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Abstract

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Full Text

Preamble

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Weak Merging Scenario of CLASH Cluster A209

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Abstract

We investigate the structural and dynamical properties of A209 based on Chandra and XMM-Newton observations. Using the contour binning method, we obtain detailed temperature, pressure, and entropy maps, revealing a hot region in the northwest (NW) direction. The X-ray brightness residual map and corresponding temperature profiles indicate a possible shock front in the NW direction and a cold front feature in the southeast (SE) direction. Combined with the galaxy luminosity density map, we propose a weak merger scenario. A young sub-cluster passing from the SE to NW direction could simultaneously explain the optical subpeak, the intracluster medium temperature map, the X-ray surface brightness excess, and the X-ray peak offset.

Key words: X-rays: galaxies: clusters -galaxies: clusters: intracluster medium -galaxies: clusters: Abell 209

1. Introduction

Galaxy clusters are the largest gravitationally bound systems in the Universe, reaching virial masses of 10^{14}-$10^{15} \cdot {}^{5}$ M_ . They typically reside at the knots of the cosmic web and are influenced by surrounding large-scale structure, continuously growing through the accretion of diffuse matter, field galaxies, and merging galaxy groups [?, ?, ?]. Merging galaxy clusters serve as ideal astrophysical laboratories for studying hydrodynamic processes such as shock waves, turbulence, and particle acceleration.

During mergers, different cluster components exhibit distinct behaviors. Dark matter halos and galaxies, acting as collisionless particles [?], are affected only by gravity, whereas the dominant baryonic component–the intracluster medium (ICM)–is shaped by gravity and pressure, and also influenced by viscosity and magnetic fields [?]. Studying the dynamics of galaxies and diffuse hot baryons provides valuable insights into the nature of dark matter, the dynamical state of clusters, and the physics of the ICM.

When halo collisions are non-head-on, the central region of the host cluster may exhibit several peculiar signatures. In particular, gas in the core begins sloshing, and the brightest central galaxy (BCG) may show an offset of tens to hundreds of kpc relative to the centroid of X-ray emission from the ICM [?, ?, ?]. The amplitude of the projected offset between the BCG position and the X-ray peak can be used to identify major mergers in clusters [?, ?].

A209 is a massive galaxy cluster at moderate redshift ($z = 0.209$) with high X-ray luminosity [?] and is included in the Cluster Lensing And Supernovae survey with Hubble (CLASH) sample. CLASH is a 524-orbit Multi-Cycle Treasury Program designed to accurately constrain the mass distributions of 25 galaxy clusters through gravitational lensing [?]. As a CLASH cluster, A209 benefits from abundant multi-band observations, including 20 orbits of HST data, one hour of VLA observations, five-band Subaru imaging, 2543 VLT spectra, and 31 ks of Spitzer data [?, see]for details]Postman2012.

A209 has not reached dynamical equilibrium. [?] demonstrated clear evidence of substructure and dynamical segregation using optical data. [?] found that the optical luminosity functions of A209 required additional Schechter components to fit faint galaxies, and the color distribution shows clear asymmetry. The reddest region of A209 surrounds the center and extends in the southeast-northwest (SE-NW) direction [?]. Similar structures appear in weak lensing mass maps, with an elongated structure extending in the same direction [?, ?]. [?] suggested this system is marginally unrelaxed based on the mass ratio between the cluster' s main component and total mass (both within $r < 500$ kpc). [?] derived an ellipticity of 0.21 ± 0.01 for this cluster. Moreover, since the temperature drop is less than 30% of the peak temperature toward the cluster center [?], and the luminosity within $0.05r_{500}$ is less than 0.17 times the total luminosity within r_{500} [?, ?], A209 is classified as a non-cool-core cluster in X-rays. Its optical center does not overlap with its X-ray peak, showing a projected offset of 14 kpc [?].

In the radio band, an extended halo in A209 was detected with the VLA at 1.4 GHz [?] and later with 610 MHz GMRT data [?]. More recently, a spectacular radio halo revealed by MeerKAT at L-band (900-1670 MHz) extends to at least a radius of 0.85 Mpc from the center [?], indicating past AGN activity or merging events.

In this work, we investigate the gas morphology and structure of A209 using Chandra and XMM-Newton observations, combined with optical data to reveal its dynamical status. This paper is organized as follows: X-ray and optical data analysis is described in Section 2, results are presented in Section 3, and discussion and conclusions follow in Sections 4 and 5. We adopt a cosmology with $H_0 = 67.4$ km s^{-1} Mpc^{-1}, Ω_m = 0.315, Ω_Λ = 0.680 [?]. At the redshift of A209, 1 corresponds to 3.346 kpc.

2. Data Analysis

2.1 X-Ray Data

A209 was observed by Chandra on 2000 September 9 for 9.96 ks (obsID 522) and on 2003 August 3 for 9.99 ks (obsID 3279), both using the Advanced CCD Imaging Spectrometer (ACIS-I) in VFAINT mode. XMM-Newton observed the cluster on 2001 January 15 (obsID 0084230301) and again on 2008 December 16 (obsID 0550960101). Since A209 is located at the very edge of the field in the later observation, we adopt only the first observation. Basic observation information is listed in Table 1 .

We retrieve Chandra data from the archive and analyze it using the standard CIAO software package (version 4.13). The chandra_{repro} script reprocesses each observation to obtain event files. High-energy background flare events are filtered using the lc_{clean} command, yielding good time intervals (GTI) of 9.02 ks and 8.78 ks for the two observations, respectively. We use merge_{obs} to create combined exposure-corrected images. Point sources within the field of view are identified by wavdetect on the Chandra 0.5–7 keV band image with a detection limit of two counts per 10^{-15} erg cm^{-2} s^{-1}, visually checked, and masked. The background region is selected away from the cluster center where the surface brightness declines to a flat level.

XMM-Newton data reduction is performed using the XMM-Newton Science Analysis System (version 20.0.0). We use epchain and emchain to process event files and extract light curves with evselect. Time periods with count rates exceeding 3σ above the mean level are removed as flares. After cleaning, we obtain GTIs of 12 ks for PN and 17 ks for MOS1 and MOS2. Point sources are excluded by visual inspection using the Chandra point source list as reference, and background is selected at the field edge using the same standard as for Chandra data.

Figure 1 [Figure 1: see original paper] shows the XMM-Newton and combined Chandra exposure-corrected X-ray images of A209 in the 0.5–7 keV band, with surface brightness contours from XMM-Newton as reference. The BCG is located at R.A. = 1h31m52.55 , decl. = -13°36 40.49 (J2000), marked by the green cross. The X-ray peak (the pixel with highest count rate) is at R.A. = 1h31m52.9 , decl. = -13°36 41.70 (J2000) with an error of 0.5 , marked by the blue cross. The projected offset between the BCG and X-ray peak is 17.5 ± 1.7 kpc. The X-ray emission of the entire cluster shows an elongated shape along the SE–NW direction.

2.2 Optical Data

To investigate the spatial distribution of A209 member galaxies, we create a galaxy luminosity density map using photometric data from the CLASH project, observed by Subaru/SuprimeCam and retrieved from SMOKA [**?**]. The Subaru catalog contains photometric data for 87,597 galaxies covering 22.65 < R.A. < 23.30, -13.86 < decl. < -13.33, with a magnitude limit of 28.9 mag in the R_C band. To verify photometric accuracy, we cross-match with spectroscopic data from CLASH-VLT [**?**], which includes 2,653 spectra covering 22.74 < R.A. < 23.20, -13.80 < decl. < -13.41, with a magnitude limit of 27.8 mag in R_C band.

We cross-match the photometric and spectroscopic catalogs for galaxies with R_C < 20.5 mag, identifying sources as the same galaxy when their projected spatial separation is within 1 . This yields 565 galaxies with both photometric and spectroscopic redshifts. From these, we select 396 galaxies with photometric redshifts within 0.21 ± 0.05 and validate their spectroscopic redshifts. The standard error σ of photometric redshift deviation is 0.041. We find that 346 galaxies (87.4%) have spectroscopic redshifts within 0.21 ± 0.02, and 317 galaxies (80.1%) within 0.21 ± 0.01. Thus, photometric redshifts for galaxies brighter than R_C $<$ 20.5 mag in this redshift bin provide a valuable complement to spectroscopic measurements.

To analyze the optical galaxy distribution of A209, we select a 0.2° × 0.2° field of view centered on A209 (R.A. = 22.97, decl. = -13.61), containing 252 galaxies (241 with spectroscopic redshifts and 11 with photometric redshifts) within z = 0.21 ± 0.01. The 11 photometric galaxies are uniformly distributed across the field. We use these 252 galaxies to generate the luminosity density map.

The luminosity density map is derived following the method of [?]. Our field is divided into 100 × 100 grids. Each galaxy’ s luminosity is calculated from its redshift and magnitude, smoothed with a 2D Gaussian window of 0.5 width. The total R_C band luminosity in each grid is the sum of contributions from all galaxies. Peaks are identified as grid bins with highest integrated luminosity. The result is shown in Figure 2 [Figure 2: see original paper].

The galaxy distribution is elongated in the NW-SE direction and contains two mass concentrations. The densest concentration is near the BCG (green cross). The subpeak center is at R.A. = 22.9325, decl. = -13.5808, marked by a purple diamond in Figure 2, approximately 2.8 away in the NW direction. This location was reported as the highest galaxy number density by [?]. Our luminosity density map is consistent with results obtained using red sequence galaxies by [?]. The subpeak indicates a sub-cluster presence.

The orange stars in Figure 2 mark the two brightest galaxies after the BCG. None of the top ten brightest galaxies in the field is near the subpeak region, suggesting this sub-cluster is composed primarily of low-mass galaxies lacking massive galaxies, indicating it may be a young group.

3. Analysis and Results

The elongated and asymmetric X-ray emission and optical subpeak presence reflect internal perturbation processes. To reveal thermodynamic properties and possible merger activity, we study the spectral characteristics of the hot gas.

3.1 Spectral Fitting

We employ the contour-binning software [?] to explore A209’ s physical property spatial distribution. With a signal-to-noise ratio of 40, the software divides the cluster into 16 regions based on the surface brightness of the combined exposure-corrected Chandra X-ray image. We use XSPEC (version 12.1.1) to fit spectra extracted from Chandra data. A209’ s X-ray emission is characterized by an absorbed APEC component from hot diffuse gas [?]. We fit spectra in the 0.5–7 keV band with the model TBABS × APEC, fixing the neutral hydrogen column density to 1.43×10^{20} cm^{-2} and redshift to 0.209, while allowing metallicity, temperature, and normalization to vary freely.

Using the same 16 regions, we extract spectra from all three XMM-Newton detectors (PN/MOS1/MOS2) and fit them simultaneously as described above. Figure 3 [Figure 3: see original paper] compares temperature values measured by both telescopes in the same regions. Chandra temperatures are systematically higher than XMM-Newton values, consistent with trends from previous studies [?, ?].

3.2 Temperature, Pressure and Entropy Maps

Temperature maps and corresponding error maps from XMM-Newton and Chandra are shown in Figure 4 [Figure 4: see original paper]. Both reveal a hot region in the NW direction, particularly prominent in the Chandra image despite relatively large errors. To evaluate temperature variation from the center toward the NW, we draw a line from the center to the northwest and plot temperatures along it, shown in Figure 5 [Figure 5: see original paper]. The ICM temperature is approximately 6 keV in the core, generally increasing to a peak at ~1.75 radius in the NW direction, then decreasing outward. Both Chandra and XMM-Newton show similar trends, though signal-to-noise is limited by large measurement errors.

This region lies between the core and optical subpeak. To investigate its thermodynamic properties, we examine pseudo-pressure and pseudo-entropy distributions. Thermal pressure and entropy are defined as P = kT n_e and S = kT n_e^{-2/3} [?], where n_e is electron density and kT is temperature. Since spectral fitting normalization is proportional to electron density squared, we convert these to P   kT norm^{0.5} and S   kT norm^{-1/3}. Normalized pressure and entropy maps from XMM-Newton and Chandra are shown in the bottom panels of Figure 6 [Figure 6: see original paper]. The hottest NW region also exhibits the largest pressure and entropy, suggesting a possible shock front.

3.3 The Brightness Residual Image

To verify shock existence, we examine the cluster’ s surface brightness residual map. Due to significant bad channel effects on XMM-Newton PN and MOS2 images, we use only the MOS1 detector for surface brightness fitting. Though its spatial resolution is lower than Chandra, the larger photon count provides better constraints on possible excess shapes. The brightness residual image, obtained by subtracting a classical double-β elliptical model, is shown in Figure 7 [Figure 7: see original paper].

Two regions show brightness excesses in the NW and SE directions. The diffuse arc-like excess in the NW overlaps with the high-temperature region, located just behind the optical subpeak (purple diamond in Figure 6). To examine physical properties more precisely, we extract surface brightness profiles (SBPs) from two sector regions (labeled NW and SE in Figure 7). Each SBP is fitted with a broken power-law model (upper-left panel of Figure 8 [Figure 8: see original paper]) to identify possible density discontinuities. We find a clear discontinuity in the NW SBP at 3.05 northwest of the BCG, marked by a dashed line in Figure 8. In the SE direction, gas density drops by a factor of 1.52 at ~1.8 from the BCG (Figure 8, right panel).

4. Discussion

4.1 The Shock Front and Cold Front

To determine the discontinuity origin, we measure gas properties before and after the discontinuity using both Chandra and XMM-Newton data. Temperature profiles for the two sectors are shown in the bottom panel of Figure 8 [Figure 8: see original paper]. In the NW direction, XMM-Newton data show a temperature ratio of $T_2/T_1 = 1.06$, which directly eliminates the possibility of a shock wave. In this case, the NW brightness excess would be merely gas buildup from sloshing. However, Chandra data show a temperature drop ratio of $T_2/T_1 = 1.96$, supporting the existence of a weak shock wave that could be driven by an infalling young sub-cluster. Its immature core might have disintegrated during the merger, though errors are too large for a solid conclusion.

In the SE direction, temperatures from both XMM-Newton and Chandra show an increasing trend, with no significant temperature jumps around the discontinuity. This region has the lowest surface brightness and notably low temperatures, pressure, and entropy (see Figures 4 and 6). The X-ray gas is slightly offset relative to the BCG in this direction, indicating this is definitely not a counter-shock but likely a cold front caused by perturbations.

4.2 The Merging Scenario of CLASH Cluster A209

Combining all available evidence, we propose a weak merger scenario illustrated in Figure 9 [Figure 9: see original paper]. A young sub-cluster without a BCG or mature core fell into the main cluster from the SE direction. Its gas moved slightly faster than the local sound speed, generating a weak shock wave in the interaction region. The gas core was disrupted while member galaxies continued propagating outward in the NW direction. Gas along the shock path was heated, and the arc-like brightness excess edge in the NW region corresponds to the shock front position. Concurrently, the primary cluster' s core gas, disturbed by these dynamics, began sloshing and formed a cold front in the SE direction, with the X-ray peak shifted relative to the BCG.

We calculate the Mach number to study possible shock heating. One method uses the density discontinuity [**?**]:

$$\mathcal{M} = \sqrt{\frac{2C}{\gamma + 1 - C(\gamma - 1)}}$$

where the density compression factor C = n_2/n_1 is the ratio between pre-shock density n_1 and post-shock density n_2, and γ is the specific heat ratio, assumed to be 5/3 [?]. We can also derive the Mach number from the temperature discontinuity:

$$\mathcal{M} = \sqrt{\frac{(\gamma + 1)T_2/T_1 + (\gamma - 1)}{2\gamma}}$$

where T_1 and T_2 are pre-shock and post-shock temperatures at the discontinuity location.

For the NW surface brightness discontinuity, we obtain C = 1.14, corresponding to a Mach number of 1.10. This is near the lower limit for shock wave existence. At the same location, the Mach number derived from Chandra temperature discontinuity is 1.19, supporting a weak shock wave.

5. Conclusions

A209 is an intriguing non-cool-core galaxy cluster with clear asymmetry and a 17.5 kpc offset between the X-ray centroid and optical position. In this paper, we study A209’ s structural and dynamical features using X-ray observations combined with optical data. Our main results are:

(i) We create a galaxy luminosity density map for A209 using optical data, revealing an elongated structure extending from SE to NW, with a subpeak ~2.8 from the BCG in the NW direction.

(ii) Using the contour binning method, we identify a NW region with the highest temperature and largest pressure and entropy. Both XMM-Newton and Chandra show similar trends, with systematic differences consistent with previous studies.

(iii) We analyze A209’s brightness residual structure using XMM-Newton data, extracting SBPs and temperature profiles from selected regions that reveal a possible weak shock front in the NW direction and a cold front feature in the SE direction.

Combining all observational evidence—the optical subpeak, X-ray temperature map, X-ray surface brightness excess, and X-ray peak offset—we suggest A209 is undergoing a weak merger. Due to limited X-ray exposure time, many merging event details remain unclear. Deeper future X-ray observations of A209 will enable better understanding of its ICM properties and dynamical status.

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