STAR FORMATION, RADIO SOURCES, COOLING X-RAY GAS, AND GALAXY INTERACTIONS IN THE BRIGHTEST CLUSTER GALAXY IN 2A0335+096

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ABSTRACT

We present deep emission-line imaging taken with the new SOAR Optical Imager of the brightest cluster galaxy (BCG) in the nearby (z = 0.035) X-ray cluster of galaxies 2A0335+096. We also present our analysis of additional, multiwavelength observations for the BCG, including long-slit optical spectroscopy, archival VLA radio data, Chandra X-ray imaging, and XMM-Newton UV imaging. Cluster 2A0335+096 is a bright, cool-core X-ray cluster, once known as a cooling flow. Within the highly disturbed core revealed by Chandra X-ray observations, 2A0335+096 hosts a luminous and highly structured optical emission-line system, spanning the BCG and its companion. We confirm that the redshift of the companion is within 100 km s^{-1} of the BCG, has certainly interacted with it, and is likely bound to it. The comparison of optical and radio images shows curved filaments in H\alpha emission surrounding the newly resolved radio source. The velocity structure of the emission-line bar between the BCG nucleus and the companion galaxy provides strong evidence for an interaction between the BCG and its northeast companion in the last \sim50 million years. The age of the radio source is similar to the interaction time, so this interaction may have provoked an episode of radio activity. We estimate a star formation rate of \geq7M_{\odot} yr^{-1} from the H\alpha and archival UV data. This rate is similar to, but somewhat lower than, the revised X-ray cooling rate of 10–30 M_{\odot} yr^{-1} in the vicinity of the BCG, estimated from XMM-Newton spectra by Peterson and coworkers. The H\alpha nebula is limited to a region of high X-ray surface brightness and cool X-ray temperatures. However, the detailed structures of H\alpha and X-ray gas differ. The peak of the X-ray surface brightness is not the peak of H\alpha emission, nor does it lie in the BCG. The estimated age of the radio lobes and their interaction with the optical emission-line gas, the estimated timescale for depletion and accumulation of cold gas, and the dynamical time in the system are all similar, suggesting a common trigger mechanism.

Key words: cooling flows — galaxies: clusters: general — galaxies: clusters: individual (2A0335+096)

1. INTRODUCTION

In the last few years, remarkable progress in our understanding of the properties of hot gas in the centers of clusters of galaxies has been made possible by the Chandra X-ray and XMM-Newton (X-Ray Multi-Mirror Mission) observatories. Stringent constraints on emission lines from the appropriate ionization species of iron and oxygen in high-resolution X-ray spectra from XMM-Newton show little evidence for simple, high-M cooling flows (Peterson et al. 2003), but they indicate the presence of gas ranging over a factor of 2 in X-ray temperature. High-resolution imaging (to \sim1") by Chandra has revealed cavities in the intracluster medium (ICM), inflated by radio plasma (McNamara et al. 2000, 2001; Birzan et al. 2004). The lack of hot rims around the bubbles suggests that the inflation has been gentle. Chandra spectroscopic imaging has also revealed X-ray fronts, which are likely to be the manifestation of cooler X-ray blobs passing through hotter gas (e.g., Markovitch et al. 2000). Very deep Chandra observations have also revealed shocks emanating from the center of at least two clusters (McNamara et al. 2005; Nulsen et al. 2005). Within 10 kpc of the core, structures in the hot X-ray-emitting plasma often trace structures seen in optical emission-line images (e.g., Fabian et al. 2001; McNamara et al. 2001; Sparks et al. 2004).

AGN feedback may be the key to stabilizing cool cores in X-ray clusters. Such explanations have become increasingly popular to account for the high frequency of clusters that have a large amount of gas with a short radiative cooling time, multitemperature gas, and nonradial spatial structures in the cluster core. The earliest hydrodynamic feedback models were produced to explain the heating and cooling of X-ray gas in elliptical galaxies (Binney & Tabor 1995; Tabor & Binney 1993). With the Chandra discoveries of bubbles in many nearby clusters, these models for elliptical galaxies evolved into feedback models for the ICM (e.g., Churazov et al. 2002; Brüggen et al. 2002; Ruzkowski & Begelman 2002; Brüggen & Kaiser 2002; Alexander 2002; Omma et al. 2004; McCarthy et al. 2004; Roychowdhury et al. 2004; Hoefl & Brüggen 2004; Dalla Vecchia et al. 2004; Soker & Pizzolato 2005; Voit & Donahue 2005). The most massive black holes in the universe, at the centers of clusters (Lauer et al. 2007), may produce winds, jets, and explosions that alter the ICM entropy and prevent catastrophic cooling from occurring in clusters.

AGN feedback also appears to be an increasingly popular and important ingredient in galaxy formation scenarios. Mergers may couple the growth of galaxies and their central black holes, thus providing a natural explanation for the unexpectedly tight
relationship, discovered by Gebhardt et al. (2000) and Ferrarese & Merritt (2000), between the masses of those black holes and their hosts' bulge luminosity and velocity dispersion (e.g., Haehnelt & Kauffmann 2000). Mergers alone cannot reproduce the exponential cutoff of the galaxy luminosity function, but mergers with AGN feedback might shut off star formation in very large galaxies (e.g., Best et al. 2006; Croton et al. 2006). The AGN heating we now observe in low-redshift systems may therefore give us insight into how AGN heating (and feedback) might have worked in the distant past. Semianalytical studies currently make general assumptions about the efficiency of AGN feedback, tuned to reproduce the exponential cutoff of the galaxy luminosity function at the high end (e.g., Croton et al. 2006; Best et al. 2006). But these studies, because of the need for computational efficiency, must omit the details of how the feedback works. State-of-the-art hydrodynamic models of individual radio sources generally neglect the complexity of the ambient ICM (e.g., Reynolds et al. 2005; De Young & Jones 2006). It is necessary, therefore, to test the assumptions going into these important models with detailed observations of individual systems, in order to further the goal of making more detailed models of such systems, including triggering and termination of AGN heating.

We describe here multiwavelength observations of the X-ray cluster 2A0335+096 that illustrate how complex these interactions can be. We obtained early science observations from a new 4 m class telescope (the Southern Observatory for Astrophysical Research [SOAR]) and its imager (the SOAR Optical Imager [SOI]). We have combined these observations with archival observations of the central galaxy in order to compare the spatial relationship of the X-ray gas, radio plasma, emission-line gas, and central galaxy and to estimate the star formation rate (SFR) from emission-line and UV indicators. We present the details of the observations, data reduction, and results in § 3, including optical imaging from SOAR and the Hubble Space Telescope (HST; § 3.1), optical long-slit spectra from the Double Spectrograph on the Palomar telescope (§ 3.2), radio images from the Very Large Array (VLA; § 3.3), X-ray archival data from Chandra (§ 3.4), and UV archival data from the XMM-Newton telescope (§ 3.5). In § 4 we discuss the implications of these multiwavelength observations, beginning with the relationship of the brightest cluster galaxy (BCG) and its companion in § 4.1. We interpret the morphology of the Hα filaments, partial rings that appear to encircle the resolved radio structures, in § 4.2. We discuss further multiwavelength identifications, including the correspondence between the X-ray, optical, and radio, in § 4.3; the dynamics of the bar and the companion in § 4.4; and the star formation and cooling rates, including UV measurements from the XMM-Newton Optical Monitor (OM) camera, in § 4.5. We present a summary of our results in § 5.

We assume a Hubble constant of 70 km s$^{-1}$ Mpc$^{-1}$. At the redshift of 2A0335+096, the corresponding angular size is 0.7 kpc arcsec$^{-1}$, and the luminosity distance is 154 Mpc.

2. THE X-RAY CLUSTER 2A0335+096

The X-ray cluster 2A0335+096 ($z = 0.035$) is a nearby X-ray-luminous cluster with a cool core and a central radiative cooling time shorter than a Hubble time. The cluster was first identified optically (Zwicky et al. 1965). Schwartz et al. (1980) confirmed its positional coincidence with an Ariel 5 X-ray source (Cooke et al. 1978) and noted the short central cooling time of the X-ray plasma. Its central galaxy hosts a spectacular filamentary emission-line nebula (Romanishin & Hintzen 1988; hereafter RH88). These optical filaments extend from a bar-shaped feature in the center of the BCG. The BCG appears to have a companion galaxy projected about 4 kpc to the northwest. Using the ROSAT High Resolution Imager detectors, Sarazin et al. (1992) revealed a similar bar in the X-ray and a larger scale X-ray elongation of the cluster emission in the same general direction. The BCG is a radio galaxy of ~33.5 mJy at 1.5 GHz diffused over a region of 29″ × 19″ (Sarazin et al. 1995). The BCG nucleus and its companion each have a radio point source (Sarazin et al. 1995).

Cluster 2A0335+096 was observed with the Chandra X-Ray Observatory (Kawano et al. 2003; Mazzotta et al. 2003, hereafter MEM03). We discuss these Chandra data further in § 3.4. The Chandra image shows a bar feature, with X-ray deficits to the northeast and southwest, identified as possible bubbles (MEM03). But the details of the X-ray structures and the Hα filaments do not coincide, except for the bar around the nucleus and the extension between the BCG and the companion. MEM03 identified a discontinuity or front feature in the X-ray gas to the south of the BCG, confirmed as a cold front by Werner et al. (2006). MEM03 estimated a pressure jump across the feature and derived a subsonic Mach number (0.75 ± 0.2), or a propagation speed of about 400 (T/2 keV) km s$^{-1}$. The two peaks in the X-ray surface brightness map lie roughly along a line defined by the centers of the BCG and its companion. MEM03 discussed possible processes explaining the optical filaments in the context of their X-ray observations, ruling out Rayleigh–Taylor instabilities but leaving open the possibility that the instabilities result from a Kelvin-Helmholtz instability. Such instabilities could cause the Hα filaments in a turbulent process.

Turbulence would result in broadened line profiles and, to some extent, the lack of systematic velocity structures across the system. Since the radial velocities of the companion and filaments were unknown to MEM03, they could not discuss the dynamics of the interaction. We present in § 3.2 previously unpublished velocity information along the axis of the interaction, redshifts, and line broadening.

3. OBSERVATIONS AND DATA ANALYSIS

3.1. Narrowband Hα+[N ii] and Broadband Imaging

We obtained broad $b$-band and narrowband images ($Δλ ≈ 75 Å$, NOAO filter ID 6781-78) centered near the redshifted Hα line on 2005 December 8 (UT) with the SOI, mounted on the SOAR telescope on Cerro Pachon in Chile. We supplemented these data with an R-band (filter F606W) HST WFPC2 image. We used the WFC2 association$^1$ ID u5a40701b, which is a basic co-addition of two 300 s snapshots (proposal ID 8301, PI: A. Edge).

The SOAR data were obtained as part of an early science run for the SOI. The pixels were binned 2 × 2, for a pixel scale of 0.154″ pixel$^{-1}$. The sky quality was excellent, with seeing below 1″ and good transparency. The telescope focus needed to be optimized on a regular basis (once every 2 hr) as the object transited. We collected nine 20 minute exposures for a total exposure time of 3 hr through the narrowband filter. Each exposure was dithered slightly. The narrowband filter is only 2 × 2 inches (5 × 5 cm), so the usable field of view is somewhat smaller than the full 5″ × 5″ field of view of the SOI. After the dithering, our useful field of view resulted in an image of 1561 × 1395 image pixels, or 4″ × 3.6″.$^1$

$^1$ This association was created with the facilities of the Canadian Astronomy Data Centre, operated by the National Research Council of Canada with the support of the Canadian Space Agency.
A single 10 minute $I$-band exposure was obtained for the purpose of estimating the stellar continuum contribution to the narrowband observation. All exposures were bias-subtracted and flat-fielded with normalized, median-filtered twilight flats taken through the appropriate filters. The $I$-band image exhibited fringing after flat-fielding. We removed the fringing signal by subtracting a scaled fringe frame constructed from dark $I$-band sky observations by SOAR observatory personnel.

We used the IRAF task `imalign` to shift, and trim the images to a common image coordinate system using five to six stars in the field as reference points. The shift uncertainties were 0.04 pixels. We then combined the narrowband images by obtaining the average in each shifted pixel after a 3 $\sigma$ clipping filter was applied. This routine removed some cosmic-ray features, but we were able to clean single-pixel cosmic-ray events using the IRAF task `cosmicrays`. The pixel scale of the SOI is significantly smaller than the stellar point-spread function, so this process was reasonably successful.

The world coordinate system (WCS) telemetry from the telescope was not fully implemented at the time of these observations, so we applied an ex post facto astrometric WCS solution to the header of the combined narrowband image using tools available in WCSTools (ver. 3.6.3, available from the Smithsonian Astrophysical Observatory). We matched the positions of 13 objects in the field to a catalog of USNO-A2 stars and galaxies. These measurements provided the central astrometric location of the image (J2000.0), the angular scale of 0.154" ($\pm$0.004") and a very small angular offset of the field from true north. The confidence of the absolute pointing is better than 1", limited by the sparse number of actual stars in our small field. Comparisons of features in the archival F606W $HST$ WFPC2 image confirmed the astrometry in the center of the field to better than 0.5".

Finally, we subtracted a coadded, fringe-corrected, scaled (by a factor of 28.57) $I$-band image from the narrowband image. The scale factor was chosen to subtract the nearby cluster galaxies from the narrowband image (Fig. 1). This figure includes indicators for the filament structures used to visually define the circles suggested by us in Figure 2, discussed further in § 3.3. Since both $[\text{N} \, \text{ii}]$ and $H\alpha$ emission features are included in the bandpass of the NOAO filter, we use the long-slit spectroscopy described in § 3.2 to apply an approximate ($\sim$15% accuracy) flux calibration to the final net emission-line image of 1 ADU s$^{-1}$ per $1.26 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ of pure $H\alpha$. This ratio assumes that the mean $H\alpha$ contribution to the total $H\alpha+[\text{N} \, \text{ii}]$ emission-line flux is 38% throughout the nebula, based on the long-slit spectra.

The emission-line structures are clearly visible in both the full and the continuum-subtracted emission-line images. No filaments or similar structures are visible in the $I$-band image, which is dominated by starlight. To make a direct comparison to fluxes reported in RH88, we measured the total observed $H\alpha$ emission-line flux from the nebula within a region of radius $r=20''$ (the bright star to the southwest) to be $9 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$, RH88 estimate an emission-line flux of $1 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$, if we assume the compatible line ratios. These numbers agree to well within our estimated mutual absolute calibration accuracies of 10%–15%. Enlarging the aperture includes a larger fraction of the detected nebula, so for the purposes of this paper we use the 35'' aperture, for which we estimate a total pure $H\alpha$ flux of $(1.1 \pm 0.1) \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$. The uncertainty quoted here is based on the uncertain sky background due to sky gradients in the $I$-band and narrowband frames. An additional uncertainty arises from the scattered-light contribution, occurring because the SOAR telescope was incompletely baffled at the time of the observation. Since this scattered-light component is smooth, it does not give rise to spurious structure in our image, but it does cause a large-scale gradient across the full field ($\sim$8% against the twilight-flattened $H\alpha$ image). We note that the total resolved flux from the nebula is almost a factor of 5 larger than that captured in the 2''x2'' spectroscopic slit.

We note that even though the observation is quite deep, we do not detect filaments at even larger projected distances from the BCG. A typical 3 $\sigma$ upper limit on such filaments, with scales of order 1''–3'', is about $3 \times 10^{-17}$ ergs s$^{-1}$ arcsec$^{-2}$ of $H\alpha$ (2.6 times larger for total emission-line flux from the $H\alpha+[\text{N} \, \text{ii}]$ complex).

The Galactic extinction in the direction of 2A0335+096 is $A_B = 1.097$ (Schlegel et al. 1998). The total pure $H\alpha$ luminosity corrected for Galactic extinction but uncorrected for any internal extinction is therefore quite large, $\sim$0.8 $\times 10^{42}$ ergs s$^{-1}$. The total SFR based on the $H\alpha$ luminosity, assuming that the conversion of SFR($M_\odot$ yr$^{-1}$) = 7.9 $\times 10^{-42}$L($H\alpha$) ergs s$^{-1}$ (Kennicutt 1998a) applies in this galaxy, is at least $6 M_\odot$ yr$^{-1}$. A similar relation for starburst galaxies (Kennicutt 1998b) predicts at least $7 M_\odot$ yr$^{-1}$.

The lack of calcium emission lines (Donahue & Voit 1993) in the nebular gas in 2A0335+096 indicates that calcium is depleted and therefore that the emission-line gas itself is dusty. This conclusion is nearly independent of the details of the production of the nebular lines. Typical dust extinction in these dusty nebulae (e.g., Abell 2597; Voit & Donahue 1997) is $A_V \sim 1$, so correcting for internal extinction would yield a higher SFR, up to 15–20 $M_\odot$ yr$^{-1}$.

The $H\alpha+[\text{N} \, \text{ii}]$ nebula in 2A0335+096 is similar in luminosity and appearance to the filamentary nebula seen in Perseus’s BCG (NGC 1275, also 3C 84; Fabian et al. 2003). Some of the emission-line structures in NGC 1275 have been identified as rising bubbles (Fabian et al. 2003; Hatch et al. 2006). The SOAR image of 2A0335+096 shows filaments wrapping around the radio source on both sides of the bar feature (Fig. 2). We discuss these emission-line structures further in § 4.2 and the radio contours in § 3.3. The SOAR emission-line image is deeper and has better spatial resolution than that of RH88, revealing additional
emission-line structures south and east of the bar. However, we have detected no emission-line counterparts to the X-ray deficits about 38 kpc to the east and 21 kpc to the northwest of the X-ray peak (MEM03).

The HST R-band image has several notable features (Fig. 3). The brightest galaxy and the companion have smooth elliptical light distributions. The large-scale light distribution of the BCG swallows the companion. The stellar light exhibits a distinct, small dust lane (1 kpc long and <150 pc wide, barely resolved) north of the companion (Fig. 3). This dust lane may extend somewhat closer to the nucleus of the companion than is visible in the figure, and a less distinct north-south dust lane, 10 kpc east of the companion nucleus, seems to be present. These dust lanes appear to be part of the general trail of material behind the companion, which suggests that the companion may have had a tiny amount of dust in it. The only potential dust feature visible in the BCG is wedge-shaped, south of the main nucleus, and pointing in the direction of the nucleus, as indicated in Figure 3. Both of these features are located in regions of Hα emission. The wedge feature is filled in with high surface brightness Hα, and the northern dust lane is in the same region as a broader, similarly aligned Hα filament north of the companion.

3.2. Long-Slit Spectroscopy

The central galaxy in 2A0335+096 was observed by M. Donahue and G. M. Voit using the 5 m telescope at the Palomar Observatory with the Double Spectrograph (Oke & Gunn 1982) on 1992 December 31 (UT). A composite spectrum of this source was presented by Donahue & Voit (1993).

A 2′ wide slit, approximately 2′ in length, was placed at a position angle of 140° east of north and centered over the galaxy and its companion. Six 30 minute exposures were taken, with the 300 line mm⁻¹ blue grating centered on 550 nm (2.17 Å pixel⁻¹) and the 1200 line mm⁻¹ red grating centered on 820 nm (0.814 Å pixel⁻¹). The spectral resolution was approximately 2 Å in the red spectrum and 6 Å in the blue. The angular scale was 0.45′ pixel⁻¹ for 2.5′; 15 μm pixels on the blue CCD. A composite spectrum from this observation was reported in Donahue & Voit (1993). The long-slit image was bias-subtracted and dome-flattened. The wavelength calibration was obtained by fitting the known line positions of a neon-argon arc observation and a hollow-cathode (Fe-Ar) lamp observation taken between each sky observation. Star observations taken at different positions along the slit and the wavelength calibration were then used to geometrically rectify each image. The sky background was removed by identifying night-sky regions on either side of the object spectrum, then fitting and subtracting a low-order polynomial function from the two-dimensional image line by line. A flux calibration for this instrumental setup was obtained from observations of the spectroscopic flux standards Feige 34 and HD 19445, obtained with 6′ wide slits set to the parallactic angle. The observations were obtained during a 50% illuminated moon, but the skies were clear. The seeing was variable and sometimes mediocre (~1′′–2′′).

We have identified four major features along the spectroscopic slit, identified jointly in Figure 4. The main nucleus is A, and the companion nucleus is B. The filament (S) to the southeast and the filament (N) to the northwest are also labeled. Figure 5 plots...
the results of fitting each row of the two-dimensional spectrum between the wavelengths of 6750 and 6850 Å, which includes the Hα-[N ii] emission-line complex. We modeled this complex with three redshifted, identical-width Gaussians centered at rest wavelengths of 6548, 6562.5, and 6584 Å and a flat continuum. The relative emission-line strengths of the two [N ii] lines were constrained to be in a ratio of 1:3. We fit the spectrum of each image column across the slit. Since the pixel scale is 0.47 pixel and the seeing conditions varied from 1″ to 2″, these plots have effectively been passed through a 3 pixel smoothing kernel. The approximate, relative slit positions of the image features, as plotted in Figure 5, are reported in the fourth column of Table 1. (For reference, the origin of the x-axis in Fig. 5 corresponds to line 63 in the original CCD frame.)

These features are distinctly seen along the slit as peaks in the Hα line intensity (Fig. 5). The locations of these peaks correspond approximately to changes in the velocity widths, relative velocity, and [N ii]/Hα ratio. The emission-line region A’, 1.5″ southeast of A and surrounding knot B, exhibits broader emission lines (FWHM  500–600 km s⁻¹) than the rest of the nebula (FWHM  200–400 km s⁻¹; Fig. 5). Since both knots are associated with radio emission, this broadening may be indicative of optical AGN-type activity in both nuclei (both of these nuclei are radio sources). The presence of bright and broadened Hα emission is correlated with a noticeable enhancement of the [N ii] λ6584/Hα ratio in B, but not so much in A and A’, where the associated peak in the [N ii] ratio occurs farther south (Fig. 5).

In the regions where the FWHM > 400 km s⁻¹, the mean [N ii]/Hα ratio is 1.3 ± 0.1, and in the regions where the FWHM was lower, the corresponding ratio is 1.1 ± 0.15. An enhanced [N ii] line relative to Hα is suggestive of a heating source with harder photons than typical of star formation regions (e.g., Baldwin et al. 1981), or possibly a source of supplemental heating above that from photoionization (e.g., Voit & Donahue 1997).

An examination of the relative velocities in Figure 5 shows the presence of at least two distinct velocity systems (z = 0.0347), with a velocity difference of about 270 km s⁻¹. The recession velocity of knot A lies (coincidentally, perhaps) near the mean, in the center of a velocity gradient that extends from A’ (at −120 km s⁻¹) to B (at +180 km s⁻¹). Both A’ and N are blueshifted about −120 to −150 km s⁻¹ relative to the mean, with the most extreme (and faint) velocity component of the northwest filament at −180 km s⁻¹. N has somewhat broadened emission lines (400 km s⁻¹), with elevated [N ii]/Hα as well. Both S and B are receding at about +170 km s⁻¹ with respect to the mean velocity of the system.

The peak of the Hα emission along the slit is somewhat more extended (by a factor of 2) than a point source. The south end of the peak has the broader emission lines, while the north end of the peak lies in the middle of the velocity gradient across the bar.

3.3. Radio

We rereduced archival high-resolution 20 cm A-configuration data from the VLA and added them to existing C- and
Fig. 4.—Position angle and slit position for the plots in Fig. 5. The line on the two-dimensional long-slit spectrum is 60 pixels long, starting from pixel 0 on the lower left-hand side. The length of that line matches the length of the slit pictured in the right panel, showing the angle and width of the spectroscopic slit. The actual full slit was 2" in length and 2000 wide. The 60 pixels (2900) spanning the length of the slit were used for the flux calibration of the SOAR emission-line image.

Fig. 5.—Top left: Hα intensity (ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) as a function of slit position. The brightest peak of the Hα emission is centered in the BCG stellar continuum. The locations of the knots are marked by vertical lines in all the figures. Knots A and B are the centers of the BCG and the companion. Knot A′ is the location of the gas with the broadest line profile, located somewhat southeast of the centroid of the brightest Hα peak. N and S mark the location of the northwest and southeast gas clouds in the slit. Bottom left: Mean width of the Hα and [N II] lines in km s$^{-1}$ at each position along the slit. A Gaussian shape was assumed to estimate the FWHM from the width $\sigma$ of the Gaussian lines, where $\text{FWHM} = 2(2 \log 2)^{1/2} \sigma$. Top right: Ratio of the integrated [N II] $\lambda 6584$ line to the Hα line, assuming that the lines are the same width. Each line of the spectrum along the slit was fit separately. Seeing correlates the measurements across 2–3 pixels. Three distinct peaks are seen. Two are associated with the brightest peaks, and the third is associated with the northwest filament. Bottom right: Mean recession velocity of all 62 positions along the slit, subtracted from the best-fit velocity to obtain a relative velocity for each slit position in km s$^{-1}$. The mean redshift measured from these spectra and used here is 0.0347.
D-configuration data. This process allowed us to produce maps at higher resolution than the 1.5 GHz image presented in Sarazin et al. (1995). We can see the inner lobes at a position angle of 65° east of north, oriented perpendicularly to the optical emission-line axis angle of 140°–145°. An extension of radio emission toward the companion is visible along the emission-line bar. The higher resolution radio map (Fig. 2) shows the radio lobes surrounded by curved Hα filaments.

We estimate the age of the radiating electrons that produce the radio emission following Myers & Spangler (1985). We assume that the spectral index between 1.4 and 5 GHz has steepened from an initial value of −0.5 to the observed value of about −1 due to synchrotron losses (see Table 4 of Sarazin et al. 1995). Our results are not very sensitive to whether we assume the existence of pitch angle scattering of the relativistic electrons. Assuming the magnetic field is at the equipartition value (taking an average value for the two radio lobes of 7 μG, from Table 4 of Sarazin et al. 1995), we estimate an age of about 25 Myr. On the other hand, in some radio sources there is evidence that the magnetic field is up to a factor of 4 less than the equipartition value (e.g., Carilli et al. 1994; Croston et al. 2005; Wellman et al. 1997). A factor of 4 weaker magnetic field implies an electron age of about 50 Myr.

3.4. Chandra X-Ray

We reanalyzed the Chandra data presented by MEM03, in order to take advantage of the most recent calibrations and to use a promising new technique developed by Diehl & Statler (2006) for creating X-ray surface brightness and temperature maps. We present adaptively binned X-ray and X-ray temperature maps. This process allowed us to produce maps at higher resolution than the 1.5 GHz image presented in Sarazin et al. (1995). We can see the inner lobes at a position angle of 65° east of north, oriented perpendicularly to the optical emission-line axis angle of 140°–145°. An extension of radio emission toward the companion is visible along the emission-line bar. The higher resolution radio map (Fig. 2) shows the radio lobes surrounded by curved Hα filaments.

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The temperature map was extracted from bins defined by an X-ray surface brightness map binned to a minimum S/N = 30.

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### Table 1

| Label | R.A. (J2000.0) | Decl. (J2000.0) | Mean Slit Pos. | Redshift |
|-------|---------------|----------------|---------------|----------|
| A     | 03 38 40.6    | +09 58 12      | 10.0          | 0.0347 (0.0343–0.0351) |
| Bridge A-B | ... | ... | ... | ... |
| B     | 03 38 40.3    | +09 58 18      | 16            | 0.0352 (0.0352–0.0353) |
| Northwest filament | 03 38 40.0 | +09 58 22 | 22.5 | 0.0343 (0.0344–0.0347) |
| Southeast filament | 03 38 41.0 | +09 58 04 | 2.0 | 0.0352 (0.0351–0.0353) |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* Each pixel in the spatial direction is 0.47 arcsec.

* These astrometric locations are approximate, within 3 arcsec.

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2 See http://cxc.harvard.edu/contrib/maxim/bg/.

3 Interactive Data Language (IDL) is data visualization and image analysis software available from ITT Visual Information Systems, http://www.itvis.com/.
the sky is severe. Within the central 7″ radius (enclosing the light of the companion), the total UVW1 luminosity is \( (5.5 \pm 0.4) \times 10^{42} \text{ ergs s}^{-1} \), after a correction for coincidence and dead-time loss. We chose to do photometry within a 7″ radius because that aperture encloses most of the UV emission. The level of diffuse UV emission beyond the aperture is highly uncertain because of the strong scattered light near the middle of the field. The Galactic extinction in the UVW1 band has also been applied (2.48 mag) based on Cardelli et al. (1989), while the internal extinction is unknown and is set to zero. The contribution from the passive stellar population is subtracted from the empirical \( L_{\text{UVW1}} - L_J \) relation derived by Hicks & Mushotzky (2005) resulting in a net near-UV luminosity excess of \( 2.9 \pm 0.5 \times 10^{42} \text{ ergs s}^{-1} \). This excess corresponds to a SFR of 3.1–5.7 \( M_\odot \text{ yr}^{-1} \) for the assumed IMF with a power-law index of 2.35–3.3.

We have also estimated the UVW2 – UVW1 color of >0.38 mag, without any correction for internal extinction. We adopt a Galactic extinction of 3.88 mag at 2050 Å, although there is quite a range of extinction across the bandpass of UVW2 (3.26–4.14 mag, also from Cardelli et al. 1989), since the UVW2 band encloses the peak of the Galactic extinction curve (≈2150 Å). This color can be compared with that of A1795’s cD (0.0–0.15 mag, from Mittaz et al. 2001). Only a small amount of internal extinction would imply that the intrinsic color of 2A0335 is similar to that of A1795’s cD.

4. DISCUSSION

4.1. Merger of the BCG and Companion Galaxy

Most importantly, from the viewpoint of previous studies of this system, we confirm that the companion galaxy to the BCG has a very similar recession velocity (\( \Delta v \sim 100 \text{ km s}^{-1} \)) to that of the nucleus of the BCG. As noted by Werner et al. (2006) and MEM03, the cool X-ray peak, offset from the BCG itself, lies in a line with the BCG and the companion galaxy, suggesting that a subcluster has fallen in along a filament that has fed the formation of the cluster. Our radial velocities of the companion and

![Fig. 6.—Left: Color-coded image of the adaptively binned (5 σ) X-ray (0.7–7.0 keV) surface brightness distribution for 2A0335+096. The color bar corresponds to the mean photon counts per 0.5″ × 0.5″ pixel in the X-ray image. The net exposure time was about 20,000 s. Note that the nuclei of the galaxies, A and B, are not located at the brightest X-ray peak but are associated with fainter X-ray peaks. Right: Contour map of the X-ray surface brightness isophotes plotted over the net Hα image from SOAR, at the same scale and orientation (north up, east left) as the left image. While the bar of Hα surrounding the BCG nucleus does appear to have a counterpart in the X-ray emission, there is no significant one-to-one correlation of X-ray and Hα surface brightness. We note that the Hα appears to be limited to the region where the X-ray surface brightness is greater than about 3 photons pixel\(^{-1}\), which is an approximate X-ray surface brightness of \( 3 \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \).](image_url)

![Fig. 7.—Gray-scale image of the net emission-line image, with the contours of the interpolated temperature map superimposed. The temperature map contour levels are 1.75, 2.0, 2.5, and 3.0 keV (inner to outer; the contours map a decrement in X-ray temperatures). The Hα filaments appear to be confined to a region where the X-ray temperature is less than 2.5 keV, and the coolest lumps (the innermost contours, where <1.75 keV) correspond to the brightest Hα regions, except for the cool X-ray lump obscured by the bright star to the southeast, which cannot be seen optically. North is up, and east is to the left.](image_url)
the BCG suggest that the companion and the BCG are not only close in projection but may be in the process of merging.

4.2. Emission-Line Filament Shapes and Motion of the AGN

The circles in Figure 2 show the positions and sizes of two apparently circular structures visible in the SOAR emission-line image, partially outlined by curved H\textalpha filaments. When we completed the circles outlined by these filaments, we obtained the circles on the sky in Figure 2. We were struck by the symmetry and the similarity in size of the arcs outlining curved structures in the image. The center of the northeast circle is at 03h38m41.1s, +09\degr58\arcmin19.9\arcsec (J2000.0). The center of the southwest circle is at 03h38m39.8s, +09\degr58\arcmin10.5\arcsec (J2000.0). The midpoint of these two positions is at 03h38m40.5s, +09\degr58\arcmin15.1\arcsec (J2000.0). If the AGN is at the peak of the H\textalpha emission, 03h38m12s, +09\degr58\arcmin12\arcsec (J2000.0), then the opening angle of the inferred structure, including the nucleus at the origin, is 141.5\deg in the plane of the sky, opening to the northwest, along the bar.

If the radio plasma in the lobes is 25–50 million years old, as we estimated in §3.3, the separation between the midpoint of the completed H\textalpha arcs and the actual radio/H\textalpha nucleus suggests that the AGN is moving through the neighboring X-ray gas at a velocity in the plane of the sky of about 55–110 km s\(^{-1}\). This velocity is less than and therefore consistent with the 400 km s\(^{-1}\) three-dimensional velocity needed to create the X-ray front feature analyzed by MEM03. The location of the extended, small-scale radio emission along what might be the leading edge of a cavity supports the suggestion of relative motion between the AGN and the X-ray gas. The opening angle between the two lobes of the radio source itself is nearly straight, ~180\deg.

While it is possible to draw other circular structures using the filaments as guides, these particular structures are the ones closest to and on opposite sides of the AGN. Therefore, the velocity in the plane of the sky that we infer here is a lower limit. The complexity of the emission-line nebula appearance indicates that there may have been multiple outburst events occurring along the interaction axis defined by the X-ray cool core, the BCG, and the companion. Multiple bubbles and a complex filamentary structure, reflecting a history of outbursts from the AGN, have been seen in the X-ray image of M87 in the center of the Virgo Cluster (Forman et al. 2005).

4.3. Other Multiwavelength Identifications

The locations of the brightest points in the BCG in the SOAR H\textalpha image, the HST WFPC2 image, and the radio image are within 0.5\arcsec of each other. We identify the nucleus of the BCG with knot A in the long-slit spectrum (Figs. 4 and 5). The center of the BCG is also detected in the UV by the OM on board XMM-Newton (§4.5). The nucleus of the BCG, as seen by HST, seems to be near the center of the brightest bar feature in the emission-line image. The brightest peak in the X-ray emission is south of the BCG nucleus by 13.7\arcsec or 9.6 kpc. The BCG nucleus corresponds to a fainter peak in the X-ray emission. Knot B (Figs. 4 and 5) also has counterparts in all data sets, including the UV OM (XMM-Newton), the 3\arcsec resolution VLA image, and the Chandra X-ray image.

The X-ray emission does not show a one-to-one structural correspondence with the H\textalpha emission (Fig. 6), but there is a choppy ridge of high X-ray surface brightness that follows the more pronounced H\textalpha bridge between the two galaxies. Just outside the H\textalpha nebula, to the south and past the X-ray peak, there is an X-ray cool front (MEM03). It is impossible to see the behavior of the optical emission-line gas in this region in the SOAR image because of a very bright star, but even the Palomar spectrum, which is less affected by the bright star, does not show much hint of extended emission in that direction. Beyond the H\textalpha nebula, the X-ray surface brightness profile drops off suddenly, as if a minimum of X-ray surface brightness were needed to host H\alpha filaments.

Our temperature map of the cluster shows that the H\textalpha emission-line region lies entirely within the 2.5 keV contour (Fig. 7). This X-ray gas has the lowest entropy and shortest cooling time in the cluster, and it has the same elongated morphology as the H\textalpha nebula. This correspondence suggests that the cool X-ray core and the BCG are related, even though the X-ray peak is not at the center of the BCG. We note that the X-ray surface brightness peaks in two cool (~1.5 keV) clumps to the southwest, one that may be associated with the southwest filament and the other where the foreground star obscures our view of the emission-line gas. Thus, the coolest X-ray gas does not correspond exactly to the H\textalpha nebula, a fact we return to in §4.5. As mentioned in §§3.3 and 4.2, the radio source may be affecting the optical filaments on either side of the optical/radio nucleus, as seen in the H\textalpha image. From this analysis, we concluded in §4.2 that the AGN may be in motion with respect to the optical nebula. This hypothesis is supported by analysis of the emission-line spectra, which we discuss next.

4.4. Dynamical Clues: Systematic Velocities along the Bar and between the Knots

We discuss here possible interpretations of the systematic velocity trends we have measured along the bar of optical line emission and surrounding filaments: a rotating filament system in a counterrotating disk or an interacting system with a bar of stripped gas. We also discuss the relationship to the motion of the cool clump seen in the X-ray images.

This bar has been interpreted as an edge-on disk by both RH88 and Sarazin et al. (1995). Sarazin et al. (1995) suggest that this disk may determine the orientation of the radio source. RH88 suggest a compact 2 kpc disk inside a 17 kpc bar. Neither of these groups had spectroscopic information about the velocities along this structure, however. It is possible to interpret the velocity structure along the bar as a large, rotating filament system around knot A with a circular velocity of 170 km s\(^{-1}\) (using the extreme ends of the bar, N and S, to define the “rotation”) and a diameter of about 20\arcmin or 14 kpc. This circular velocity and size imply a gravitational mass of at least 5 \times 10^{10} M_{\odot}. The center of this system lies close to the center of the BCG.

The inner structure of the bar could be a counterrotating disk, as suggested by RH88, with a diameter of about 7.5\arcmin or 5.25 kpc and a circular velocity of ~120–150 km s\(^{-1}\). The mean redshift of the bar may be somewhat greater than that of the more extended system, but only by about 30 km s\(^{-1}\). The intensity peak of the H\textalpha emission (knot A) lies at or near the center of this bar. The implied mass interior to \( r = 3.5 \) kpc is approximately 1.4 \times 10^{10} M_{\odot}. A similar but larger scale structure was seen in 3C 275.1 (Hintzen & Stocke 1986), but we note that even the gradient in this structure was not considered a strong indication of rotation by these authors.

A second, possibly more compelling interpretation of the velocity system is that it is the result of a stripping interaction between the two nuclei, knots A and B. Stripping tails have been seen in the X-ray by Sun et al. (2006) in Abell 3627 and in the optical (Gavazzi et al. 2001) in Abell 1367; see also M. Sun et al. (2007, in preparation) on Abell 3627. The portion of the long-slit spectrum with the broadest emission lines seems to lie closer to the southern end of this bar, rather than in the center of it. The bar
of emission between knots A and B may be stripped material, with a range of velocities along the stream, stretching from knot A toward B. If the overall direction of motion is from northwest to southeast, as suggested by the orientation of the cool front and the BCG, it is possible that the BCG, moving in the same general direction as the core cloud, passed through B, stripping material from B in the process.

A tidal origin for the bar seems unlikely due to the lack of a similar feature in the stellar continuum image, unless the tides also induce physical processes that light up the emission-line and X-ray gas without significantly affecting the I-band light distribution from stars.

Knot A and the companion galaxy (knot B) have a velocity separation of about 100 km s\(^{-1}\) along the line of sight and a projected separation of 6.6\(\pm\) or 4.6 kpc. The crossing time, therefore, is several times 10\(^7\) yr. (We have made the simplifying approximation that the physical separation of the two knots is \(\sqrt{3}\) larger than the projected separation, and that there is no motion in the plane of the sky.) The gravitational free-fall time \(t_{\text{ff}} \approx (Gm)^{-1/2}\) for a system with \(M \approx 10^{10}\ M_\odot\) and \(r = 7\) kpc is about 2 \(\times 10^9\) yr.

Interesting dynamical information also comes from the X-ray image. Recall that the shape of the X-ray edge and pressure differential imply that a cool clump is moving to the south with a Mach number of \(\sim 0.75\) (MEM03). This Mach number implies that the cool clump is moving with respect to the larger cluster at \(\sim 500\) km s\(^{-1}\). The relative positions of the circular H\(_\alpha\) filaments and the AGN suggest that the AGN may be moving with respect to the local ICM in the same direction as the cool clump, in the plane of the sky. The filaments defining the circular structure are arranged symmetrically around the radio source, with a slight offset suggesting a lower limit to the velocity in the plane of the sky of \(\sim 50\)–100 km s\(^{-1}\). These clues indicate that the AGN may be moving in the same general direction as the cool clump, but possibly at a lower speed.

### 4.5. Star Formation Rates and Mass Cooling Rates

One problem with the original cooling flow model was the large discrepancy between the high X-ray mass cooling rates and the low SFRs. In § 3.1 we derived a minimum SFR (with no intrinsic dust extinction correction) of at least \(7 M_\odot\) yr\(^{-1}\) from the SOAR H\(_\alpha\) imaging data. Peterson et al. (2003) constrained the cooling rate of the X-ray gas in the core of 2A0335+096 with measurements and limits on X-ray emission lines seen in the spectroscopic grating data from the XMM-Newton RGS instrument. Individual X-ray lines provide independent constraints on the cooling rate, so the cooling constraints depend on the spectral regime under consideration. They derive \(M(0.8 – 0.4\) keV) = \(20 \pm 10\) \(M_\odot\) yr\(^{-1}\) and \(M(0.4 – 0.2\) keV) < \(84\) \(M_\odot\) yr\(^{-1}\). While the uncertainty is large, this updated cooling rate of the X-ray gas is close to the SFR in the cD galaxy.

From the UV observations, we derived a near-UV luminosity excess of \((2.9 \pm 0.5) \times 10^{42}\) ergs s\(^{-1}\). This excess corresponds to a SFR of \(3.1–5.7 M_\odot\) yr\(^{-1}\), for the assumed IMF with a power-law index of 2.35–3.3 and zero internal extinction. If we apply an internal extinction correction corresponding to \(A_V \approx 1\) (typical for cooling flow nebulae; e.g., Voit & Donahue 1997), the estimated SFR would be up to 10 times larger. The rate inferred without internal extinction is somewhat less than that inferred from the H\(_\alpha\) emission, but that is to be expected, since even tiny amounts of extinction would increase the UV estimate substantially. We note that the H\(_\alpha\) emission spans a much larger region \((r \sim 35\text{"})\) in radius than the UV emission (within a 7\" radius), but that most of the H\(_\alpha\) is concentrated close in. We conclude that the observed UV excess is consistent with the SFR inferred from the H\(_\alpha\) observations.

Yet another independent constraint on star formation was sought from the IUE data archive. We inspected two archival IUE observations of 2A0335+096, SWP 24934, and SWP 43531. The short-wavelength (SWP) camera on IUE, a 45 cm UV telescope (1978–1996), was sensitive to UV emission from 115 to 200.0 nm in a large aperture of 10\(^\prime\) < 20\(^\prime\), blueward of the XMM-Newton OM UVW1 band. An upper limit to the UV continuum was reported from an earlier observation of 10,800 s by Crawford & Fabian (1993). We analyzed a longer, later IUE observation of 24,000 s, but we made only a marginal improvement on Crawford et al.’s original upper limit. Cosmic-ray events obscured the spectrum at the position of redshifted Ly\(_\alpha\) at the nominal pointing position. A 3\(\sigma\) limit of <\(2.4 \times 10^{35}\) ergs s\(^{-1}\) cm\(^{-2}\) \(\AA\)\(^{-1}\), measured between 128 and 136 nm, was obtained, corresponding to a Galactic extinction-corrected flux limit of \(6 \times 10^{-14}\) ergs s\(^{-1}\) cm\(^{-2}\) \(\AA\)\(^{-1}\). (No emission, extended or otherwise, is visible in the IUE field.) A Ly\(_\alpha\) line with a width of 500 km s\(^{-1}\) would be unresolved in an IUE spectrum (1.67 \(A\) per element), so a 3\(\sigma\) limit would have to be about \(4 \times 10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\) \(\AA\)\(^{-1}\), corresponding to an upper limit of about 5 \(\times 10^{41}\) ergs s\(^{-1}\) on Ly\(_\alpha\) luminosity and 1.3 \(\times 10^{41}\) ergs s\(^{-1}\) on continuum emission in a bandpass between 128 and 136 nm, corrected for an extinction of \(E(B – V) = 0.41\) and a Cardelli et al. (1989) law. This limit is about 50% of what one would expect based on the H\(_\alpha\) luminosity we estimate for the system with no internal extinction. However, the amount of dust required by these IUE data to push the Ly\(_\alpha\) line below detectability is extremely small. Therefore, the lack of detection of either a Ly\(_\alpha\) line or a UV continuum from 2A0335+096 by IUE, together with detections by the XMM-Newton OM and SOAR, indicates that there is some internal dust in the BCG of 2A0335+096.

The total amount of molecular gas in the galaxy was estimated by Edge & Frayer (2003) based on CO observations to be \((1.1 \pm 0.4) \times 10^9 h_{70}^2 M_\odot\). Such a gas supply, if not replenished by cooling or accretion, would be completely used up by star formation in 100 million years. Therefore, this system could be classified as a starburst galaxy. However, since the SFR is similar to the estimated cooling rate from the hot ICM by Peterson et al. (2003), we suggest that it is possible the gas supply is being replenished by cooling.

Radio emission is thought to be related to accretion onto an AGN. This accretion may be fueled by a recent interaction with a gas-rich system. It is possible that a galaxy-galaxy interaction has induced star formation in gas accumulated from the ICM or an ISM gas source. We point out that a scenario where hot ICM has cooled and started to form stars is less tenable if the star-forming gas turns out to be dusty (Donahue & Voit 1993). Based on the expression for the dust-sputtering time provided by Draine & Salpeter (1979), the hot gas in the core of a typical cluster spatters refractory grains with size \(a < 0.1\) \(\mu m\) (the majority of dust grains by number) in about \(2 \times 10^5 a_1^{-2} a_0^{-1}\) yr, where \(n_2 = n_h/10^{-5} \text{ cm}^{-3}\) and \(a_0 = a/0.1\) \(\mu m\), so theoretical prejudice is that such cooled ICM gas would be dust-free.

### 5. SUMMARY AND CONCLUSIONS

We summarize our results as follows:

1. Our SOAR H\(_\alpha\) image of 2A0335+096 is deeper and more sensitive and has better seeing than that presented in RH88. We clearly detect the emission-line filaments on both the north and south sides of the galaxy, and we see filamentary details in excellent relief. We do not detect much more H\(_\alpha\) beyond \(\sim 25\) kpc...
from the central galaxy. These observations limit the presence of somewhat lower low surface brightness emission-line gas at large radii (∼3 × 10^{-17} ergs s^{-1} cm^{-2} arcsec^{-2} on scales of 1"−3")

2. We present velocity information along the interaction axis defined by the X-ray cool front, the BCG, the X-ray and Hα bar, and the companion galaxy that show that the companion galaxy is likely to have interacted with the BCG. The velocity structure along the X-ray and optical emission-line bar suggests that ram pressure stripping might be a relevant process here.

3. In the frame of the AGN (indicated by the center of the BCG, knot A), the north/northwest filament/blob is moving toward us, and the south/southeast filament/blob is moving away from us. However, a two-dimensional velocity map would be required to confirm whether the large-scale nebula is rotating in the frame of the AGN. We cannot tell whether the large-scale system is rotating with these data.

4. The main evidence for an earlier interaction between A and B comes from the morphology of the emission bar extending between A and B and the continuous transition of radial velocities from A to B seen in the long-slit spectrum.

5. Because the companion (knot B) seems to have already interacted with the BCG, we conclude that knot B is now beyond the BCG, pulling out a bar of emission-line gas with it. Since both galaxy cores are also emission-line sources, it is impossible to say whether B is stripping gas from A, A is stripping gas from B, or both galaxies are stripping gas from each other. The passage of the companion galaxy through the BCG may have induced star formation, possibly in preexisting gas accumulated from a cooling flow or in cold gas the companion may have contributed to the system. A stream of emission-line gas and dust extends past the companion to the north, suggesting that some of the companion’s motion is also in the plane of the sky, and B may soon be proceeding back toward the southeast, toward A. One hint that this may be the case is that the gas in the northwest filament has the same systematic velocity as A. Possibly, ICM interactions and gravity have decelerated that gas trailing companion B, and so its relative velocity to the BCG is now zero.

6. The interaction may have also triggered a radio source by providing fuel or by exciting instabilities in gas orbiting the central supermassive black hole; however, this scenario cannot be distinguished from fueling the radio source with gas condensing from the ICM. The higher resolution image we present here shows two close-in lobes of radio plasma. The optical emission-line filaments near the lobes seem to arc around the radio plasma. The higher resolution radio data from the VLA and the deeper, higher resolution emission-line imaging from SOAR provide complementary information to this source.

7. We have derived a star formation rate from the UV OM images of 2A0335+096. These rates are marginally consistent with, and lower than, the constraints on the X-ray mass cooling rate from XMM-Newton RGS spectra. The approximate total Hα luminosity is also consistent with the estimated SFR and rate of gas cooling from X-ray-emitting temperatures. This consistency suggests, in this system at least, that the star formation is a possible sink for gas cooling from X-ray temperatures.

We note an interesting similarity in three timescales: (1) the consumption or production timescale of the molecular gas (the quantity of the cold gas divided by either the X-ray cooling rate or the SFR), (2) the estimated age of the radio source derived from the synchrotron age of the electrons, and (3) the approximate time of last interaction between the companion and the BCG. The similarity in timescales suggests that the common triggering mechanism for the radio source and the starburst in this system may be the interaction of a companion with a BCG residing in low-entropy ICM gas.

Our detailed study of this cluster core reveals details about this system that suggest that the interaction of a companion galaxy with the BCG is the trigger for the radio source and the starburst event. Whether the cooling flow was required to supply the gas that feeds the black hole and supplies the starburst is uncertain, but the mass cooling rates inferred from the XMM-Newton RGS spectrum are consistent with the SFRs inferred from the Hα and UV observations presented here. A two-dimensional study of the emission-line system, possibly with an integral field unit, could further distinguish the dynamical models suggested by our Hα data.

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