CHANDRA OBSERVATION OF A WEAK SHOCK IN THE GALAXY CLUSTER A2556

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ABSTRACT

Based on a 21.5 ks Chandra observation of A2556, we identify an edge on the surface brightness profile at about 160 h\textsuperscript{-1}\textsubscript{71} kpc northeast of the cluster center, and it corresponds to a shock front whose Mach number \(M\) is calculated to be 1.25\textsuperscript{±0.02}. No prominent substructure, such as sub-cluster, is found in either the optical or X-ray band that can be associated with the edge, suggesting that the conventional supersonic motion mechanism may not work in this case. As an alternative solution, we propose that the nonlinear steepening of an acoustic wave, which is induced by the turbulence of the intracluster medium at the core of the cluster, can be used to explain the origin of the shock front. Although nonlinear steepening weak shock is expected to occur frequently in clusters, why it is rarely observed still remains a question that requires further investigation, including both deeper X-ray observation and extensive theoretical studies.

Key words: galaxies: clusters: individual (A2556) – intergalactic medium – shock waves – X-rays: galaxies: clusters

Online-only material: color figures

1. INTRODUCTION

Radiative loss via X-ray emission in galaxy clusters has long been supposed to be the origin of substantial gas inflow, namely the “cooling flow” (see Fabian 1994 for a review). However, X-ray spectra from ASCA and XMM-Newton observations fail to show line emission from ions with intermediate or low temperatures, which implies that the cooling rate is only at most 20\% of the previously assumed value (e.g., Kaarstra et al. 2001; Peterson et al. 2001, 2003; Xu et al. 2002; Tamura et al. 2003). Chandra observations have also confirmed such small cooling rates (McNamara et al. 2000). There must be a heating source in the cluster core region. The most popular candidate for the heating source is the active galactic nucleus (AGN) at cluster centers. The AGN dissipates energy via bubbles, jets, sound waves, and weak shocks evolved from sound waves (Fabian & Sanders 2009). In the Perseus and Virgo Clusters, previous works have observed the sound waves and weak shocks generated by activities of central AGNs (Fabian et al. 2003; Ruszkowski et al. 2004; Forman et al. 2005). Besides the AGN activity, there have also been some other heating mechanisms involved in the last decade. Even since the launch of Chandra, shock fronts have been revealed clearly in the intracluster medium (ICM) of galaxy clusters through X-ray imaging-spectroscopic studies, which can efficiently convert the kinetic energy of gas into thermal energy. Such a heating process may be associated with the feedback mechanism that balances the radiative cooling in galaxy clusters.

This work studies the weak shock front in the galaxy cluster A2556 by using Chandra observation. A2556 (R.A. = 23\textsuperscript{h}13\textsuperscript{m}03\textsuperscript{s}, decl. = −21\textdegree37\arcmin40\arcsec, J2000.0; richness 1) is located at \(z \approx 0.0871\) in the Aquarius supercluster (Batuski et al. 1999), an overdense region of the universe. It is moderately luminous in the X-ray band \((L_X \approx 2 \times 10^{44} \text{ erg s}^{-1};\text{ Ebeling et al. 1996}),\) possessing a velocity dispersion of \(\approx 872 \text{ km s}^{-1}\) (White et al. 1997) and a virial mass of \(\approx 2.5 \pm 0.1 \times 10^{15} M_\odot\) (Reimers et al. 1996).

We describe the data reduction, imaging, and spectroscopy analysis in Section 2; we discuss and summarize our results in Sections 3 and 4, respectively. Throughout this paper, we adopt the cosmological parameters \(H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.27,\) and \(\Omega_\Lambda = 0.73,\) so that 1\arcmin\ corresponds to 96.7 h\textsuperscript{-1}\textsubscript{71} kpc at such distance. We utilize the solar abundance standards of Grevesse & Sauval (1998), where the iron abundance relative to hydrogen is \(3.16 \times 10^{-5}\) in number. Unless stated otherwise, all quoted errors are derived at the 68\% confidence level.

2. DATA ANALYSIS

2.1. Observation and Data Reduction

The Chandra observation of A2556 was carried out on 2001 October 5 (ObsID 2226) for a total exposure of 21.5 ks with CCDs 3, 5, 6, 7, and 8 of the Advanced CCD Imaging Spectrometer (ACIS) in operation. Events were collected with a frame time of 3.2 s and telemetered in the VeryFaint mode. The focal plane temperature was set to \(−120^\circ\text{C}.\) The center of A2556 was positioned nearly on the ACIS-S3 chip with about 0.2 arcmin offset. Most of the X-ray emissions of A2556 are covered by the S3 chip. Therefore, this work focuses on the data drawn from the S3 chip. The Chandra data analysis package CIAO software (version 3.4) is used to process the data from the S3 chip. We keep events with ASCA grades 0, 2, 3, 4, and 6, and remove all the bad pixels, bad columns, columns adjacent to bad columns, and node boundaries. No background flare is found during the live operating time.

2.2. X-Ray Surface Brightness

We show the raw Chandra ACIS-S3 image of A2556 in the 0.7–7.0 keV band in Figure 1(a), and have all the point sources excluded, which could be detected at the confidence level of 3\sigma by the CIAO tool ccddetect. The black cross in the center of Figure 1(a) indicates the X-ray peak of A2556. The core region of A2556 shows no complex irregularity and should
be composed of a single nucleus; the outer region shows a slight elongation toward the northwest. The X-ray morphology roughly shows a generally relaxed appearance, except that there is an arm-like structure with an edge at approximately 160 $h_{71}^{-1}$ kpc northeast of the cluster center, and the edge spans about 85° azimuthally from southeast to northeast. We highlight the edge spanned by two white lines in Figure 1(a). Figure 1(b) shows the Sloan Digital Sky Survey (SDSS) $B$-band image of A2556 with the Chandra 0.7–7.0 keV X-ray intensity contours overlaid. The X-ray peak is consistent with the centroid of the cD galaxy 2MASX J23130142–2138039 within 1″. The cD galaxy shows an elongation in the same direction as the X-ray morphology, which may due to the nearby A2554.

To gain more insight into the edge of this arm-like structure, we extract the exposure-corrected surface brightness profile (SBP) from a series of narrow elliptical annuli, which are parallel to the east (E) region show in Figure 1(b). In order to obtain a comparison, we also extract SBPs of three other directions in Figure 1(b), namely, the south (S), west (W), and north (N) regions. The energy band for these profiles is restricted to 0.7–7.0 keV. We show such extracted SBPs in Figure 2. In region E, a substantial discontinuity of the SBP could be observed at approximately 160 $h_{71}^{-1}$ kpc, while the other three regions do not present such a characteristic.

To quantitatively describe the discontinuity of the SBP in region E, we fit observed SBP with a modeled gas emissivity distribution, which corresponds to the function

$$\varepsilon(r) = \begin{cases} \varepsilon_1 (r/R_{\text{cut}})^{\alpha_1} & r \leq R_{\text{cut}} \\ \varepsilon_2 (r/R_{\text{cut}})^{\alpha_2} & r > R_{\text{cut}} \end{cases}$$

(1)

where $r$ represents the radius of the projected SBP; the gas emissivity distribution, $\varepsilon(r)$, is broken at the truncation radius, $R_{\text{cut}}$, and described with two power-law components; and $\varepsilon_1$, $\varepsilon_2$, $\alpha_1$, and $\alpha_2$ are four fitting parameters. The solid line in Figure 2 shows the best-fit SBP obtained with Equation (1). The best-fit $R_{\text{cut}} = 158.26_{-0.42}^{+0.54} h_{71}^{-1}$ kpc corresponds to the edge of the arm-like structure. $\varepsilon_1$ and $\varepsilon_2$ represent the plasma emissivities inside and outside the edge, respectively. The best-fit emissivity jump $\varepsilon_1/\varepsilon_2 = 1.90^{+0.04}_{-0.03}$. Since the gas density is related to the emissivity according to $\varepsilon \sim \rho^2$, the density jump across the edge is calculated to be $\rho_1/\rho_2 = (\varepsilon_1/\varepsilon_2)^{1/2} = 1.37^{+0.02}_{-0.03}$.

### 2.3. Spectral Analysis

In the Chandra spectral analysis, there are two usual ways to obtain a background spectrum, including cosmic, instrumental, and non-X-ray particle components. First, the observed data
set can be directly used to extract the background spectrum from a local and uncontaminated region on Chandra chips, which must be located far enough away from the source. Second, one can draw the background spectrum from the Chandra blank field data sets from the same detector region where the source spectrum is extracted. Since the core radius of A2556 is 350 $h^{-1}_7$ kpc (White et al. 1997) and it should cover most of ACIS-S3 CCD, we have to utilize the Chandra blank-sky template as the background for A2556. The template is tailored to match the actual pointing and the background spectrum is extracted and processed identically to the source spectrum. Then, the background spectrum is rescaled by normalizing its instrumental background at higher energies and calibration uncertainties at lower energies, the spectrum fitting is restricted to 0.7–7.0 keV.

2.3.1. Temperature across the Edge

In order to derive the temperature profile across the SBP edge, we extract the spectra from four elliptical annuli in region E of Figure 1(b), so that the SBP edge lies exactly at the boundaries of a certain elliptical annulus, and the elliptical annulus covers the azimuthal angle, where the edge is most prominent. We use the XSPEC 12.4.0 package to perform the deprojected spectral analyses. In the spectral fitting process, the gas emission is modeled with an absorbed APEC component and the PROJCT model, which performs a three-dimensional to two-dimensional projection of prolate ellipsoidal shells onto elliptical annuli and evaluates the influence of the outer ellipsoidal shells on the inner ones. The absorption column density $N_{H}$ is fixed at the Galactic value $N_{H} = 2.07 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). Best-fit temperature values are shown in Figure 3(a). The temperature behind the edge of the arm-like structure is much higher than that of the ambient regions. The calculated temperature jump across the edge is $T_1/T_2 = 1.93^{+0.51}_{-0.72}$. Both gas density and temperature jumps across the edge of the arm-like structure indicate that the edge is a weak shock front.

The Mach number, $M$, of the weak shock front can be determined by employing the Rankine–Hugoniot shock relation (Landau & Lifshitz 1959)

\[
\frac{\rho_1}{\rho_2} = \frac{(1 + \gamma)M^2}{2 + (\gamma - 1)M^2}
\]

and

\[
\frac{T_1}{T_2} = \frac{(2\gamma M^2 - (\gamma - 1))(2 + (\gamma - 1)M^2)}{(\gamma + 1)^2 M^2},
\]

where $T_1$ and $T_2$ denote the temperature behind (the “post-shock”; region 1 in Figure 1(b)) and ahead (the “pre-shock”; region 2 in Figure 1(b)) of the shock, respectively; $\rho_1$ and $\rho_2$ denote the density behind and ahead of the shock, respectively. For the intracluster gas, $\gamma = 5/3$, which is the adiabatic index for monatomic gas. For weak shock fronts, the accuracy of $M$ derived from the density discontinuity is better than that from the temperature discontinuity (Markevitch & Vikhlinin 2007). Therefore, with the density jump $\rho_1/\rho_2 = 1.37^{+0.02}_{-0.03}$ and Equation (2), we derive the Mach number $M = 1.25^{+0.02}_{-0.03}$. According to Equation (3), a temperature jump of $T_1/T_2 = 1.24^{+0.02}_{-0.01}$ is indicated, which confines the spectroscopic value to $1.93^{+0.51}_{-0.72}$ within errors.

We crosscheck the detected temperature jump by examining the two-dimensional temperature distribution of the gas in A2556. In Figure 3(b), the projected temperature map of A2556 (Gu et al. 2009) exhibits a substantial high-temperature region exactly behind the edge of the arm-like structure, which is coincident with the temperature profile shown in Figure 3(a).

2.3.2. Classification of Weak Cool Core Cluster

To test whether a cooling flow model fits the spectrum of A2556, we apply four types of models to fit the spectrum in a circular region with radius of 237 $h^{-1}_7$ kpc, centered on the X-ray peak. The circular region covers nearly the whole Chandra ACIS-S3 CCD. First, we use the WABS×APEC model (hereafter 1TA) and WABS×MEKAL model (hereafter 1TM) to describe the X-ray emission only by a single isothermal plasma. In these two models, temperatures and elemental abundances are

Figure 3. (a) Deprojected gas temperature profile across the shock in region E. $R$ represents the distance from the X-ray peak of A2556. A substantially high temperature is observed around $R = 160 h^{-1}_7$ kpc, which exactly corresponds to the shock front in A2556. (b) The two-dimensional projected temperature map derived from Gu et al. (2009). The white elliptical annulus corresponds to region 1 in Figure 1(b).

(A color version of this figure is available in the online journal.)
allowed to vary. Second, in order to feature a cooling flow, we employ a single-temperature MEKAL model plus a multi-phase cooling flow component MCKFLOW, where their abundances are tied together and allowed to vary; the temperature of MEKAL and the higher gas temperature of MCKFLOW are also tied together and allowed to vary. We consider two cases for this model: the lower bound on the gas temperature in the MCKFLOW fixed at 0.1 keV and VC represents this component set free.

The best-fit spectral parameters of the four models with 90% confidence level are presented in Table 1. All models do a reasonably good job fitting the spectrum, where reduced $\chi^2$ values are around 1.1. The 1TA and the 1TM give nearly the same $\chi^2$/dof $= 27.87/17$ and the Kolmogorov–Smirnov statistic shows that the observed distribution has a 95% probability of being a single Gaussian profile, which indicates that A2556 is very unlikely to have a subcluster. (A color version of this figure is available in the online journal.)

Table 1: Four Spectra Model Fittings for A2556 in Section 2.3.2

| Model | $T$ (keV) | $Z$ (Z$_\odot$) | $T_{\text{lim}}$ (keV) | $M$ ($M_\odot$ yr$^{-1}$) | $\chi^2$/dof |
|-------|-----------|----------------|-------------------------|--------------------------|---------------|
| 1TA   | 3.21 ± 0.09 | 0.43$^{+0.06}_{-0.05}$ | ... | ... | 1.13 |
| 1TM   | 3.25 ± 0.01 | 0.39 ± 0.05 | ... | ... | 1.13 |
| FC    | 3.46 ± 0.15 | 0.44 ± 0.06 | 0.10 | 19.99 ± 10.14 | 1.10 |
| VC    | 3.46 ± 0.15 | 0.43 ± 0.06 | 0.15$^{+0.06}_{-0.05}$ | 20.13$^{+0.56}_{-0.85}$ | 1.10 |

Note. 1TA represents the WABS×APEC model, 1TM represents the WABS×MEKAL model. For the MEKAL + MCKFLOW model, FC represents the lower bound on the gas temperature in the MCKFLOW fixed at 0.1 keV and VC represents this component set free.

3. DISCUSSION

In Section 2, we present robust evidences for the existence of the weak shock front located at approximately 160 h$_{70}^{-1}$ kpc northeast of the cluster center. As in the Perseus, Hydra A, and several other clusters, AGN activity might be the cause of the weak shock in A2556. However, partly due to the poor photons statistics, we fail to find robust evidence of AGN bubbles and disturbances on cluster scales. In this section, we shall discuss the two other possible origins of this weak shock front in more detail.

3.1. Lack of Supersonic Substructure

A2556 has a cD galaxy which is consistent with the X-ray peak within 1$''$ as shown in Figure 1(b). This indicates that A2556 has no violent disturbance caused by a major merger in recent $\sim 10^9$ yr. The difference in photometric magnitudes between the two most luminous galaxies, namely the magnitude (luminosity) gap $\Delta$mag$_{12}$, is the simplest measurable statistic to quantify the dynamical age of a system (Milosavljević et al. 2006); larger $\Delta$mag$_{12}$ indicates an older dynamical age. According to the absolute total magnitudes of the brightest (2MASX J23130142−2138039) and second-brightest (2MASX J 23132498−2137390) galaxies from Smith et al. (2004), $\Delta$mag$_{12} = 0.851$ in the R band. Comparing it with the mean magnitude gap of 730 clusters (Milosavljević et al. 2006), $\langle \Delta$mag$_{12} \rangle \simeq 0.75$, we conclude that A2556 is a dynamical old cluster.

Krick & Bernstein (2007) measured the flux, SBP, color, and substructure in the diffuse intracluster light of A2556. They concluded that this cluster is dynamical relaxed and shows no subcluster. Therefore, the weak shock front in A2556 may not be formed by the supersonic infalling of the subcluster.

Previously observed shock fronts in ICM of galaxy clusters, for instance the bullet cluster (Markevitch et al. 2002) and A520 (Markevitch et al. 2005), could be attributed to supersonic infalling subclusters. However, there are indications that A2556 possibly has no subcluster. Therefore, the weak shock front in A2556 may not be formed by the supersonic infalling of the subcluster.

3.2. Nonlinear Steepening Weak Shock in A2556

Besides the supersonic flow, the nonlinear steepening from a normal acoustic wave could also generate a shock front (Landau & Lifshitz 1959). Such nonlinear steepening is a possible cause for the weak shock front in A2556, since the supersonic infalling of the subcluster may not be the origin of the shock front in it.

First, we would like to discuss the origin of normal acoustic waves in clusters. From their numerical simulations, Nagai et al. (2003) showed that even for relatively relaxed cluster gas, turbulent velocity in the ICM can reach up to about 20%–30% of the local sound speed, and this result is not ruled out by...
current observational upper limits (e.g., Sanders 2011). Such turbulence generates an acoustic wave in the ICM (Fujita et al. 2003), which can be described by Euler’s equation. Since the turbulent velocity $v$ is comparable to the sound velocity $c_s$, the nonlinear term $(v \cdot \nabla) v$ in Euler’s equation cannot be neglected (Landau & Lifshitz 1959). This leads the acoustic wave to inevitably steepen into a shock wave. According to this mechanism, the ICM turbulence of A2556 could be the origin of the shock front we detected.

Second, these shock waves would dissipate the energy and heat the surrounding gas of the clusters. We perform a schematic calculation for the nonlinear steepening weak shock. Following the method of Stein & Schwartz (1972), when an acoustic wave steepens, the crest overtake the trough in a distance given by

$$\int \frac{\gamma + 1}{2} v dt = \int \frac{\gamma + 1}{2} c_s dL = \frac{\lambda}{2},$$  \hspace{1cm} (4)

where $\gamma = 5/3$ is the adiabatic index for monatomic gas, $\lambda$ is the sound speed (for A2556, $c_s = 900$ km s$^{-1}$ according to its average temperature 3.2 keV), and $L$ is the distance the excited sound wave travels before it steepens into the shock front. Since the energy flux of the acoustic wave $F \propto \rho v^2$ and assuming the acoustic wave prior to shock formation does not dissipate any energy, we get the relation $v \propto \rho^{-1/2}$. Additionally, with a single $\beta$ distribution $\rho = \rho_0 [1 + (L/r_c)^2]^{-\beta/2}$ for the gas density in the ICM, where $r_c$ is the core radius, we obtain

$$\lambda = 2 \int_0^L \frac{\gamma + 1}{2} \frac{v_0}{c_s} [1 + (L/r_c)^2]^{\beta/4} dL,$$  \hspace{1cm} (5)

where $v_0$ is the initial velocity amplitude. Suppose the acoustic wave originates from the cluster center. The distance it travels before steepening into the shock front is $L \simeq 160 h_{71}^{-1}$ kpc in A2556. According to Equation (5), $\lambda \simeq 400 h_{71}^{-1}$ kpc, which means the period of the acoustic wave generated by the turbulence in the cluster center is $\simeq 0.43$ Gyr.

4. SUMMARY

The Chandra observation of A2556 reveals a weak shock front located at approximately $160 h_{71}^{-1}$ kpc northeast of the cluster center with $M = 1.25^{+0.02}_{-0.03}$. Since no subcluster associated with the weak shock front is observed in the optical or X-ray band, we cannot ascribe the formation of the shock front to the supersonic infalling of the subcluster. We suggest the steepening of the acoustic wave could be a possible origin of such a shock front, and such an acoustic wave could be induced by the turbulence of the ICM in the cluster core.

The nonlinear steepening shock front should be a ubiquitous phenomenon in the ICM. In contrast, the observation of a nonlinear steepening weak shock front is rare. This may be ascribed to the fact that the weak shock wave is difficult to observe. However, to solve this question requires further investigation, including both deeper X-ray observation and extensive theoretical studies.

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