# Postprint: A Study of the Properties of Shocks and Cold Fronts in the Merging Galaxy Cluster Abell 4067

**Authors:** Wang Shuai1, Ge Chong2

**Date:** 2023-06-07T00:00:00+00:00

## Abstract

The Chandra X-ray Observatory conducted a 1.3 × 105s observation of the merging galaxy cluster Abell 4067, and by processing these data, a preliminary analysis of its internal merging substructures was performed. The analysis reveals that a shock wave exists on the eastern side of the galaxy cluster, located 280 kpc from the cool core center of the eastern subcluster. The electron density jump ratio and temperature jump ratio caused by the shock are 2.19+0.16−0.09 and 2.86+1.08−1.02, respectively, and the calculated Mach numbers of the shock are M =1.91+0.16−0.09 and MT =2.54+0.67−0.63, respectively. At the opposite position of this shock, there also exists a shock wave, with Mach numbers of M =1.36+0.02−0.02 and MT =1.33+0.17−0.20, respectively. On the eastern and northern sides of the galaxy cluster, two cold fronts were also discovered, located at distances of 27 kpc and 12 kpc from their respective cool core centers. The electron density jump ratios caused by the cold fronts are 1.23+0.017−0.002 and 2.21+0.08−0.11, respectively. Based on these results, it can be inferred that there exists a merging event on each of the eastern and northern sides of this galaxy cluster.

## Full Text

## Preamble

**Progress in Astronomy**, Vol. 40, No. 2
June 2022
doi: 10.3969/j.issn.1000-8349.2022.02.06

# The Study of Properties of Shocks and Cold Fronts in Abell 4067

**WANG Shuai**[1], **GE Chong**[2]
[1] Department of Astronomy, Beijing Normal University, Beijing 100875, China
[2] Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210042, China

## Abstract

The Chandra X-ray observatory performed a 1:3 (cid:2) $10^5$ s observation of the merging galaxy cluster Abell 4067. By processing these data, we conducted a preliminary analysis of its internal merging substructures. Our analysis reveals a shock front on the eastern side of the cluster, located 280 kpc from the center of the eastern subcluster's cool core. The shock produces electron density and temperature jump ratios of 2.19+0:16 (cid:0)0:63, respectively. At the opposite position of this shock, another shock front exists, with Mach numbers of M(cid:26)=1.36+0:02 (cid:0)0:02 and MT =1.33+0:17 (cid:0)0:20.

Two cold fronts are also identified on the eastern and northern sides of the cluster, located 27 kpc and 12 kpc from their respective cool core centers. The electron density jump ratios produced by these cold fronts are 1.23+0:017 (cid:0)0:11 and 2.21+0:08 (cid:0)0:002, respectively. Based on these results, we infer that two merging events are occurring in this cluster—one on the eastern side and one on the northern side. The calculated Mach numbers for the shocks are M(cid:26)=1.91+0:16 (cid:0)0:09 and MT =2.54+0:67 (cid:0)0:63, respectively.

**Keywords:** merging galaxy cluster; X-ray; shock fronts; cold front

## 1 Introduction

As the largest self-gravitating bound systems in the universe, galaxy clusters are believed to form through continuous merging of smaller subclusters. Cluster mergers represent the most violent astronomical events since the Big Bang, releasing approximately $10^{57}$ J of energy that is transferred into the intracluster medium (ICM), generating shocks and turbulence and accelerating particles. These mergers provide valuable opportunities to study ICM physics, including thermal conduction, viscosity, dark matter self-interaction, and particle acceleration [1].

During cluster mergers, two types of substructures can be observed: cold fronts (CF) and shock fronts (SF), with the Bullet Cluster being the most famous example [1]. Both structures affect the electron density distribution within the cluster, manifesting as discontinuities in the ICM surface brightness profiles in X-ray observations. As a subcluster falls toward the main cluster, ram pressure strips its gas. Ascasibar and Markevitch [2] demonstrated through simulations that whether the subcluster gas is completely stripped depends on the depth of the potential well, infall velocity, and gas density. If the gas is not fully stripped, a cold front forms at the interface between the subcluster's cool core and the main cluster's hot ICM; if completely stripped, no cold front appears. Cold fronts are the most common features in X-ray observations of merging clusters, with some systems exhibiting multiple cold fronts [3]. They also appear in relaxed clusters [3], such as RX J1720.1+2638 [4], where studies show they are primarily caused by gas sloshing [5]. Regardless of their origin, cold fronts create discontinuities in X-ray surface brightness and exhibit characteristic temperature jumps, with higher ICM temperatures ahead of the front and lower temperatures behind [1]. Cold fronts serve as important diagnostic tools for studying clusters; Vikhlinin et al. [6] used Kelvin-Helmholtz instabilities to investigate cluster magnetic fields, while simulations reveal their significance for understanding magnetic fields and thermal conduction [1, 7–9].

Simulations show that most cluster mergers generate shock fronts, which produce temperature jumps opposite to those of cold fronts—the ICM temperature ahead of a shock is lower than behind it. Generally, shock velocities are less than three times the local sound speed (Mach 3). While numerous shocks have been observed, most have Mach numbers between 1 and 2, with Mach 3 shocks being extremely rare. Galaxy clusters with two opposite shocks observed in X-rays are even rarer. Compared to simulation data, observational shock data remain relatively scarce [3] for three main reasons: First, during observation, shocks may have propagated to the cluster outskirts where ICM surface brightness discontinuities are difficult to discern. Second, projection effects can hide surface brightness discontinuities if the merger does not occur in the plane of the sky. Third, because shock velocities are typically less than Mach 3, the resulting temperature jumps are relatively small [1], making shock observations challenging. As another crucial tool for studying merging clusters, shocks are vital for investigating cluster dynamics [10], dark matter [1, 11], and plasma physics [6].

Although both cold fronts and shocks produce surface brightness jumps, their properties differ fundamentally. Beyond their opposite effects on ICM temperature, they also affect gas pressure and entropy differently. Across a shock, gas pressure shows a large jump, while across a cold front, pressure varies almost continuously. Conversely, gas entropy changes little across a shock but varies dramatically across a cold front [12]. Botteon et al. [13] analyzed substructures in 33 non-cool-core clusters, using imaging to visually demonstrate these physical quantity changes across cold fronts and shocks, which generally agree with theoretical expectations.

Our target, Abell 4067 (A4067), also known as RXCJ2359.3-6042, is a merging cluster at redshift 0.0992. Chon and Bohringer (2015) analyzed XMM-Newton X-ray data spectroscopically, concluding that the subcluster merges along a southwest-northeast direction, generating a shock that heats the eastern ICM gas, with ram-pressure-stripped gas mixing with the main cluster's diffuse ICM to form a bright trail [14]. Further analysis of these images suggests an additional merging event may be occurring in the northern region, with potential shock structures present in both the northern and western sectors [15].

In this work, we utilize Chandra X-ray observatory data, leveraging its 0.5 spatial resolution to perform more precise analysis of the cluster's internal cold front and shock structures. Section 2 briefly describes the data sources and image processing methods. Section 3 presents our data analysis and results. Section 4 provides a brief analysis of these results and speculation about the cluster's merging history. Section 5 summarizes our findings and outlines future work. Throughout this paper, we adopt the WMAP standard cosmology with parameters $\Omega\ = 0.3$, $\Omega\_\Lambda = 0.7$, $H_0 = 70\ \mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$, and redshift $z = 0.0992$, where 1 arcsecond corresponds to 1.83 kpc. All uncertainties are quoted at the $1\sigma$ level.

## 2 Data and Processing

Our data were obtained from the Chandra X-ray Observatory, with observation details listed in Table 1. Following the procedures of Ge et al. [16], we processed the data using CIAO 4.11 and CALDB 4.9.1. We first reprocessed the data using the *chandra_{repro}* script in VFAINT mode, then removed flares and point sources using the *deflare* and *wavdetect* scripts, respectively.

For background subtraction, we normalized the telescope's internal background using the count rate in the 9.5–12 keV band. For the cosmic X-ray background (CXB), we employed a three-component model: an unabsorbed thermal spectrum (kT = 0.1 keV), an absorbed thermal spectrum (kT = 0.25 keV), and an absorbed power-law spectrum ($\Gamma = 1.46$). We further constrained the CXB by extracting and jointly fitting ROSAT All-Sky Survey (RASS) spectra from a 1°–2° annulus around A4067. Spectral fitting was performed using XSPEC 12.11.0, with the Galactic HI column density fixed at $N\_H = 1.41 \times 10^{20}\ \mathrm{cm}^{-2}$.

**Table 1** Chandra observational data

| Observation ID | R.A. (J2000) | Dec (J2000) | Exposure Time (ks) | Effective Exposure Time (ks) |
|---|---|---|---|---|
| +23:58:38.60 | (cid:0)60:37:32.96 | 20.65 | | |

## 3 Results

After merging the four observations and subtracting the instrumental background, we obtained an exposure-corrected image. Figure 1 [Figure 1: see original paper] shows the exposure-corrected map smoothed with a 12-pixel kernel for the 0.7–2 keV band. The ICM appears diffuse as the cluster is undergoing a merger.

We identify two merging events in this cluster. The first occurs along the southwest-northeast direction, where the subcluster's cool core (CC1 in Figure 1) is relatively bright, with ram-pressure-stripped gas forming a prominent trail behind it. Near this cool core, the surface brightness shows a sharp decline along the merger direction (CF1 in Figure 1), with a second decline at approximately 100 (SF1 in Figure 1). Additionally, a second merging event appears to be occurring in the northern region, moving from south to north. Relative to CC1, this subcluster's cool core (CC2 in Figure 1) is smaller and fainter, with two surface brightness declines along the merger direction (CF2 and SF2 in Figure 1), though the decline at SF2 is less pronounced. Finally, we note another sharp surface brightness drop in the western region, which we speculate may also be a shock structure (SF3 in Figure 1). Our analysis focuses primarily on the cold front and shock structures in the northern and western regions.

### 3.1 Surface Brightness Profiles

Shock and cold front structures alter the electron density distribution within clusters, creating discontinuities in surface brightness profiles that serve as our primary diagnostic for identifying these features.

Based on preliminary image analysis, we divided the cluster into three sectors (eastern, western, and northern) as shown in Figure 2 [Figure 2: see original paper], extracting surface brightness profiles from regions before and after each potential shock or cold front. The upper-right panel of Figure 2 shows an enlarged view of the northern cool core and the extraction region for the inner surface brightness profile. We fitted the data using an elliptical model [17], where the cluster's X-ray emissivity follows different power-law behaviors before and after a cold front or shock:

$$\epsilon(r) = \begin{cases} \epsilon_i (r/r_{\text{edge}})^{-2p_i} & r < r_{\text{edge}} \\ \epsilon_o (r/r_{\text{edge}})^{-2p_o} & r > r_{\text{edge}} \end{cases}$$

where $r_{\text{edge}}$ represents the location of the cold front or shock. The X-ray surface brightness is then given by:

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

with $I_{\text{in}}(r)$ and $I_{\text{out}}(r)$ defined as:

$$I_{\text{in}}(r) = \begin{cases} I_i A^{-2p_i+1} \frac{1}{I_{A^2(p_i-0.5,0.5)}} & A^2 < 1 \\ I_i A^{-2p_i+1} & A^2 > 1 \end{cases}$$

$$I_{\text{out}}(r) = \begin{cases} I_o A^{-2p_o+1} I_{A^2(p_o-0.5,0.5)} & A^2 < 1 \\ I_o A^{-2p_o+1} & A^2 > 1 \end{cases}$$

In equations (3) and (4), $A = (r/r_{\text{edge}})$, and $I_{A^2}(a, b)$ is the normalized incomplete beta function. The jump ratio $R$ in gas surface brightness across the shock or cold front can be calculated via:

$$I_i = RI_o \frac{B(p_i - 0.5, 0.5)}{B(p_o - 0.5, 0.5)}$$

where $B$ is the beta function. The shock Mach number can then be determined from:

$$M^2 = \frac{4C}{C + 3}$$

where $C = R$ is the electron density jump ratio [18].

Figure 3 [Figure 3: see original paper] presents the fitted surface brightness profiles for each region. Using the above model, we extracted and fitted surface brightness profiles before and after eastern CF1 (Figure 3a) and SF1 (Figure 3c), northern CF2 (Figure 3b), and western SF3 (Figure 3d). The black points represent surface brightness extracted from the X-ray images, the red lines show the best-fit models, and key fitting parameters are listed in Table 2. The black dashed lines in the images indicate regions where surface brightness jumps are observed, allowing us to determine the locations and jump ratios of the cold fronts and shocks. CF1 is located approximately 28 kpc from CC1's center with a surface brightness jump ratio of 1.52+0:042 (cid:0)0:006. SF1 and SF3 are located approximately 280 kpc and 395 kpc from their respective centers, with surface brightness jump ratios of 4.83+0:73 (cid:0)0:41 and 2.33+0:095 (cid:0)0:106, respectively. In Figure 3b, the green line shows the Chandra point spread function (PSF); comparison with the surface brightness profile behind CF2 confirms that CC2 is a cool core rather than a point source. CF2 is located approximately 13 kpc from CC2's center with a surface brightness jump ratio of 4.91+0:37 (cid:0)0:53. We also extracted the surface brightness at SF2 (Figure 4 [Figure 4: see original paper]), but could not obtain a satisfactory fit. While our surface brightness fitting can identify the locations of cold fronts and shocks, it cannot distinguish between the two types of structures; spectral fitting is required to determine temperatures for further classification.

**Table 2** Properties of shocks and cold fronts

| Feature | $R$ | $T_2/T_1$ | $M$ | $M_T$ |
|---|---|---|---|---|
| CF1 | 1.52+0:042 (cid:0)0:006 | 0.32+0:10 (cid:0)0:03 | - | - |
| CF2 | 4.91+0:37 (cid:0)0:53 | 0.479+0:16 (cid:0)0:14 | - | - |
| SF1 | 4.83+0:73 (cid:0)0:41 | 2.86+1:08 (cid:0)1:02 | 1.91+0:16 (cid:0)0:09 | 2.54+0:67 (cid:0)0:63 |

| Feature | $R$ | $T_2/T_1$ | $M$ | $M_T$ |
|---|---|---|---|---|
| SF3 | 2.33+0:095<br>(cid:0)0:106 | 1.32+0:17<br>(cid:0)0:20 | 1.36+0:02 (cid:0)0:02 | 1.33+0:17<br>(cid:0)0:20 |

*Note: $R$ is the surface brightness jump ratio, $T_2$ is the temperature behind the cold front or shock, $T_1$ is the temperature ahead, $T_2/T_1$ is the temperature jump ratio, $M$ is the Mach number derived from the electron density jump, and $M_T$ is the Mach number derived from the temperature jump.*

### 3.2 Spectral Analysis

In merging clusters, cold fronts form when a subcluster's cool core enters the main cluster's hot ICM, so the temperature ahead of the front is typically higher than behind. Shocks exhibit the opposite behavior: as they propagate, they heat the ICM they traverse, resulting in higher temperatures behind the shock front. This temperature contrast provides our primary means of distinguishing between these structures.

Based on the surface brightness profile results from Section 3.1, we extracted spectra from regions before and after each SF and CF, fitting them with a *tbabs*apec* model to determine temperatures. The temperature fitting results are shown as blue points in Figure 3, with detailed parameters given in Table 2. The ICM temperature increases across CF1 and CF2 but decreases across SF1 and SF3, confirming that CF1 and CF2 are cold fronts while SF1 and SF3 are shock fronts. The shock velocity can be calculated from the temperature jump using:

$$M^2 = \frac{5(T_2/T_1) - 1}{4}$$

where $T_1$ and $T_2$ represent the pre-shock and post-shock temperatures, respectively [18]. Combining surface brightness and spectral fitting results, we determined shock locations and calculated Mach numbers: SF1 has $M = 1.91 + 0 : 16(cid : 0)0 : 09$ and $M_T = 2.54 + 0 : 67(cid : 0)0 : 63$, while SF3 has $M = 1.36 + 0 : 02(cid : 0)0 : 02$ and $M_T = 1.33 + 0 : 17(cid : 0)0 : 20$. Here $M$ and $M_T$ denote Mach numbers calculated using surface brightness and temperature jump ratios, respectively.

## 4 Conclusion

Through the fitting and calculations presented in Section 3, we confirm that a merger is indeed occurring in the eastern region of the cluster, producing a shock structure that aligns with previous work by Chon et al. Building upon this, our Chandra data further reveal a shock structure in the western region.

We speculate that these two shocks originate from the same merging event, possibly representing a reverse shock generated during the merger. During this process, the subcluster gas is ram-pressure stripped, mixing with the main cluster's ICM to form a bright trail. Additionally, we find evidence for a cold front in the northern region, though the shock structure there remains unconfirmed. Nevertheless, we favor the interpretation that a merging event is occurring in the north. The inability to clearly identify the shock structure may stem from two factors: (1) the region lies near the cluster outskirts where the ICM is too diffuse for effective X-ray detection, and (2) the ICM velocity may be subsonic, insufficient to produce a shock.

## 5 Summary and Outlook

Using Chandra X-ray observatory data, we have performed a detailed analysis of substructures within the Abell 4067 galaxy cluster. We confirm a merging event in the eastern region and, building upon Chon et al.'s work, further identify two opposing shock structures generated by this event. We also confirm the presence of a cold front in the northern region and, based on X-ray observations, speculate that an additional merger may be occurring there. However, data quality limitations prevent us from obtaining stronger evidence for a northern shock. Deeper observations would be necessary to verify this hypothesis. Furthermore, combining multi-wavelength data could enable more rigorous analysis. For instance, optical observations demonstrating distinct galaxy populations within the cluster would help confirm whether a merging event is occurring in the northern region.

## References

[1] Markevitch M, Vikhlinin A. *Physics Reports*, 2007, 443: 1
[2] Ascasibar Y, Markevitch M. *ApJ*, 2006, 650: 102
[3] Pascut A, Hughes J P. *ApJ*, 2019, 874: 71
[4] Mazzotta P, Markevitch M, Vikhlinin A, et al. *ApJ*, 2001, 555: 205
[5] Ghizzardi S, Possetti M, Molendi S. *A&A*, 2010, 516: A32
[6] Vikhlinin A, Markevitch M, Murray S S. *ApJ*, 2001, 551: 160
[7] ZuHone J A, Roediger E. *Journal of Plasma Physics*, 2016, 82: 48
[8] ZuHone J A, Markevitch M, Ruszkowski M, et al. *ApJ*, 2013, 762: 69
[9] Xiang F, Churazov E, Dolag K, et al. *MNRAS*, 2007, 379: 1325
[10] Markevitch M, Govoni F, Brunetti G, et al. *ApJ*, 2005, 627: 733
[11] Molnar S. *Frontiers in Astronomy and Space Sciences*, 2016, 2: 7
[12] Markevitch M, Gonzalez A H, David L, et al. *ApJ*, 2002, 567: L27
[13] Botteon A, Gastaldello F, Brunetti G. *MNRAS*, 2018, 476: 5591
[14] Chon G, Bohringer H. *A&A*, 2015, 574: A132
[15] Ge C. Chandra proposal ID #19800185, 2017
[16] Ge C, Liu R Y, Sun M, et al. *MNRAS*, 2020, 497: 4704
[17] Korngut P M, Dicker S R, Reese E D, et al. *ApJ*, 2011, 734: 17
[18] Sarazin, Finoguenov A, Wik D, et al. 2016, arXiv: 1606.07433