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AN EXTREMELY MASSIVE DRY GALAXY MERGER IN A MODERATE REDSHIFT CLUSTER

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ABSTRACT

We have identified perhaps the largest major galaxy merger ever seen. While analysing *Spitzer* IRAC images of CL0958+4702, an X-ray-selected cluster at z=0.39, we discovered an unusual plume of stars extending $\gtrsim 110h^{-1}$kpc outward from the bright central galaxy (BCG). Three galaxies 1-1.5 mag fainter than the BCG lie within 17 kpc (projected) of the BCG and are probably participating in the merger. The plume is detected in all four IRAC channels and at optical wavelengths in images from the WIYN telescope; the surface brightness is remarkably high ($\mu_r \approx$24.8 mag arcsec^{-2} at 50 kpc). The optical and infrared colors are consistent with those of other BCGs, suggesting that the plume is composed of old stars and negligible recent star formation (hence a "dry merger"). The luminosity in the plume is at least equivalent to a $4L^*$ galaxy. A diffuse halo extending $110h^{-1}$kpc from the BCG in one IRAC image suggests the total amount of diffuse light is $L_r \sim 1.3\times10^{11}h^{-2}L_\odot$. A *Chandra* observation shows an X-ray image and spectrum typical of moderate-mass clusters. We use MMT/Hectospec to measure 905 redshifts in a 1 deg^2 region around the cluster. The velocities of two of the BCG companions indicate a merger timescale for the companion galaxies of ∼110 Myr and ∼0.5-1 Gyr for the plume. We conclude that the BCG and intracluster light of CL0958 is formed by major mergers at moderate redshifts. After the major merger is complete, CL0958 will likely become a fossil cluster.

Subject headings: galaxies: clusters: individual (CL0958+4702) — galaxies: interactions — galaxies: cD — galaxies: kinematics and dynamics

1. INTRODUCTION

Galaxies in the centers of clusters likely experience many mergers during their formation. Numerical simulations of cluster formation often show frequent mergers of small galaxies with a larger, central galaxy (e.g., Dubinski 1998). Supporting this view, many central cluster galaxies contain multiple components, and some cluster galaxies at high redshift are apparently merging pairs (Lauer 1988; van Dokkum et al. 1999; Yamada et al. 2002; Tran et al. 2005). One bright galaxy (the "Spiderweb") in a protocluster at z=2.16 is apparently undergoing several minor mergers (Miley et al. 2006). Some of these mergers likely produce the intracluster light seen in nearby clusters (Zwicky 1951; Gonzalez et al. 2000; Mihos et al. 2005; Krick & Bernstein 2007). Deep optical observations of early-type field galaxies also reveal features associated with either ongoing mergers or merger remnants (van Dokkum 2005). These features typically contribute ∼5% of the total starlight: features of this brightness can be produced by either major or minor mergers (van Dokkum 2005; Kawata et al. 2006).

We report here the biggest major galaxy merger ever seen (to our knowledge), involving the near-complete disruption of a galaxy comparable to a brightest cluster galaxy (BCG). This cosmic collision is set in CL0958+4702, an X-ray cluster at moderate redshift (z=0.39) discovered with *ROSAT*. Molthagen et al. (1997) identified a galaxy with z=0.39 as the optical counterpart (although they did not classify it as a cluster). CL0958 was reidentified in the 400 Square Degree serendipitous survey (400d) of clusters and groups in pointed *ROSAT* observations (Burenin et al. 2006).

As part of a multiwavelength observing campaign of 400d clusters, we discovered that CL0958 displays an unusual plume of emission in *Spitzer* IRAC images. Further analysis indicates that the emission is coming from an old stellar population at the redshift of the cluster. This evidence suggests that CL0958 is undergoing a major dry merger. The amount of starlight in the plume is at least equal to a $4L^*$ galaxy.

CL0958 presents a dramatic example of intracluster light; extended emission is clearly detected in optical images from the WIYN telescope and in mid-infrared images from *Spitzer* IRAC data. We determine that CL0958 will probably evolve into a fossil cluster, i.e., a cluster in which the second-brightest member is $\gtrsim$2 mag fainter than the BCG (Ponman et al. 1994; Jones et al. 2000). Fossil groups and fossil clusters are thought to be produced either from unusual initial conditions or from the mergers of several bright cluster members into one dominant BCG (e.g., Milosavljević et al. 2006). CL0958 provides a dramatic example of the merger scenario in progress.

A more complete description of the properties of CL0958 will be made in Rines et al. (2007). Here we describe the basic features of the multiwavelength data. We assume cosmological parameters of Ω_m=0.3, Ω_Λ=0.7, and H_0=100$h$km s^{-1} Mpc^{-1}. At the redshift of the cluster (z=0.39), the spatial scale is 1″=3.7 h^{-1}kpc.

2. OBSERVATIONS

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2.1. *Optical Imaging*

We observed CL0958 (and other 400d clusters) with the WIYN telescope in 2005 December. We obtained *griz* imaging with the OPTIC camera (Tonry et al. 2002; Howell et al. 2003) with the goal of identifying cluster members up to 3 mag fainter than M^*. Figure 1 shows the r image from a non-photometric night with 0.″5 seeing. Surrounding the main component of the BCG are three faint components and an asymmetric plume of low surface brightness emission extending primarily NW of the BCG (outlined by contours). The morphology of the plume is very similar to that seen in the late stages of simulations of dry mergers (e.g., Figure 4 of Dubinski 1998, Figure 1 of van Dokkum 2005). The extended emission shows little small-scale structure at the resolution of these images. Note that merger features identified in early-type field galaxies similarly show little small-scale structure in contrast to tidal features seen around late-type galaxies (van Dokkum 2005). Using the Sloan Digital Sky Survey (SDSS, Stoughton et al. 2002) for calibration, we estimate that the outer contour in Figure 1 is $\mu_r \approx 24.8$ mag arcsec^{-2}. Corrected for cosmological surface brightness dimming, the plume in CL0958 has much higher surface brightness ($\mu_r \approx 23.4$) than intracluster light and even some cD envelopes in nearby clusters (e.g., Schombert 1988; Gonzalez et al. 2000; Mihos et al. 2005; Krick & Bernstein 2007).

The three companions to the BCG are likely cluster galaxies participating in the major merger. Assigning flux to the various components is challenging. We use SExtractor (Bertin & Arnouts 1996) to measure relative magnitudes of the BCG and its three companions within 1" diameter apertures: the N,E, and SE companions are respectively +1.32,+1.09, and +1.29 mag fainter than the BCG. The BCG has absolute magnitude $M_r \approx$-21.6 or $L_r \sim 3\times10^{10} h^{-2} L_\odot$ (we use Table A1 of Wake et al. 2006, to correct for bandpass shifting and passive evolution). The plume has a total magnitude r$\sim$18.8 ($L_r \sim 5\times10^{10} h^{-2} L_\odot$) and contains $\sim$46% of the total light in the region enclosed by the contours in Figure 1, although this fraction depends sensitively on the parameters used to estimate the contribution of the BCG and BCG companions (e.g., see Gonzalez et al. 2005). The plume is visible to a similar spatial extent in i band, and is marginally detectable in g and z, consistent with the plume having colors typical of an old stellar population.

2.2. *Mid-Infrared Imaging*

We are observing several 400d clusters with *Spitzer* to measure the star formation rates in X-ray clusters and their dependence on redshift and cluster mass (GO2 Program 20225). CL0958 was imaged with IRAC with 100 s exposures using the 12-point Realeaux dither pattern with "medium" dither size. We processed the Basic Calibration Data (BCD) files with the Post-BCD software MOPEX after using the IRAC artifact mitigation codes provided by Sean Carey.

Figure 1 shows IRAC images from the 3.6 and 4.5μm channels. The emission seen in the WIYN images is clearly visible. The emission is weakest in the 8.0 μm band, so we measure the colors of the BCG and the plume in two regions where the emission is significant

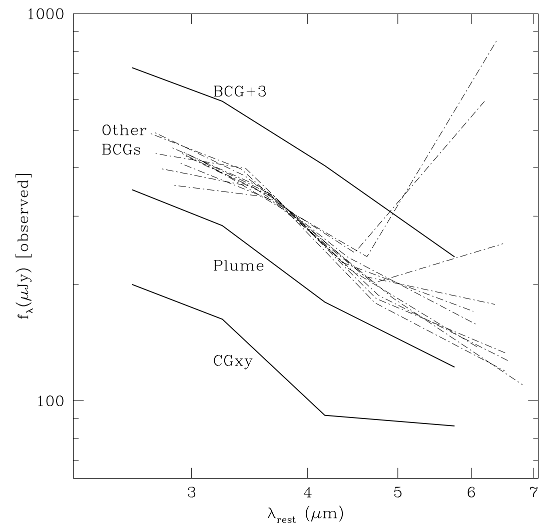

FIG. 2.— Spectral energy distribution of the BCG (including companions) and the plume of emission. SEDs of another cluster member (labeled "CGxy") and of several BCGs from Egami et al. (2006, dash-dotted lines, scaled to cross at around 4μm) are shown for comparison. Note that the IRAC resolution complicates separating the BCG light from the companions. The spectra of the BCG and two of the companions show early-type populations, so the color differences are probably small.

at 8.0 μm. Specifically, we measure the flux in two boxes of 11×8 IRAC pixels, or 35×50 h^{-1}kpc (shown in Figure 1) as well as for another cluster galaxy and background regions. The box containing the BCG also contains the three BCG companions. The IRAC colors (Figure 2) agree very well with those of non-star-forming BCGs observed by Egami et al. (2006). The luminosity contained in the box around the plume is $\approx$48% of that contained in the box containing the BCG and companions. Note that the luminosity of the plume may be slightly overestimated due to both light from the wings of the PSF of the BCG and to the IRAC calibration technique, which is optimized for photometry of point sources.[5] These two effects could lead to a $\sim$10-20% overestimate of the flux of the plume within this box. Intracluster light and merger remnants in the nearby universe typically extend to extremely low surface brightnesses (e.g., Mihos et al. 2005; van Dokkum 2005), so the above is probably a lower limit on the total light in the plume. Indeed, the 3.6 μm image clearly shows extended low surface brightness emission $\gtrsim 110 h^{-1}$kpc from the BCG (Fig. 1). Using SExtractor to estimate the light in different apertures, we estimate the total diffuse light in this halo to be $L_r \sim 1.3\times10^{11} h^{-2} L_\odot$ [rest-frame r-band corrected for passive evolution; we estimate $(r - 3.6\mu m) \approx 4.2$ from 8 spectroscopically confirmed cluster members]. Comparison to the BCGs observed by Egami et al. (2006) shows that CL0958 is anomalous: most moderate-redshift clusters contain several bright galaxies near the X-ray center, and none show extended emission similar to that in CL0958.

The IRAC colors of both the BCG and the plume indicate that the ongoing merger is a dry merger: i.e., there is little or no star formation triggered by the merger. This result shows that the progenitor galaxies contained little

[5] See http://ssc.spitzer.caltech.edu/irac/calib/extcal/index.html

or no gas, suggesting that the gas around cluster galaxies is efficiently removed by the cluster, e.g., by tidal stripping or ram pressure stripping by the intracluster medium (Gunn & Gott 1972; Merritt 1985). The fact that the plume is composed of an old stellar population demonstrates that the plume is not created by recent star formation, e.g., from a massive cooling flow not centered on the BCG. Further, comparison to the BCGs of Egami et al. (2006) indicates that the plume has less recent star formation than some BCGs. We conclude that the plume was recently created through a "dry" merger, i.e., a merger where the progenitor galaxies contain little or no gas such that little star formation is triggered by the merger (e.g., Bell et al. 2006).

2.3. *X-ray Observations*

CL0958 was observed with *Chandra* for 35 ks as part of a *Chandra* survey of 400d clusters. Complete details on these observations will be presented in Vikhlinin et al. (2007). The X-ray emission is regular and shows a slight elongation in the direction of the stellar plume. The spectrum yields a temperature of 3.6 ± 0.8keV. The X-ray luminosity is L_X=5.0×10$^{43}h^{-2}$erg s^{-1}, making CL0958 a moderately luminous cluster, intermediate in both L_X and T_X to Virgo and Abell 2199 (Rines & Diaferio 2006). There is no evidence for a cooling flow in CL0958, supporting our conclusion from the IRAC colors that the plume is not created by cooling of the ICM and subsequent star formation. The X-ray data show little evidence of the dynamical activity suggested by the extended optical light. We find no evidence of any AGNs in the *Chandra* field. The upper limit on AGNs at the cluster redshift is L_X<6×10^{41}erg s^{-1}.

2.4. *Optical Spectroscopy*

We obtained optical spectroscopy of CL0958 with MMT/Hectospec with the 270-line grating (yielding 6.2Å FWHM resolution, Fabricant et al. 2005) in 2007 February. Because the Hectospec field (1° diameter) is much larger than the WIYN images (10′×10′), we used imaging data from SDSS to select targets for spectroscopy. We observed CL0958 with four configurations (one in marginal conditions) and obtained 905 redshifts. A full discussion of the spectroscopy will be presented in Rines et al. (2007). Here we highlight the results relevant to the major merger.

A spectrum of the BCG shows a typical early-type galaxy with no evidence of recent star formation from either [OII] in emission or Hδ in absorption. The 4000Å break is strong, typical of an old stellar population. We obtained spectra of the N and SE BCG companions, which have early-type spectra and rest-frame velocities of -63±41km s^{-1} and +86±41km s^{-1} respectively relative to the BCG (redshift uncertainties estimated from repeat observations, see Fabricant et al. 2005). These redshifts provide strong evidence that the N and SE BCG companions are physically close to the BCG; it is highly unlikely that they are chance projections of cluster members from the outskirts of the cluster. This close association supports the possibility that these companions are the remaining nuclei of larger galaxies disrupted in the merger.

We identify 21 galaxies within 1 Abell radius of the BCG as likely cluster members based on the redshift-radius distribution (Rines et al. 2007). These members yield a projected velocity dispersion of σ_p=521$^{+107}_{-66}$km s^{-1} using the procedure of Danese et al. (1980). However, there is a noticeable core of 11 galaxies within 0.8h^{-1}Mpc with a projected velocity dispersion of σ_p=244$^{+80}_{-41}$km s^{-1}. Assuming the galaxies trace the dark matter, the scaling relation of Evrard et al. (2007) yields a virial mass estimate of M_{200} ≈9.2 (1.0)×10$^{13}h^{-1}M_\odot$ using the upper (lower) estimates of the velocity dispersion. Identification of more cluster members is required to robustly estimate the projected velocity dispersion.

3. DISCUSSION

With the multiwavelength data, we can estimate the timescale of the merger. The spatial scale is set by the limit of the plume, which extends to ≈110 *kpc* in the 3.6 μm image. Assuming that the plume has similar velocity to the BCG companions, the velocity scale is $\lesssim$100km s^{-1}. These scales suggest a timescale of order 0.5-1 Gyr for the merger remnant to form a relaxed distribution around the BCG. This timescale suggests that major mergers might be fairly common in deep images of galaxy clusters.

The BCG companions lie much closer to the BCG than the plume; thus, they will likely merge more quickly. The dynamical friction timescale can be estimated as

$$T_{\rm fric} = \frac{2\times 10^5 r^2 v_c}{M \log\Lambda}{\rm Gyr} \quad (1)$$

(Patton et al. 2000). Correcting for projection assuming random orientation of r_p and v_p $[r^2 v_c = (3/2) r_p^2(\sqrt{3}) v_p]$, we estimate $T_{\rm fric}$≈110 Myr for a companion galaxy mass of $\approx 5\times10^{10}M_\odot$ (the BCG companions are ≈L^* galaxies and we assume $M/L_r \approx 5M_\odot/L_\odot$). We are therefore observing CL0958 at a fairly special time in its history. The unusual properties of CL0958 have implications for at least two categories of cluster studies: intracluster light and the origin of fossil groups and clusters.

3.1. *Intracluster Light*

The unusual extended emission around the BCG of CL0958 provides a powerful confirmation of the importance of intracluster light to the total optical luminosity and direct evidence for its origin. The surface brightness and spatial extent of the emission is perhaps the largest detected to date. The dearth of cluster galaxies (other than the BCG companions) with magnitudes comparable to the BCG suggests that the BCG is forming via a major merger. The intracluster light could be the leftover stars from bright galaxies that have recently been disrupted or stars that have been stripped from the BCG companions. CL0958 demonstrates that at least some intracluster light is produced by extreme dynamic events in cluster centers as opposed to slower mechanisms. Indeed, the detailed simulations of Murante et al. (2006) suggest that most intracluster light is produced by the mergers that form the BCG rather than from tidal stripping.

Major ongoing dry mergers appear to be rare in BCGs: images of 35 BCGs at z<0.1 in Figure 3 of von der Linden et al. (2006) show no mergers similar to that in CL0958, although several BCGs have multiple components: these may be major mergers observed at an earlier stage (Lauer 1988). CL0958 indicates that ongoing mergers may be more common at higher redshift, as would be expected in hierarchical models of BCG formation (De Lucia & Blaizot 2007).

3.2. *The Origin of "Fossil" Groups and Clusters*

The multiwavelength properties of CL0958 clearly indicate that it is a moderately massive cluster with X-ray properties (and possibly also velocity dispersion) comparable to (1-5)$\times 10^{14} h^{-1} M_\odot$ clusters. Once the three BCG companions merge with the BCG, the BCG will be $\sim$1.3 mag brighter than the next-brightest galaxy (in observed r-band). Depending on the fraction of the plume that accretes onto the BCG, within $\sim$1 Gyr the BCG will be $\sim$2 mag brighter than the next-brightest galaxy. These properties would make CL0958 a "fossil cluster", that is, a fossil group with $M \gtrsim 10^{14} h^{-1} M_\odot$ (Khosroshahi et al. 2006).

There are two basic mechanisms that could produce fossil groups and fossil clusters. Either initial conditions of the forming group lead to the formation of an extremely dominant BCG/BGG, or several bright group galaxies merge after the initial collapse of the group. One difficulty with the merger hypothesis is that dynamical friction is less efficient for cluster galaxies that have been tidally stripped by the cluster potential (Merritt 1985). However, more recent theoretical models suggest that cluster merger variance should occasionally produce such systems (Milosavljević et al. 2006). The major dry merger in CL0958 shows that fossil clusters and groups can be produced by major mergers of bright galaxies in the system centers. Deep optical and infrared observations of the other known fossil clusters and groups may reveal less dramatic evidence of merger activity.

4. CONCLUSIONS

We have identified a massive stellar plume formed by a major dry merger in an X-ray cluster at z=0.39. The amount of light contained in the merger suggests that the equivalent of a $4L^*$ galaxy in stars is currently visible as a merger remnant; an additional $\sim 10^{11} L_\odot$ is visible in a diffuse halo of intracluster light. To our knowledge, this is the most massive major galaxy merger ever identified (the "Spiderweb" galaxy is an ensemble of minor mergers Miley et al. 2006). The colors of the plume indicate that it is composed of an old stellar population, consistent with origin in early-type cluster galaxies and inconsistent with recent star formation. This remnant will likely merge with the BCG in $\lesssim$1 Gyr, while three galaxies very close to the BCG will probably merge within $\sim$110 Myr. After these galaxies and the plume have merged with the BCG, CL0958 will likely form a "fossil cluster". Theoretical models of BCG assembly indicate that BCGs can be assembled quite late, but these models predict that most of this growth occurs through minor mergers De Lucia & Blaizot (2007). Possible substructure in the galaxy dynamics complicates the measurement of the velocity dispersion. The existence of this major dry merger demonstrates that intracluster light can be formed in extreme dynamic events and that fossil clusters are at least sometimes formed by major mergers in their centers.

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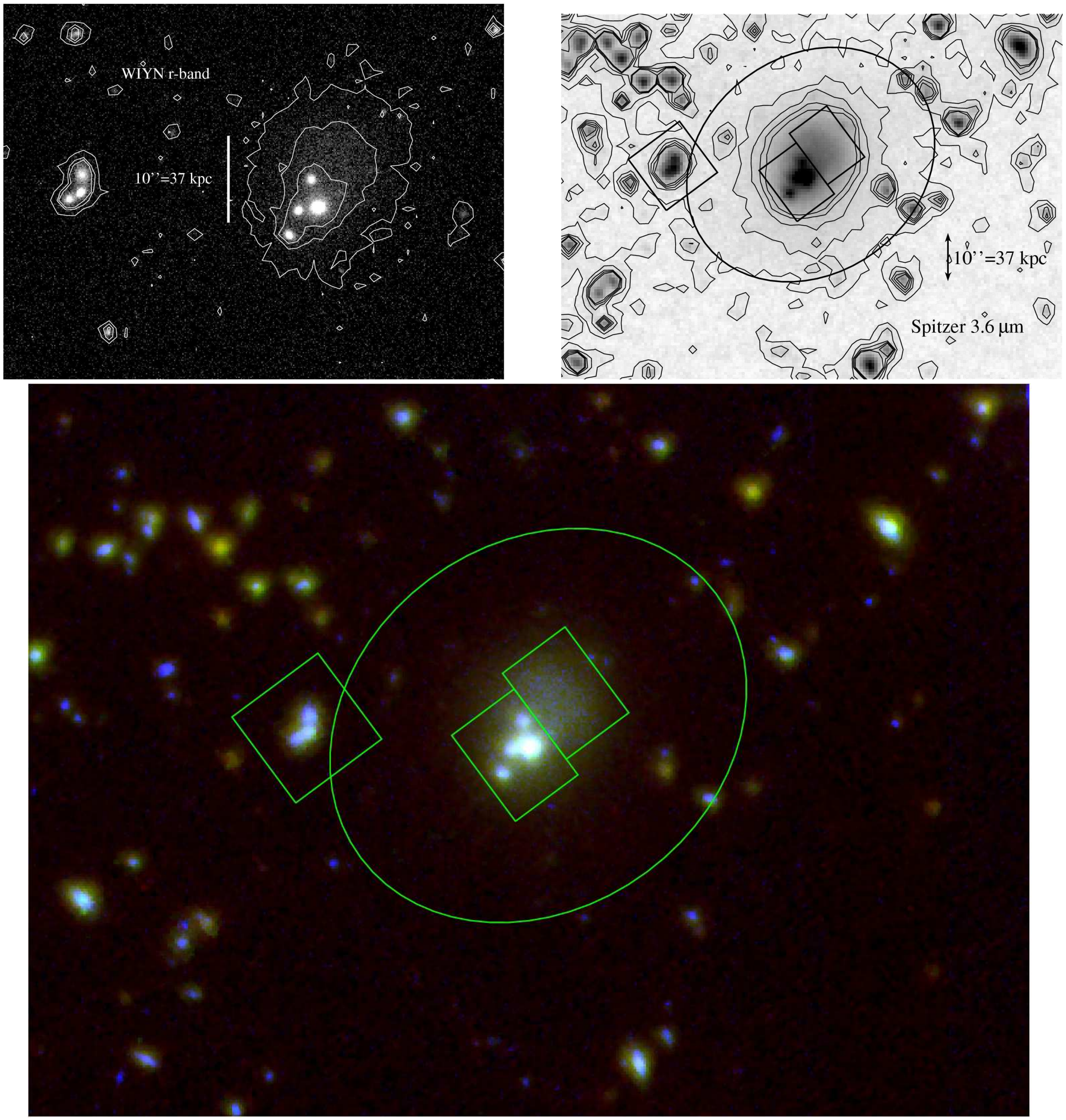

FIG. 1.— Upper left: 2×120-s r-band WIYN image taken with OPTIC in $0\farcs5$ seeing. The contours show surface brightness levels of μ_r = 24.82,24.79, and 24.76 mag arcsec^{-2}. The BCG has three companion galaxies within $17h^{-1}$kpc to the N, E, and SE. Upper right: IRAC 3.6μm image. Contours are linearly spaced between 0.07 and 0.11 MJy ster^{-1}. The ellipse approximately indicates the spatial extent of the plume. Boxes identify the regions used to measure the SED of the plume, BCG+3, and a nearby cluster galaxy (itself a likely merger in progress). Bottom: False-color image of CL0958. WIYN r-band image in blue, *Spitzer* IRAC 3.6μm image in green, IRAC 4.5μm image in red. All images are oriented with North up and East to the left.