Revealing a Head-on Major Merger in the Nearby NGC 6338 Group with Chandra and VLA Observations

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Received 2017 January 17; revised 2018 November 7; accepted 2018 November 12; published 2019 January 16

Abstract

By analyzing the Chandra archival data of the nearby NGC 6338 galaxy group, we identify two X-ray bright clumps (N-clump and S-clump) within the central 100 h⁻¹ Mpc, and detect an arc-like X-ray brightness discontinuity at the south boundary of the N-clump, which is defined as a cold front with a gas flow Mach number of M < 0.8. Furthermore, at the northeast boundary of the S-clump (dominated by galaxy NGC 6338) another X-ray edge is detected that corresponds to a weaker cold front. Therefore, the two clumps are approaching each other approximately from opposite directions, and the group is undergoing a head-on collision that is in a stage of pre-core passage. This merger scenario is also supported by the study of the line-of-sight velocity distribution of the group member galaxies. The merger mass ratio is about 1:1.8 as estimated from the central gas temperature of the two clumps, which suggests the merger is most likely to be a major merger. We also analyze the Very Large Array 1.4 and 4.9 GHz radio data, but we do not detect any extended radio emission that is associated with the merger.

Key words: galaxies: groups: individual (NGC 6338 group) – ISM: kinematics and dynamics – X-rays: galaxies: clusters

1. Introduction

In the framework of hierarchical structure formation, galaxy clusters grow in size by merging with subunits, releasing as much as 10⁶⁴ erg of kinetic energy as thermal energy by driving shocks (Sarazin 2002), with each merger event typically lasting for about 2–5 Gyr (e.g., Roettiger et al. 1997; Ascasibar & Markevitch 2006). It is expected that major merger processes can generate remarkable hydrodynamic substructures in the intracluster medium (ICM), such as shocks and cold fronts that show arc-shaped or edge-like morphologies, corresponding to gas density and temperature jumps (e.g., Markevitch & Vikhlinin 2007 and references therein). These substructures can be used to determine the kinematics of the merger and to study the conditions and transport processes in the ICM, including electron–ion equilibrium and thermal conduction (e.g., Markevitch 2005).

It is likely that a fraction of the shock energy can be converted into the acceleration of relativistic particles (e.g., Blandford & Eichler 1987), and in cluster mergers this process could produce synchrotron radio emission (e.g., Feretti et al. 2012; Brunetti & Jones 2014). Giant radio halos and relics have been observed in galaxy clusters (e.g., Feretti & Giovannini 2008), and recent years, many more radio halos and/or relics in lower frequencies have been detected in relaxed clusters, even in poor clusters (e.g., Feretti et al. 2012), some of which have been explained by gas sloshing in the core (e.g., ZuHone et al. 2013). However, as radio emitting electrons have short radiative lifetimes (∼10⁷–10⁸ yr), it is difficult to explain the megaparsec size of extended radio halos (for a review, see Brunetti & Jones 2014). And some dynamically disturbed clusters exist that do not show any evidence of a radio halo, such as the well-known merging cluster A119 (Giovannini & Feretti 2000). Also, Cassano et al. (2010) found four such clusters: A141, A781 (that has been found to host a radio halo in Govoni et al. 2011), A2631, and MACS J0228.5+2036. On the scale of the galaxy group, some possible signals for extended radio sources related to the intergalactic magnetic field have been found (e.g., Nikiel-Wroczyński et al. 2017), while the evidence for radio relics or halos in the groups is not yet conclusive. The above indicates that the formation mechanism of radio halos is currently not fully understood.

As we know, a large fraction of the baryons in the nearby universe resides in galaxy groups with X-ray luminosities ∼10⁴¹–10⁴³ erg s⁻¹ and gas temperature ∼0.3–2 keV (e.g., Ponman & Bertram 1993; Mulchaey 2000). Galaxy groups are much more representative gravitational systems than rarer rich clusters of galaxies (e.g., Geller & Huchra 1983; Tully 1987) and important for understanding the gravitational and thermal evolution of most of the matter in the universe. The effects of nongravitational heating, such as AGN feedback and merger shocks, are expected to be more significant in lower mass systems as the energy input from these sources is comparable to the binding energy of the group (e.g., Ponman et al. 1996, 1999; Helsdon & Ponman 2000). Major and minor group mergers, and their subsequent relaxation, govern the formation of the largest scale structures and can have a considerable impact on their constituent galaxies. However, studies of galaxy group mergers have been limited due to their faint X-ray emission and low galaxy densities. And there are...
not many research works focused on group mergers (e.g., Kraft et al. 2006, 2011; Machacek et al. 2010, 2011; Russell et al. 2014; Schellenberger et al. 2017) when compared with a large number of studies on galaxy cluster mergers.

In this paper, we present a nearly head-on merger discovered in the Chandra observation of the nearby NGC 6338 galaxy group ($z = 0.02824$; Wegner et al. 1999). The brightest galaxy NGC 6338 (cD, S0, $M_B = 13.6$; $z = 0.02743$) and the member galaxy 2MASX J17152326+5725585 (hereafter 2MASX J1715; E0, $M_B = 15.4$; $z = 0.03212$; Smith et al. 2004) present some evidence of galaxy–galaxy interaction in the optical band, as shown on the SDSS image (Figure 1(a)). Both NGC 6338 and 2MASX J1715 (located north about 1.3 from NGC 6338) are elongated in the north–south direction. In particular, the latter contains a double nucleus (Berlind et al. 2006; Figure 1(a)), and has an asymmetrical optical morphology that is possibly due to tidal forces. In the Very Large Array (VLA) NVSS map (Condon et al. 1998; Figure 1(a)), a point-like radio source is shown at the center of NGC 6338, as reported by Dong et al. (2010) and Pandge et al. (2012). We also find an extended radio emission located in the southeast side of the group, which infers that the group has a radio relic.

In Section 2, we describe the Chandra and VLA observations and data reductions. In Section 3, we present the X-ray image and VLA radio map. In Section 4, we analyze the velocity distribution of the identified member galaxies. In Section 5, we discuss and summarize our results. Throughout the paper, we adopt the cosmological parameters $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.044$, $\Omega_b = 0.027$, and $\Omega_L = 0.73$. Unless stated otherwise, the quoted errors stand for 90\% confidence limits.

2. Observations and Data Reductions

2.1. Chandra

The NGC 6338 galaxy group was observed by Chandra on 2003 September 17–18 (47.94 ks, ObsID 4194) with chips 0, 1, 2, 3, 6, and 7 of the Advanced CCD Imaging Spectrometer (ACIS) operating in VFAINT mode. We use the Chandra data analysis package CIAO version 4.4 and CALDB version 4.5.1 to process the data, by starting with the level-1 raw event file in order to apply the latest corrections for the charge transfer inefficiency to improve the energy resolution of the CCDs and to remove most of the effects of the apparent gain shift. We keep events with ASCA grades 0, 2, 3, 4, and 6, and removed all the bad pixels, bad columns, and columns adjacent to bad columns and node boundaries. We examine the 0.3–12.0 keV lightcurves extracted from the background regions defined on the four ACIS-I chips, and find that there are almost no strong background flares that increased the background count rate to $>115\%$ of the mean quiescent value. The obtained net exposure is 47.13 ks.

For the spectral analysis, we extract the Chandra spectra in the 0.7–7.0 keV band. Background spectra are extracted from the Chandra blank-sky fields; a cross-check based on the use of local background yields essentially the same result.

2.2. VLA

We use the radio data of the NGC 6338 group observed with the Very Large Array (VLA) on 1998 July 28 at the frequency of 1.4 GHz (L-band) in B-array (AP690) and on 1997 June 27 at the frequency of 4.9 GHz (C-band) in C-array (AE0110). The observations were carried out with 50 MHz bandwidth for the total integration time of 950 s and 630 s for L-band and C-band, respectively. In these observations, 3C 48 is used as the primary flux density calibrator, while 3C 343 and 1739+522 are used to determine the complex antenna gains, respectively. The NRAO achieved data is analyzed in AIPS7 (version 31DEC16) using the standard procedures. Self-calibration is applied to remove residual phase variations. The final images are produced by AIPS task IMAGR.

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7 https://www.aips.nrao.edu/index.shtml
3. Results

3.1. X-Ray Image

In Figure 1(b), we show the ACIS-I image of the central 200 kpc × 200 kpc (5.8' × 5.8') region of the NGC 6338 group in the 0.3–5.0 keV band, which has been corrected for exposure but not for background. Two X-ray bright clumps are clearly visible in the center region with a projected separation of about 48 h_75^{-1} kpc (83''); 1 arcsec = 0.575 h_75^{-1} kpc at the redshift of z = 0.02824. The X-ray peak of the south clump (hereafter S-clump) is consistent with the optical centroid of NGC 6338 within 3'', and the X-ray peak of the north clump (hereafter N-clump) is found at 2.8 h_75^{-1} kpc (5'') north of member galaxy 2MASX J1715. In Figure 1(b), two arc-shaped edges can be seen at the south boundary of N-clump (hereafter N-edge) and the northeast boundary of S-clump (hereafter S-edge); and two X-ray stripped tails also are found located roughly north of N-clump and southwest of S-clump, respectively. These above findings indicate that two clumps are approaching each other approximately from opposite directions, and the group is undergoing a nearly head-on merger.

To study the edges in a quantitative way, we extract the exposure-corrected X-ray surface brightness profiles (SBPs; Figures 2(a) and (b)) in the 0.3–2.0 keV band using two sets of semi-annuli, which are defined in two semi-circles as shown in Figure 1(b). We find that both profiles show clear surface brightness discontinuities at the edges; across the N-edge, the surface brightness increases inward by a factor of 2.1 within 3.6 h_75^{-1} kpc (6''), and across the S-edge, it increases by a factor of 1.6 within 6.4 h_75^{-1} kpc (11''). Surface brightness discontinuities appear usually due to the jumps in gas density accompanied with temperature jumps, and often indicate the existence of shocks (e.g., 1E 0657–56, Markevitch et al. 2002; A520, Markevitch et al. 2005) or cold fronts (e.g., A1795, Markevitch et al. 2001; A168, Hallman & Markevitch 2004).

3.2. Temperature and Metal Abundance Distributions

In order to investigate the thermal properties of the head-on merging group, we obtain the two-dimensional gas temperature and metal abundance distributions (Table 1) by extracting spectra from the regions including the semi-annuli of two clumps (north semi-annuli of N-clump, hereafter NN; south semi-annuli of N-clump, SN; northeast semi-annuli of S-clump, NS; and southwest semi-annuli of S-clump, SS) and Box (a–l) as shown in Figure 3. We fit each spectrum with an absorbed APEC model coded in the XSPEC v12.4.0 software by fixing the redshift and absorption to z = 0.02824 and the Galactic value N_H = 2.23 × 10^{20} cm^{-2} (LAB Survey of Galactic HI; Kalberla et al. 2005), respectively. Allowing the redshift to vary does not improve the fits. Except for the spectrum extracted in the north middle semi-annulus of S-clump (Region NS2), no more than Galactic absorption is needed.

In the central region, each of two clumps has a cool core with the gas temperature of 1.0–1.3 keV for N-clump and 1.3–1.5 keV for S-clump. The gas temperatures between two clumps (Region SN2 and NS3) are up to 3.9 keV, which are significantly higher than those of Regions NN2 and SS3 (2.0–2.6 keV). With the two clumps approaching each other, the gas between two clumps is compressed, and it is most likely heated by shocks generated in the merger. In the surroundings, the gas temperatures of Boxes (a), (e), (f), and (i) with the value of 3.2–4.0 keV are significantly higher than those of Boxes (c), (d), (g), (h), (k), and (l) with the value of 1.9–2.5 keV. The above four high-temperature boxes are on either sides of the central merger region, the gas of which is probably the hot gas expelled from the collision axis areas in the merger process, as shown in simulation works (e.g., Ricker & Sarazin 2001).

The stripped gas of the S-clump (Boxes (g), (k), and (l)) has a higher metal abundance in a range of 0.5–1.5 Z⊙ (Table 1), comparing with the average metal abundance of 0.25±0.08 Z⊙ (Rasmussen & Ponman 2007). In the tail of N-clump (Box (c) and (d)) no enhanced metal abundance is found.

3.3. Two Cold Fronts

We show the gas temperature profiles across the N-edge and S-edge in Figures 2(c)–(d). After correction for projection effects (Table 1), we find that the gas temperatures outside both of the edges (4.0^{-0.7}_{+0.5} keV and 3.6^{-0.5}_{+0.5} keV) are significantly higher than those inside (1.1 ± 0.1 keV and 1.9 ± 0.1 keV) at 90% confidence level, which confirm the existence of two temperature jumps at the N-edge and S-edge, respectively. Note that the temperature jumps cannot be smeared out by abundance variations allowed by the data; to show this, in Figure 4 we plot the two-dimensional fit-statistic contours of temperature and abundance at 68%, 90%, and 99% confidence levels inside and outside N-edge and S-edge, respectively, all obtained in the above deprojected fittings.

To estimate the gas flow of the two clumps, we attempt to fit each of the exposure-corrected SBPs with two density models, respectively, by applying the best-fit deprojected spectral parameters (Table 1). The first density model (model A) is composed of two β components as

\[ n_β(R) = \begin{cases} n_{β,1} \left[ 1 + (R/R_1)^2 \right]^{-3β_1} + n_{β,2} \left[ 1 + (R/R_2)^2 \right]^{-3β_2} & R < R_{cut} \\ n_{β,1} \left[ 1 + (R/R_{cut})^2 \right]^{-3β_1} & R \geq R_{cut} \end{cases} \]

(1)

where R is the 3D radius, R_c is the core radius, and β is the slope. The second density model (model B) is composed of one truncated power-law component and one β component,

\[ n_β(R) = \begin{cases} n_{β,1} \left[ 1 + (R/R_{cut})^2 \right]^{-α} & R < R_{cut} \\ n_{β,2} \left[ 1 + (R/R_2)^2 \right]^{-3β_2} & R \geq R_{cut} \end{cases} \]

(2)

where R_{cut} is the truncation radius to be determined in the fittings. For each of the SBPs, an acceptable fit is obtained with model B only (Table 2; Figure 2), and we show the gas density inside and outside of these two edges in Table 3. The density jump is in a factor of 2.0^{0.6}_{-0.4} across the N-edge, and 1.4 ± 0.1 across the S-edge.

Following the method of Vikhlinin et al. (2001), to estimate the Mach number of gas flow we need to investigate the gas pressure in both the stagnation point and the undisturbed free stream. The gas pressure at the stagnation point must be equal to that inside the edge, which can be well determined by the X-ray gas density and temperature of the N-clump and S-clump (Tables 1 and 3). Because the gas between the two clumps (Region SN2 and NS3; Table 1) is significantly heated by the merger as shown in Section 3.2, it cannot be thought of as the gas temperature of free stream. Thus, we assume the undisturbed gas in the north semi-annulus of N-clump (Region NN2) and the southwest semi-annulus of S-clump (Region SS3) as the free stream. Then, we
calculate the average thermal gas pressure inside of the edge and in the corresponding free stream as $P_m$ and $P_a$, and find that the pressure ratio is $P_m/P_a = 1.1^{+0.5}_{-0.3}$ for N-edge and $1.0 \pm 0.3$ for S-edge (Table 3), respectively, which indicates that the pressure equilibrium has been established across the two edges. Also, from Bernoulli’s equation (Landau & Lifshitz 1959) we estimate that the Mach number of the gas is $M_N,edge < 0.8$ (corresponding to a velocity of 580 km s$^{-1}$) for the N-clump. Because the above is a rough estimate and no shock-like edge is found in the X-ray image, it is believed that the N-clump moves toward the south in a subsonic flow, which is consistent with that found by Dupke & Martins (2013). For the S-edge, the Mach number is $M_S,edge < 0.6$, corresponding to a velocity less than 430 km s$^{-1}$. Based on the above results, we conclude that the N-clump comes from north to merge with the S-clump, and a cold front is observed at its south boundary. At the same time, the S-clump is moving northeast at a slower speed, and correspondingly, the other cold front is formed at the northeast boundary of S-clump. Therefore, the head-on merger is in a stage of the pre-core passage.

### 3.4. Radio Properties

In Figures 5(a) and (b), we show the VLA 1.4 GHz and 4.9 GHz contours of the central 200 kpc $\times$ 200 kpc (5′8 $\times$ 5′8) region of NGC 6338 group. Their synthesized beams and noise levels are $\theta_{1.4} = 3''3 \times 5''6$ and $\sigma_{1.4} = 0.01$ mJy/beam, $\theta_{4.9} = 3''4 \times 5''1$ and $\sigma_{4.9} = 0.03$ mJy/beam, respectively. In Figure 6, we plot the 1.4 GHz contours on the exposure-corrected X-ray image. We find no extended radio emission directly associated with the merger of NGC 6338 group in 1.4 and 4.9 GHz maps.

In the 1.4 GHz map, the radio source in the center of NGC 6338 is resolved, and the radio emission displays an X-shaped appearance. The radio lobes, extending in the northeast and southwest directions, are associated with two possible X-ray cavities (Figure 6), which Pandge et al. (2012) found by analyzing Chandra X-ray data. These indicate that these two radio lobes were inflated by jets originating from the central AGN activity. The radio substructures, extending to the northwest and southeast with the size scale of 8.6 $h_{75}^{-1}$ kpc (15″) and 7.7 $h_{75}^{-1}$ kpc (13″) over 10$\sigma$, respectively, are roughly perpendicular to the older radio lobes, and they are coincident with two X-ray filaments (Figure 6; Pandge et al. 2012) and HST $H_\alpha$ filaments (Martel et al. 2004). Pandge et al. (2012) also detected HST I-band filaments (usually associated with the interstellar dust) in the center of galaxy NGC 6338, which extends up to about 3.6 kpc in the southeast direction. The spatial correspondence of radio, X-ray, $H_\alpha$, and optical filaments provides strong evidence that these features have been inflated by jets from the central AGN in its vicinity.
The redshift and absorption are latest outburst. In the VLA 4.9 GHz map, the radio source is not.

Notes.

a An absorbed APEC model is used to fit the spectra extracted from the semi-anulni centered on the X-ray peaks of N-clump (Region NN1-2 and SN1-2) and S-clump (Region NS1-3 and SN1-3), and Box (a–1) as shown in Figure 3.

Table 1

| Region | Radius (h_71 kpc) | N_H (10^{20} cm^{-2}) | T (keV) | Z (Z_{sol}) | χ^2/dof |
|--------|------------------|-----------------------|---------|-------------|---------|
|        |                  |                       |         |             |         |
| PROJECTED* |
| NN1 0–8.0 fixed | 1.00 ± 0.06     | 2.02 ± 0.11          | 62.7/49 |
| NN2 8.0–17.9 fixed | 1.97 ± 0.19 | 2.03 ± 0.13          | 57.5/59 |
| SN1 0–8.0 fixed | 1.27 ± 0.08     | 0.16 ± 0.09          | 49.0/56 |
| SN2 8.0–17.9 fixed | 3.92 ± 1.03 | 0.53 ± 0.48          | 38.4/58 |
| NS1 0–8.5 fixed | 1.49 ± 0.10     | 0.84 ± 0.28          | 76.6/57 |
| NS2 8.5–25.6 fixed | 2.24 ± 0.40 | 1.21 ± 0.27          | 53.4/57 |
| NS3 25.6–39.3 fixed | 3.90 ± 0.64 | 0.54 ± 0.44          | 78.7/57 |
| SS1 0–8.5 fixed | 1.27 ± 0.03     | 0.73 ± 0.22          | 99.4/58 |
| SS2 8.5–25.6 fixed | 1.91 ± 0.10 | 1.10 ± 0.05          | 55.0/59 |
| SS3 25.6–39.3 fixed | 2.63 ± 0.42 | 0.74 ± 0.61          | 80.3/59 |

| DEPROJECTED* |
| SN1 0–8.0 fixed | 1.06 ± 0.13     | 0.19 ± 0.28          | 101.1/117 |
| SN2 8.0–17.9 fixed | 4.04 ± 0.99 | 0.66 ± 0.70          | 216.8/173 |
| NS1 0–8.5 fixed | 1.35 ± 0.06     | 0.80 ± 0.27          | 216.8/173 |
| NS2 8.5–25.6 fixed | 1.87 ± 0.11 | 0.96 ± 0.25          | 160/40 |
| NS3 25.6–39.3 fixed | 3.56 ± 1.03 | 0.53 ± 0.42          | 99.2/59 |

Database within a radius of 31′ (~1 Mpc) centered at the weighted centroid of the group galaxy distribution (R.A. = 17°15′34″ Dec. = +57°24′39″; Pearson et al. 2015). To including possible substructures a velocity cut of ±2000 km s^{-1} centered on the group redshift (z = 0.02824) is applied. Then, 82 galaxies are identified to belong to the group, in which the two nuclei of 2MASX J1715 are defined as two galaxies.

First, we plot the line-of-sight velocity distribution of the member galaxies in Figure 7(a), which shows that a high-velocity plateau is located at about 9800 km s^{-1}. We fit the observed distribution with a single Gaussian profile, and then we calculate the Kolmogorov–Smirnov statistic for the observed distribution against the best-fit Gaussian model (χ^2/dof = 63.8/15), which shows that the observed distribution has a probability of <20% of being Gaussian. We attempt to fit the observed distribution with a two-component Gaussian model. The best-fit (χ^2/dof = 23.7/12) gives an average velocity of v = 8600 ± 40 km s^{-1} and a corresponding variance of σ_v = 430±40 km s^{-1} for the main Gaussian component, and v = 9690±60 km s^{-1} and σ_v = 160±40 km s^{-1} for the high-velocity plateau. By applying the F-test and the Kaye’s Mixture Model (McLachlan & Basford 1988; Ashman et al. 1994) test, the latter of which is based on a maximum likelihood algorithm, we find that the second Gaussian component is required at the 99% confidence level and preferred at a significant probability of 90%, respectively.

Following the method of Wang et al. (2010), to investigate whether the galaxies in the high-velocity plateau form a real substructure, we divide the identified galaxies into two subgroups: one subgroup with a low-velocity of 7500–9500 km s^{-1} and the other with a high-velocity of 9500–10,600 km s^{-1}, which consist of 70 and 12 galaxies, respectively. According to the best-fit two-Gaussian model, these subgroups roughly corresponds to two Gaussian components, respectively, with up to about two of the
Steering Starbursts in NGC 6338: Implications for the Future of the Group

2MASX J1715 and NGC 6345 mostly in the northeast part, which includes the member galaxies belonging to the high-velocity subgroup are distributed across the S-edge (Figures 2(d) and (f)), respectively.

The galaxies in the low-velocity subgroup that is dominated by galaxy NGC 6338, on the other hand, are scattered symmetrically in the field. These results suggest that the galaxy velocity separation has a dynamical nature and the group is undergoing a merger.

5. Discussion and Summary

Based on our X-ray analysis, we find that in the central 100 h⁻¹ kpc of NGC 6338 group an X-ray brightness discontinuity is detected at the south boundary of the N-clump (associated with the high-velocity subgroup), and at the northeast boundary of the S-clump (related to the low-velocity subgroup) the other X-ray edge is also found, each of which is defined as a cold front. Therefore, the group is undergoing a head-on collision that is in the pre-core passage stage.

As shown in Figure 1(b) and Table 1, both of the subgroups have a cool core that is not significantly affected by the merger. Because both N- and S-clumps are gas rich, we can use their X-ray properties to simply estimate the mass ratio of two subgroups. We get the spectrum of N-clump extracting from both Region NN1 and SN1, and that of S-clump from all Regions NS1, NS2, SS1, and SS2. Then we fit each spectrum with the absorbed APEC model as used in Section 3.2. The obtained gas temperatures are T_N = 1.16 ± 0.07 keV and T_S = 1.66 ± 0.04 keV for N-clump and S-clump, respectively.

According to the study of Hudson et al. (2010), cool-core clusters have a systematic central temperature drop, as T_c ∝ 0.4 T_vir, where T_c is the cool-core temperature and T_vir is the virial temperature of the galaxy cluster. Based on the scale relation of M_vir ∝ T_vir²/₄ for galaxy groups and clusters (Sun et al. 2009), the merger mass ratio of two subgroups is
In Section 3.3, the speed of N-clump is <1010 km s\(^{-1}\) relative to S-clump roughly in the plane of the sky. In Section 4, the high-velocity subgroup has a velocity of \(\sim 1090\) km s\(^{-1}\) relative to the low-velocity subgroup along the line-of-sight direction. According to the Pythagorean Theorem, the high-velocity subgroup (N-clump) has a comprehensive velocity of \(<1490\) km s\(^{-1}\) to the low-velocity subgroup (S-clump). Assuming the two clumps move along the projected distance 48 \(h_\odot^{-1}\) kpc at their currents velocities, they would totally collide with >30 million year.

Considering the relation between radio relic luminosity and system total mass (de Gasperin et al. 2014), and the total mass of NGC 6338 group as \(M_{500} = 9.0 \pm 0.5 \times 10^{15} M_\odot\) (Pearson et al. 2015), the expected luminosity of one radio relic would be \(2.0 \times 10^{22}\) W Hz\(^{-1}\), corresponding to the flux density of about 10 mJy at 1.4 GHz at the redshift of NGC 6338 group. One radio relic with a flux of 1.0 mJy and a size scale of \(10 \times 50\) kpc\(^2\) \((17\'4 \times 87\'0)\) would be detected at the present flux sensitivity of 0.01 mJy/beam \((\theta_{1.4} = 3\'3 \times 5\'6;\ Section 3.4)\). However, no extended radio emission directly associated with the merger of NGC 6338 group is found (Section 3.4). It is possible that the group has a lower merger-caused radio luminosity than that which the luminosity–mass relation predicts. In addition, radio relics and halos are usually expected to form after core passage, while the merger in the NGC 6338 group in still in the pre-core passage stage. This could be another reason why no merger-caused radio emission is detected in the group.

In the center of galaxy NGC 6338, we find an X-shaped radio structure in the 1.4 GHz map, which is spatially overlapped by two pairs of radio lobes possibly caused by two different AGN activities. The two radio lobes in the northeast and southwest directions, associated with two possible X-ray cavities (Figure 6), are inflated by jets in AGN activity; and the others in the northwest and southeast directions originate from the center AGN in its latest outburst, because they spatially correspond to X-ray jets, H\(_\alpha\), and optical.

**Figure 5.** (a) VLA 1.4 GHz contours \((\theta_{1.4} = 3\'3 \times 5\'6, \sigma_{1.4} = 0.01\) mJy/beam, and contour levels = 0.1, 0.2, 0.4, 0.8, 1.6 mJy/beam) in central 200 \(\times\) 200 kpc\(^2\) \((5'8 \times 5'8)\) region for NGC 6338 group. (b) VLA 4.9 GHz contours \((\theta_{4.9} = 3\'4 \times 5\'1, \sigma_{4.9} = 0.03\) mJy/beam, and contour levels = 0.2, 0.4, 0.8 mJy/beam) in the same region as (a).

**Figure 6.** Exposure-corrected and background-subtracted Chandra ACIS-I image in central 200 \(\times\) 200 kpc\(^2\) \((5'8 \times 5'8)\) region for NGC 6338 group. The VLA 1.4 GHz contours shown in Figure 5(a) are overlaid.

\[
R = \frac{M_N}{M_S} \propto \left( \frac{T_{SR-N}}{T_{SR,S}} \right)^{1.65} \propto \left( \frac{T_{N}}{T_{S}} \right)^{1.65} = 1:1.8, \]

which supports that the merger is most likely to be a major merger. Here, we do not use the velocity variance ratio of two subgroups (Section 4) to calculate the merger mass ratio, because the number of member galaxies of the high-velocity subgroup is small (only 12 galaxies) and the uncertainty of error will be large.
filaments. Employing a simple assumption that a radio bubble is launched from the nucleus and travels at approximately the sound speed $c_s$, and the time it takes to rise to its projected position is the sound crossing time $t_c = R/c_s$, where the sound speed is $c_s = \sqrt{\gamma kT/(\mu m_H)} \approx 1100 \sqrt{T/5} \text{keV km s}^{-1}$ with $\gamma \approx 5/3$, and $\mu \approx 0.62$. The estimated inflated time is $1.5 \times 10^4$ yr for the younger lobes. This indicates that the AGN in the center of galaxy NGC 6338 changed the direction of its jets about $1.5 \times 10^4$ yr ago, which is usually explained by axis precession (e.g., Sternberg & Soker 2008; Falceta-Gonçalves et al. 2010).

We thank the Chandra team for making data available via the High Energy Astrophysics Science Archive Research Center (HEASARC). This work was supported by the Ministry of Science and Technology of China (grant No. 2018YFA0404601), the National Science Foundation of China (grant Nos. 11103057, 11433002, 11533004, 11621303, and 61371147).

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Figure 7. (a) Line-of-sight velocity distribution of 82 member galaxies identified in the NGC 6338 group. The distribution is fitted with a two-Gaussian model (solid) and a single Gaussian model (dashed; Section 4), respectively. (b) DSS optical image for central $2100 \times 2100$ kpc$^2$ region of the group, where the low-velocity ($v < 9500$ km s$^{-1}$) and high-velocity ($v > 9500$ km s$^{-1}$) member galaxies are marked with small and big circles, respectively. The positions of 2MASX J1715’5 two nuclei are very close on the image, which is pointed out with one big circle for clarity.