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THE SPIDERWEB GALAXY: A FORMING MASSIVE CLUSTER GALAXY AT $z \sim 2$

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ABSTRACT

We present a deep image of the radio galaxy MRC 1138−262 taken with the *Hubble Space Telescope* (*HST*) at a redshift of $z = 2.2$. The galaxy is known to have properties of a cD galaxy progenitor and be surrounded by a 3 Mpc–sized structure, identified with a protocluster. The morphology shown on the new deep *HST* ACS image is reminiscent of a spider's web. More than 10 individual clumpy features are observed, apparently star-forming satellite galaxies in the process of merging with the progenitor of a dominant cluster galaxy 11 Gyr ago. There is an extended emission component, implying that star formation was occurring over a 50 × 40 kpc region at a rate of more than 100 $M_{\odot}$ yr^{-1}. A striking feature of the newly named "Spiderweb galaxy" is the presence of several faint linear galaxies within the merging structure. The dense environments and fast galaxy motions at the centers of protoclusters may stimulate the formation of these structures, which dominate the faint resolved galaxy populations in the Hubble Ultra Deep Field. The new image provides a unique testbed for simulations of forming dominant cluster galaxies.

Subject headings: galaxies: active — galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: high-redshift

1. INTRODUCTION

Distant powerful radio galaxies are important laboratories for studying the formation and evolution of massive galaxies, because they are among the most luminous and largest known galaxies in the early universe and likely progenitors of dominant cluster galaxies (e.g., Miley 2000).

They are generally embedded in giant (cD-sized) ionized gas halos (e.g., van Ojik et al. 1997) surrounded by galaxy overdensities, whose structures have sizes of a few Mpc (Pentericci et al. 2000; Venemans et al. 2002, 2005). The radio galaxy hosts have clumpy optical morphologies (Pentericci et al. 1998, 1999), spectra indicative of extreme star formation (e.g., Dey et al. 1997), and large stellar masses (Villar-Martín et al. 2006). Because the radio lifetimes (few times 10^7 yr) are much smaller than cosmological timescales, the statistics are consistent with every dominant cluster galaxy having gone through a luminous radio phase during its evolution (Venemans et al. 2002). Hence, distant radio galaxies may be typical progenitors of galaxies that dominate the cores of local clusters.

The radio source MRC 1138−262, identified with a galaxy at $z = 2.168$, is one of the most intensively studied distant radio galaxies (Pentericci et al. 1997, 1998). Several of its properties are those expected of the progenitor of a dominant cluster galaxy. The *K*-band luminosity corresponds to a stellar mass of $\sim 10^{12}\, M_{\odot}$ (Pentericci et al. 1998), implying that MRC 1138−262 is one of the most massive galaxies known at $z > 2$. The host galaxy is surrounded by a giant Lyα halo (Pentericci et al. 2000; Kurk et al. 2004b), and the Faraday rotation of the radio source is among the largest known (Carilli et al. 1997), indicating that the system is embedded in a dense hot ionized gas with an ordered magnetic field.

The radio galaxy is associated with a 3 Mpc–sized structure of galaxies, of estimated mass $\sim 2 \times 10^{14}\, M_{\odot}$, the presumed antecedent of a local cluster. The presence of this "protocluster" has been deduced using three independent selection techniques. There are overdensities of Lyα and Hα emission lines objects and galaxies having 4000 Å break continuum features at the approximate redshift of the radio galaxy (Pentericci et al. 2000; Kurk et al. 2004a, 2004b).

Previous observations of MRC 1138−262 with the *Hubble Space Telescope* (*HST*) indicated that its optical emission is clumpy (Pentericci et al. 1998), indicative of a merging structure. Here we present a new *HST* image of the radio galaxy that reaches 2 mag fainter than previous images and shows the merging processes in unprecedented detail.

Throughout this Letter we assume a standard cosmology with $H_0 = 72$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$, implying that at the distance of MRC 1138−262, an angular scale of 1″ corresponds to a projected linear scale of 8.3 kpc.

2. OBSERVATIONS

We obtained deep images of MRC 1138−262 with the Advanced Camera for Surveys (ACS; Ford et al. 1998) on the *HST*. The center of the 1138−262 protocluster was observed with the ACS during 2005 May 17–22 in two 3′.4 × 3′.4 ACS fields that overlapped by 1′ in a region that includes the radio galaxy. The total exposure time in the overlapping region was nine orbits with the F475W (g_{475}) filter and 10 orbits with the F814W (I_{814}) filter. The filters were selected to sample the continuum radiation with maximum sensitivity and color discrimination, while minimizing contamination from bright emission

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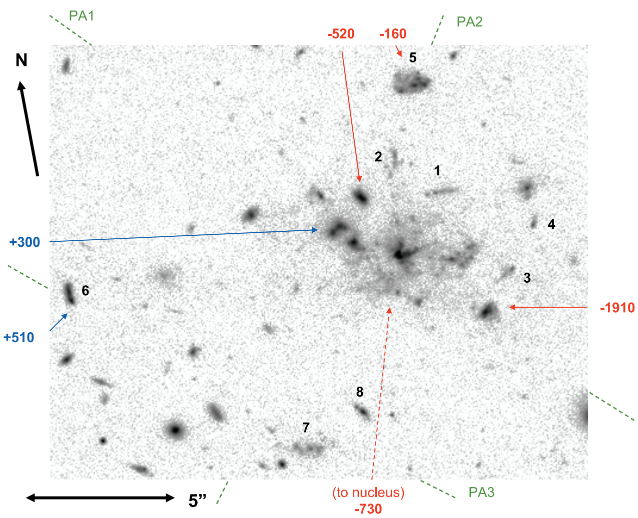

FIG. 1.—Composite image of a 23″ × 18″ region at the core of the MRC 1138−262 protocluster taken with the ACS through the $g_{475} + I_{814}$ filters, using a total of 19 orbits. Also shown are hitherto unpublished rest-frame Lyα emission velocities in kilometers per second, measured through 1″ wide spectrograph slits in three position angles indicated by the dashed lines. These were obtained using the FORS on the Antu telescope of the VLT during 2000 March and April (Kurk 2003). The velocities were measured at the peaks of the Lyα emission profiles and are relative to the median velocity of Lyα absorption. Following Kurk (2003) the nucleus is taken to be the position of the peak Hα. This coincides with the peak in ACS continuum emission, indicated by the extrapolation of the red arrow corresponding to -730 km s^{-1}, the velocity of the nuclear Lyα emission. Eight of the satellite galaxies (flies) that have chain, tadpole, or clumpy morphologies are indicated by numerals 1–8.

lines. Although the C IV λ1549 and He II λ1640 lines fall within the g_{475} passband, their measured rest-frame equivalent widths are 6 and 10 Å, respectively (Röttgering et al. 1997), implying that their effect on the continuum image is negligible. The observations were processed through the ACS GTO pipeline (Blakeslee et al. 2003) to produce registered, cosmic-ray rejected images. A deep 19 orbit composite image of the continuum emission was then produced by adding the g_{475} and I_{814} images. The 2 σ depth in the overlapping region is 29.3 and 29.0 mag in the respective g_{475} and I_{814} images measured in a square 0″.45 diameter aperture.

3. RESULTS

The *HST* image of the host galaxy and its immediate surroundings is shown in Figure 1, with rest-frame velocities of the Lyα emission corresponding to several of the ACS continuum clumps. Figure 2 illustrates the relation of the continuum optical emission to the associated gaseous halo and relativistic plasma. The giant gaseous halo extends by at least 25″ (~200 kpc) and is one of the largest Lyα structures known in the universe.

There are several features in the figures that are of interest:

1. The optical continuum emission of the galaxy consists of at least 10 distinct clumps. The clumps are presumably satellite galaxies that are still merging with MRC 1138−262. They have sizes of typically ~0″.1–0″.5, corresponding to ~1–5 kpc, i.e., comparable to the typical sizes of Lyman break galaxies (Ferguson et al. 2004; Bouwens et al. 2004).

2. Several of the satellites have elongated structures reminiscent of chain and tadpole galaxies recently found to dominate the resolved population of the Hubble Ultra Deep Field (HUDF; Elmegreen et al. 2005; Straughn et al. 2006). Examples are denoted by numbers 1, 3, and 4 in Figure 1. Another linear, distorted galaxy is seen 3″ north of the nucleus (2), and several galaxies having double (6, 8) or clumpy morphologies embedded in diffuse emission (5, 7) lie at slightly larger distances from the main complex. These objects have $g_{475} - I_{814}$ colors of between 0.1 and 0.7 mag and I_{814} magnitudes of between 24.3 and 27.7, consistent with star formation at rates between 0.5 and 26 $M_\odot$ yr^{-1} (Madau et al. 1998).

To determine whether there is a concentration of such objects around the radio galaxy, we analyzed the statistics of tadpole and chain galaxies having $23 < I_{814} < 27$ in the whole 3′ × 5′ ACS field around MRC 1138−262. To minimize systematic effects, the morphologies were classified manually by somebody not previously associated with the project (E. H.)

In the 10″ × 10″ area around the radio galaxy, three such objects were found (objects 1, 3, and 4 in Fig. 1). This should be compared with an expected number of 0.22 from our analysis of the whole field, a value consistent with the HUDF analysis of Elmegreen et al. (2005). Taking into account the clustering of these objects, the probability of finding three such galaxies within a 10″ × 10″ region was estimated to be parts in 1000. This implies that the chain and tadpole galaxies are concentrated at the position of the radio galaxy and connected with the forming massive galaxy at the protocluster center.

3. Faint diffuse emission is visible between the obvious clumps. This extended emission is unlikely to be dominated by scattered light of an obscured nuclear quasar, because its morphology is not reminiscent of a scattering cone. Furthermore, its mean color is comparable to that of the star-forming clumps, consistent with the occurrence of ongoing star formation over the whole central 50 × 40 kpc region. The total extended luminosity (comprising 45% of the total emission in g_{475} implies a star formation rate of >100 $M_\odot$ yr^{-1}).

4. Lyα was detected from all of the satellite galaxies in the halo that have been studied spectroscopically. The width of the Lyα profile in the halo is consistent with the observed velocity dispersion of the associated protocluster, indicating that the

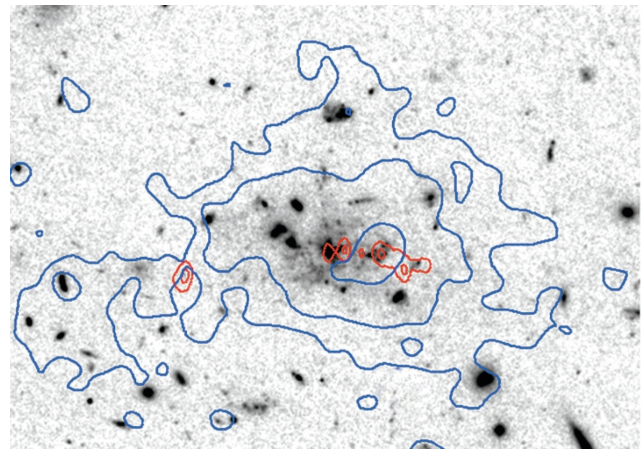

FIG. 2.—VLT Lyα contours (*blue*, resolution ~1″ FWHM) delineating the gaseous nebula and the VLA 8 GHz contours (*red*, resolution ~0″.3) delineating the nonthermal radio emission are superimposed on the composite (g_{475} + I_{814}) ACS image. The image shows a 33″ × 23″ region rotated 10° from north. The gaseous nebula extends for >200 kpc and is comparable in size with the envelopes of cD galaxies in the local universe.

galaxies are moving relative to each other with radial velocities of up to a few thousand kilometers per second.

5. Although the optical structure is extended approximately along the radio axis, most of the galaxy is located outside the narrow region occupied by the radio source and is therefore unlikely to be influenced directly by the radio source.

4. DISCUSSION

4.1. *Evolution of Dominant Cluster Galaxies*

The obvious interpretation of the new *HST* image is that it shows hierarchical merging processes occurring in a forming massive cD galaxy. The morphological complexity and clumpiness observed in the MRC 1138−262 system agrees qualitatively with predictions of hierarchical galaxy formation models (e.g., Larson 1992; Dubinski 1998; Gao et al. 2004; Springel et al. 2005b). Because of its striking appearance and its probable nature, we name the host galaxy of MRC 1138−262 the "Spiderweb galaxy" and refer to the small satellite galaxies located within and around it as "flies." With relative velocities of several hundred kilometers per second (Fig. 1), these flies will traverse the 100 kpc extent of the Spiderweb many times in the interval between $z \sim 2.2$ and 0, consistent with the merger scenario.

Vigorous merging also provides a plausible mechanism for fueling the supermassive black hole, which may subsequently quench any ongoing star formation through radio feedback (e.g., Croton et al. 2006). Using recent infrared spectroscopic observations of the gas in MRC 1138−262, Nesvadba et al. (2006) show that the pressure of the radio source is sufficiently large to expel ∼50% of the gas during the radio source lifetime. After the gas available for star formation has been expelled, the growth of such a massive galaxy will proceed primarily through merging (De Lucia & Blaizot 2006).

Assuming that the flies are undergoing single ∼1 Gyr starbursts, their star formation rates imply a final stellar mass for each satellite galaxy of several times $10^9\ M_\odot$ and a total mass for all the flies of $\sim 5 \times 10^{10}\ M_\odot$. This is less than a tenth of the mass of the whole galaxy, derived from its *K*-band luminosity (Pentericci et al. 1998), implying that a large fraction of the galaxy mass has already assembled by $z \sim 2.2$. Such a relatively early growth disagrees with the predictions of some models for typical evolution of the dominant galaxies in the most massive clusters (De Lucia & Blaizot 2006).

4.2. *Nature of Chain and Tadpole Galaxies*

The most intriguing feature in our *HST* image is the association of the linear flies (chains and tadpole morphologies) with the merging massive host galaxy. In the HUDF the frequency of such objects increases dramatically at faint magnitudes ($i_{775} > 24$; Elmegreen et al. 2005). Because such peculiar galaxies dominate the faint resolved galaxy population, they are likely to be an important source of star formation in the early universe.

The nature of these objects is unclear. There are several possibilities:

1. They may be spiral galaxies observed edge-on (Elmegreen et al. 2005). However, it is difficult to account for the large numbers of faint linear galaxies observed in the HUDF by such selection effects.

2. Their elongated appearance may be due to star formation associated with radio jets (Rees 1989) produced by primeval massive black holes (Silk & Rees 1998). Radio synchrotron jets are known to occur on varying scales, ranging from the most luminous galactic nuclei to X-ray binaries and jets are sometimes associated with star formation (van Breugel et al. 1985; Bicknell et al. 2000).

3. They may be formed as the result of merging, either of galaxies that are formed along filamentary gravitational instabilities (Taniguchi & Shioya 2001) or in major events ∼0.7 Gyr after the merging process has commenced (Springel et al. 2005a; Di Matteo et al. 2005; Straughn et al. 2006).

The fact that the Spiderweb linear flies are located in an environment where vigorous galaxy interactions are taking place is consistent with a merger hypothesis for their origin. The motions of the flies with velocities of several hundred kilometers per second through the dense gaseous halo, perturbed by superwinds from the nucleus (Zirm et al. 2005) and the radio jet, could result in shocks. The shocks would then lead to Jeans-unstable clouds, enhanced star formation along the direction of motion, and chain and tadpole morphologies.

5. CONCLUSIONS

The morphology of the Spiderweb galaxy provides a unique new testbed for simulations of forming massive galaxies at the centers of galaxy clusters. The occurrence of tadpole and chain galaxies in the dense central environment of the protocluster places constraints on (1) evolution models for dominant cluster galaxies and (2) the nature of the chains and tadpoles, an important constituent of the early universe. Our results are consistent with a merger scenario for the formation of these peculiar linear galaxies.

Deep observations with the *HST* of similar objects over a range of redshifts are needed to study whether linear flies are generally present in the vicinity of cD galaxy progenitors and how their luminosity functions in these special regions compare with those of other types of galaxies. The positions and morphological parameters of flies in Spiderweb galaxies at $z > 2$ together with Hubble data on dominant cluster galaxies at $z \sim 1$ will provide new constraints for models of massive galaxy formation. Future spectroscopic observations will delineate the velocity field and color distributions of MRC 1128−262 in more detail, thereby elucidating further how the flies are being captured by the Spiderweb galaxy.

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Facilities: HST (ACS), VLT (FORS), NRAO (VLA).

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