Radio Bubbles, Cooling X-ray Gas, Galaxy Interactions, and Star Formation 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 Imaging camera 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, multi-wavelength observations for the BCG, including long-slit optical spectroscopy, archival VLA radio data, Chandra X-ray imaging, and XMM 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, including the brightest cluster galaxy and its companion. Our analysis reveals the presence of Hα emission bubbles, centered on the BCG and inflated by a radio source. The velocity structure of the emission-line bar between the BCG nucleus and the companion galaxy provides strong evidence for a tidal interaction between the BCG and its northeast companion in the last ~ 50 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. A star formation rate of $\gtrsim 7$ solar masses per year is derived from the Hα and archival UV data. This rate is similar to the revised X-ray cooling rate of 10-30 solar masses per year in the vicinity of the BCG, derived from X-ray spectra. The
Hα nebula is limited to a region of high X-ray surface brightness and cool X-ray temperatures. However the detailed structures of Hα and X-ray gas differ. The peak of the X-ray surface brightness is not the peak of Hα emission, nor does it lie in the BCG. The estimated age of the lobes and their interaction with the X-ray and 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.

**Subject headings:** galaxies:clusters:general — galaxies:clusters:individual (2A0335+096) — cooling flows

### 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 (X-ray Multi-Mirror) observatories. Stringent constraints on emission lines from the appropriate ionization species of iron and oxygen in high-resolution X-ray spectra from XMM show little evidence for simple, high $\dot{M}$ cooling flows (Peterson et al. 2003), yet indicate the presence of gas ranging over a factor of two in X-ray temperature. High resolution imaging (to $\sim 1''$) by Chandra has revealed bubbles in the intracluster medium (ICM), gently inflated (not shocked) by radio plasma (McNamara et al. 2001, 2000; Birzan et al. 2004), as well as X-ray fronts, which are a likely to be the manifestation of cooler X-ray blobs passing through hotter gas (e.g. Markevitch 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, multi-temperature gas, and the non-radial 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; Ruszkowski & Begelman 2002; Brüggen & Kaiser 2002; Alexander 2002; Omma et al. 2004; McCarthy et al. 2004; Roychowdhury et al. 2004; Hoeft & Brüggen 2004; Dalla Vecchia et al. 2004; Soker & Pizzolato
The most massive black holes in the universe, at the centers of clusters (Lauer et al. 2006), 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 host’s bulge luminosity and the velocity dispersion (e.g. Haehnelt & Kauffmann 2000). Mergers alone can not explain 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. Semi-analytic studies currently make general assumptions about the efficiency of AGN feedback, tuned to suppress the formation of over-luminous, blue galaxies at the centers of clusters and to reproduce the exponential cut-off 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 multi-wavelength 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-meter class telescope (Southern Observatory for Astrophysical Research, or SOAR) and its imager (SOAR Imaging camera). We have combined these observations with archival observations of the central galaxy in order to compare the spatial relationship of the X-ray gas, the radio plasma, the emission-line gas, and the central galaxy and to estimate the star formation rate 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 (§ 3.1), optical long-slit spectra from Palomar (§ 3.2), radio images from the Very Large Array (§ 3.3), and X-ray archival data from Chandra (§ 3.4). We discuss the correspondence of Hα bubbles and VLA structures in § 4.1, further multi-wavelength identifications, including the correspondence between the X-ray, optical, and radio in § 4.2, the properties of the emission-line system 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 Optical Monitor 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 V 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, RH88 hereafter). These optical filaments extend from a bar-shaped feature in the center of the brightest cluster galaxy (BCG). The BCG appears to have a companion galaxy about 4 kpc projected to the NW. Using the ROSAT HRI detectors, Sarazin et al. (1992) revealed a similar bar in the X-rays, and a larger scale X-ray elongation of the cluster emission in the same general direction. The BCG is a radio galaxy of $\sim 33.5$ mJy at 1.5 GHz diffused over a region of $29'' \times 19''$ (Sarazin et al. 1995). The BCG nucleus and its companion each have a radio point source (Sarazin et al. 1995).

2A0335+096 was observed with the Chandra X-ray Observatory (Kawano et al. 2003; Mazzotta et al. 2003). We will discuss these Chandra data further in § 3.4. The Chandra image shows a bar feature, with X-ray deficits to the NE and the SW, identified as possible bubbles. But the details of the X-ray structures and the H$\alpha$ filaments do not coincide, except for the bar around the nucleus, and the extension between the BCG and the companion. Mazzotta et al. (2003, MEM hereafter) identified a discontinuity or front feature in the X-ray gas to the south of the BCG. They estimated a pressure jump across the feature, and derived a sub-sonic Mach number ($0.75 \pm 0.2$), 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. They 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 H$\alpha$ 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 the filaments were unknown to MEM, the dynamics of the interaction were not possible to discuss in detail.
3. Observations and Data Analysis

3.1. Narrow-Band Hα+ [N II] and Broad-band Imaging

We obtained broad I-band and narrow-band images (Δλ ∼ 75Å, NOAO filter ID 6781-78) centered near the redshifted Hα line on Dec. 8, 2005 (UT) with the SOAR Optical Imager (SOI), mounted on the SOAR telescope on Cerro Pachon, in Chile. We supplemented these data with an R-band (filter F606W) Hubble Space Telescope WFPC2 image. We used the WFPC2 association\(^1\) ID u5a40701b, which is a basic co-addition of two 300-second snapshots (Proposal ID 8301, PI Alastair 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″ per pixel. 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 two hours) as the object transited. We collected nine 20-minute exposures for a total exposure time of 3 hours through the narrow band filter. Each exposure was dithered slightly. The narrow-band filter is only 2 inches × 2 inches, so the usable field of view is somewhat smaller than the full 5′ × 5′ FOV of the SOI. After the dithering, our useful field of view resulted in an image of 1561 × 1395 image pixels, or 4′ × 3.6′.

A single 10 minute I-band exposure was obtained for the purpose of estimating the stellar continuum contribution to the narrow-band 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 align, 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 narrow-band images by obtaining the average in each shifted pixel, after a 3σ 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 PSF, 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 a post-facto astrometric WCS.

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\(^1\)This research utilized the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency.
solution to the header of the combined narrow-band image using tools available in WCSTools (v. 3.6.3, available from the Smithsonian Astrophysical Observatories). 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), the angular scale of 0.154 arcseconds ($\pm 0.004''$), 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 co-aligned, fringe-corrected, scaled (by a factor of 28.57) I-band image from the narrow-band image. The scale factor was chosen to subtract the nearby cluster galaxies from the narrow band image (Figure 1). Since both [N 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 $1.26 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ of pure H$\alpha$. This ratio assumes that the mean H$\alpha$ contribution to the total H$\alpha$+[N II] emission-line flux is 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 23'' of the BCG (masking out a region of $r = 20''$ from the bright star to the southwest) to be $9 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. RH88 estimate an emission line flux of $1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, if we assume the compatible line ratios. These numbers agree 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 will use the a 35'' aperture, for which we estimate a total pure H$\alpha$ flux of $(1.1 \pm 0.1) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. The uncertainty quoted here is based on the uncertain sky background due to sky gradients in the I-band and narrow-band frames. An additional uncertainty arises from the scattered light contribution, arising 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 ($\sim 8\%$ across the twilight-flattened H$\alpha$ image). We note the total resolved flux from the nebula is almost a factor of 5 larger than that captured in the $2'' \times 2'$ spectroscopic slit.

We note that even though the observation was 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 $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ of H$\alpha$ (2.6 times larger
for total emission line flux from the H\(\alpha\)-[N II] complex.)

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

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 relatively independent of the details of the production of the nebular lines. Typical dust extinction in these dusty nebula (e.g. Abell 2597; Voit & Donahue (1997)) is \(A_V \sim 1\), so correcting for internal extinction would yield a higher star formation rate, up to 15-20 solar masses a year.

The H\(\alpha\)+[NII] nebula in 2A0335+096 is similar in luminosity and in appearance to the filamentary nebula seen in Perseus’s BCG (NGC1275, also 3C84) (Fabian et al. 2003). Some of the emission-line structures in NGC1275 have been identified as rising bubbles (Fabian et al. 2003). The SOAR image of 2A0335+096 shows filaments wrapping around possible bubbles on both sides of the bar feature (Figure 2). We will discuss these bubbles further in § 4.1 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 holes about 38 kpc to the east and 21 kpc to the NW of the X-ray peak (MEM).

The HST R-band image has several notable features (Figure 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 (1-2 kpc long and < 150 pc wide, barely resolved) north of the companion (Figure 3). This dust lane may extends somewhat closer to the nucleus of the companion than visible in the figure, and a less distinct N-S dust lane, 1\(''\) east of the companion nucleus may also 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 H\(\alpha\) emission. The wedge feature is filled in with high surface-brightness H\(\alpha\), and the northern dust lane is in the same region as a broader, similarly aligned, H\(\alpha\) filament north of the companion.
3.2. Long-Slit Spectroscopy

The central galaxy in 2A0335+096 was observed by Donahue and Voit using the 5-meter Palomar Observatory with the Double Spectrograph (Oke & Gunn 1982) on Dec 31, 1992 (UT). Six 30-minute exposures were taken, with the 300-line/mm blue grating centered on 550 nm (2.17 Å per pixel) and the 1200-line/mm (0.814 Å per pixel) red grating centered on 820 nm. 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 degrees east of north, and centered over the galaxy and its companion. The spectral resolution was approximately 2Å in the red spectrum and 6Å in the blue. The angular scale was 0.47″ per pixel for 24 µm pixels on the red CCD, and 0.78″ per pixel for 2 × 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 HC 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 2D image line by line.

A flux calibration was obtained from an observation of the spectroscopic flux standards Feige 34 and HD19445, 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″).

3.3. Radio

We re-reduced archival high-resolution 20-cm A-array data from the Very Large Array (VLA), and added it to existing C- and D-array 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 degrees east of north, oriented perpendicularly to the optical emission-line axis angle of 140-145 degrees. An extension of radio emission towards the companion is visible along the emission-line bar. The higher resolution radio map (Figure 2) shows the clear relationship between the radio-emitting plasma, the Hα filaments wrapping around the radio lobes, and the inner X-ray cavities in this cluster.

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 \(-1\) (See Table 4 of Sarazin et al. (1995)) due to synchrotron losses. 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 \(\mu\)G, 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 four weaker magnetic field implies an electron age of about 50 Myr.

3.4. Chandra X-ray

We re-analyzed the Chandra data presented by MEM, in order to take advantage of the most recent calibrations and to utilize 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 of 2A 0335+096 created from the 20,000 second Chandra observation (Kawano et al. 2003) (OBSID 919). This observation was made with the back-illuminated Advanced CCD Imaging Spectrometer (ACIS) S3 CCD on September 6th, 2000. The data were prepared using CIAO v3.3 and the calibration files in CALDB v3.2.1. Spectral fitting was performed with XSPEC 11.3.2 (Arnaud 1996) over the energy range 0.7 – 7.0 keV.

To create the surface brightness and temperature maps, we employed the adaptive binning code of Diehl & Statler (2006). Their technique uses weighted Voronoi tessellation (WVT) to create spatial bins which maintain a given signal-to-noise (S/N) and uses an input background spectrum specific to the observation. The events associated with hot pixels, bad pixels, and point sources were not included in the S/N estimation for the definition of the spatial bins. Regions of the detector near the edges with less than 40% of the total exposure were not included in the final X-ray image. The X-ray surface brightness map was binned to a minimum \(S/N = 5\) (Figure 4).

The temperature map was extracted from bins defined by an X-ray surface brightness map binned to a minimum \(S/N = 30\). The high S/N for the temperature map insures sufficient counts in each spectral bin to obtain a interesting constraint on the plasma temperature. To generate the temperature map, a spectrum was extracted from each WVT-defined bin. A corresponding background spectrum for each spatial bin was extracted from the appropriate deep background file (provided in the Chandra CALDB by Maxim Markevitch\(^2\)), which was

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\(^2\)http://cxc.harvard.edu/contrib/maxim/bg/
reprojected and matched in gain to the current observation. Each spectrum was fit with a projected single-temperature MekaL thermal spectrum and Galactic absorption model using a fixed Galactic value of $N_H = 1.81 \times 10^{21} \text{ cm}^{-2}$. The metallicity, temperature, and normalization were free parameters. The best-fit temperatures then populate a temperature map. The best fit temperatures were also projected onto a uniform grid and interpolated using the IDL procedure `triangulate` and `griddata` \(^3\). We confirmed that this interpolation did not introduce any spurious features into the temperature map by comparing the same contour lines of both maps. The contours of the raw map oscillated around the smoother contours of the interpolated map, so we have chosen to show the contours of the interpolated temperature map in Figure 5, overlaid on the net H$\alpha$ image from SOAR.

4. Discussion

4.1. Emission-Line Bubbles and Motion of the AGN

Circles in Figure 2 show the positions and sizes of two apparently circular structures visible in the SOAR emission-line image, outlined by curved H$\alpha$ filaments. We were struck by the symmetry and the similarity in size of the bubbles. The center of the NE bubble is at $3^h \, 38^m \, 41.15^s, \, +09^\circ \, 58' \, 19.9''$ (J2000). The center of the SW bubble is at $3^h \, 38^m \, 39.8^s, \, +09^\circ \, 58' \, 10.5''$ (J2000). The mid-point of these two positions is $3^h \, 38^m \, 40.5^s, \, +09^\circ \, 58' \, 15.1''$ (J2000). If the AGN is at the peak of the H$\alpha$ emission, of $3^h \, 38^m \, 12^s, \, +09^\circ \, 58' \, 12''$ (J2000), then the opening angle of the inferred structure, including the nucleus, is $141.5^\circ$ in the plane of the sky, opening to the northwest, along the bar.

If the radio plasma in the bubbles is 25-50 million years old, as we estimated in § 3.3, the separation between the midpoint of the H$\alpha$ bubbles and the actual radio/H$\alpha$ 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 the 400 km $s^{-1}$ 3D velocity needed to create the X-ray front feature analyzed by MEM. The location of the extended, small-scale, radio emission along what presumably may be the leading edge of the bubble supports the suggestion of relative motion between the AGN and the X-ray gas. The bending angle of the radio source itself is nearly straight, $\sim 180$ degrees.

The X-ray plasma does not show a specific correspondence to the NE bubble, while the SE bubble does seem to coincide with an X-ray depression outlined by a partial ridge of

\(^3\)Interactive Data Language (IDL) is data visualization and image analysis software available from ITT Visual Information Systems, http://www.ittvis.com/.
higher X-ray surface brightness to the west. A partial ring of similar size (radius of 8.3"")
partial ring, with highest X-ray brightness along the western half of the ring is visible near
the NE bubble location. But it is centered at 03:38:41.2, +09°58′13.7″, approximately
6″ (4.2 kpc) south of the NE bubble. It may be a related bubble structure.

4.2. Other Multi-wavelength Identifications

The locations of the brightest points in the BCG in the SOAR Hα image, in the
HST/WFPC2 image, and in the radio image are within 0.5″ of each other. We identify
the nucleus of the BCG with Knot A in the long-slit spectrum (Figure 6, § 4.3). The center
of the BCG is also detected in the UV by the Optical Monitor on board XMM (§ 4.5). The
nucleus of the BCG, as seen by HST, seems to be near the middle 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″ or 9.6 kpc. The BCG nucleus is a faint peak in the X-ray emission. Knot
B (Figure 6, § 4.3) also has counterparts in all datasets, including the UV Optical Monitor
(XMM), the 3″ resolution VLA image, and the Chandra X-ray image.

The X-ray emission does not show a one-to-one structural correspondence with the Hα
emission (Figure 4), but there is a choppy ridge of high X-ray surface brightness that follows
the more pronounced Hα bridge between the two galaxies. Just outside the Hα nebula, to
the south, and past the X-ray peak, there is an X-ray edge (MEM). It’s 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 Hα nebula,
the X-ray surface brightness profile drops off suddenly, as if a minimum of X-ray surface
brightness were needed to host Hα filaments.

Our temperature map of the cluster shows that the Hα emission-line region lies entirely
within the 2.5 keV contour (Figure 5). This X-ray gas has the lowest entropy and shortest
cooling time in the cluster, and it has the same elongated morphology as the Hα 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 SW, one which may be associated with the
SW 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 Hα nebula, a fact we
will return to in § 4.5. As mentioned in § 3.3 and in § 4.1, the radio source appears to be
excavating bubbles on either side of the optical/radio nucleus, as seen in the Hα image and
(less prominently) in the X-ray image. From this analysis, we concluded in § 4.1 that the
AGN is probably in motion with respect to the optical nebula. This hypothesis is supported by the emission-line spectra analysis, which we will discuss next.

### 4.3. Velocity and Excitation Structure in the Emission Line System

We have identified four major features along the spectroscopic slit, identified jointly in Figure 6. The main nucleus is A, the companion nucleus is B. The filament to the SE and the filament gas to the NW are also labeled. Figures 7-8 plot the results of fitting each row of the 2-D spectrum between the wavelengths of 6750Å and 6850Å, which includes the Hα-[N II] emission line complex. We modeled this complex with three redshifted, identical-width Gaussians centered at rest wavelengths of 6548Å, 6562.5Å, and 6584Å, respectively, 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$^{-1}$ 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 Figures 7-8 are reported in the fourth column of Table 1. (For reference, Line 0 in Table 1 and in Figures 7-8 corresponds to Line 63 in the original CCD frame.)

These features are distinctly seen along the slit as peaks in the Hα line intensity (Figure 7). The locations of these peaks correspond approximately to changes in the velocity width (Figure 8), relative velocity (Figure 9), and [N II]/Hα ratio (Figure 10). The emission line regions somewhat SE of knot A and surrounding knot B exhibit broader emission lines (FWHM $\sim$ 500 – 600 km s$^{-1}$) than the rest of the nebula (FWHM $\sim$ 200 – 400 km s$^{-1}$) (Figure 8). Since both knots are associated with radio emission, this broadening may be indicative of AGN type activity in both nuclei. The presence of broadened emission line features is correlated with an noticeable enhancement of the [N II]6584 / Hα ratio (Figure 10). In the regions where the FWHM $> 400$ km s$^{-1}$, the mean [N II]/Hα ratio is $1.3 \pm 0.1$ and in the regions where the FWHM was lower, the corresponding ratio is $1.1 \pm 0.15$. 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 a source of supplemental heating above that from photoionization (e.g., Voit & Donahue 1997).

An examination of the relative velocities in Figure 9 shows the presence of at least two distinct velocity systems ($\bar{v} = 0.0347$), with a velocity difference of about 270 km s$^{-1}$. Knot A and the NW filament lie at about −120 to −150 km s$^{-1}$ relative to the mean, with the extreme velocity component of the NW filament at −180 km s$^{-1}$. The NW filament has somewhat broadened emission lines (400 km s$^{-1}$) with elevated [N II]/Hα as well. The SE
filament and Knot B are receding at about $+170 \text{ km s}^{-1}$ with respect to the mean velocity of the system.

The peak of the H$\alpha$ emission along the slit is somewhat more extended (by a factor of two) 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.

### 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 counter-rotating disk or an interacting system, with a tidally-induced bar. We also discuss the relationship to the motion of the cool clump seen in the X-ray images.

One interpretation of the complex optical emission-line velocity structure is that the filaments on either end of our extracted slit represent a large, rotating system around Knot A with a circular velocity of $170 \text{ km s}^{-1}$, and a diameter of about $20''$ or $14 \text{ kpc}$. This circular velocity and size implies a gravitating mass of at least $5 \times 10^{10} \text{ M}_\odot$. The center of this system lies close to the center of the BCG.

In this interpretation, the inner structure of the bar could be a counter-rotating disk, with a diameter of about $7.5''$ or $5.25 \text{ kpc}$ and a circular velocity of $150 \text{ km s}^{-1}$. The mean redshift of the bar may be somewhat greater than that of the more extended system, but only by about $30 \text{ km s}^{-1}$. The intensity peak of the H$\alpha$ emission lies near the center of this bar. The implied mass interior to $r = 3.5 \text{ kpc}$ is approximately $1.4 \times 10^{10} \text{ M}_\odot$.

A second, possibly more compelling interpretation of the velocity system is that it is the result of an interaction between the two nuclei, Knots A and B. The portion of the longslit spectrum with the broadest emission lines seems to lie closer to the southern end of this bar, not in the center of it. The bar of emission between Knots A and B may be a tidal stream of material, with a range of velocities along the stream, stretching from Knot A towards B. In this scenario, B passed between us and A, moving from east to west, drawing out a bar of hydrogen gas. It is now looping behind A, from our vantage point, with a component of velocity away from us and another component from west to east in the plane of the sky. The velocity of the filament gas to the west of B suggest that it either has decelerated to the velocity from of A, or belonged to A originally.

Knot A and the companion galaxy (Knot B) have a velocity separation of up to $300 \text{ km}$
s\(^{-1}\) along the line of sight, and a projected separation of 6.6\(''\) or 4.6 kpc. The crossing time therefore is about \(2.6 \times 10^7\) years. (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 \((\frac{G \rho}{2})^{1/2}\) for a system with \(M \sim 10^{10} M_\odot\) and \(r = 7\) kpc is about \(2 \times 10^8\) years.

Interesting dynamical information also comes from the X-ray image. Recall 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 \(\sim 0.75\) (MEM). This Mach number implies that the cool clump is moving with respect to the larger cluster at \(\sim 500\) km s\(^{-1}\). The relative position of the circular H\(\alpha\) bubbles and the AGN suggest that the AGN is 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 two bubbles are arranged symmetrically around the radio source, with a slight offset suggesting velocity in the plane of the sky of \(\sim 50 - 100\) km s\(^{-1}\). These clues indicate that the AGN may have originally been moving with the cool clump, but has not been decelerated by the drag against the surrounding ICM, like the cool clump has.

### 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 star formation rates (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 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 an \(\dot{M}(0.8 - 0.4\) keV\) = \(20 \pm 10\) M\(_\odot\) yr\(^{-1}\) and \(\dot{M}(0.4 - 0.2\) 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.

In order to obtain an independent estimate of the star formation rate in 2A0335+096, we reduced the X-ray MultiMirror Observatory (XMM) Optical/UV Monitor (OM) data of 2A0335+096, taken on August 4, 2003 (DataID 0147800201). OM is a 30 cm optical telescope mounted on the XMM which obtains optical and UV observation simultaneously with the X-ray observation. The BCG has a significant detection (15\(\sigma\)) in the UVW1 band (240-360 nm). The total UVW1 luminosity of the galaxy is \(5.8 \pm 0.4 \times 10^{42}\) erg s\(^{-1}\), after correcting for coincidence, deadtime loss, and Galactic extinction. The Galactic extinction of 2.48 magnitudes in the UVW1 band is based on Cardelli et al. (1989). Internal extinction is
unknown and is not included in this estimate. If we subtract the contribution from the passive stellar population, based on the empirical relation derived by Hicks & Mushotzky (2005), we derive a near UV-luminosity excess of $3.3 \pm 0.5 \times 10^{42} \, \text{erg s}^{-1}$. This excess corresponds to a SFR of $3.5 - 6.5 \, M_\odot \, \text{yr}^{-1}$ for an assumed Salpeter initial mass function with a power-law index of $2.35 - 3.3$. If we apply an internal extinction correction corresponding to $A_V \sim 1.0$ (typical for cooling flow nebulae, cf., 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 Hα emission. We note the Hα emission spans a much larger region ($r \sim 35''$ in radius) than that of the UV emission (within $7''$ radius). We conclude that the observed UV excess is consistent with the SFR inferred from the Hα observations.

Yet another independent constraint on star formation was sought from the IUE data archive. We inspected two archival IUE observations of 2A0335+096, SWP24934 and SWP43531. The short wavelength (SWP) camera on IUE, a 45-cm UV telescope (1978-1996) was sensitive to UV emission from 115-200.0 nm in a large aperture of $10'' \times 20''$, blueward of the XMM/OM UVW1 band. An upper limit to UV continuum was reported from the former observation of 10,800 seconds by Crawford & Fabian (1993). We analyzed a longer, later IUE observation, of 24,000 seconds, but we make only a marginal improvement on Crawford et al.’s original upper limit. Cosmic ray events obscure the spectrum at the position of red-shifted Lyman-α at the nominal pointing position. A $3\sigma$ limit of $< 2.4 \times 10^{-15} \, \text{erg s}^{-1} \, \text{cm}^{-2} \, \text{Å}^{-1}$, measured between 128 and 136 nm, was obtained, corresponding to a Galactic extinction-corrected flux limit of $6 \times 10^{-14} \, \text{erg s}^{-1} \, \text{cm}^{-2} \, \text{Å}^{-1}$. (No emission, extended or otherwise, is visible in the IUE field.) A Lyman α line with a width of 500 km s$^{-1}$ would be unresolved in an IUE spectrum (1.67 Angstroms per element), so a $3\sigma$ line would have to be about $4 \times 10^{-15} \, \text{erg s}^{-1} \, \text{cm}^{-2}$, corresponding to an upper limit of about $5 \times 10^{41} \, \text{erg s}^{-1}$ on Lyman α luminosity and $< 1.3 \times 10^{43} \, \text{erg s}^{-1}$ on continuum emission in a bandpass between 128-136 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 Hα luminosity we estimate for the system with no internal extinction. However, the amount of dust required to push the Lyman-α line below detectability by these IUE data is extremely small. Therefore, the lack of detection of either a Lyman-α line or an ultraviolet continuum from 2A0335+096 by IUE, together with detections by the XMM 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 $1.1 \pm 0.4 \times 10^{9} h_7^{2} \, \text{M}_\odot$. The gas supply would be completely used up in 100 million years, so technically, this system is arguably in a starburst, radio-emitting phase, either triggered by a recent interaction with a gas-rich system, or the interaction set off fireworks in gas accumulated from a modestly cooling ICM. The scenario of
cooling ICM is less tenable if the gas turns out to be dusty (Donahue & Voit 1993). Referring to the dust sputtering time in hot gas from Draine & Salpeter (1979), the hot gas in the core of this cluster sputters refractory grains with size $a < 0.1 \mu m$ (the majority of dust grains by number) in about $2 \times 10^7 n_{2}^{-1} a_{0.1}$ years where $n_2 = n_H/10^{-2} \text{ cm}^{-3}$ and $a_{0.1} = a/0.1 \mu m$.

5. Summary and Conclusions

We summarize our results as follows.

1. Our SOAR H$\alpha$ image of 2A0335+096 is deeper, more sensitive, and has better seeing than the one presented in RH88. We clearly detect the emission-line bubble on the other side of the galaxy, and we see filamentary details in excellent relief. We don’t detect much more H$\alpha$ beyond $\sim 25 \text{ kpc}$ from the central galaxy. These observations limit the presence of somewhat lower low-surface brightness emission-line gas at large radii ($\sim 3 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ on scales of $1'' - 3''$).

2. In the frame of the AGN (indicated by the center of the BCG, Knot A), the NW filament/blob is moving toward us, and the SE filament/blob is moving away from us. However, a 2-D velocity map would be required to confirm whether the large-scale nebula is rotating in the frame of the AGN.

3. The main evidence for a 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.

4. 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. The passage of the companion galaxy may have induced star formation possibly in pre-existing 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 is now proceeding back SE. The gas in the NW filament has the same systematic velocity as A. It is possible that tidal stripping or drag against the ICM has decelerated the gas trailing companion B to be co-moving with the BCG and its surrounding X-ray gas.

5. 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 radio image we present here shows two close-in lobes of radio plasma. The optical emission-line filaments and the X-ray emitting plasma filaments and Hα filaments 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 completes the picture of the X-ray/optical/radio bubble structure in this source.

6. We have derived a star-formation rate from the UV/OM images of AGN, which is consistent with constraints on the X-ray mass cooling rate from XMM RGS spectra. The total Hα luminosity is also consistent with the estimated star formation rate and rate of gas cooling from X-ray emitting temperatures. This consistency suggests 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 either by the X-ray cooling rate or the star formation rate), (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 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 the interaction of a companion galaxy with the BCG is the trigger for the radio source and the starburst event. Whether or not the cooling flow was required to supply the gas that feeds the black hole and that supplies the starburst is uncertain, but the mass cooling rates inferred from the XMM RGS spectrum are consistent with the star formation rates inferred from 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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are presenting data obtained with the Southern Astrophysical Research Telescope, which is a joint project of Conselho Nacional de Pesquisas Científicas e Tecnológicas CNPq-Brazil, the University of North Carolina at Chapel Hill, Michigan State University, and the National Optical Astronomy Observatory. Palomar data were obtained by MD through an agreement between the California Institute of Technology and the Observatories of the Carnegie Institution of Washington in Pasadena, California. We would like to acknowledge the valuable contributions of the Palomar telescope operator Juan Carrasco and of the SOAR service observer Dr. Kepler de Souza Oliveira.

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Fig. 1.— A logarithmically-scaled version of the continuum-subtracted emission-line image of 2A0335+096 from SOAR Optical Imager. North is up and East is to the left in this figure. The nuclei of the BCG and the companion are labeled A and B respectively. The emission-line image shows both emission-line knots embedded in filaments. The filaments curve in arcs that extend above and below the emission line bar.
Fig. 2.— Radio contours of the highest resolution VLA image (3″) overlaid on the optical emission line greyscale image. The radio data were obtained Sept 22, 1987 and reprocessed on March 30, 2006. The (red) radio contour levels are 0.5, 1.0, 1.5, 2.0, 6.0 mJy per beam. The black circles are the approximate locations of the circular emission-line features, 8.25″ and 8.29″ in radius. The NE bubble is on the left, the SW bubble is on the right. The peak of the radio source aligns within 1″ of the peak of the emission-line source in the BCG.
Fig. 3.— A grey scale image of 2A0335+096 from the archival HST WFPC2 red (F606W) filter imaging. North is up and East is to the left in this figure. The grey scale image to the right is a high contrast scaled image of the same image, indicated by the box on the left image.
Fig. 4.— Left, a color-coded image of the adaptively-binned (5σ) 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 seconds. 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, a contour map of the X-ray surface brightness isophotes are 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. However, some X-ray structure does coincide with the general distribution of emission-line gas, including the correspondence of X-ray and Hα holes to the west of the bar, and a long emission feature extending N-S about 10 kpc to the east of the bar. We note also that the Hα appears to be limited to the region where the X-ray surface brightness is greater than about 3 photons per pixel, which is an approximate X-ray surface brightness of $3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. 
Fig. 5.— A grey-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 (< 1.5 keV correspond to the brightest Hα lumps (except for the X-ray lump obscured by the bright star to the south-east.) North is up, East is left.
Fig. 6.— The position angle and slit position position for the next 4 plots. The line on the 2-D long-slit spectrum is 60 pixels long, starting from the pixel 0 on the lower left hand side. The length of that line matches the length of the slit pictured on the right-hand image showing the angle and width of the spectroscopic slit. The actual full slit was 2 arcminutes in length and 2 arcseconds wide. The 60 pixels (29 arcseconds) spanning the length of the slit was used for the flux calibration of the SOAR emission-line image.
Fig. 7.— Hα intensity as a function of slit position. The brightest peak of the Hα emission is centered in the BCG stellar continuum. A comparison of this figure with Figure 8 and inspection of the 2D grey scale will show that the broadest emission lines are located somewhat SE of the brightest Hα peak.
Fig. 8.— The mean width of the H\(\alpha\) and [N II] lines in \(\text{km s}^{-1}\) at each position along the slit. A Gaussian shape was assumed to estimate the FWHM from the width \(\sigma\) of the Gaussian lines, where \(\text{FWHM} = 2(2 \log 2)^{1/2}\sigma\).
Fig. 9.— The mean recession velocity of all 62 positions along the slit was 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.
Fig. 10.— The ratio of the integrated [N II] 6584 line to the Hα line, assuming that the lines were 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 NW filament.
Table 1. Summary of Emission-Line Features

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<tr>
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<tbody>
<tr>
<td>A</td>
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<td>16-25</td>
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<td></td>
<td>26-29</td>
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<td>37-60</td>
<td>0.0343 (0.0341-0.0347)</td>
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<tr>
<td>SE Fil. b</td>
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<td>+09:58:04</td>
<td>0-10</td>
<td>0.0352 (0.0351-0.0353)</td>
</tr>
</tbody>
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aEach pixel in the spatial direction is 0.47 arcseconds. The slit width was 2 arcseconds.

bThese locations are approximate, within 3″.