Chandra Observations of the Double-Shock Galaxy Cluster Abell 4067 (Preprint)

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Abstract

Observations of the dynamically complex galaxy cluster Abell 4067 (A4067, $z = 0.0992$) were conducted using the Chandra X-ray Observatory. The study reveals that A4067 is a structure formed by the merger of a compact subcluster with a larger diffuse cluster along the east-west axis, where the core temperature of the subcluster is approximately 1.37 keV and the average temperature of the main cluster is approximately 2.44 keV. X-ray imaging and spectral analysis show that A4067 possesses complex structures, including surface brightness discontinuities, indicating that A4067 is undergoing merger activity.

Three surface brightness edges were observed from the radial distribution of X-ray surface brightness and the temperature profile. One of these is a cold front generated by the cluster merger, while the other two are merger shocks. The two merger shocks are located on the eastern and western sides of the cluster, respectively, suggesting that A4067 is likely a rare source with a double-shock merger structure. Combined with the properties of the eastern shock SF1, the merger timescale of A4067 is estimated to be approximately (0.51 ± 0.01) Gyr, indicating that the cluster is in the intermediate stage of merging.

Furthermore, by incorporating the Mach number of the cold front, the lower limit of the regional magnetic field is estimated to be approximately 7.17×10^{-6} G. The dynamical structure of A4067 is consistent with an east-west merger model between a small compact cluster and a large diffuse cluster, similar to the merger structure of the Bullet Cluster.

Full Text

Preamble

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Chandra Observations of the Double-Shock Galaxy Cluster Abell 4067

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Abstract

Galaxy clusters are the largest gravitationally bound structures in the universe, and their merging processes are among the most energetic events since the Big Bang. During these mergers, massive amounts of kinetic energy are converted into thermal energy and non-thermal energy of the intracluster medium (ICM) through shocks and turbulence. In this study, we present a detailed analysis of the galaxy cluster Abell 4067 using deep X-ray observations from the *Chandra* X-ray Observatory. Abell 4067 is a merging system characterized by a complex morphological structure. Our analysis reveals the presence of two distinct shock fronts located at the periphery of the cluster core. By extracting surface brightness profiles and performing spatially resolved spectroscopy, we characterize the properties of these shocks. We measure the density and temperature jumps across the shock fronts to estimate the Mach numbers. The results indicate that Abell 4067 is undergoing a major merger event, with the double-shock structure providing critical insights into the dynamics and energy dissipation mechanisms in merging clusters. These findings contribute to our understanding of the thermal history of the ICM and the role of shocks in the evolution of large-scale structures.

Keywords: galaxies: clusters: individual: Abell 4067 —X-rays: galaxies: clusters —shock waves —intergalactic medium

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1 Introduction

In the standard ΛCDM cosmological framework, galaxy clusters form and grow through the hierarchical merger of smaller groups and subclusters. These merger events are highly energetic, releasing gravitational binding energies on the order of $10^{63} - 10^{64}$ ergs. A significant

A4067 is a structure formed by the merger of a dense sub-cluster with a larger, diffuse galaxy cluster along the east-west axis. The core temperature of the sub-cluster is approximately 1.37 keV, while the average temperature of the main

cluster is approximately 2.44 keV. X-ray imaging and spectral analysis reveal complex structures within A4067, including surface brightness discontinuities, indicating that the system is currently undergoing merger activity. Three surface brightness edges are observed in the radial surface brightness and temperature distribution maps: one is a cold front generated by the cluster merger, and the other two are merger shocks. These two merger shocks are located on the eastern and western sides of the cluster, respectively, suggesting that A4067 is likely a rare source possessing a double-shock merger structure. Based on the properties of the eastern shock (SF1), the merger timescale for A4067 is estimated to be approximately (0.51 ± 0.01) Gyr, indicating that the cluster is in the intermediate stage of merging. Furthermore, by combining the Mach number of the cold front, the lower limit of the regional magnetic field is estimated to be approximately 10^{-7} Gs. The dynamical structure of A4067 is consistent with a model of an east-west merger between a small dense cluster and a large diffuse cluster, resembling the merger structure of the Bullet Cluster.

Keywords: Galaxies: clusters: intracluster medium, X-rays: merger scenarios, Shocks: cold fronts, Magnetic fields **CLC number:** P157; **Document code:** A

While we observe these changes, our comprehensive understanding of how galaxies themselves are affected by such transitions remains incomplete. Merger shocks triggered by galaxy cluster collisions typically produce discontinuities in the intracluster medium (ICM), and the manifestations of these discontinuities—namely surface brightness edges—can be detected in the X-ray band. By observing these brightness edges, we can study the properties of the cluster medium at both microscopic and macroscopic scales. This is of significant value for research involving gravity, thermal pressure, magnetic fields, relativistic particles, thermal conduction, electron-ion equilibration, and the viscosity of the intracluster medium [**?**].

Surface brightness edges manifested in merging galaxy cluster systems should be ubiquitous. To date, high-resolution and high-sensitivity X-ray observation facilities, such as the Chandra X-ray Observatory···

Introduction

In a universe characterized by hierarchical growth, galaxy clusters are the last structures to collapse and reach stability. There are three primary growth modes for massive galaxy clusters: the steady inflow of matter from the surrounding large-scale fibrous structures, the accretion of individual galaxies or galaxy groups, and major cluster merger events. Galaxy cluster mergers are the most energetic events since the Big Bang, with total kinetic energies typically reaching 10^{64} erg [**?**]. Although most of this kinetic energy resides in the form of dark matter, given its dominance in mass, a significant fraction of the total energy is dissipated into the intracluster medium (ICM) through shock heating. This violent restructuring of galaxy clusters leads to rapid changes in the environments of their member galaxies. Observations from X-ray telescopes have revealed numerous surface brightness edges associated with these mergers. Based on the variations in temperature and entropy across these edges, they are generally classified into shock fronts (SF) and cold fronts (CF).

Shock fronts formed during the merger process should be quite common, as verified by numerous simulations [**?**]. However, despite indirect evidence—such as regions in the ICM exhibiting shock heating [**?**]—direct observations of shocks, characterized by simultaneous steep jumps in gas density and significant leaps in temperature, have been found in only a few clusters. The lack of direct shock observations is primarily due to three factors: (1) observations must be conducted before the merger shock moves to the cluster outskirts, where low surface brightness and dominant X-ray background radiation make detection difficult; (2) the merger must occur as close as possible to the plane of the sky to minimize projection effects that can smear out density and temperature jumps; and (3) merger velocities are typically around several thousand kilometers per second, which often results in relatively low Mach numbers ($M \approx 1-3$). Consequently, the contrast in density and temperature across the shock may be low, requiring high-quality observational data for precise measurement. Despite these challenges, studying shock properties provides critical information regarding the merger history and dynamical mechanisms of galaxy clusters, making them a vital scientific target for astronomical observations.

Cold fronts are more easily observed than shock fronts [**?**] and have proven to be invaluable tools for studying the physical properties of the ICM [**?**]. They also serve as effective indicators for assessing cluster merger activity [**?**]. Simulation studies of galaxy cluster mergers indicate that cold fronts can form in various ways depending on the specific merger scenario [**?**]. Generally, cold fronts produced by cluster mergers are categorized into two types [**?**]: merger cold fronts [**?**] and sloshing cold fronts [**?**].

The subject of this study is Abell 4067 (hereafter A4067), also known as RXCJ2359.3-6042, which is located at a redshift of $z = 0.0989$. Previously, Chon et al. [**?**] analyzed A4067 using data from the X-ray Multi-Mirror Mission (XMM-Newton). They concluded that the system is a merging galaxy cluster structure occurring near the plane of the sky. Furthermore, they observed it to be a merger where a primary cluster with low X-ray surface brightness is being penetrated by a cooler subcluster, whose core remains intact. By mapping the spectral temperature and metallicity of different regions using XMM-Newton data, they found evidence supporting this conclusion. Additionally, they estimated the mass of the primary cluster (excluding the cold core) to be approximately $M_{500} \approx 2.5 \times 10^{14} M_{\odot}$. In their final discussion, they noted that the XMM-Newton data revealed a significant temperature increase in the eastern region of the cluster along the merger axis. This phenomenon is likely the result of shock heating generated by the merger. Due to the angular resolution limits of XMM-Newton, the data could not precisely determine the trajectory of the infalling subcluster, necessitating more quantitative details regarding the shock to infer the merger dynamics. Consequently, we proposed observations of A4067 using the Chandra X-ray Observatory (CXO). The point spread function (PSF) of CXO is the best among current X-ray space telescopes, corresponding to a linear scale of less than 1 kpc. This is smaller than the classical collisional mean free path of the ICM or the typical size of a galaxy, providing us with detailed observations of physical processes within the Mpc-scale gas halos of galaxy clusters. Using CXO, we can identify the distinct features of the "cold front" driven by the subcluster during the merger process.

This paper presents the results of the analysis of 129.53 ks of CXO observational data for the galaxy cluster A4067. The eastern part of A4067 shows signs of a shock-heated region with elevated temperatures. Through spectral analysis, we derived the temperature and metallicity distributions of several regions in the cluster. We found that a cold core has traversed the primary cluster relatively intact, with a temperature of approximately 3.0 keV and a metallicity of about $0.75 Z_\odot$. The core of the merging component survived as a cold core, while the stripped gas likely remained in the center of the primary cluster.

Through the study of A4067, we aim to achieve a more comprehensive understanding of the physical properties of the galaxy cluster merger process. By revealing the effects of shocks and cold fronts on the intracluster gas, this work contributes to deepening our knowledge of large-scale structure and cosmic evolution.

This paper adopts a standard cosmological model with a Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}, a matter density parameter $\Omega_m = 0.3$, and a dark energy density parameter $\Omega_\Lambda = 0.7$. Under these parameters, the luminosity distance is $d_L = 455.5$ Mpc, and the corresponding physical scale is 1.83 kpc per arcsecond. Unless otherwise specified, all errors reported in this paper represent the 1σ confidence level.

2 Data Processing

We conducted four observations of A4067 using the *Chandra X-ray Observatory* (CXO) in 2019, with a total exposure time of 129.53 ks. Detailed information regarding the duration of each observation is provided in .

We utilized the Chandra Interactive Analysis of Observations (CIAO) software, released by the *Chandra X-ray Observatory*, to process the data.

$M \leq 3$ at $z = 0.0992$: $2\times10^{14} M_\odot$. For $0.5''$ (1.37 ± 0.46), we assume a cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. The constants are $k = 1.38 \times 10^{-23}$ J K^{-1} and $k = 8.62 \times 10^{-5}$ eV K^{-1}. At $z = 0.0992$, the luminosity distance is $D_L = 456.4$ Mpc, where $1'' \approx 1.83$ kpc. Wang Yelin et al.: Chandra Observations of the Double-Shock Galaxy Cluster Abell 4067. We utilized the Chandra Interactive Analysis of Observations (CIAO; version 4.15.2) software and the Calibration Database (CALDB; version 4.10.4). Our data reduction followed the standard analysis pipeline as described by Ge et al. [?] (2018).

The Advanced CCD Imaging Spectrometer (ACIS) on the Chandra X-ray Observatory (CXO) consists of 10 CCDs with an observing energy range of 0.2-10 keV. Six of these CCDs are arranged in a row, satisfying the requirements for high-resolution observations of small-scale structures in ACIS-S mode (back-illuminated chips). The other four CCDs are arranged in a 2×2 grid, providing a larger field of view in ACIS-I mode (front-illuminated chips), which is typically used for survey observations. In this study, we primarily selected the ACIS-I mode to observe the cluster-scale structures. The primary dataset provided by ACIS is a Level-1 event file, which records information such as the spatial position, arrival time, and energy of the detected X-ray photons. These Level-1 event files were reprocessed using the `chandra_{repro}` script. This process applies the latest detector calibrations, including the most recent charge transfer efficiency (CTE) corrections, time-dependent gain adjustments, and gain maps, to generate appropriate response files, new bad pixel files, and processed Level-2 event files.

We then employed the `VFAINT` mode for improved background screening. The `lc_{clean}` script (developed by Markevitch et al. [?]) was used to detect and remove flares and periods of abnormally low count rates from the input light curves. As shown in Table 1, the data were generally clean, resulting in a final total exposure time of 128.95 ks after cleaning.

The reprocessed files were merged using the `merge_{obs}` script to generate a combined image of the four observations in the soft X-ray band (0.7-2 keV). The `merge_{obs}` script combines the functionalities of `reproject_{obs}` and `flux_{obs}`. It creates a merged event file, projects multiple observations onto the same coordinate frame, and subsequently generates exposure maps and exposure-corrected images.

The next step involved removing point sources from the exposure-corrected images. First, the `wavdetect` tool was used for identification, with the wavelet scales set between 1 and 16 pixels. The detection threshold was set to approximately 10^{-6} to ensure that the number of false sources per CCD was close to one. Subsequently, we performed a visual inspection to exclude regions containing bright point sources and then used the `dmfilth` script to fill these excluded regions. This script replaces the pixel values in the excluded areas using interpolation from the surrounding regions based on a Poisson probability distribution. We utilized instrumental background data to assist in subtracting the non-X-ray background, as well as foreground emission along the line of sight (such as the Galactic Halo and Local Hot Bubble) and unresolved faint background sources. The instrumental background files were based on the Chandra "stowed" background files, which were then reprojected to match the coordinates of our observations. Finally, we rescaled the generated instrumental background files to match the 9.5-12 keV count rates of our observations to ensure data consistency.

Furthermore, we analyzed the ACIS-I observation data listed in Table 1. We used the `specextract` script to extract the spectra and response files from the four observations of A4067 and performed fitting using the X-ray Spectral Fitting Package (XSPEC) [?] (version 12.9.1). Regarding background analysis, the instrumental background was addressed by using the CXO stowed background, which was subtracted as a background spectrum after scaling it to the 9.5–12 keV band count rate. The non-instrumental X-ray background spectrum was fitted with a model consisting of three components [?]: an unabsorbed thermal plasma model (Astrophysical Plasma Emission Code, APEC) to characterize the contribution of the Local Bubble, with a temperature of $kT \approx 0.1$ keV; an absorbed APEC model ($kT \approx 0.25$ keV) to represent the emission from the Galactic Halo gas; and a power-law model [?] (with a spectral index fixed at $\Gamma \approx 1.46$) to represent the absorbed extragalactic cosmic X-ray background. Additionally, the ROSAT All-Sky Survey (RASS) spectra from an annular region of 1° to 2° surrounding the cluster were fitted simultaneously with the cluster spectra to better constrain the non-instrumental background contribution. We used an absorbed APEC thermal emission model [?] to characterize the X-ray emission from the galaxy cluster. Atomic data were obtained from the Atomic Database for Astrophysicists (AtomDB, version 3.0.8), and solar abundances were taken from the data summarized by Nordlund et al. [?] in 2009. The cluster metallicity was fixed at $0.3Z_\odot$, and the redshift was set to $z = 0.0992$. We employed the Tuebingen-Boulder absorption model (TBabs) to describe the X-ray absorption by the interstellar medium, using the `NHtot` tool [?] to retrieve the Galactic absorption value and fixing the total hydrogen column density N_H at 1.83×10^{20} cm^{-2}.

3 Imaging Analysis

Figure 1 [Figure 1: see original paper] displays the background-subtracted and exposure-corrected composite *Chandra* X-ray Observatory (CXO) images in the 0.7–2 keV energy band. The upper panel shows the image before point source subtraction, while the lower panel shows the image after point source subtraction. To reduce noise and suppress small-scale structures, the images have been smoothed using a two-dimensional Gaussian function with a standard deviation of σ and an influence radius of R.

The overall X-ray emission exhibits significant asymmetry, and its morphology is consistent with previous *XMM-Newton* observations. The structure depicts a smaller, compact subcluster traversing a larger, more diffuse cluster along the east-west direction. Notably, the cold core structure of the subcluster has remained intact throughout the merging process. We determine that a violent cluster merger event is occurring along the east-west axis and infer that specific merging-related structures, such as shocks, may be produced in this direction. Furthermore, a cold front structure associated with the cluster merger is clearly visible in the image. It is evident that the cold front in A4067 belongs to the “merger cold front” category, a type similar to the one observed in the Bullet

Cluster. However, the shock structure cannot be precisely identified or localized from the exposure-corrected A4067 image alone, necessitating further analysis of the data.

We analyzed the exposure-corrected and point-source-subtracted images in conjunction with Gaussian Gradient Magnitude (GGM) filtered images, following the methodology established by Walker et al. [**?**].

GGM (Gaussian Gradient Magnitude) is a processing algorithm used for astronomical FITS (Flexible Image Transport System) images. Typically, intensity variations at structures such as shock edges manifest as extreme values in the filtered images. Consequently, the GGM filter serves as an effective brightness edge detection algorithm. Furthermore, it provides corresponding interactive tools that allow for the combination of FITS images filtered at different scales.

In our research and analysis of the *Chandra* X-ray Observatory (CXO) imaging of A4067, we applied varying degrees of smoothing to the reprocessed synthetic photon count images. The final results of this image processing are displayed in [Figure 2: see original paper].

By observing and analyzing the A4067 imaging processed with the GGM gradient filter, a surface brightness edge is clearly visible in the eastern region in [Figure 2: see original paper] (c). Located approximately 567 kpc from the cluster center, and consistent with previous analyses by Chon et al. [**?**] using *XMM-Newton* observation data, this eastern region likely contains a shock front. Furthermore, upon analyzing [Figure 2: see original paper] (d), another surface brightness edge appears to exist in the western region at approximately 733 kpc from the cluster center. We reasonably speculate that these are likely reciprocal shocks generated by a cluster merger in the east-west direction. Additionally, through the analysis of [Figure 2: see original paper] (a) and (b), a cold front structure at the cluster center can be clearly observed and its position confirmed.

Based on the above analysis, we have defined the probable locations of the shocks and the cold front. Building upon [Figure 1: see original paper], we use white dashed lines to define the brightness edges of the eastern and western shocks, SF1 and SF2. A green solid line is used to define the brightness edge of the cold front, CF1. The resulting visualization is shown in [Figure 3: see original paper]. We extracted radial surface brightness profiles for the regions in [Figure 3: see original paper] where shocks and cold fronts were potentially captured. In Section 4, we will describe in detail the procedure for fitting the radial surface brightness to analyze the various properties of SF1, SF2, and CF1.

The obtained results—including the photon number density jump ratio across the brightness edges, the Mach number derived from the density jump (M_ρ), the temperature jump ratio, the Mach number derived from the temperature jump (M_T), and the spectral fit goodness-of-fit (χ^2/d.o.f.)—are all listed in .

4 Radial Surface Brightness Analysis

Combined with imaging analysis, we performed surface brightness extraction using the `dmextract` tool in CIAO for the radial sector regions corresponding to the brightness edges identified in Figure 3. Based on the extracted surface brightness data, we obtained the fitting results for the SF1, SF2, and CF1 surface brightness profiles, as shown in Figure 4 [Figure 4: see original paper]. In these plots, the vertical axis represents the average X-ray photon flux per unit time within the sector area along the radius of curvature of the shock or cold front. The horizontal axis, labeled "Radius," represents the radial distance from the center of the circular arc corresponding to the shock or cold front structure (noting that the absolute values of these distances are used for spatial localization and do not imply independent physical significance).

In the figures, the solid lines represent the best-fit curves, while the dashed lines indicate the coordinates on the horizontal axis where the brightness jumps occur. Figure 1 [Figure 1: see original paper] displays the Chandra imaging of A4067 in the 0.5-7.0 keV band. The upper panel shows the image before point source subtraction, and the lower panel shows the image after point source subtraction.

Fig. 1 Imaging of A4067 in the keV band. The upper panel shows the image without point source subtraction; the lower panel shows the image with point source subtraction.

In this section, we briefly introduce our fitting model. We utilize an ellipsoidal model [?] to characterize the density distribution of the intracluster medium (ICM) in galaxy clusters, which allows us to fit the X-ray flux across shocks and cold fronts. We assume that the X-ray emissivity of the entire cluster exhibits an ellipsoidal discontinuity. Within this framework, the emissivity inside and outside the ellipsoid follows a power-law function of the elliptical radius. Let r_{edge} denote the radius at the discontinuity, and let ϵ_{in} and ϵ_{out} represent the internal and external emissivities, respectively. If the corresponding power-law indices are p_{in} and p_{out}, then the relationship between the emissivity $\epsilon(r)$ and the radius r is given by:

$$\epsilon(r) = \begin{cases} \epsilon_{\text{in}} \left(\frac{r}{r_{\text{edge}}}\right)^{-2p_{\text{in}}}, & r < r_{\text{edge}} \\ \epsilon_{\text{out}} \left(\frac{r}{r_{\text{edge}}}\right)^{-2p_{\text{out}}}, & r \geq r_{\text{edge}} \end{cases} \tag{1}$$

Based on this, the X-ray surface brightness $I_X(r)$ as a function of r is derived from the following formula:

[Figure 1: see original paper]

In this context, $I_X(r)$ is expressed using the standardized incomplete Beta function, where $B(x; a, b)$ is the incomplete Beta function, $B(a, b)$ is the Beta function, and $\Gamma(x)$ is the Gamma function. Combining equations (3) and (4), we obtain:

In these expressions, the physical significance of $I_X(r_{\text{edge}})$ is the value of the surface brightness at the brightness edge, while the ratio $\mathcal{C} = \epsilon_{\text{in}}/\epsilon_{\text{out}}$ represents the jump ratio of the X-ray emissivity across the discontinuity (between the interior and exterior of the ellipsoidal model).

[Figure 2: see original paper] Images processed with a Gaussian gradient filter. Panels (a), (b), (c), and (d) show the images after smoothing with scales of $\sigma = 1$, $\sigma = 2$, $\sigma = 4$, and $\sigma = 8$, respectively.

Fig. 2 GGM filtered image. Panels (a), (b), (c), and (d) show images smoothed with , and Gaussian kernels, respectively.

In the following section, we analyze the calculation process for the Mach numbers of the shocks and the cold front. The X-ray emissivity jump across the surface brightness edge is obtained by fitting the galaxy cluster using an ellipsoidal model. For the density jump Mach number of the shock, we can directly apply the following:

$$I_X(r) = I_{\text{in}}(r) + I_{\text{out}}(r) \tag{2}$$

$$I_{\text{in}}(r) = I_i A^{-2p_{\text{in}}+1} \begin{cases} 1 - I_{A^2}(p_{\text{in}} - \frac{1}{2}, \frac{1}{2}) & A^2 < 1 \\ 0 & A^2 \geq 1 \end{cases} \tag{3}$$

$$I_{\text{out}}(r) = I_o A^{-2p_{\text{out}}+1} \begin{cases} I_{A^2}(p_{\text{out}} - \frac{1}{2}, \frac{1}{2}) & A^2 < 1 \\ 1 & A^2 \geq 1 \end{cases} \tag{4}$$

$$A \equiv (r/r_{\text{edge}}), \quad I_x(a,b) \equiv B_x(a,b)/B(a,b)$$

$$B_x(a,b) \equiv \int_0^x t^{a-1}(1-t)^{b-1}dt, \quad B(a,b) = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)}$$

$$I_i = RI_o \frac{B(p_{\text{in}} - \frac{1}{2}, \frac{1}{2})}{B(p_{\text{out}} - \frac{1}{2}, \frac{1}{2})} \tag{5}$$

$$R \equiv \epsilon_{\text{in}}/\epsilon_{\text{out}}$$

[Figure 1: see original paper]

Wang Yelin et al.: Chandra Observations of the Double-Shock Galaxy Cluster Abell 4067. Here, γ is the adiabatic index of the gas, taken as $\gamma = 5/3$. The term C represents the photon number density jump ratio across the brightness edge, which can be derived from the X-ray emissivity jump ratio R in equation (5), specifically $C = \sqrt{R}$. For the cold front, determining its Mach number M requires the derivation of cold front Mach numbers as discussed in the general theory of shocks and cold fronts [?]. By combining the cold front temperature jump ratio $T_{\text{in}}/T_{\text{out}}$ obtained through spectral fitting with the relationship between pressure parameters across the front, we can calculate the temperature (or pressure) jump Mach number M. The specific process is as follows:

Where P_{out} and P_{in} are the pressures outside and inside the cold front, respectively. In the above equation, M also represents the Mach number of the gas relative to the sound speed in the free-flow region. In summary, the analysis and processing yield the following results: for shock SF1, $M = 1.24 \pm 0.05$; for shock SF2, $M = 1.31 \pm 0.08$. For the cold front CF1, we find $M = 0.42 \pm 0.11$. Detailed relevant parameters are provided in .

5 Spectral Analysis

For cold front CF1, we conducted a separate analysis that specifically accounts for radial diffusion during the formation process of the cold front. Consequently, we partitioned the regions ahead of and behind the cold front and utilized sector-shaped regions with area-gradient increments to extract the spectra. The specific extraction method is illustrated in [Figure 5: see original paper], where we have marked four white sector-shaped regions (labeled 1, 2, 3, and 4) to extract the spectra across the cold front. This approach allows for a more precise representation of the temperature variation trends in these areas. The spectral fitting process followed the methodology described in Section 2. The resulting spectral fitting data for each corresponding region are listed in . By analyzing the temperatures in , we can confirm the structure and properties of the cold front: the temperature is lowest in Area 1, followed by a sharp increase in the shock regions (Areas 2–4), and a subsequent gradual decline. This temperature variation trend, which corresponds to the surface brightness edge, is consistent with the standard structure of a cold front.

Figure 3: Positional map of the shocks and the cold front. The white dashed lines mark the two potential shock regions, while the green solid line marks the potential region of the cold front.

Fig. 3 Shock Front and Cold Front location map, the white dashed lines mark the two possible shock front regions, and the green solid line marks the possible cold front region.

Furthermore, we can derive the shock Mach number based on the temperature jump conditions of the shock wave. By extracting spectra from specific regions upstream and downstream of the surface brightness edges, we can determine the pre-shock (or pre-cold front) temperature and the post-shock (or post-cold front) temperature through spectral fitting.

The relationship between the temperature jump ratio and the Mach number is as follows: calculating the Mach number from temperature jump conditions is more complex than using density jump conditions because temperature is an intensive variable. Following the standard Rankine-Hugoniot jump conditions [**?**], which constrain the fluxes of mass, momentum, and energy, we define the intermediate variables:

The calculation of the temperature jump Mach number M_T can be transformed as follows. Given the adiabatic index $\gamma = 5/3$ for a monoatomic gas, the temperature jump ratio T_2/T_1 is related to the Mach number M_T by:

$$\frac{T_2}{T_1} = \frac{[2\gamma M_T^2 - (\gamma - 1)][(\gamma - 1)M_T^2 + 2]}{(\gamma + 1)^2 M_T^2} = \frac{5M_T^4 + 14M_T^2 - 3}{16M_T^2}. \tag{7}$$

By defining an intermediate variable C based on the temperature ratio:

$$C = \frac{(\gamma + 1)^2}{8\gamma}\left(\frac{T_2}{T_1} + 1\right) - 1 = \frac{8}{9}\left(\frac{8T_2}{T_1} - 7\right), \tag{8}$$

the Mach number M_T can be solved as:

$$M_T^2 = C + \sqrt{C^2 + \frac{16\gamma}{(\gamma + 1)^2}} = \frac{(8T_2/T_1 - 7) + [(8T_2/T_1 - 7)^2 + 15]^{1/2}}{5}. \tag{9}$$

For the cold front, the pressure ratio p_0/p_1 is related to the Mach number by:

$$\frac{p_0}{p_1} = \begin{cases} [1 + \frac{\gamma-1}{2}M^2]^{\frac{\gamma}{\gamma-1}}, & M \leqslant 1 \\ \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} M^2 \left[\gamma - \frac{\gamma-1}{2M^2}\right]^{-\frac{1}{\gamma-1}}, & M > 1 \end{cases}. \tag{10}$$

Table 2: Parameters and properties of the shocks and cold front in A4067. Notes: a) The density jump ratio mentioned in equation (6). b) For the cold front, this represents the temperature in Area 1 (Fig. 5); for the shock front, it represents the post-shock temperature. c) For the cold front, this represents the temperature in Area 2 (Fig. 5); for the shock front, it represents the pre-shock temperature. d) The density Mach number M_ρ calculated by equation (6). e) For the cold front, M is given by equation (10); for the shock front, M_T is given by equation (9). f) Represents the reduced χ^2 of the temperature fit.

Figure 4: Surface brightness fitting results for SF1, SF2, and CF1, respectively. The dashed lines indicate the position of the brightness jump, and the solid lines represent the best-fit curves.

Fig. 4 Sequentially SF1, SF2 and CF1 surface brightness fitting results, the dashed lines indicate the positions of brightness jumps, and the solid lines represent the fitting curves.

Wang Yelin et al.: Chandra Observations of the Double-Shock Galaxy Cluster Abell 4067. Furthermore, following the data processing methodology described in Section 2, we have partitioned A4067 into ten irregular regions based on the attenuation of luminosity, as illustrated by the green contours in [Figure 6: see original paper]. These regions are labeled 1 through 10, with Region 1 representing the cold core of the galaxy cluster. The overall extent of the cluster is represented by a magenta circle centered on the core of A4067. Spectra were extracted from each of these defined regions to determine the global temperature distribution of A4067. The specific fitting results for the spectra in these corresponding regions are summarized in Table 3.

[Figure 5: see original paper] Arrows point to the extracted spectral regions labeled sequentially from 1 to 4. Spectral fitting results from XSPEC. Total Front Properties, Region Number, Temperature/kT, χ^2/d.o.f.

Region1 Region2 Region3 Region4 Region5 Region6 Region7 Region8 Region9 Region10 Area1 Area2 Area3 Area4 Cluster a The regions are shown in Fig. 5 and Fig. 6.

Circleb b Within a radius of , excluding the Cool Core.

Figure 6: Spectral partitioning of A4067. The cluster is divided into 10 regions based on luminosity variations, indicated by green contours. Region 1 represents the cool core, while the magenta circle denotes the approximate overall extent of the galaxy cluster.

Fig. 6 The spectral partitioning of A4067, the cluster is divided into 10 regions using green contours based on luminosity variations, with region 1 identified as the cool core; the magenta circle represents an approximation of the overall cluster.

Based on the results presented in Table 3, the region-temperature line plot shown in [Figure 7: see original paper] illustrates the temperature variations across different regions. Analyzing the temperature profiles of the ten regions in [Figure 7: see original paper], we observe that the temperatures in Regions 1–3 are relatively low. Although these regions exhibit an overall upward temperature trend, they remain below the global temperature of the galaxy cluster. In contrast, Regions 4–8 exhibit higher temperatures that remain relatively consistent with one another.

In summary, the spectral fitting results further corroborate our analysis of the merger dynamics of the galaxy cluster A4067 from the perspective of temperature distribution. Specifically, the data support a scenario in which a smaller, compact galaxy cluster has traversed a larger, diffuse galaxy cluster. As shown in [Figure 7: see original paper], this is manifested by the cold core of Region 1 (with an average temperature of 1.37 keV) passing through the main cluster (which has an average temperature of approximately 2.44 keV), with the core of the sub-cluster surviving as a remnant cold core.

[Figure 7: see original paper] Region-Temperature line plot. The black dashed line represents the cluster-wide average temperature, and the gray shaded area indicates the corresponding errors.

6.1 A4067 的激波

In this paper, we utilize *Chandra* (CXO) observations to detect two merging shocks in the Abell 4067 (A4067) galaxy cluster, located at the eastern (SF1) and western (SF2) sides of the cluster, respectively. Through X-ray spectral analysis, we derived the temperature jumps before and after the shock heating, from which we calculated the temperature-jump Mach numbers to be $\mathcal{M}_T =$

1.53±0.18 (SF1) and $\mathcal{M}_T = 1.67 \pm 0.11$ (SF2). Furthermore, by extracting radial surface brightness profiles across the regions swept by the shocks, we obtained the density-jump Mach numbers: $\mathcal{M}_\rho = 1.36 \pm 0.04$ (SF1) and $\mathcal{M}_\rho = 1.51 \pm 0.20$ (SF2). In our subsequent analysis, we adopt the density-jump Mach number $\mathcal{M}_\rho$ due to its smaller uncertainties and substitute it for $\mathcal{M}$ in the following equations to calculate the velocity of shock SF1. According to the relationship between the Mach number and the shock velocity u:

where c_s is the local sound speed of the intracluster medium (ICM). We can determine the temperature T by fitting the cluster spectrum [?], using the relation: $c_s = \sqrt{\gamma kT/\mu m_p}$. Here, the adiabatic index is $\gamma = 5/3$, the mean molecular weight is $\mu = 0.6$, and $m_p = 1.67 \times 10^{-27}$ kg. Taking the average ICM temperature of the cluster measured from X-rays as $T \approx 2.44 \pm 0.03$ keV, we find the velocity of SF1 to be approximately 1095.6 ± 32.9 km s^{-1}. Combined with the shock positions, if we calculate the merger timescale based on the displacement between the cold front CF1 and the eastern shock SF1 (142.7″), we obtain a lower limit of approximately 0.23±0.01 Gyr. If we instead use the projected distance from the center of A4067 to the eastern shock SF1 (approximately 310.6″), the resulting merger timescale is approximately 0.51 ± 0.01 Gyr. Based on the temperature distribution map obtained from our spectral analysis and the identified characteristics of the eastern (SF1) and western (SF2) shocks, we propose a simplified physical model as shown in [Figure 8: see original paper] (it must be emphasized that our observations of A4067 are limited to the X-ray band; a more precise merger configuration would require detailed multi-wavelength observations). [Figure 8: see original paper] illustrates the process by which the merger of two subclusters in A4067 generated SF1 and SF2. Prior to the merger, a diffuse, high-temperature non-cool-core cluster (represented by the large gray ellipse in [Figure 8: see original paper]) and a compact, smaller cool-core cluster (the gray circle in [Figure 8: see original paper]) encountered each other in the plane of the sky, with their mutual gravitational potential energy continuously decreasing. During the merger, due to the uneven mass distribution within the cool-core cluster, the higher-density cool core (the small black circle in [Figure 8: see original paper]) underwent a relative positional shift (as discussed in detail by Markevitch et al. [?] in 2007). Finally, the merger of these two clusters formed the structure of A4067 currently observed, which features two distinct shock structures labeled SF1 and SF2. Both shocks originated from the violent dynamical perturbations during the cluster merger.

We compare the shock characteristics of A4067 with merging shocks in other galaxy clusters. For example, in the well-known Bullet Cluster (1E 0657-56) [?], which features high-Mach-number shocks, the Mach number reaches $\mathcal{M} \approx 3.0$, corresponding to shock velocities as high as 4500 km s^{-1}. In contrast, the Mach number of A4067 is relatively low and the shock velocity is significantly smaller, indicating that its merger event is relatively moderate.

Notably, the shock structure of A4067 bears some similarity to that of A2146

[?]. The latter was the first double-shock merger cluster identified with a reverse shock, featuring a bow shock ($\mathcal{M} \approx 2.1$) and an upstream shock ($\mathcal{M} \approx 1.6$). Both A4067 and A2146 exhibit double-shock structures and relatively low Mach numbers ($\mathcal{M} < 2$). Compared to high-Mach-number clusters ($\mathcal{M} > 2$) such as A521 [?] or A2744 [?], the shocks in both A4067 and A2146 fall within the low-to-moderate Mach number range. Regarding the merger timescale, Russell et al. [?] provided a conservative estimate for A2146 of $\sim$ 0.1–0.2 Gyr, while we provide a lower limit for the merger timescale of A4067 at approximately 0.23 Gyr. Overall, these values are quite similar, suggesting that both clusters are in the intermediate stage of a merger that has not yet fully concluded. However, in terms of shock symmetry, the double shocks in A2146 are relatively compact, whereas in A4067, the eastern shock has a lower Mach number and the western shock has a larger radius of curvature. These differences may be caused by the merger direction of A4067 or the intrinsic properties of the primary and secondary subclusters (such as the merger mass ratio and cluster shape) being different from those of A2146. Additionally, no significant synchrotron radiation or radio relics have been observed in A2146 [?]. Generally, prominent radio relics might be detected in regions swept by shocks because shocks can effectively accelerate high-energy electrons. As there are currently no radio observation results for A4067, further research is required to investigate its non-thermal properties.

[Figure 8: see original paper] Merger model diagram for A4067. The large gray ellipse represents the larger diffuse cluster, the gray circle represents the smaller compact subcluster, the small black circle represents the cool core, and the dashed arcs represent the shocks.

Fig. 8 Merger model of A4067. The large gray ellipse represents the larger, diffuse galaxy cluster, the gray circle indicates the smaller, compact subcluster, the black circle denotes the cold core, and the bow-shaped dashed lines represent the shock fronts.

The results of this study indicate that the merger shock in A4067 is a typical low-Mach number shock, consistent with the characteristics of moderate-intensity shocks widely observed during galaxy cluster mergers. Furthermore, it is highly probable that this represents another rare instance of a double-shock structure in a galaxy cluster featuring a reverse shock.

The lower Mach number suggests a relatively low merger rate for the system, indicating that the merger process may still be ongoing. Additionally, comparative analysis with other galaxy clusters such as A3667 [?] supports the prevalence of low-Mach number shocks in the dynamical evolution of clusters. This suggests that merger events may continue to influence the dynamical and thermodynamic states of the intracluster medium (ICM) over extended timescales. In the future, high-resolution X-ray observations—such as those from the X-Ray Imaging and Spectroscopy Mission (XRISM) or the Advanced Telescope for High ENergy Astrophysics (ATHENA)—combined with radio observations will allow for further investigation into the processes of high-energy electron acceleration by shocks in A4067. Such studies will provide a better understanding of the physical mechanisms underlying non-thermal phenomena during galaxy cluster mergers.

6.2 冷锋与磁场

For A4067, the cold front formed at the core exhibits a high degree of symmetry. Furthermore, considering the velocity of the sub-cluster during the merger process, the cold front should be rapidly perturbed by the Kelvin-Helmholtz instability (hereafter referred to as K-H instability). The K-H instability refers to the instability that occurs within a continuous fluid with shear velocity or at the interface between two different fluids with a velocity differential. It can be used to predict the instability of fluids with different densities moving at different velocities, as well as the boundary where laminar flow transitions into turbulence. A common example is the instability of waves on a water surface when wind blows across it. This unstable condition is more frequently observed in clouds, oceans, Saturn' s cloud bands, Jupiter' s Great Red Spot, and the solar corona.

In states where the wavelength is sufficiently short, if surface tension is neglected, instability will exist at the interface of two fluids of different densities moving in parallel at different velocities, regardless of the velocity magnitude. However, surface tension can counteract short-wavelength instabilities, and theoretical models predict stability until a specific velocity threshold is reached. Theories incorporating surface tension can roughly predict the threshold for wave generation when wind blows across a water surface.

Regarding the cold front CF1 in A4067, it possesses a clear and smooth shape within a certain sector, assuming this range is aligned with the direction of velocity. Observationally, in a sectorial region of approximately $\phi_{cr} = \pm 30^\circ$ around the radial symmetry axis, one can observe a blurring of the front edge due to the K-H instability not being suppressed. The scale of this blurring is roughly equal to the wavelength of the perturbation mode that has entered the nonlinear growth stage.

We first rule out the possibility that this smooth shape is formed by the sub-cluster' s gravity suppressing the K-H instability. Estimates suggest that this gravitational force is too weak to achieve such a degree of suppression. Instead, we propose that a magnetic field layer forms parallel to the cold front. This magnetic field provides a tension similar to surface tension, making it difficult for any surface deformations to grow (as shown in [Figure 9: see original paper], where the parallel curves drawn along the front represent the magnetic field providing an effect analogous to surface tension). This suppresses the growth of the K-H instability when the tangential velocity is less than the critical value V_{cr}. The wavy lines represent the regions where the front is blurred, and the arrows correspond to the velocity vector field formed by the incompressible fluid. The formation of this parallel magnetic field is due to “magnetic draping,” where the magnetic field is stretched as the surrounding intracluster medium flows past the cold front, creating an enhanced magnetic layer parallel to the front surface [**?**]; we will not discuss this in further detail here.

[Figure 9: see original paper] Schematic diagram of the suppression of Kelvin-Helmholtz instability on a cold front surface [**?**]. The parallel curves along the cold front represent the magnetic field layer, and the arrows represent the velocity vector field formed by the incompressible fluid.

Fig. 9 Schematic diagram of the cold front surface suppressing the instability of Kelvin-Helmholtz[1]. The parallel curve along the cold front represents the magnetic field layer, and the arrow represents the velocity vector field formed by incompressible fluids.

As the tangential velocity of the flow increases while moving outward from the stagnation point along the cold front, the surface tension provided by the magnetic field layer may become insufficient at a certain angle (indicated in Figure 9). Consequently, Kelvin-Helmholtz (K-H) instabilities begin to grow. Therefore, the extent of the undisturbed sector of the cold front can be utilized to derive a lower limit for the stabilizing magnetic field strength. Let the magnetic field strengths on the hot and cold sides be B_h and B_c, respectively; similarly, let the gas temperatures on the hot and cold sides be T_h and T_c, and the gas pressure at the cold front be P. The K-H instability is suppressed when the following condition is satisfied:

By combining the observed temperatures and flow velocities, considering the stability of the cold front within the corresponding sector shown in Figure 9, and accounting for relevant uncertainties, we obtain a lower limit for the magnetic field of $B \gtrsim 7$ μGs when adopting the hot-side pressure. If the cold-side pressure is used instead, the lower limit for the magnetic field is $B \gtrsim 15$ μGs. These values provide the average lower limits for the magnetic field across the two gas phases:

If the significant blurring of the cold front observed outside the stable sector is interpreted as the onset of K-H instabilities, this lower limit can be converted into an estimated value for the magnetic field strength.

7 总结

Through a series of image analyses and spectral fitting, we confirm that a merger process is indeed occurring along the east-west axis of A4067, which has generated a shock structure on the eastern side of the galaxy cluster. The Mach number for this shock, SF1, is $\mathcal{M} \approx 1.6$, which is consistent with previous studies [**?**]. Building upon this, our analysis of the *CXO* data further reveals the presence of a shock structure on the western side of the cluster as well. The Mach number for SF2 is $\mathcal{M} \approx 1.3$. We speculate that these two shocks originate from the same merger event, with SF2 likely representing a reverse shock produced during the merger. Furthermore, we estimate that with a propagation velocity for SF1 of approximately 1200 km/s, the merger timescale for the A4067 cluster is roughly 0.5 Gyr. This indicates that A4067 is currently in the intermediate stage of a merger that has not yet reached completion. X-ray images and temperature maps show that the gas of the sub-cluster is being stripped by ram pressure and mixing with the intracluster medium (ICM) of the main cluster; however, the central cold core remains preserved. Based on these observations, we also identified a cold front located to the east of the central cold core. This cold front, CF1, has a Mach number of $\mathcal{M} \approx 0.9$. By incorporating the Mach number of this cold front, we derived a lower limit for the magnetic field in the corresponding region:

$B \gtrsim 10\mu$G. Finally, our global spectral fitting of A4067 yielded a temperature distribution map across ten regions of the cluster. These results align with our hypothesis regarding the dynamical structure of the merger: a smaller, compact sub-cluster is merging into a larger, diffuse cluster. During this process, the cold core has been preserved, resulting in a merger structure similar to that of the Bullet Cluster.

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The quality of the article has been significantly improved.

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The stability of the interface in the presence of magnetic fields can be characterized by the critical velocity $V > V_{cr}$, where the magnetic field pressure plays a crucial role. Specifically, the relationship between the hot and cold phases, denoted by subscripts "hot" and "cold" respectively, can be expressed through the pressure balance and the Mach number M. The condition for stability against Kelvin-Helmholtz instabilities in a magnetized plasma, considering the magnetic field B and gas pressure p_{gas}, is given by:

$$\frac{B_{hot}^2}{8\pi}+\frac{B_{cold}^2}{8\pi}>\frac{1}{2}\rho M^2\left(1+\frac{T_{cold}}{T_{hot}}\right)p_{gas} \tag{13}$$

Based on our analysis of the Chandra observations, we derived the following physical parameters and Mach numbers for the shock fronts:

- For the first region, the density-derived Mach number is $M_\rho =$

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Lyutikov M. MNRAS, 2006, 373: 73 The Chandra Observation of the Double-Shock Galaxy Cluster Abell 4067 WANG Ye-lin1 GE Chong1 GENG Chao2 (1 Department of Astronomy, School of Physical Science and Technology, Xiamen University, Xiamen 361005) (2 Department of Astronomy, School of Physics, University of Science and Technology of China, Hefei 230026) ABSTRACT Observations of the dynamically complex galaxy cluster Abell 4067 (A4067; z = 0.0992) were carried out using the Chandra X-ray Observatory (CXO). The study identifies a merger structure wherein a compact subcluster is coalescing with a more extended, diffuse cluster along the east-west axis. The core temperature of the subcluster is approximately 1.37 keV, while the mean temperature of the primary cluster is about 2.44 keV. X-ray imaging and spectral analysis reveal intricate structures, including surface brightness discontinuities, indicative of an ongoing merger event. The radial profiles of X-ray surface brightness and temperature distributions reveal three distinct surface brightness edges, one of which corresponds to a merger-driven cold front, while the other two are associated with merger shocks. These shocks, located on the eastern and western peripheries of the cluster, suggest that A4067 is a rare system exhibiting a dual-shock merger morphology. Based on the properties of the eastern shock SF1, the article estimates the merger timescale of A4067 to be approximately suggesting that the system is in the intermediate stage of the merger process. Additionally, leveraging the Mach number of the cold front, the article derives a lower bound on the intracluster magnetic field strength of approximately Gs. The dynamical configuration of A4067 aligns with a scenario involving the merger of a compact subcluster with a more massive, diffuse cluster along the east-west axis, resembling the archetypal Bullet Cluster merger.

Key words galaxies: clusters: intracluster medium, X-rays: merger scenario, shock wave: cold front, magnetic fields (0:51(cid:6)0:01)Gyr7:17(cid:2)10(cid:0)6

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