STRANGE FILAMENTARY STRUCTURES (“FIREBALLS”) AROUND A MERGER GALAXY IN THE COMA CLUSTER OF GALAXIES

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ABSTRACT

We found an unusual complex of narrow blue filaments, bright blue knots, and Hα-emitting filaments and clouds, which morphologically resembled a complex of “fireballs,” extending up to 80 kpc south from an E+A galaxy RB 199 in the Coma Cluster. The galaxy has a highly disturbed morphology indicative of a galaxy-galaxy merger remnant. The narrow blue filaments extend in straight shapes toward the south from the galaxy, and several bright blue knots are located at the southern ends of the filaments. The Re band absolute magnitudes, half-light radii, and estimated masses of the bright knots are ~−12 to −13 mag, ~200−300 pc, and ~10^6−10^7 M⊙, respectively. Long, narrow Hα-emitting filaments are connected at the south edge of the knots. The average color of the fireballs is B−Rc ≈ 0.5, which is bluer than RB 199 (B−R = 0.99), suggesting that most of the stars in the fireballs were formed within several times 10^8 yr. The narrow blue filaments exhibit almost no Hα emission. Strong Hα and UV emission appear in the bright knots. These characteristics indicate that star formation recently ceased in the blue filaments and now continues in the bright knots. The gas stripped by some mechanism from the disk of RB 199 may be traveling in intergalactic space, forming stars left along its trajectory. The most plausible fireball formation mechanism is ram pressure stripping by high-speed collision between the galaxy and the hot intracluster medium. The fireballs may be a snapshot of diffuse intracluster population formation, or halo star population formation in a cluster galaxy.

Subject headings: galaxies: clusters: general — galaxies: dwarf — galaxies: evolution — galaxies: kinematics and dynamics — intergalactic medium

Online material: color figures

1. INTRODUCTION

Clusters of galaxies are ideal experimental laboratories for studying environmental effects on galaxy evolution (e.g., Boselli & Gavazzi 2006). Cluster galaxy density varies widely from edge to core; the intergalactic space is often filled with X-ray-emitting hot gas, and the cluster’s large mass forms a very deep gravitational potential around its center. These properties give us observational means to investigate how galaxy density, ambient gas-galaxy interaction, and strong gravitational drag force affect galaxy evolution.

Several lines of observational evidence suggest that drastic galaxy evolution occurred in clusters of galaxies from redshift z ~ 1 to the present. Early-type galaxies form a dominant population in the inner region of local rich clusters, and in particular, S0 galaxies are preferentially found in and around the cluster core region (Dressler 1980, 1994; Dressler et al. 1997; Postman & Geller 1984; Goto et al. 2003; van der Wel et al. 2007). This relationship—the morphology-density relationship—is also observed at high redshift (z ~ 1). However, this enhancement of the fraction of S0 galaxies around a cluster core is less remarkable in high-redshift clusters than in local clusters (Smith et al. 2005; Postman et al. 2005). In addition, a higher blue galaxy fraction has been established for high-redshift clusters (Butcher & Oemler 1978, 1984). Furthermore, a rapid rise in the luminosity function (LF) of member galaxies toward the faint end has been reported in several local rich clusters (Popesso et al. 2005; Trentham et al. 2005; Popesso et al. 2006; Milne et al. 2007; Adami et al. 2007; Yamanoi et al. 2007). However, the LFs of some rich clusters at z ~ 0.3 may exhibit no such rapid increase at those faint ends (Harsono & De Propris 2007). These observational facts suggest that in terms of morphology, color, and population, rapid evolution of galaxies occurred in clusters from z ~ 1 to the present.

Several environmental effects that explain the evolution of cluster galaxies have been proposed, including galaxy-galaxy interaction (Farouki & Shapiro 1981; Ike 1985), galaxy harassment (Moore et al. 1996), tidal interaction with cluster potential (Henriksen & Byrd 1996), ram pressure stripping (Gunn & Gott 1972; Vollmer et al. 2001; Kronberger et al. 2008), turbulent viscous stripping (Nulsen 1982), and galaxy starvation ( Larson et al. 1980; Bekki et al. 2002). In addition, many observational studies have been made to identify the dominant environmental processes in clusters (cf., Boselli & Gavazzi 2006 and references therein). However, the kinds of physical processes that are dominant in rapid galaxy evolution in clusters are still unclear.

Recently, Cortese et al. (2007, hereafter C07) found two peculiar galaxies near the central regions of rich clusters Abell 1689 and Abell 2667 at z ~ 0.2. These galaxies have disturbed morphology and are associated with many small blue blobs extending toward one side of the galaxies. These blobs have absolute magnitudes of M_B ≈ −11 to −12, corresponding to masses of 10^6 to 10^8 M⊙. C07 detected [O ii] emission from some of the blobs and
between the blobs and the host galaxies. The brightness and the size of the blobs are similar to those of dwarf elliptical galaxies or ultracompact dwarf galaxies (Drinkwater et al. 2004). C07 suggested that the phenomena they found may be snapshots of the transformation of spiral galaxies to S0 galaxies, and may give insight into the origin of cluster faint-end populations.

Here we report the discovery of a strange complex of narrow blue filaments and knots extending toward one side of a disturbed E+A galaxy, RB 199, in the Coma Cluster. New deep optical broadband and narrowband (Hα) imaging observations of the central region of the Coma Cluster revealed this structure. The morphology of the structure is very similar to that of the phenomena reported in C07, and the sizes and the luminosities of the knots in the structure are comparable to C07’s blobs. This structure may be a nearby counterpart of C07’s phenomena.

We assumed the cosmological parameters (h0, Ωm, ΩΛ) = (0.73, 0.24, 0.72) and the distance modulus of the Coma Cluster to be 35.05 (Yagi et al. 2007). The linear scale at the Coma Cluster is 474 pc arcsec⁻¹ under this assumption.

2. OBSERVATION AND DATA REDUCTION

We observed a 34′ × 27′ region near the Coma Cluster center α = 12h59m26.7s, δ = +27°44′16.0″ (J2000.0) with Suprime-Cam (Miyazaki et al. 2002) attached to the Subaru Telescope on 2006 April 28 and May 3 and 2007 May 13–15 (Table 1). The main purpose of these observations was to study the faint-end population and star formation in the Coma Cluster. We used two broadband filters, B and Rc, and a narrowband filter (N-A-L671, hereafter Hα NB). The Hα NB filter is designed for observing Hα-emitting objects in the Coma Cluster at z = 0.0225, and has a bell-shaped transmission with a central wavelength of 6712 Å and a FWHM of 120 Å.

We reduced the imaging data in the standard manner. Since some data have low S/N because of bad weather, we chose better S/N images to make combined images. Photometric calibration was performed using photometric standard stars observed on 2006 May 3 (Yagi et al. 2007). We corrected Galactic extinction using the extinction calculator provided on the NASA/IPAC Extragalactic Database (NED) Web site. The basic extinction data were obtained from Schlegel et al. (1998). We assumed the cosmological parameters (h0, Ωm, ΩΛ) = (0.73, 0.24, 0.72) and the distance modulus of the Coma Cluster to be 35.05 (Yagi et al. 2007). The linear scale at the Coma Cluster is 474 pc arcsec⁻¹ under this assumption.

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The lengths and distances given in the following sections are all projected. Since the inclination angles with respect to the sky plane of the features that we found are not known, we do not apply any projection correction. The magnitudes are expressed in the Vega system unless otherwise specified.

3. RESULTS

A false color image made with the B (blue), the Rc (green), and the Hα NB (red) images around an amorphous galaxy RB 199 (α = 12h58m43.1s, δ = +27°45′43″” (J2000.0)) is shown in Figure 1. The centering error of the three color images is less than 0.1 pixels, corresponding to 0.02″. The continuum light is not subtracted from the Hα NB image in Figure 1. Contour maps of the B image and the Rc image are shown in Figures 2 and 3. Figure 4 shows a gray-scale image of the pure Hα image. A remarkable complex of blue filaments and blobs and Hα-emitting clouds extends toward the south from RB 199 (Figs. 1–4). The overall morphology of the complex resembles a group of fireballs (large meteors) shooting from the galaxy toward the south (see Fig. 1). The complex is thus referred to as the “fireballs.”

Figure 5 is a B – Rc color map of RB 199 and the bright part of the fireballs. We describe the morphological and color characteristics of RB 199 and this strange newly observed feature in the following subsections.

3.1. RB 199

RB 199 is an E+A galaxy whose projected distance from the center of the Coma Cluster is about 18′, corresponding to 0.5 Mpc at the cluster (Poggianti et al. 2004). RB 199’s amorphous morphology is clearly seen in Figure 6. The stellar system of RB 199 is highly disturbed, indicating that this galaxy is a galaxy-galaxy merger remnant. A past merger event probably induced a starburst in the galaxy and now the star formation activity is in its decay phase, i.e., poststarburst phase. E+A characteristics of the spectrum of the galaxy (Poggianti et al. 2004) suggest that massive OB stars have already died, whereas A-type stars are still alive. The Hα absorption–dominant poststarburst region is distributed around the nucleus of RB 199, as shown in the pure Hα image (see Fig. 4).

The main structure of RB 199 can be divided into two parts: a central disturbed bright “ellipse” and a smooth “disk” extending west of the ellipse (Fig. 6). The position angles of the ellipse and the disk are 70° and −70°, respectively.

The B – R color of RB 199 within a 163″ aperture diameter is B – R = 0.99 (Poggianti et al. 2004). Our B – Rc color map (Fig. 5) reveals a complex inner structure of color distribution in the galaxy. The central ellipse is bluer than the disk. The central blue region in the central ellipse has a thick V-shaped structure and a B – Rc color of ≈0.8–0.9. The blue V-shaped structure is surrounded by slightly redder components whose B – Rc color and position angle are ≈1.0 and ≈70°, respectively. The disk has a B – Rc color of ≈1.2. Color distribution of the disk is smooth and no clear color gradient appears.

These characteristics suggest that a past merger concentrated the gas and stars of the progenitor galaxies into the bottom of the gravitational potential of the system and induced a starburst. Some of the newly formed stars from the merging process might have mixed with the preexisting disk stars and formed the disk of RB 199.

### Table 1: Observation Log

| Filter | PSF Size (arcsec) | S_Blim* | Date (UT) | Exposure (s) |
|--------|-------------------|---------|-----------|-------------|
| B ...... | 1.06              | 28.8    | 2006 Apr 28 | 5 × 450     |
|         |                  |         | 2006 May 3  | 3 × 450     |
|         |                  |         | 2007 May 13 | 5 × 600     |
| Rc ...... | 0.81              | 28.0    | 2006 Apr 28 | 11 × 300    |
|         |                  |         | 2007 May 14 | 5 × 360     |
|         |                  |         | 2007 May 15 | 1 × 300     |
| NB ...... | 0.82              | 27.8    | 2006 Apr 28 | 5 × 1800    |
|         |                  |         | 2007 May 15 | 8 × 1800    |

* S_Blim represent 1σ fluctuation of a circular aperture of 2″ diameter. The Rc and NB are calibrated by short exposures taken on 2006 May 3, but the mosaic image does not include them.

The lengths and distances given in the following sections are all projected. Since the inclination angles with respect to the sky plane of the features that we found are not known, we do not apply any projection correction. The magnitudes are expressed in the Vega system unless otherwise specified.
3.2. The Fireballs
3.2.1. Morphology

The most striking feature around RB 199 is a complex of strange faint blue knots and filaments and Hα-emitting ionized gas clouds extending toward the south from the galaxy (the fireballs: Figs. 1–4). The whole structure of the fireballs is schematically drawn in Figure 7. We labeled several characteristic features in the fireballs, such as bright knots, remarkable filaments, and extended faint clouds, as “knot 1,” “filament 1,” “cloud 1,” and so forth (Fig. 7). The enlarged false-color images of knots 1–5 are shown in Figure 8.

The bright knots are located at the end of the bright blue filaments; for example, knot 1 is located at the southern end of filament 1. Strong Hα emission appears at the south sides of the bright knots. Figures 8 and 9 clearly show this configuration. The intensity peaks of the Hα emission are slightly displaced to the south of the B-band intensity peaks of the bright knots (see Figs. 8 and 9).

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Fig. 1.—False color (B band: blue; Rc band: green; Hα NB: red) image of area around RB 199. North is right and east is up. RB 199 is located at the right side of the image.

Fig. 2.—B contour map around RB 199. The orientation is the same as in Fig. 1. To improve the signal-to-noise ratio of the faint features, the original images were smoothed by 4 × 4 pixels running mean to produce the contour maps here and in Fig. 3. The lowest contour level of this image is 28.5 (AB)mag arcsec−2 and the contour interval is 1 mag. G1–G5 are galaxies near RB 199. The object lying to the east of the galaxy G4 is a foreground star.
The blue filaments (filaments 1–5) consist of several filaments with narrow, long, straight, or slightly curved shapes, and lengths of \( \sim 10 \text{–} 30 \text{ kpc} \). The roots of the filaments appear to be connected to the central ellipse of RB 199 (Fig. 1; see also Fig. 7). The most prominent filament is filament 1. It extends linearly toward knot 1, which is the brightest knot in the blue filaments, and connects to filament 2 at the west side of knot 1. Filament 3 contains two straight parallel filaments extending outward from the central ellipse. Filament 4 ends at knots 3 and 4. Knot 4 is bright in \( \text{H} \alpha \) emission and is smoothly connected to the most remarkable \( \text{H} \alpha \) feature, \( \text{H} \alpha \) filament 1. \( \text{H} \alpha \) filament 1 has a linear, slightly wiggled morphology with a length of \( \approx 15 \text{ kpc} \) and a width of \( \approx 2 \text{ kpc} \).

The bright knots are spatially resolved. Their sizes, measured at \( B \)-band surface brightness of 28 mag arcsec\(^{-2} \), are \( \sim 1 \text{–} 2 \text{ kpc} \) (Table 2). To estimate the half-light radii (the effective radii, \( r_e \)) of the knots, we fitted Gaussian profiles blurred by the point-spread function (PSF) to the light profiles of the knots. Then we derived \( r_e \) using the relation \( r_e \approx 1.18 \sigma \). The \( r_e \) of the knots are \( \approx 200 \text{–} 300 \text{ pc} \). Although the light distributions of the knots are unlikely to exhibit Gaussian profiles, the light profiles of the knots, in particular knots 1, 2, and 5, are well represented with Gaussians. Thus, the \( r_e \) are good approximations of the knot sizes.

About 50 kpc from RB 199 (Fig. 1) is a faint, diffuse filament. This filament, filament 5, is slightly displaced to the east from the line connecting filaments 3, 4, and \( \text{H} \alpha \) filament 1 (see also Fig. 7).
Filament 5 is marginally detected in $R_C$ band, indicating that it is very blue. In addition, at the east and west of an elliptical galaxy G5 (located about 80 kpc from RB 199) are faint, diffuse Hα clouds (Fig. 1). They are very faint, but are marginally seen in the pure Hα image (Fig. 4). They are also observed as faint red diffuse clouds in Fig. 1.

3.2.2. Optical Photometry

The results of the photometry of the fireballs are summarized in Table 2. The bright continuum knots have absolute magnitudes of $M_R \sim -12$ and $M_B \sim -12$ to $-13$. The typical $r_e$ is $\approx 200-300$ pc (see § 3.2.1). These values are similar to those of faint dwarf ellipticals in the Virgo Cluster (e.g., Ichikawa et al. 1986) or the faint ends of local dwarf galaxies (Belokurov et al. 2007). Assuming a mass to luminosity ratio $M/L_{R} = 1$ for these knots, their masses are $\sim 10^6-10^7 M_{\odot}$. The mean color of the blue filaments are $B - R_C \approx 0.5$, corresponding to early F stars in the main sequence. The Hα luminosities of the bright knots are on the order of $10^{38}$ erg s$^{-1}$. We did not apply flux correction of possible contamination of [N ii] $\lambda 6548/6583$ emission for the Hα photometry. Thus, the Hα fluxes and luminosities in Table 2 are upper limits, possibly decreased by a few tens percent due to [N ii] contamination. This uncertainty, however, does not affect the following discussion. Assuming that all the Hα emission comes from star-forming regions, and using the $L_{H\alpha}$ to star formation rate (SFR) conversion relationship by Kennicutt (1998) we found that the corresponding SFRs of the knots are on the order of $10^{-3} M_{\odot}$ yr$^{-1}$ (Table 2). The internal reddening correction was not applied in this calculation. The SFRs are thus lower limits of the true SFRs.

The fireballs are much bluer than any region of RB 199 (Fig. 5). This suggests that the stellar population or the dust contents of the fireballs is different from those of the galaxy disk. Figure 10 shows the color distribution in the fireballs. The filaments clearly grow bluer with distance from the nucleus of RB 199. This means either that the stellar population becomes younger farther out from the galaxy, or that the filaments become dustier at shorter distances.

3.2.3. Ultraviolet Data

To investigate star formation activity in the fireballs, we downloaded UV images around RB 199 from the Web site of the second data release of the Galaxy Evolution Explorer (GALEX) Nearby Galaxy Survey8 (Martin et al. 2005). The FUV (1344–1786 Å) and NUV (1771–2831 Å) contour maps are superposed on the gray-scale $B$-band image in Figures 11 and 12.

Note that most of the bright knots in the fireballs are bright in both the FUV and NUV bands. Knots 1–5 are clearly visible both in the FUV and NUV images. In contrast, knot 6 can be seen only in the FUV image. Filaments 1 and 3 are also visible in the NUV image. In addition, very faint features are marginally detected in both FUV and NUV images at the position of filament 5 (Figs. 11 and 12).

The UV magnitudes listed on the GALEX Web site and the FUV $- B$ and NUV $- B$ colors in the AB system for the bright knots are summarized in Table 3. All the bright knots are detected in the FUV band. Although knot 5 is visible in the NUV image (Fig. 12), the NUV magnitude is not listed on the Web site. We thus measured the NUV magnitude of knot 5 directly from the NUV image, calibrating using the magnitude of knot 1. We also obtained the NUV magnitudes of filaments 1 and 3 in the NUV image (Table 3). Knot 6 was not detected in the NUV image.

Knot 1 and 2 have FUV magnitudes of $\approx 21.5$ and the FUV $-\text{NUV}$ colors of these knots are almost flat. Knots 3 and 4 are about 1 mag fainter than knots 1 and 2 in the NUV, and slightly redder. Knot 5 and 6 are almost 2 mag fainter than knots 1 and 2 in the FUV band. Using the conversion formula from FUV and NUV magnitudes to SFR by Iglesias-Paramo et al. (2006) we

8 See http://galex.stsci.edu/GR2/.
Fig. 6.— $B$-band image of RB 199 (contour map overlaid on the gray-scale image). The lowest contour level and the contour interval are 26.5 (AB)mag arcsec$^{-2}$ and 0.5 mag, respectively.

Fig. 7.— Schematic view of the fireballs of RB 199. [See the electronic edition of the Journal for a color version of this figure.]
derived the SFRs of knots 1–3 as \(\approx(2–5) \times 10^{-3} \, M_\odot \, \text{yr}^{-1}\) from the FUV magnitudes and \(\approx(6–10) \times 10^{-3} \, M_\odot \, \text{yr}^{-1}\) from the NUV magnitudes. These values are somewhat larger than, but still consistent with, the SFRs derived from H\(\alpha\) luminosities (see Table 2).

Note that the FUV \(-\, B\) colors of the bright knots are all very blue, \(-0.5\) to \(-0.9\), indicating that active star formation occurs in the knots. These blue colors and the strong H\(\alpha\) emission seen at the southern sides of the bright knots strongly support the argument that the knots are current star-forming sites. Comparison of the optical-UV colors of the fireballs with color evolution models of star-forming galaxies is made in the next section.

### 3.2.4. Comparison of the Colors with Star Formation Models

To estimate the age of the filaments, we compared their colors with model calculations of color evolution of star-forming stellar systems using PEGASE version 2 (Fioc & Rocca-Volmerange...
We assumed that the initial mass function (IMF) follows the Salpeter IMF from 0.1 to 120 $\solarmass$ for star formation (CS model), and exponentially decaying star formation calculations. We derived color evolutions for four cases: constant model with an age of several times $10^8$ yr to 1 Gyr. Figure 13 also shows that the colors of the blue filaments close to the galaxy trends are shown as arrows at the bottom right corners of both panels of Figure 13. We derived the extinction trends using the reddening curve of star-forming galaxies proposed by Calzetti et al. (2000). The extinction trends almost follow the model loci along the age sequence. If dust extinction is present in the knots, their predicted ages are much younger; in other words, the ages estimated with Figure 13 are the maximum values for the knots. We thus conclude that the average maximum age of the bright knots is several times $10^8$ yr, and the maximum ages of the blue filaments that are located closer than the knots to the galaxy are around 1 Gyr.

Although we have no UV data for the other filaments of the fireballs, we roughly estimate their ages using optical $B - R_C$ color only. Using the E300 model, the ages of $\sim 700$ Myr, $\sim 1.2$ Gyr, and $\sim 500$ Myr are estimated for filament 2, filament 4, and H$\alpha$ filament 1, respectively, in the case of no dust extinction. The most distant blue filament, filament 5, is very blue, and its age is estimated to be much younger than 500 Myr. In conclusion, the maximum age of the filaments within 20 kpc from the galaxy is $\sim 1$ Gyr, that of the knots at 20–40 kpc from the galaxy is $\sim 500–1000$ Myr, and that of the farthest filaments is $\leq 500$ Myr.

This age trend indicates that the stellar components of the fireballs would be formed after the stripping event. In other words, the gas stripped by some mechanism from the disk of RB 199 travels in the intergalactic space, forming stars and leaving the formed stars along its trajectory. This hypothesis is supported by the spatial distribution of the H$\alpha$ emission and the bright knots. The bright H$\alpha$ clouds are located at the southern edges of the bright knots and almost no H$\alpha$ emission is observed in the blue filaments. This indicates that active star formation is now ongoing at the far end of the blue filaments. The hypothesis may also be supported by the fact that the ages of the filaments and knots are roughly consistent with the travel time from the galaxy to the edge of the fireballs ($\sim 60–80$ kpc), assuming that the outflow velocity of the stripped material is on the order of $10^2$ km s$^{-1}$. Although the velocities of the filaments and the knots are not known, outflow velocities of an order of $10^2$ km s$^{-1}$ were observed in similar stripping phenomena (e.g., Yoshida et al. 2004; Cortese et al. 2006; Yagi et al. 2007).

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**TABLE 2**

| ID          | Distance$^a$ | Size$^b$ | $m_B$  | $m_B$ | $B - R_C$ | $M_\text{L}^b$ | $L_{\text{H} \alpha}^d$ | SFR$^e$ |
|-------------|--------------|----------|--------|--------|-----------|-----------------|---------------------|--------|
| Knot 1      | 23           | 2.6 x 0.9| 22.52 + 0.03 | 22.04 + 0.03 | 0.47 + 0.04 | 8.8             | 34                   | 27     |
| Knot 2      | 24           | 1.8 x 1.0| 22.18 + 0.02 | 21.53 + 0.02 | 0.65 + 0.03 | 14              | 59                   | 47     |
| Knot 3      | 32           | 1.9 x 0.6| 23.19 + 0.03 | 22.68 + 0.03 | 0.51 + 0.04 | 4.8             | 9.9                  | 7.8    |
| Knot 4      | 34           | 0.7 x 0.7| 25.13 + 0.12 | 24.88 + 0.13 | 0.25 + 0.18 | 0.76            | 2.1                  | 1.7    |
| Knot 5      | 35           | 0.7 x 0.7| 24.06 + 0.04 | 23.66 + 0.04 | 0.40 + 0.06 | 2.3             | 30                   | 23     |
| Knot 6      | 28           | 0.6 x 1.6| 24.23 + 0.06 | 23.66 + 0.05 | 0.57 + 0.08 | 2.0             | 3.2                  | 2.5    |
| Filament 1  | 14           | 14       | 22.03 + 0.03 | 21.36 + 0.03 | 0.67 + 0.04 | 16              | ...                  | ...    |
| Filament 2  | 24           | 9        | 22.53 + 0.04 | 22.28 + 0.03 | 0.25 + 0.04 | 6.7             | 0.9                  | 0.7    |
| Filament 3  | 11           | 10       | 22.10 + 0.02 | 21.32 + 0.05 | 0.78 + 0.06 | 16              | ...                  | ...    |
| Filament 4  | 26           | 5        | 22.83 + 0.04 | 22.39 + 0.03 | 0.44 + 0.05 | 6.4             | 5.9                  | 4.7    |
| Filament 5  | 59           | 8        | 23.22 + 0.15 | 23.36 + 0.11 | 0.14 + 0.16 | 2.5             | 3.8                  | 3.0    |
| H$\alpha$ filament 1 | 44 | 14 | 25.39 + 0.48 | 25.39 + 0.32 | 0.00 + 0.48 | 0.68            | 28                   | 23     |
| H$\alpha$ filament 2 | 40 | 4 | 24.86 + 0.12 | 25.07 + 0.23 | -0.21 + 0.26 | 0.52            | 12                   | 9.2    |
| H$\alpha$ cloud 1 | 80 | ... | 26.04 + 0.25 | ...          | ...          | 0.62$^f$        | 9.0                  | 7.2    |
| H$\alpha$ cloud 2 | 79 | ... | 26.29 + 0.62 | ...          | ...          | 0.50$^f$        | 11                   | 8.6    |
| Total       | 83$^g$       |          | 19.87    | 19.33   | 0.54      | 110             | 225                 | 179    |

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$^a$ Distance from the nucleus of RB 199 in units of kpc.

$^b$ Sizes of the knots, filaments, and cloud in units of kpc. The sizes are measured at the $B$-band surface brightness of 28 mag arcsec$^{-2}$.

$^c$ Mass derived from $R_C$-band magnitude in units of $10^6$ $M_\odot$, assuming that $M/L_B = 1$.

$^d$ $H\alpha$ luminosity in unit of $10^{38}$ ergs s$^{-1}$. Contamination of [N$\text{ii}$] $\lambda\lambda 6548/6583$ emission and internal dust extinction is not corrected.

$^e$ Star formation rate calculated from $L_{H\alpha}$ in units of $10^{-4}$ $M_\odot$ yr$^{-1}$ assuming that all the $H\alpha$ emission is produced by star-formation activity.

$^f$ Derived from $B$-band magnitude assuming that $M/L_B = 1$.

$^g$ Distance between the edge of the H$\alpha$ cloud 1 and the nucleus of RB 199.

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![Figure 10](image.png)

**Fig. 10.** $B - R_C$ colors of the knots and filaments of the fireballs are shown with respect to the distance from the nucleus of RB 199. The horizontal error bars indicate the length of the features.
The color gradient in the blue filaments could also be interpreted as due to dust absorption. If this is the case, the above discussion of age gradient loses its meaning. However, the stellar population of the fireballs is certainly very young because dust absorption correction makes the true colors of the fireballs bluer than the observed ones (see Fig. 13), which strengthens the premise that the stars were formed very recently.

4. FORMATION MECHANISM OF THE FIREBALLS

The newly found strange feature, the “fireballs,” around RB 199 is extended in one direction from the galaxy as a group of narrow blue filaments and bright knots with which Hα/C11 and UV emission are associated. Here we discuss possible fireball formation mechanisms.

C07 found many small blobs extending to one side of galaxies near the cores of two z = 0.2 rich clusters in the course of a cluster survey with the Hubble Space Telescope Advanced Camera for Survey. Sun et al. (2007) also reported many star-forming blobs distributed around a very long X-ray/Hα tail of a galaxy in the nearby rich cluster Abell 3627. The blobs found by C07 are distributed in faint optical filaments (C07). They detected [O ii] emission around some of the blobs, which indicates that star formation is under way in and around the blobs. The morphology and colors of the blobs and the filaments found by C07 are very similar to the fireballs of RB 199. They argued that tidal stripping by interaction between deep cluster gravitational potential and/or ram pressure stripping by high-speed collision between the galaxies and the intracluster medium (ICM) are responsible for forming the strange blobs they found. Following C07, we examine the above two processes for validity as the formation mechanism of the fireballs.

4.1. Tidal Stripping

Tidal forces induced by galaxy-galaxy interaction disrupt the stellar disks and often throw stars far from the galaxies. Since RB 199 appears to be a merger, it is natural to interpret the fireballs as tidal tails formed by tidal force induced by the merging process.
The morphology of the fireballs is, however, very strange compared to other merger tidal tails such as NGC 4038/39 (Schweizer 1978), NGC 7252 (Hibbard & van Gorkom 1996), Arp 299 (Hibbard & Yun 1999), and IRAS 19254–7245 (Mirabel et al. 1991). In many cases, tidal tails of merging galaxies have long smooth morphologies extending in one or two directions from the merger main body (Hibbard & van Gorkom 1996). The disrupted, multiple filamentary, “splash”-like morphology of the fireballs of RB 199 is very rare and peculiar. Thus, from a morphological point of view, it is unlikely that a past merging event is responsible for forming the fireballs, although we cannot rule out some special situation or conditions during the merger that produced such peculiar tidal features.

Tidal forces induced by interactions between RB 199 and its nearby galaxies may strip the disk gas and stars of RB 199 and may form the fireballs. In fact, several galaxies appear in the vicinity of RB 199 (G1–G4 in Fig. 2). Among these galaxies, G1 has a radial velocity of 6665 km s$^{-1}$ (Colless & Dunn 1996), indicating that this galaxy is a Coma member. However, no tidal features—bridges, tails, ripples, and so on—appear around G1. Those features are also not found around G2–G4. Another candidate galaxy that can strip the disk gas of RB 199 is the galaxy about 80 kpc south of RB 199 (G5 in Fig. 2). This galaxy is located in the extension line of the fireballs, but the morphology of this galaxy exhibits no sign of strong tidal disturbances. To strip the outer disk of a galaxy through tidal forces in close encounters with other galaxies, without disturbing the perturbing galaxies, the perturbers must be more massive than the mass of the perturbed galaxy. All of the above mentioned galaxies are, however, much fainter than RB 199, meaning that these galaxies are less massive than RB 199. Furthermore, the colors of G2, G3, and G4 are significantly redder than the average color of Coma ellipticals, indicating that these are background galaxies. In fact, the photometric redshifts of these galaxies determined by the SDSS project are $\sim 0.3–0.4$. Therefore, it is not plausible that these galaxies significantly perturbed RB 199 in the past.

The deep gravitational potential of a rich cluster of galaxies exerts strong tidal forces on galaxies crossing its core region. When a galaxy crosses a cluster core region, if the radial acceleration by the cluster gravity exceeds the centrifugal acceleration of the crossing galaxy, the outer part of the galaxy is stripped by the tidal force of the cluster (C07). The radial acceleration $a_r$ by a cluster core whose mass within $r$ is $M_c$ is written as

$$a_r = G M_c \left( \frac{1}{r^2} - \frac{1}{(r + R)^2} \right),$$

(1)

TABLE 3

| ID         | $GALEX$ ID          | $GALEX$ FUV* (AB mag) | $GALEX$ NUV* (AB mag) | $FUV - B$ (AB mag) | $NUV - B$ (AB mag) |
|------------|---------------------|-----------------------|-----------------------|-------------------|-------------------|
| Knot 1     | J125841.9 + 274451  | 21.44 ± 0.16          | 21.46 ± 0.09          | $-0.94 \pm 0.16$  | $-0.92 \pm 0.10$  |
| Knot 2     | J125843.8 + 274450  | 21.51 ± 0.14          | 21.19 ± 0.08          | $-0.53 \pm 0.14$  | $-0.85 \pm 0.09$  |
| Knot 3 + 4 | J125842.9 + 274427  | 22.36 ± 0.30          | 21.76 ± 0.17          | $-0.69 \pm 0.30$  | $-1.29 \pm 0.21$  |
| Knot 5     | J125841.0 + 274429  | 23.12 ± 0.34          | 22.43 ± 0.33          | $-0.80 \pm 0.34$  | $-1.49 \pm 0.33$  |
| Knot 6     | J125843.4 + 274439  | 23.53 ± 0.45          | ...                   | $-0.56 \pm 0.46$  | ...               |
| Filament 1 | ...                 | 22.37 ± 0.41          | 21.84 ± 0.40          | 0.48 ± 0.41       | $-0.19 \pm 0.40$  |
| Filament 3 | ...                 | 22.48 ± 0.45          | 21.91 ± 0.43          | 0.52 ± 0.45       | $-0.19 \pm 0.43$  |

a Taken from the Web site of $GALEX$ data release 2 (DR2), except for the NUV and FUV magnitudes of filament 1 and filament 3, and the NUV magnitude of knot 5.

b Directly measured in the NUV image calibrated by the $GALEX$ DR2 NUV magnitude of knot 1.

FIG. 13.—Color-color diagram of $B - R_c$ vs. FUV $- B$ (left) and $B - R_c$ vs. NUV $- B$ (right) for the bright knots and the blue filaments of the fireballs. The filled squares represent the knot colors (knots 1–6; knot 6 was not detected in the NUV band, thus the data point is not shown in the right panel). The open squares represent the knot colors (knots 1–6; knot 6 was not detected in the NUV band, thus the data point is not shown in the right panel). The dot-dashed lines, the dashed lines, and the dotted lines are the predictions of exponential decaying star formation models with decay timescales of 100 Myr ($E_{100}$ model), 200 Myr ($E_{200}$ model), and 300 Myr ($E_{300}$ model), respectively. The arrows show the effect of internal dust extinction on the observed colors.
where $R$ is the radius of the crossing galaxy and $r$ is the distance between the galaxy and the cluster center. The centrifugal acceleration of the galaxy is written as

$$a_{\text{gal}} = G \frac{M_{\text{gal}}}{R^2},$$

where $M_{\text{gal}}$ is the mass of the galaxy. The projected distance from the center of the Coma Cluster and RB 199 is $\approx 0.5$ Mpc. The total (stars + gas + dark matter) mass of the Coma Cluster within the radius of 0.5 Mpc was estimated as $\approx 3 \times 10^{14} M_\odot$ (Lokas & Mamon 2003). The R-band luminosity of RB 199 is $1.4 \times 10^8 L_\odot$ (Mobasher et al. 2001). Thus, assuming $M/L_R \sim 2$–3, which is a typical value of disk $M/L$ ratios for nearby spiral galaxies (Forbes 1992; Palunas & Williams 2000; Yoshino & Ichikawa 2008), the mass of the disk of RB 199 is calculated as $(3$–$4) \times 10^9 M_\odot$. The roots of the blue filaments are all connected to the central ellipse of RB 199; thus, the effective radius of the disturbed region of the galaxy is that of the ellipse, i.e., $R \sim 5$ kpc. With these values, one can surmise that $a_{\text{gal}}$ is 1 order of magnitude larger than $a_r$. This means that the cluster potential can hardly strip the outer disk component of RB 199. Even if the $M/L_R$ of the galaxy is almost unity, $a_{\text{gal}}$ is still larger than $a_r$. Therefore, tidal stripping by cluster-galaxy interaction is not a possible candidate for a formation mechanism of the fireballs around RB 199.

4.2. Ram Pressure Stripping

When a gas-rich disk galaxy collides with the hot ICM at high speed ($v \sim 10^3$ km s$^{-1}$), ram pressure from the ICM strips massive amounts of gas from the galaxy. This process, ram pressure stripping, has been discussed in many studies as an efficient gas-removing mechanism for galaxies in clusters (Gunn & Gott 1972; Abadi et al. 1999; Fujita & Nagashima 1999; Vollmer et al. 2001; Schulz & Struck 2001; Bekki & Couch 2003; Roediger & Brüggen 2007). From an observational point of view, Cayatte et al. (1990, 1994) found that $H$ gas is significantly deficient for spiral galaxies in the core region of the Virgo Cluster. Bravo-Alfaro et al. (2000, 2001) found strong $H$ deficiency for bright spiral galaxies inside a radius of 0.6 Mpc from the center of the Coma Cluster. In addition, detailed case studies have been carried out for many objects through optical and radio observations (NGC 4388: Yoshida et al. 2002, 2004; Vollmer & Huchtmeier 2003; Oosterloo & van Gorkom 2005; NGC 4402: Crowl et al. 2005; NGC 4438: Chemin et al. 2005; NGC 4522: Kenney & Koopmann 1999; Vollmer et al. 2004).

The position and velocity of RB 199 suggest that the galaxy suffers strong ram pressure from the ICM through high-speed collision with it. RB 199 is located at the edge of the dense ICM associated with the main body of the Coma Cluster (Poggianti et al. 2004). In addition, the radial velocity of RB 199 ($v \approx 8700$ km s$^{-1}$; Mobasher et al. 2001) is quite large with respect to the mean radial velocity of the Coma Cluster ($v \approx 6500$ km s$^{-1}$). To determine whether the disk gas of RB 199 can be stripped, we try to estimate the ram pressure stripping radius $R_{\text{strip}}$ for the RB 199 case. When the distribution of stars and gas of the galaxy disk is a double exponential, $R_{\text{strip}}$ is estimated as

$$R_{\text{strip}} = 0.5 R_0 \ln \left[ \frac{GM_{\text{star}} M_{\text{gas}}}{v^2 \rho_{\text{ICM}} 2 \pi R_0^2} \right],$$

where $M_{\text{star}}$ and $M_{\text{gas}}$ are the mass of the stars and the gas in the galaxy disk, respectively, $v$ is the galaxy velocity relative to the ICM, $\rho_{\text{ICM}}$ is the density of the ICM, and $R_0$ is the radial scale length of the disk (Domainko et al. 2006). Substituting $4.2 \times 10^9 M_\odot, \sim 10^9 M_\odot$, $\sim 10^{-4}$ cm$^{-3}$, and $\sim 2000$ km s$^{-1}$ for $M_{\text{star}}, M_{\text{gas}}, \rho_{\text{ICM}}$, and $v$, respectively, we obtain

$$R_{\text{strip}} = 0.5 \left( \frac{R_0}{\text{kpc}} \right) \ln \left[ 25.4 \left( \frac{R_0}{\text{kpc}} \right)^{-4} \right].$$

We fitted an exponential disk function to the light profile of the central ellipse of RB 199 along P.A. = 70° and found that $R_0 \approx 1.5$ kpc. Note that RB 199 has an irregular shape and does not have a clear exponential disk. Hence, the $R_0$ we derived above is not a correct “effective radius.” This $R_0$ is, however, an indicator of the surface density distribution of the galaxy, and thus is useful for determining whether the disk gas of RB 199 can be stripped by the ram pressure of the ICM. With this value, we derived $R_{\text{strip}} \approx 1.2$ kpc. This means that almost all the gas in the disk of RB 199 would be stripped by the ram pressure of the ICM.

The morphology of the fireballs also supports the ram pressure stripping hypothesis. The fireballs extend from one side of RB 199, and many numerical simulations have predicted that ram pressure stripping forms a filamentary structure extending on one side from the colliding galaxy (Abadi et al. 1999; Quilis et al. 2000; Roediger & Hensler 2007; Kronberger et al. 2008). Observationally, a number of one-sided long tails of ionized gas which were plausibly formed by ram pressure stripping have been found in rich clusters of galaxies (e.g., Gavazzi et al. 2001; Sun et al. 2007; Yagi et al. 2007). In addition, the configuration in which the ionized gas is far more extended than the stars (the blue filaments and the bright knots) is naturally explained by ram pressure. The gas clouds undergo the ram pressure of the ICM and are accelerated by it continuously after the stripping, whereas the stars are not affected by the ram pressure and suffer the gravitational force of the galaxy. Hence, the gas clouds stretch far away from the galaxy while the stars remain relatively nearby. Therefore, we propose that ram pressure stripping is the primary formation mechanism of the fireballs.

A major argument against the ram pressure stripping hypothesis is the fact that the blue filaments and the bright knots of the fireballs consist mainly of stars. Ram pressure stripping can remove only gas from a galaxy and cannot greatly affect the stellar system of the galaxy. Stars are too massive, and their collisional cross sections are too small, to respond to drag force from the ram pressure of the ICM flow. However, note that the stellar population of the fireballs is very young and must largely have been formed after stripping from the host galaxy. In other words, only the gas in the disk was stripped in the initial phase, and the stars were then formed in the stripped gas.

Sun et al. (2007) also argued that the blue blobs they found may have been formed in the stripped gas by the ram pressure. Recently, Kronberger et al. (2008) performed numerical simulations focusing on star formation due to ram pressure stripping and found that strong star formation is triggered in the central region of their model galaxy as well as in the stripped gas filaments behind the galaxy. The star formation blobs, whose sizes and masses are of an order of 1 kpc and $10^7 M_\odot$, respectively, extended up to 100 kpc from the galaxy (Kronberger et al. 2008). In their simulations, the stripped gas filaments have narrow and slightly wiggled straight shapes, whereas the newly formed stars form somewhat diffuse wide filaments. Note that the mass and size of the blobs and the morphology of the complex of the blobs and the filaments derived in the simulations of Kronberger et al. (2008) strongly resemble those of the fireballs we found around RB 199. Accordingly, Kronberger et al.’s results strongly support the hypothesis that the fireballs are formed by ram pressure stripping.
In the case that ram pressure stripping is the primary fireball formation driver, the stripped neutral hydrogen (H\textsc{i}) gas would be observed around RB 199. Bravo-Alfaro et al. (2000, 2001) made deep H\textsc{i} observations of the Coma Cluster using the VLA. RB 199 and its surrounding area were within the observation areas of fields 7 and 10 in their study (Bravo-Alfaro et al. 2000). They observed no sign of H\textsc{i} gas around RB 199. The primary cause for this is that the recession velocity of RB 199 (∼8700 km s\(^{-1}\)) is far outside the frequency bands (6.25 MHz) of their observations, which were centered at radial velocities of 5500 km s\(^{-1}\) (field 7) and 7300 km s\(^{-1}\) (field 10) (Bravo-Alfaro et al. 2000).

4.3. Ram Pressure Stripping with Galaxy-Galaxy Merger

The morphology of RB 199 indicates that this galaxy is a merger remnant. We are thus led to the idea that a galaxy-galaxy merger in addition to ram pressure of the ICM may have played an important role in efficiently stripping the gas from RB 199. A galaxy-galaxy merger perturbs the interstellar gas in the galaxy disk significantly, and some portion of the gas would flare up above the disk. A combination of this effect and the ram pressure may make gas stripping from the galaxy very efficient. Struck & Brown (2004) performed numerical simulations of ram pressure stripping for merging galaxies infalling to a cluster. Their results support that the above simple picture is correct in principle. They found that strongly interacting galaxy pairs tend to be stripped of much more gas than isolated galaxies by the ram pressure of the ICM (Struck & Brown 2004). This process may be very efficient in stripping the interstellar medium from a galaxy disk, and may strip heavy elements other than H\textsc{i} gas, such as metals, molecules, or dust that make star formation in the stripped gas possible.

One of the most striking features formed by a combination of galaxy-galaxy interaction and ram pressure stripping ever found is the blue infalling group (BIG) in Abell 1367 (Sakai et al. 2002; Gavazzi et al. 2003; Cortese et al. 2006). Very extended ionized gas filaments and blue tails are observed in the BIG (Cortese et al. 2006). In addition, many star-forming dwarf galaxies are distributed in the BIG (Sakai et al. 2002). Cortese et al. (2006) concluded that the combined action of tidal forces among the galaxies and ram pressure by the ICM produced that peculiar structure. Although the BIG is much larger and more luminous than the fireballs around RB 199, the phenomena appear similar. In addition, the host galaxies of the blobs of C07 and Sun et al. (2007) have disturbed morphologies, suggesting a past merger. These observational results support the idea that a galaxy-galaxy interaction/merger in addition to ram pressure stripping may make a significant contribution to the formation of fireballs and similar objects.

In conclusion, ram pressure stripping is the key driver in fireball formation. A galaxy-galaxy merger in addition to the ram pressure may make a considerable contribution to their formation. Tidal interactions between RB 199 and the gravitational potential of the Coma Cluster would not be strong enough to play a major role in formation of the fireballs.

5. SUMMARY

We found a strange complex (the “fireballs”) of blue filaments and H\textalpha\ clouds that extends up to 80 kpc toward the south from the merging galaxy RB 199 in the Coma Cluster. The narrow blue filaments are extended in straight shapes and several bright blue knots are located at the south end of the blue filaments. Strong H\textalpha\ emission is associated with the knots. In addition, faint, narrow H\textalpha\-emitting filaments extend farther from the southern edge of the knots.

The total \(B\) and \(R_C\) magnitudes of the fireballs are 19.87 and 19.33, respectively. The luminosities of the H\textalpha\ emission associated with the bright knots are \((1−6) \times 10^{38} \text{ erg s}^{-1}\), which correspond to a star formation rate of \(\sim 10^{-3} \text{ M}_\odot \text{ yr}^{-1}\), assuming all the H\textalpha\ comes from star-forming activity. The average color of the fireballs is \(B−R_C \approx 0.5\), which is bluer than RB 199 (\(B−R_C = 0.99\)), and the blue filaments and the bright knots grow bluer with distance from the nucleus of the galaxy. These observational facts suggest that the stars of which the fireballs are composed were formed within several times 10\(^8\) yr and that the stellar population grows younger farther from the galaxy.

Most no H\textalpha\ emission is observed in the blue filaments but strong H\textalpha\ and UV emissions are associated with the bright knots. These characteristics indicate that star formation has already ceased in the blue filaments and is now in progress in the bright knots. The gas stripped by some mechanism from the disk of RB 199 may be traveling in the intergalactic space, forming stars and leaving the formed stars along its trajectories. The \(R_C\)-band absolute magnitudes, the half-light radii, and the estimated masses of bright knots in the fireballs are \(\sim −12\) to \(−13\) mag, \(\sim 200−300\) pc, and \(\sim 10^6−10^7\) \(M_\odot\), respectively. These values are similar to those of faint dwarf spheroidals in the Virgo Cluster or the faint end of local dwarf galaxies. This suggests that the bright knots are gravitationally self-bound systems.

The most plausible formation mechanism of the fireballs is ram pressure stripping by the hot ICM. Tidal stripping by galaxy-galaxy interaction or galaxy-cluster interaction would not be a primary mechanism for the formation of the fireballs. A galaxy-galaxy merger, however, is probably important to make subsequent ram pressure stripping of the ICM more effective in forming this strange structure.

Although whether the stars in the fireballs are all gravitationally bound to RB 199 is not known, some structures close to the galaxy may fall back to the galaxy in the future, oscillating between the two sides of the galaxy disk and eventually forming the halo star population of RB 199.

Some part of the fireballs may be stripped from RB 199 in the future by tidal interaction with nearby galaxies or the cluster gravitational potential, even if they are currently bound to the galaxy. If this is the case, the stripped stars may form a diffuse intracluster population ( Gregg & West 1998; Okamura et al. 2002; Murante et al. 2004; Krück et al. 2006; Gerhard et al. 2007).

The fireballs we found in the Coma Cluster resemble the compact young blobs found by C07 and Sun et al. (2007) around some cluster galaxies. C07 argued that formation of these compact blobs is rather rare in clusters at \(z \approx 0.2\). They found only two examples out of 130 cluster spiral galaxies at \(z \approx 0.2\). They also predicted that these features would be more remarkable at \(z \geq 0.2\) because the galaxy infalling rate and the gas content of each galaxy are higher in high-\(z\) clusters than in local clusters. However, our findings show that formation of compact stellar systems like C07’s blobs around cluster galaxies is still ongoing in the local universe. The Coma Cluster has a large substructure of the ICM and a group of galaxies associated with this substructure, indicating that this cluster itself is a merging system (Colless & Dunn 1996). RB 199 is located near the border between the main body and the substructure of the ICM (Poggianti et al. 2004). The special conditions of the Coma Cluster and RB 199 may produce a special environment around RB 199 namely, high-density ambient gas, high-speed infall, and/or frequent galaxy-galaxy interactions.

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