Gaussian component with an average velocity of 9280 ± 170 km s^{-1} and a variance of 80 ± 30 km s^{-1}. The higher-velocity part is described by a Gaussian component with an average velocity of 9960 ± 20 km s^{-1} and a variance of 20 ± 9 km s^{-1}. According to the F-test, the second Gaussian component is required at the 99% confidence level.

We show the galaxies of the low-velocity subgroup as red circles and those of the high-velocity subgroup as green circles in Figure 5(c). No significant anisotropic distribution is found on the sky plane yet. To further study the distribution of galaxies, we refine the line-of-sight velocity distribution of the member galaxies with a bin size of 80 km s^{-1}, as shown in Figure 5(b). There are seven galaxies (including the cD galaxy IC 1262) in a narrow velocity bin, which we plot as white boxes in Figure 5(c). Three of these galaxies (including the IC 1262 galaxy) are very close on the sky plane, within 10 kpc (15). This indicates that these three galaxies, which are close in both line-of-sight velocity and on the sky plane, are dynamically integrated as a whole and dominate the movement of the high-velocity subgroup.

The IC 1262 group is undergoing a merger between the high-velocity subgroup dominated by the cD galaxy IC 1262 and the low-velocity subgroup with IC 1263 as its main galaxy.

5. Discussion and Summary

Based on our X-ray analyses, we find that the X-ray bow-shaped structure about 17 kpc (25) to the east of the IC 1262 galaxy group is a cold front moving eastward with a Mach number of $M = 0.7 \pm 0.1$ and a corresponding velocity of 550 ± 80 km s^{-1}. Furthermore, the line-of-sight velocity distribution of the member galaxies is clearly divided into two subgroups, which indicates that the galaxy group is undergoing a merger.

In Section 4, the brightest galaxy of the low-velocity group is IC 1263 ($M_V = -20.77 \pm 0.64$), while the cD galaxy of the high-velocity subgroup is IC 1262 ($M_V = -22.04 \pm 0.21$). According to hierarchical structure formation theory and assuming the same mass-to-light ratio, the mass ratio of the merger between the low-velocity subgroup and the high-velocity subgroup is roughly 1:3. When using almost all member galaxies (15 low-velocity galaxies and 18 high-velocity galaxies) whose near-infrared magnitudes can be found in NED, the obtained mass ratio is about 2:3. These results support that the merger is most likely a major merger. Here, we do not use the velocity variance ratio of the two subgroups to calculate the merger mass ratio because the number of member galaxies in each subgroup is small and the uncertainty would be large.

In Figure 2(b), the central region of the IC 1262 group shows a lower temperature (about 1.3 keV), which suggests the group has a cooler core. In Section 4, the cD galaxy IC 1262 and its two neighboring galaxies, all of which belong to the high-velocity subgroup, are very close in terms of both line-of-sight velocity and position on the sky plane. So far, during the merging process, the cooler core of the group as a whole has not been destroyed by the merger. In the radio map (Figure 1(c)), the two radio lobes caused by previous AGN activity appear as two tails of galaxy IC 1262, which indicates the galaxy is moving eastward. Thus, the high-velocity subgroup dominated by the cD galaxy IC 1262 has a component of eastward movement. Therefore, it can be naturally explained that the cold front appears on the east side of the group center.

The high-velocity subgroup has a velocity of ~ 680 km s^{-1} relative to the low-velocity subgroup along the line-of-sight direction. The cold front is moving eastward roughly in the plane of the sky. According to the Pythagorean theorem, the high-velocity subgroup has a total velocity of 870 ± 190 km s^{-1} relative to the low-velocity subgroup. For the environment of the IC 1262 group, the corresponding Mach number is > 0.9. This indicates that the group is one of the strong candidates for detecting shock waves, although we have not yet detected them in the group.

In Section 3.4, we find a region with higher metal abundance about 230 kpc (350) north of the IC 1262 galaxy, which is roughly adjacent to the northern boundary of the north-side radio lobe as shown in Figure 4(b). To analyze the reason for its formation, following the method of [27] and [7], we calculate the cooling time as 2.9×10^{10} yr and the buoyant time as 2.5×10^{9} yr, the latter of which is one order of magnitude smaller than the former. These cannot definitively support that the appearance of the high-abundance region is caused by AGN activity of the IC 1262 galaxy, because the merger of the galaxy group is an important reason for the transport of gas abundance from the center to the outskirts [10].

Acknowledgments

We thank the Chandra team for making data available via the High Energy Astrophysics Science Archive Research Center (HEASARC). This work was supported by the National Natural Science Foundation of China (grant Nos. 11103057 and 12003014).

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Note: Figure translations are in progress. See original paper for figures.