FEEDBACK AND BRIGHTEST CLUSTER GALAXY FORMATION: ACS OBSERVATIONS OF THE RADIO GALAXY TN J1338–1942 AT $z = 4.1$

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ABSTRACT

We present deep optical imaging of the $z = 4.1$ radio galaxy TN J1338–1942, obtained using the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope, as well as ground-based near-infrared imaging data from the European Southern Observatory (ESO) Very Large Telescope (VLT). The radio galaxy is known to reside within a large galaxy overdensity (both in physical extent and density contrast). There is good evidence that this “protocluster” region is the progenitor of a present-day rich galaxy cluster. TN J1338 is the dominant galaxy in the protocluster in terms of size and luminosity (in both the optical and near-infrared) and therefore seems destined to evolve into the brightest cluster galaxy. The high spatial resolution ACS images reveal several kiloparsec-scale features within and around the radio galaxy. The continuum light is aligned with the radio axis and is resolved into two clumps in the $i775$ and $z850$ bands. These components have luminosities $\sim 10^9 L_\odot$ and sizes of a few kpc. The estimated nebular continuum, scattered light, synchrotron- and inverse Compton-scattering contributions to the aligned continuum light are only a few percent of the observed total, indicating that the observed flux is likely dominated by forming stars. The estimated star formation rate for the whole radio galaxy is $\sim 200 M_\odot$/yr. A simple model in which the jet has triggered star formation in these continuum knots is consistent with the available data. A striking, but small, linear feature is evident in the $i775$ aligned light and may be indicative of a large-scale shock associated with the advance of the radio jet. The rest of the aligned light also seems morphologically consistent with star formation induced by shocks associated with the radio source, as seen in other high-$z$ radio galaxies (e.g., 4C 41.17). An unusual feature is seen in Lyα emission. A wedge-shaped extension emanates from the radio galaxy perpendicularly to the radio axis. This “wedge” naturally connects to the surrounding asymmetric, large-scale ($\sim 100$ kpc) Lyα halo. We posit that the wedge is a starburst-driven superwind associated with the first major epoch of formation of the brightest cluster galaxy. The shock and wedge are examples of feedback processes due to both active galactic nucleus and star formation in the earliest stages of massive galaxy formation.

Subject headings: galaxies: active — galaxies: halos — galaxies: high-redshift — galaxies: individual (TN J1338–1942)

1. INTRODUCTION

The most massive galaxies in the local universe reside in the centers of rich clusters. Within the context of hierarchical models of biased galaxy formation, the mass of a galaxy and its clustering properties are naturally connected via the initial density fluctuations (e.g., Kaiser 1984). Therefore, not only locally, but throughout cosmic time, massive galaxies mark the densest regions of the universe. The study of young overdensities at high redshift (“protoclusters”) then also traces the history of the future brightest cluster galaxies.

Many observing programs, spanning wavelengths from radio to X-ray, have been devoted to identifying galaxy overdensities over a large range of redshifts (e.g., Postman et al. 1996, 2002; Scharf et al. 1997; Stanford et al. 1997, 2002; Rosati et al. 1998, 1999).
1999; Oke et al. 1998; Holden et al. 1999, 2000; Kurk et al. 2000; Pentericci et al. 2000b; Donahue et al. 2001, 2002; Francis et al. 2001; Mullis et al. 2003; Miley et al. 2004). To date, the most distant protoclusters have been found at $z \sim 5$ (Shimasaku et al. 2003; Venemans et al. 2004). Do these very young overdensities already contain a dominant, massive galaxy?

There are several observational clues to the mass of a high-redshift galaxy. One is the observed $K$-band magnitude, which probes the rest-frame optical data out to $z \sim 4$. Another is the presence of a high-luminosity active nucleus (a supermassive accreting black hole), which implies the existence of a large spheroidal host galaxy at least locally (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000). High-redshift radio galaxies (HzRGs) are bright at the $K$ band and harbor powerful nuclei (Jarvis et al. 2001a; De Breuck et al. 2002; Willott et al. 2003; Jarvis & McLure 2002). Therefore, the fields surrounding HzRGs are important targets for studying the earliest examples of massive galaxies and clusters. Using a narrowband Ly$\alpha$ imaging program, Miley and collaborators discovered an overdensity of star-forming galaxies around all four radio galaxies observed to sufficient depth out to $z = 5.2$ (Venemans et al. 2004). The resulting set of protoclusters is the subject of several ongoing studies. This discovery also implies that the radio galaxies are the seeds of the brightest cluster galaxies.

The brightest cluster galaxies (BCGs) are the most massive galaxies known in the local universe, with stellar masses in excess of $10^{12} M_\odot$ (Jorgensen et al. 1996; Bernardi et al. 2003). The luminosities and sizes of BCGs are not drawn from the same distributions as those for the majority of the galaxy population (Oegerle & Hoessel 1991). BCGs at low redshifts lie on the extrapolated fundamental plane of elliptical galaxies (Oegerle & Hoessel 1991). The surface brightness profiles of some BCGs, the cD galaxies, extend out to hundreds of kpc. These shallow power-law stellar envelopes blur the distinction between the galaxy and the diffuse intracluster light. Such extreme sources are clearly very useful laboratories for studying the processes inherent in massive galaxy and cluster formation. In fact, several authors have shown that the observed buildup of BCGs can provide key constraints on the hierarchical theory of galaxy formation (Aragon-Salamanca et al. 1998; Burke et al. 2000). The present discrepancies between the predicted (using semi-analytic models) and observed abundance of massive galaxies imply that fundamental processes are not being accounted for in the current models (Cole et al. 2000; Baugh et al. 2003; Somerville et al. 2004). One possible way to solve this discrepancy is to postulate the existence of strong interactions between accreting black holes, star formation, and their host galaxy and surroundings (i.e., “feedback”).

Galaxies that host powerful radio sources are peculiar in several respects. The most striking property is the radio-optical “alignment effect.” This effect is the strong tendency of the rest-frame ultraviolet continuum light of the radio host to be aligned with the axis defined by the radio source. Several explanations for this behavior have been put forward: recent star formation induced by the radio jet, nebular continuum from emission-line gas that is photoionized or shock-ionized by the active galactic nucleus (AGN), light from the central engine scattered into the line of sight by either dust or electrons, and inverse Compton scattering of the microwave background or other local photon fields (McCarthy et al. 1987; Chambers et al. 1987; Daly 1992; Dickson et al. 1995). These explanations of the alignment, particularly that of the jet-induced star formation, are excellent examples of feedback on the galaxy formation process.

The giant (~100 kpc) Ly$\alpha$-emitting halos surrounding distant radio galaxies may be an observable consequence of feedback from galaxy formation (e.g., van Ojik et al. 1997; Reuland et al. 2003). The enormous line luminosities of these objects, often in excess of $10^{44}$ ergs s$^{-1}$, imply that they are massive reservoirs of gas (Kurk et al. 2000; Steidel et al. 2000). What is the origin of this gas: outflow from the galaxy or infall of primordial material? There are several pieces of circumstantial evidence that these halos are connected with the AGN. The halos are often aligned with the FR II radio axis, and in some cases Ly$\alpha$ emission is directly associated with radio structures (Kurk et al. 2003). Perhaps photoionization by the AGN or shocks due to the radio source expansion are responsible for the extended line emission. Spectroscopically, Ly$\alpha$ absorption is seen in addition to the bright halo emission (e.g., van Ojik et al. 1997; Wilman et al. 2004). There is a good correlation between the amount of absorption and the size of the radio source (Jarvis et al. 2001b). A possible scenario is that a neutral hydrogen shell initially surrounds the radio source but is subsequently ionized during the growth of the radio source. There are also some halos known that do not contain a bright radio source (Steidel et al. 2000), suggesting that perhaps the halo phenomenon is associated with the more general processes of galaxy formation rather than being specific to active nuclei.

The radio galaxy TN J1338−1942 ($z = 4.1$; De Breuck et al. 1999) resides in one of the youngest protoclusters known (Venemans et al. 2002; Miley et al. 2004). This galaxy lies within a large Ly$\alpha$ halo that shows unusually asymmetric morphology when compared to other similar radio sources (Venemans et al. 2002). In this paper we present high spatial resolution Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) imaging of this radio galaxy. These data provide the clearest view of a young BCG to date. Images in four broadband filters ($g_{475}$, $r_{625}$, $i_{775}$, and $z_{850}$) have been obtained. The resulting magnitudes and colors have been used to apply the “Lyman break” technique to select galaxies at the same redshift as the radio galaxy (Miley et al. 2004). The exquisite spatial resolution of the HST ACS allows us to study the detailed morphology of the radio galaxy. Using these data we present a scenario that describes the observed morphology (both continuum and Ly$\alpha$) and the measured kiloparsec-scale colors and magnitudes within a self-consistent formation framework for TN J1338−1942 (hereafter TN J1338).

This paper is structured as follows: we describe the observations and data reduction in §2, we present the results of our analysis of the combined multiwavelength data set in §3, and we discuss these results in §4. We adopt the “concordance” cosmology (Spergel et al. 2003) with $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$. Within this cosmology, the angular scale at the redshift of TN J1338, $z = 4.1$, is 7.0 kpc arcsec$^{-1}$. We use the AB magnitude system (Oke & Gunn 1983), except where noted.

2. OBSERVATIONS AND DATA REDUCTION

2.1. ACS Imaging

The ACS data of TN J1338 were taken with two primary goals in mind: first, to enable color selection of faint protocluster members using the Lyman break technique, and second, to investigate the detailed morphological structure of the brightest protocluster galaxies, including the radio galaxy. To achieve these goals, images were taken in four broadband filters: $g_{475}$ ($F475W$), $r_{625}$ ($F625W$), $i_{775}$ ($F775W$), and $z_{850}$ ($F850LP$). The $g_{475}$ band is below the Lyman break for galaxies at $z \gtrsim 4.1$. The
18 orbits was split between the broadband filters: 9400 s in $z_g$ the Wide Field Channel of the ACS. The total observing time of the 1/C27 B using SExtractor (Bertin & Arnouts 1996). The final images have aged through “drizzling,” and object detection and photometry and rotations, the rejection of cosmic rays, the combining of im-
ing steps include the empirical determination of image offsets as described in Miley et al. (2004) and R. Overzier et al.

However, we note that one emission line, C iv, may be affecting the z850-band morphology of the radio galaxy. The g475, r625, and i775 observations were carried out between 2002 July 8 and 12, and the z850 images were taken between 2003 July 11 and 12 with the Wide Field Channel of the ACS. The total observing time of 18 orbits was split between the broadband filters: 9400 s in g475, 9400 s in r625, 11,700 s in i775, and 11,800 s in z850. Each orbit was split into two 1200 s exposures to facilitate the removal of cosmic rays. The g475 dropout targets were selected using the g475, r625, and i775 bands as described in Miley et al. (2004) and R. Overzier et al. (2005, in preparation). This effort was very successful and confirmed the presence of a galaxy overdensity around TN J1338. In this paper we present the first discussion of the radio galaxy itself and its role as the dominant protocluster galaxy.

The ACS data were reduced using the ACS pipeline science investigation software (Apsis; Blakeslee et al. 2003), developed for the ACS Guaranteed Time Observation (GTO) program. After the initial flat-fielding of the images through CALACS at the Space Telescope Science Institute (STScI), the Apsis processing steps include the empirical determination of image offsets and rotations, the rejection of cosmic rays, the combining of images through “drizzling,” and object detection and photometry using SEXtractor (Bertin & Arnouts 1996). The final images have a scale of 0.05 pixel−1 and (2 σ) limiting (AB) magnitudes of 28.46 (g475), 28.23 (r625), 28.07 (i775), and 27.73 (z850) in 0.2 arcsec2 apertures (corrected for Galactic extinction).

2.2. VLT Optical Imaging and Spectroscopy

Deep VLT FORS2 (Focal Reducer and Spectrograph 2) images (6.8 × 6.8”) of the TN J1338 field were made in 2001 March in both the broadband R filter ($\lambda_c = 6550$ Å, $\Delta\lambda_{FWHM} = 1650$ Å) and a custom narrowband filter ($\lambda_c = 6195$ Å, $\Delta\lambda_{FWHM} = 60$ Å) to target the redshifted Lyα emission line (Venemans et al. 2002). The 1 σ limiting surface brightennesss are 28.6 and 29.2 arcsec−2 for the narrow and broad bands, respectively. These images were used to identify candidate Lyα-emitting galaxies (Venemans et al. 2002). For the current paper, these images are used to elucidate the larger scale structure of the Lyα emission and to compare it to the structures seen in the ACS images.

A follow-up spectroscopy program using FORS2 in multi-
object mode was carried out in 2001 May. These spectra have a dispersion of 1.32 Å pixel−1 (using the 600R1 grism) and cover the wavelength range from 5300 to 8000 Å. Candidate Lyα galaxies were placed on two slit masks (Venemans et al. 2002). The radio galaxy itself was included on both slit masks, providing a deep spectrum along the radio axis that covers both the Lyα and C iv λ1549 emission lines.

2.3. VLT Near-Infrared Imaging

Our Ks-band images of TN J1338 were obtained in two separate observing runs. One on 2002 March 24–26 collected 2.1 hr of total exposure time using the Infrared Spectrometer and Array Camera (ISAAC) on UT1 of the VLT. The second run, using the same instrument, was done in service mode at the VLT between the nights of 2004 May 27 and June 13. The total exposure time for this run was 5.7 hr. All the data were processed, sky-subtracted, and combined using the XDIMSUM package within IRAF18 (Tody 1993). The final image has a scale of 0.148” pixel−1, a seeing of 0.75” and a (2 σ, 1 arcsec2 aperture) limiting magnitude of 25.6. ISAAC has some geometrical distortion across the face of the detector. We have not corrected the distortion in detail because the Ks morphology of the radio galaxy matches features seen in the continuum ACS observations.

The Ks band is the only band that probes wavelengths long-
ward of the 4000 Å break, beyond which an old stellar population should dominate the emergent flux (see Fig. 1). It should be noted, however, that the bandpass is not entirely at $\lambda > 4000$ Å. However, these data still provide a crucial point on the spectral energy distribution (SED) of the radio galaxy.

2.4. Radio Imaging

The radio source TN J1338 was originally selected because of its ultrasteep spectrum (between 365 MHz and 1.4 GHz), which has been shown to be an indicator of high redshift (De Breuck et al. 2000b). The first radio data were culled from the

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TABLE 1

| Bandpass | AB Magnitude | Estimated Line Contamination |
|----------|--------------|-----------------------------|
| g475     | 25.92 ± 0.28 | ≤0.05a                      |
| r625     | 22.46 ± 0.01 | ~1.3 (Lyα)                  |
| i775     | 23.23 ± 0.03 | ~0.3 (C iv λ1549, He ν λ1640) |
| z850     | 23.11 ± 0.04 | ~0.2 (He ν λ1640, C m] λ1909) |
| Ks       | 21.9 ± 0.2   | ≤0.01b                      |

a Calculated using the observed spectrum of TN J1338−1942.
b Calculated assuming the composite spectrum of McCarthy (1993).

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18 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Texas and NVSS (NRAO VLA Sky Survey) catalogs (Douglas et al. 1996; Condon et al. 1998). Follow-up observations were made with the Very Large Array (VLA) at 4.71 and 8.46 GHz in 1998 March (Pentericci et al. 2000a). The noise levels are 25 and 50 \( \mu \)Jy beam\(^{-1} \) for the 8 and 5 GHz maps, respectively. The resolution is 0\(^{\prime}\).23 for the 8 GHz map and 0\(^{\prime}\).43 for the 5 GHz map. These are the primary radio data used in this paper (see overlay in Fig. 2). The radio source has three distinct components at both these frequencies: the northwest (\( S_{\text{NW}} \) at 4.7 GHz = 21.9 mJy) and southeast (\( S_{\text{SE}} \) at 4.7 GHz = 1.1 mJy) lobes (separated by 5\(^{\prime}\).5) and the likely radio core (\( S_{\text{core}} \) at 4.7 GHz = 0.3 mJy), located very close (1\(^{\prime}\).4) to the northwest lobe (De Breuck et al. 1999). The radio source is highly asymmetric, with the northwest lobe nearly 20 times brighter at 4.7 GHz than the southeast lobe. The radio asymmetry may indicate an asymmetry in the ambient medium (McCarthy et al. 1991).

2.5. Image Registration

The center position, orientation, and angular resolution all differ between the ground-based and space-based data sets. To facilitate comparison among these data sets, we registered them all to a common reference frame and pixel scale. The ACS images were registered with respect to each other in the ACS GTO pipeline. We chose the ACS \( r_{625} \) frame as the common grid. For the ground-based \( R \) and \( K_s \) data, this registration requires interpolation from plate scales of 0\(^{\prime}\).201 and 0\(^{\prime}\).148 pixel\(^{-1} \) to 0\(^{\prime}\).05 pixel\(^{-1} \), respectively. The shifts, rotations, and rebinning were all done in a single interpolation step using the IRAF tasks geomap and geotran. We fitted a general coordinate transformation using second-order polynomials in both axes. The rms deviations of the data from the fits were on the order of 0.3 input pixels (0\(^{\prime}\).04) for the \( K_s \) image and 0.07 input pixels (0\(^{\prime}\).01) for the FORS2 narrow- and broadband images. The calculated transformations were done using “sinc” interpolation within geotran. At least 15–20 unsaturated stars were matched within the ACS \( r_{625} \) band and each of the ground-based images to calculate the appropriate transformations. We applied these transformations to the ground-based \( R \)-band, narrowband, and \( K_s \)-band images.

The optical/near-infrared frame is defined by stellar positions, and that of the radio image is defined by the positions of radio point sources (quasars). The radio image of the TN J1338 field is sparse, so a direct matching of sources does not produce a robust transformation between the two frames, particularly when we do not want to use the radio galaxy itself. Therefore, the accuracy limit to the radio-optical registration is determined solely by the systematic error in the optical reference frame. To better quantify this we have used two different optical frames, those of the USNO and the GSC-2.0, and have compared the astrometric solutions using each one to the radio data. This gives us a conservative amplitude of 0\(^{\prime}\).3 to the error on the position of the radio core with respect to the optical structures in the ACS and ground-based data. Therefore, we can confidently associate the radio core with the region...
near the peak of the $K_s$-band flux and at one tip of the ACS galaxy.

2.6. Continuum Subtraction

To model the continuum in the $r_{625}$ band, we have used a power-law extrapolation from the relatively emission line–free $i_{775}$ and $z_{850}$ bands. While these filters are not strictly line-free due to the presence of C iv $\lambda 1549$ in the $i_{775}$ band, He ii $\lambda 1640$ in both passbands, and, to a lesser extent, C iii] $\lambda 1909$ in the $z_{850}$ band, none of these lines are expected to dominate the continuum (based on spectroscopic data; see Table 1). We assume that the continuum follows a simple power law in $F_\nu \propto \nu^{-\alpha}$ that extrapolates through to the ACS $r_{625}$ bandpass, the VLT $R$ band, and narrow bands. We have accounted for the intergalactic absorption shortward of the emission line and the relative throughput of the filter curves.

Light at wavelengths shorter than that of Ly$\alpha$ is easily absorbed by neutral hydrogen located between the source and the observer. This greatly affects the amount of continuum light detected in any bandpass shortward of the emission line. We have therefore adopted the model of the intergalactic hydrogen optical depth presented in Madau (1995): $\tau_{\text{eff}} = 0.0036(z_{850}/1.3)^{3.46}$. This is the optical depth due to Ly$\alpha$ forest lines, not due to higher order Lyman series or metal lines. These two opacity sources make negligible contributions to the total optical depth at this redshift (Madau 1995). We integrate this attenuation over the filter curve shortward of Ly$\alpha$ to determine the amount of continuum flux absorbed in the intergalactic medium (IGM). This correction decreases the amount of continuum by 23.9%, 16.9%, and 36.2% in the ACS $r_{625}$ band, the VLT $R$ band, and the VLT narrow bands, respectively. In addition, the continuum flux detected in the images is affected by the filter throughput curves. The extrapolation from the continuum measured in some filters (in our case, the ACS $i_{775}$ and $z_{850}$) to other bandpasses depends on the relative filter curves. We have used the total integrated throughputs to correct for the differential sensitivities. The final value of $\beta$ for the entire radio galaxy is $-1.32$ (or $\alpha = 0.62$, where $F_\nu \propto \nu^\beta$).

3. RESULTS

The ACS and VLT images are shown in Figure 3. The rest-frame ultraviolet morphology of TN J1338 is complex and multifaceted. The radio galaxy exhibits the usual alignment between its continuum, line emission, and radio axis (Chambers et al. 1987; McCarthy et al. 1987; Best et al. 1998a). Two kiloparsec-sized clumps along the radio axis dominate the continuum structure in the $i_{775}$ and $z_{850}$ bands. This is similar to many powerful 3CR radio galaxies at $z \sim 1$ (Best et al. 1998; Zirm 2003; Zirm et al. 2003). In the $r_{625}$ band, the ACS image reveals both concentrated and diffuse Ly$\alpha$-emitting regions. In this section we quantify the line and continuum flux distributions for the radio galaxy by performing photometry in a set of varied apertures.

3.1. Estimating the Contributions to the Aligned Light

The presence of a powerful radio source has several effects on the emitted spectrum. As mentioned above, at least three of these effects tend to align the observed continuum emission with the axis defined by the double radio lobes. Any remaining continuum flux we attribute to a young stellar population.

Ionized gas emits not only emission lines, but also continuum photons from two-photon recombination, bremsstrahlung recombination, and standard recombination. For a given gas temperature and density, this nebular continuum spectrum can be calculated (see Fig. 1). Observationally, the normalization of the nebular spectrum is determined by using the emission-line spectrum. For TN J1338–1942 we have a spectrum that was taken along the radio axis and that spatially averages the entire optical extent of the radio galaxy (RG). Ideally, one would measure Balmer recombination emission lines. These lines directly correspond to the nebular continuum. At $z = 4.1$, these lines have shifted out of the optical window visible from the ground. As a “Balmer proxy,” we use the He ii $\lambda 1640$ emission line (Vernet et al. 2001), which has a flux of $\approx 1.7 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ (C. De Breuck 2004, private communication). Assuming the He ii/H$\beta$ ratio (≈3.18) from a high-redshift RG composite spectrum (McCarthy 1993), we estimate the H$\beta$ flux to be $5.4 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. If these emission lines arise in a 15,000 K gas, at densities low enough that collisional de-excitation is negligible, then the corresponding nebular continuum flux densities in the $r_{625}$, $i_{775}$, and $z_{850}$ bands are $1.5 \times 10^{-31}$, $3.1 \times 10^{-31}$, and $3.8 \times 10^{-31}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$, respectively. Thus, at its brightest the nebular continuum averaged over the entire galaxy is only $z_{850}(AB) = 27.4$, much fainter than even the individual components of TN J1338. We subtract the nebular continuum from all quoted magnitudes and fluxes by scaling the subtracted amounts for the subcomponents by their estimated Ly$\alpha$ flux.

The same population of electrons that is responsible for the radio synchrotron emission can also inverse Compton (IC) scatter ambient photon fields. The primary seed photons are those making up the cosmic microwave background (CMB), with secondary contributions from the synchrotron photons themselves (synchrotron self-Compton [SSC]) and other AGN emission. By assuming equipartition to calculate the magnetic field in the northern radio lobe of TN J1338, we find a $B$ field on the order of a few hundred mG. If we use the extrapolation to the rest-frame UV as calculated by Daly (1992), this translates to an IC CMB...
contribution of only a few times \(10^{-31}\) ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\), or fainter than 28 mag (AB). The estimated energy density in the synchrotron field is similar to that of the CMB at this high redshift, so the SSC contribution adds a similar amount to the aligned continuum. These two contributions combined are negligible. As with the spectroscopy above, these values are spatially averaged over the entire galaxy.

Optical spectropolarimetry of the entire galaxy reveals a polarization of 5% \(\pm\) 3% (C. De Breuck 2004, private communication). This value is much lower (about a factor of 2) than similar measurements of \(z \sim 1\) RGs (e.g., Dey et al. 1996; Cimatti et al. 1996, 1997; Solórzano-Inárrua et al. 2004) but similar to other powerful RGs at \(z \sim 4\) (Dey et al. 1997). The amount of scattered light is related to the percent polarization by the intrinsic polarization, \(P_i\). The value of \(P_i\) depends on the type of scatterer (either dust or electrons) and the geometry of the scattering, neither of which is well constrained for TN J1338. Therefore, we can only put a lower limit on the percentage of scattered light of \(5\%\). However, we also note that for \(z \sim 1\) 3CR radio galaxies, the observed polarizations are high and suggest that \(P_i\) is also high. We therefore conclude that for TN J1338, the aligned continuum contains some scattered light (\(\sim 10\%\)) but is substantially diluted by unpolarized sources. We have already shown that neither the nebular continuum nor the IC scattering can account for this dilution.

Clear evidence for the presence of young stellar populations in radio galaxies has proven difficult to find. The same spectral region, the ultraviolet, where massive stars are brightest, coincides with the bright region of the AGN SED. Therefore, the detection depends on being able to find stellar-specific features in very deep spectra (e.g., the \(S\) \(v\) \(\lambda 1502\) photospheric absorption feature in 4C 41.17 at \(z = 3.8\); Dey et al. 1997). Existing spectra of TN J1338 do not show such features. In this case the presence of young massive stars must be inferred from the UV excess after subtracting the other known contributors to the aligned light. As we have shown above, there seems to be such an excess in TN J1338, which implies the existence of many young stars. We examine this result further below.

3.2. Large-Aperture Photometry

To perform integrated photometry over the whole galaxy, we used a Kron aperture (Kron 1980) to approximate a total galaxy magnitude in the ACS and VLT images. This enables easy comparisons between the space-based and ground-based observations of TN J1338. This aperture is optimized to be as large as possible while still retaining a high signal-to-noise ratio. The magnitudes were determined using SExtractor (Bertin & Arnouts 1996). The Apsis pipeline deblends the radio galaxy into two distinct objects. We therefore reset the SExtractor deblending parameters to maintain the radio galaxy as a single object. We overplot the aperture in Figure 3. The total magnitudes within this aperture are listed in Table 1.

The radio galaxy is \(> 1.4\) mag brighter than the next brightest dropout or Ly\(\alpha\) -emitting galaxy (within similarly defined apertures). This is true even in the \(K_s\) band, where the light from older stars is presumed to dominate the emission rather than processes related to the AGN. Therefore, the radio galaxy is securely identified as the dominant and likely most massive galaxy within the protocluster and as the probable progenitor of a present-day BCG.

3.3. Rest-Frame Optical Surface Brightness Profile

The \(K_s\) band samples the rest-frame optical continuum emission, mostly longward of the 4000 \(\AA\) break and shortward of the potentially bright \([\text{O} \text{\,\,iii}]\) \(\lambda 4959, 5007\) and \(\text{H}\beta\) lines. At these wavelengths it is likely that the galaxy luminosity is dominated by older, low-mass stars. We show the final ISAAC image of the radio galaxy in Figure 3e and show the raw surface brightness profile of the radio galaxy and a star in this band in Figure 4. This profile is centered on the peak of the \(K_s\) -band light. It is clear that the galaxy is resolved, but it is not possible to measure the size of the galaxy robustly from these data. A simple \(r^{1/4}\) law fit roughly estimates the effective radius at \(0.7\) or \(\sim 5\) kpc. This is considerably smaller than the corresponding radii of local BCGs (e.g., Graham et al. 1996). In fact, the observed morphology in the \(K_s\) image is very similar to that seen in the ACS \(i_{775}\) band. The galaxy is highly elongated and is nearly perfectly aligned with the radio axis. There are no bright emission lines within the bandpass, and none of the continuum processes discussed above are bright in the \(K_s\) band. Therefore, we conclude that the stellar distribution is aligned with the radio axis.

3.4. Multicomponent Decomposition and Diffuse Light

The rest-frame ultraviolet morphology of TN J1338 can be decomposed into several discrete components. To better understand the morphology of the galaxy, we have extracted multiband photometry of these individual components. We divided the radio galaxy into distinct regions, both in the line-dominated \(r_{625}\) band and in the continuum-dominated \(i_{775}\) band. The resulting segmentation map is shown in Figure 5. The regions are numbered 1–6. Regions 1, 2, and 3 (the "wedge") are found only in the emission line–dominated \(r_{625}\) band. Conversely, regions 4 and 5 are most prominent in the continuum bands (\(i_{775}\) and \(z_{850}\)). Finally, region 6 contains a linear feature in \(z_{850}\).

For each region we have measured the magnitude in each ACS band and in the ACS Ly\(\alpha\) (continuum-subtracted \(r_{625}\)) image. Using these values we have derived the UV continuum slope and line flux independently for each portion of the galaxy.
In addition, we have measured the magnitudes in the $K_s$ band for the two primary continuum clumps visible in the ACS data (regions 4 and 5). The $(i_{775} - K_s)_{AB}$ color for region 5 is $\approx$0.2 mag redder than that of region 4. The sum of the light contained within these clumps is about 1 mag fainter in the $i_{775}$ band than the total radio galaxy, indicating that there is some “diffuse” light detected in these high angular resolution images. This remains the case in the $z_{850}$ band, with the extended light apparently having the same color as the mean color of the entire galaxy. The magnitudes and Ly$\alpha$ fluxes are presented in columns (3)–(6) of Table 2.

3.5. Azimuthal Binning

While the aligned light is a common feature of high-redshift radio galaxies, the wedge of extended line emission to the southwest of the radio galaxy (region 3 in Fig. 5) is unusual. We have measured the azimuthal surface brightness distribution of this feature by extracting photometry in angular bins. The bins are shown in Figure 6. The angular regions are sized and placed to cover the entire visible extent of the wedge and to be small enough to accentuate the internal structure of the feature. The flux in each bin was summed using the IRAF task `polyphot`. The corresponding errors were calculated by performing the same aperture photometry on the error maps. The pixels within the radio galaxy (as defined by the extent of the $i_{775}$-band continuum) were masked out. The resulting flux histogram is shown in Figure 7 for the wedge (solid line), for the opposite side of the galaxy in the line image (the “antiwedge”; dashed line), and for the $i_{775}$-band continuum in the wedge region (dotted line).

The bins covering the wedge show a clear excess of flux with respect to both those for the opposite side of the galaxy and those for the continuum. There also appears to be some structure to the azimuthal profile. The azimuthal profile has relatively sharp cutoffs at either side. There is no evidence for limb brightening toward the edges of the wedge. However, the spatial resolution ($\approx$1.5 kpc bin$^{-1}$) is insufficient to resolve a thin shell of limb-brightened emission.

3.6. Semicircular Annuli

To measure the radial profile of the wedge, we have constructed semicircular annuli that cover the same region(s) as the angular bins above (Fig. 8). We have increased the width of the annuli toward the outer edge of the wedge to maintain a constant signal-to-noise ratio per annulus. The annular photometry again shows that the line emission is significantly brighter in the wedge than either on the opposite side of the galaxy or in the continuum. The surface brightness profiles for the wedge (solid line), antiwedge (dashed line), and continuum (dotted line) are shown in Figure 9. The errors for each data point were derived by performing identical photometry on the corresponding error map. There does not seem to be evidence for limb brightening toward the outer edge of the wedge. Also shown are power-law

| Number | Piece    | $g_{225}$ | $i_{775}$ | $z_{850}$ | Ly$\alpha$ Flux (10$^{-16}$ ergs s$^{-1}$ cm$^{-2}$) | Ly$\alpha$ Rest-Frame Equivalent Width (Å) | Extinction $E(B-V)$ | Star Formation Rate UV Continuum (Ly$\alpha$) |
|--------|----------|-----------|-----------|-----------|-----------------------------------------------|-------------------------------------------|-------------------|------------------------------------------|
| 1...... | Line 1   | 27.14     | 26.82     | 26.80     | 1.17                                          | 448                                       | 0.02              | 3 (17)                                   |
| 2...... | Line 2   | 27.66     | 27.34     | 27.32     | 0.80                                          | 492                                       | 0.02              | 2 (12)                                   |
| 3...... | Wedge    | 26.19     | 26.36     | 26.81     | 4.20                                          | 645                                       | 0.00              | 3 (61)                                   |
| 4...... | Continuum 2 | 25.74 | 25.48     | 25.51     | 3.73                                          | 390                                       | 0.00              | 9 (54)                                   |
| 5...... | Continuum 1 | 25.33   | 24.98     | 24.92     | 1.69                                          | 121                                       | 0.06              | 24 (24)                                  |
| 6...... | Shock    | 26.54     | 26.20     | 26.15     | 2.45                                          | 536                                       | 0.04              | 7 (35)                                   |

* Calculated for the Ly$\alpha$-subtracted image, where the line flux is determined from power-law continuum fits to the $i_{775}$ and $z_{850}$ bands for each piece.

* Star formation rate as calculated by the UV continuum magnitude and the Ly$\alpha$ flux (in parentheses).
profiles of the form $SB(r) \propto r^\alpha$ with $\alpha$ values of $-1$ and $-2$ (dot-dashed lines). The wedge profile has a profile much closer to the $\alpha = -1$ curve. We consider these profiles further in the discussion.

4. DISCUSSION

The unparalleled spatial resolution provided by HST and the Advanced Camera for Surveys has allowed us to observe kiloparsec-scale structures within the radio galaxy TN J1338–1942 at $z = 4.1$. The rest-frame ultraviolet continuum and line emission of the host galaxy is morphologically complex and consists of several distinct components. In this section we discuss these features and their implications for the formation of this galaxy and attempt to construct a possible scenario for the ongoing processes in this source.

4.1. Ongoing Star Formation

Are we witnessing the formation of the bulk of the final stellar mass in this radio galaxy? Previous studies based on ground-based optical and millimeter imaging suggest that the current star formation rate (SFR) within TN J1338 is very high, on the order of several hundred $M_\odot$ yr$^{-1}$ (Venemans et al. 2002; De Breuck et al. 2004). The current study not only confirms this estimate, under different assumptions, but also determines the spatial gradients in star formation activity. This new spatial information allows us to constrain both the timescale and possible physical origin of the current star formation episode.

There are two methods to estimate the SFR in TN J1338 using the ACS imaging data: one using the Ly$\alpha$ luminosity and the other using the UV continuum luminosity. Both estimates are based on the assumption that the UV light we see from the galaxy is due solely to star formation. As we have shown earlier, the UV continuum is relatively unpolluted by the nonstellar contributors to the aligned light. Conversely, for the line emission, the high observed equivalent widths argue in favor of nonstellar excitation (e.g., Charlot & Fall 1993). Therefore, the line emission provides an upper limit (modulo dust extinction) to the SFR, while the UV continuum provides a lower limit. The comparison of these two derived values provides an estimate of the mean SFR for each portion of the galaxy.

For a given Ly$\alpha$ flux, we calculate the corresponding Balmer line flux and hence the SFR (Kennicutt 1998). This SFR is a lower limit locally due to Ly$\alpha$ being a resonantly scattered line and very susceptible to dust. For example, the Ly$\alpha$ flux of the wedge (region 3 in Fig. 5) is $3.3 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$, corresponding to an intrinsic luminosity of $5.2 \times 10^{43}$ ergs s$^{-1}$ at $z = 4.1$. If we adopt a case B Ly$\alpha$/H$\alpha$ ratio of 8.7 (Brocklehurst 1971) and use the relation between H$\alpha$ line flux and SFR, we find that region 3 is forming stars at a rate of 40 $M_\odot$ yr$^{-1}$. The analogous results for the other regions are listed in Table 2. The total Kron Ly$\alpha$ SFR is 290 $M_\odot$ yr$^{-1}$. The sum of the individual SFRs does not equal this total, underpredicting it by $\approx 90 M_\odot$ yr$^{-1}$. There is a considerable amount of low surface brightness line.
emission even within the Kron aperture ($\sim$18 kpc $\times$ 7 kpc). We have not corrected for the observed H$\alpha$ absorption (De Breuck et al. 1999; Wilman et al. 2004).

The $i_{775}$ and $z_{850}$ bands probe the rest-frame UV of TN J1338–1942 at $\sim$1500 and $\sim$1775 Å, respectively. We can use the ACS continuum magnitudes to estimate the current SFR under the assumption that the UV luminosity is dominated by the light from late O to early B stars on the main sequence. We measure total (Kron) SFRs of 86 and 96 $M_\odot$ yr$^{-1}$ for the $i_{775}$ and $z_{850}$ bands, respectively, assuming a Salpeter initial mass function (IMF). The derived SFRs are lower limits, since they are dependent on the amount and the distribution of dust present in the UV-emitting regions. The slope of the UV continuum can also be used to measure the extinction. We measure the slope of the continuum from the $i_{775} - z_{850}$ color and use a template spectrum of a typical star-forming galaxy redshifted to $z = 4.1$ to convert the measured slope to a color excess, $E(B - V)$. For the template spectrum we have used the stellar population synthesis models of Bruzual & Charlot (2003) to create a typical Lyman break galaxy spectrum with an exponentially declining star formation history (with time constant, $\tau = 10$ Myr), an age of 70 Myr, 0.2 Z$_\odot$ metallicity, and a Salpeter IMF. The parameters of this template are taken from the best-fit SED at $z \sim 3$ of Papovich et al. (2001). We varied the dust content by applying the attenuation curve of Calzetti et al. (2000) to this template. We find $E(B - V) = 0.12$, yielding a dust-corrected SFR of $\sim$220 $M_\odot$ yr$^{-1}$, in good agreement with the emission-line estimate above. If we repeat this calculation for each discrete region of the galaxy [allowing for $E(B - V)$ and SFR to change for each; see Table 2], we again find evidence for diffuse UV light and star formation. The sum of the SFRs for all the regions again falls short of the total by a factor of 4.5, “missing” 170 $M_\odot$ yr$^{-1}$.

4.1.1. Shocks and Jet-induced Star Formation

One of the primary explanations for the alignment effect is that the passage of the radio jet through the interstellar gas induces star formation (e.g., Rees 1989). Strong large-scale shocks associated with the expanding radio source overpressure molecular gas clouds, which then collapse to form stars. The presence of powerful shocks in radio galaxies at $z \leq 2$ has been inferred via their ultraviolet emission-line ratios (e.g., Best et al. 2000; De Breuck et al. 2000a). For TN J1338, most of the important diagnostic emission lines are unobservable from the ground. However, we can use morphological information to search for possible signatures of shock processes in this radio galaxy.

In these respects, useful analogies can be drawn between TN J1338 at $z = 4.1$ and 4C 41.17 at $z = 3.8$. The shock properties of 4C 41.17 were studied and modeled in detail by Bicknell et al. (2000). In addition to HST imaging of 4C 41.17, these authors also used deep emission-line spectra and high angular resolution radio imaging to study the relationship between the radio source, the gas, and the stars. We apply a similar analysis to TN J1338.

A bow shock is formed at the tip of the advancing radio jet (cf. Fig. 3 in Bicknell et al. 2000). Due to the unresolved radio structure, we cannot robustly determine the location of the jet interaction. We assume that region 4 in the continuum ACS image is the primary site where the jet has shocked or is still impacting the gas. This continuum knot is very blue and has a morphological structure that is suggestive of jet-cloud interaction, namely, a paraboloid oriented along the radio axis. From the spatially resolved optical images we estimate the interaction area to be $\sim 2 \times 10^{44}$ cm$^2$ by assuming that the emission we see is emitted by a spherical shell. The jet is most likely well collimated, and therefore the area of the jet itself is much smaller than the total; we assume 10%. If we assume that most of the momentum flux of the jet is dissipated in this interaction, the shock velocity (see eq. [1] of Bicknell et al. 2000) is greater than $v_{sh} \geq (300–2000) F_{E_{1042}}^{1/2} \beta_{jet}^{-1/2} n_{H}^{-1/2}$ km s$^{-1}$,

$$L(C IV) \approx (2 \times 10^{42}) \frac{\alpha(C IV)}{0.01} \frac{A_{sh}}{A_{p}} \frac{v_{sh}}{1000} (\frac{\rho}{3 \text{ cm}^{-3}}) M_\odot \text{yr}^{-1},$$

where $F_{E_{1042}}$ is the energy flux of the jet in units of $10^{46}$ ergs s$^{-1}$, $\beta_{jet}$ is the relativistic Doppler parameter, and $n_{H}$ is the hydrogen density per cm$^3$ in the cloud. Comparison between model and observed C IV $\lambda\lambda1548, 1550$ doublet fluxes can help to constrain the preshock gas density and the energy flux of the jet. Assuming that the ACS UV/Ly$\alpha$ image also shows the spatial distribution of C IV, we can constrain the area from which the line is being emitted. We use the observed C IV/Ly$\alpha$ flux ratio to convert the Ly$\alpha$ image to a C IV image. If we follow Bicknell et al. (2000) and take $A_p$ to be the projection of the true area of the shock $A_{sh}$ in region 4 and predict the C IV line luminosity for our estimated shock velocity, we find

$$L(C IV) \approx (2 \times 10^{42}) \frac{\alpha(C IV)}{0.01} \frac{A_{sh}}{A_{p}} \frac{v_{sh}}{1000} (\frac{\rho}{3 \text{ cm}^{-3}}) M_\odot \text{yr}^{-1}.$$
population (e.g., Heckman et al. 1990). Whether such outflows actually achieve escape velocity and enrich the IGM is still an outstanding question (Heckman 2001; Heckman et al. 2000; Martin 2005). However, these winds, along with nuclear outflows, are the only processes observed to transport material into the outer halos of galaxies and are therefore prime candidates for injecting the metals and energy that are observed in the IGM. At high redshift, at which these processes are likely to be even more prevalent due to the higher global SFRs, the strongest evidence for the presence of outflows is spectroscopic. However, the spectroscopic features observed are of ambiguous origin and could be due to inflow, outflow, or rotation (e.g., van Ojik et al. [1997], but see also Adelberger et al. [2003]). Spatially resolved imaging of the emission-line gas can provide a more certain indication of outflow if the gas is collimated or exhibits the bipolar morphology of low-redshift superwinds. In §§ 4.2.1, 4.2.2, and 4.2.3, we consider several possible origins for the wedge: the photoionization cone of an AGN or young stellar population, in situ star formation, scattering by dust, and an ionized outflow associated with a starburst (i.e., a superwind).

4.2.1. Photoionization

In several low-redshift Seyfert galaxies, cone-shaped regions of high ionization are observed, consistent with photoexcitation by an active nucleus (e.g., Wilson & Tsvetanov 1994). In some cases these cones extend to distances of 15–20 kpc from the nucleus, similar to the size of the Lyα wedge seen in our ACS image (Wilson & Tsvetanov 1994). Both the ionized cone and our wedge have high equivalent widths. We derive a lower limit to the Lyα rest-frame equivalent width of 650 Å for the wedge emission. Furthermore, powerful radio galaxies are known, on the basis of emission-line diagnostics and imaging of low-redshift sources, to photoionize their surroundings. Generally, both the line and the UV continuum emission are elongated and aligned with the radio axis, particularly at z > 0.7 (McCarthy et al. 1987; Chambers et al. 1987).

Conversely, however, the principal wedge axis is perpendicular to that of the radio source. The unified model for AGNs posits that the observed radiation is anisotropic (Antonucci 1993) due to a combination of obscuration close to the nucleus and the intrinsically anisotropic radiation. For radio-loud galaxies, this preferential radiation axis is traced by the line connecting the dual radio lobes. The misalignment of the wedge therefore argues against photoionization due to the AGN or shocks due to the radio jet. Furthermore, the most likely position of the accreting black hole powering the radio emission and therefore also the primary source of hard ionizing radiation is where the radio core and the Kα-band surface brightness peak coincide. The apex of the wedge does not coincide with this position. It is possible that a second AGN (this one radio-quiet), coinciding with region 4 in Figure 5, could ionize the wedge. However, this additional black hole would have to have its primary axis roughly perpendicular to the radio-loud AGN and be much less luminous at the Kα band. While not impossible, this explanation is ad hoc and not preferred.

4.2.2. In Situ Star Formation or Galaxy Interaction

Ongoing star formation within the wedge itself and perhaps extending into the outer Lyα halo (outside the Kron radius) would also produce bright line emission. However, there is a robust upper limit to the Lyα equivalent width produced by normal massive stars of $W_\lambda = 400$ Å (Charlot & Fall 1993). For the wedge we estimate a significantly higher equivalent width. We also note that dust extinction decreases the observed equivalent width from its true value; the resonant scattering of Lyα photons increases their optical depth relative to continuum photons. This equivalent-width argument also applies to tidal debris ejected from the galaxy via a merger or interaction. It therefore seems unlikely that stars are directly responsible for the wedge emission.

4.2.3. Superwind: Comparison with M82

In Heckman et al. (1990) the authors use their observations of local starburst galaxies to determine the minimal condition for driving a galactic-scale outflow powered by supernovae explosions, or a superwind. They phrase this criterion in terms of the star formation rate per unit area ($\Sigma_{\text{SFR}}$) and empirically determine the minimum to be $\Sigma_{\text{SFR}} \geq 0.1 M_\odot$ yr$^{-1}$ kpc$^{-2}$. If we adopt this minimal value for TN J1338 and apply it to the resolved area where we see the wedge emerging from the galaxy (assuming a circular region seen in projection), we derive a lower limit to the SFR over this same area of $1.5 M_\odot$ yr$^{-1}$. Above we have shown that the SFR for this galaxy greatly exceeds this limit, even in region 4, where the wedge may originate.

Galactic-scale winds have been observed in detail around local starburst galaxies, of which M82 is a well-studied example (e.g., Heckman et al. 1990). Morphologically, these superwinds are bipolar structures emanating from the galaxy nucleus and along the minor axis of the galaxy. They are detected as emission-line filaments, extended X-ray lobes, and bipolar thermal dust emission (Heckman et al. 1990). In M82, the emission-line gas is photoionized in the innermost regions and is primarily shock-excited in the outskirts. The optically emitting gas flows from M82 in filaments that trace the biconical surface. The outflows have double-peaked emission lines (due to the two surfaces of the cone being separated in velocity) and also, depending on geometry and spectral resolution, emission lines with blueshifted absorption. On the basis of these spectroscopic signatures, galactic winds seem to be a generic feature of high-redshift star-forming galaxies (Pettini et al. 2001). All the existing spectroscopy of TN J1338 has been taken along the radio axis, where the dynamics of the gas are presumably dominated by the AGN outflow and jet-cloud interactions (see above and, e.g., Villar-Martín et al. 1999; Solórzano-Iñarrea et al. 2001). So we must rely on morphology alone to infer the presence of a superwind emanating from this radio galaxy along the wedge.

Comparison of the recent ultraviolet Galaxy Evolution Explorer (GALEX) image of M82 (Hoopes et al. 2005) with our TN J1338 image reveals a striking degree of similarity (Fig. 10). The scales of the two outflows are somewhat different; in M82 the narrowest collimated section is only 1.5 kpc across, while in TN J1338 the similarly defined region is approximately twice that. The surface brightness profile is also similar between the wedge and the M82 far-UV outflow (see Fig. 9). The shallow drop-off of emission-line surface brightness is consistent with having shock ionization dominate at these large radii rather than photoionization by a central source.

Why do we see only one side of the presumably bipolar outflow? This could be due to obscuration of the line emission on one side of the galaxy. If the radio galaxy is flattened (perpendicular to the plane of the sky) and inclined with respect to the line of sight, then any dust in the galaxy would naturally obscure the side tilted away from the observer. This is the primary explanation for the observed asymmetry in the bipolar superwind in M82 (Shopbell & Bland-Hawthorn 1998). Alternatively, the lack of line emission on the northeast side may be due to a strong gradient in the ambient gas density.

Alternatively, if the pressure is higher on the northeast side of the galaxy, a situation that could arise due to the motion of the
radio galaxy within the protocluster medium, i.e., ram pressure, then the outflow would be impeded on that side of the galaxy. Marcolini et al. (2004) have made simulations (albeit for dwarf galaxies) that show that motion through the IGM does not greatly affect the dynamics of galactic outflows until the ram pressure becomes comparable to the static thermal pressure of the galactic ISM. This result should be extendable to the case of TN J1338.

To estimate the thermal pressure in the galaxy, we must first estimate a density for the gas. If we assume that the observed Lyα emission is due to case B recombination at \( T = 15,000 \) K, then we can use the fiducial Lyα/\( \text{H}_\alpha \) ratio of \( 10 \) to deduce the number of ionized hydrogen atoms. Given the observed geometry of the wedge, we can assume further that the emitting gas is contained in the surface of a cone with half-angle 30° and length 10 kpc. The thickness of the gas layer cannot be larger than a few hundred pc due to the absence of significant limb brightening in the azimuthal profile of the wedge. Consequently, the number density and mass of ionized hydrogen are

\[
\begin{align*}
    n_e &= 1.0 L_{\text{H}_\beta,41}^{1/2} v_{\text{cone,kpc}}^{-1/2} \text{cm}^{-3}, \\
    M_{\text{H}_\alpha} &= (7.6 \times 10^8) \mu_p L_{\text{H}_\beta,41}^{1/2} v_{\text{cone,kpc}}^{1/2} M_\odot,
\end{align*}
\]

where \( \mu_p \) is the mean particle mass, which we have taken to be the proton mass, and \( L_{\text{H}_\beta,41} \) is the \( \text{H}_\beta \) luminosity in units of \( 10^{41} \) ergs s\(^{-1} \). The true electron density is likely to be higher than this, but only within smaller clouds or filaments, as is seen in the M82 outflow. The resulting thermal pressure is equivalent to the ram pressure produced by a relative velocity of 300 km s\(^{-1} \) (if the surrounding gas has a density 1/1000 times that in the wedge). This provides some evidence that the radio galaxy is not in the center of the galaxy overdensity and that motion toward the center would provide the requisite ram pressure (H. Intema et al. 2005, in preparation). We conclude that the wedge is likely to be a supernova-driven outflow, with the current episode of star formation possibly triggered by the radio jet. This superwind is one-sided due to ram pressure inhibiting the flow on one side.

4.3. The Outer Lyα Halo

In Figure 11, the extended Lyα (out to \( \sim 100 \) kpc), as detected in the very deep VLT narrowband image, is shown as contours. The TN J1338 halo has a somewhat asymmetric plume that is
aligned with the radio axis. It is clear from the underlying ACS image showing the wedge that there is a natural connection between the high surface brightness wedge (out to 20–30 kpc) and the larger scale lower surface brightness halo along the southwest direction. However, the halo at larger distances appears to be aligned with the radio axis of TN J1338. What is the relation, if any, between the wedge and the large-scale Lyα structure?

If the wedge is an outflow, as we conclude above, the resulting bubble will stall at some radius where gravity and the amount of swept-up intergalactic matter balance the input energy. The gas deposited at this radius would naturally flow along the boundary of the excavated cavity and follow any density gradients in the ambient medium. The halo-radio alignment would then be a natural consequence if lower density regions were located preferentially along the radio axis. This would be the case if either the current radio source extended farther out in radius than our current radio observations indicate or the radio source was previously (either during this accretion episode or an earlier one) much larger and had excavated the region along the radio axis. However, there is no evidence in the current radio data for a relic radio source at larger distances. In any case, if the ionized gas had originated in the starburst, the observed alignment implies that the AGN had already imprinted the region before the starburst was triggered. We discuss this possibility and its implications further in § 4.4.

4.4. A Self-Consistent Scenario

The host galaxy of the powerful radio source TN J1338–1942 at $z = 4.1$ is unique. It is arguably the youngest brightest cluster galaxy known to date and has been the subject of several multiwavelength investigations. In this paper we have presented imaging from the HST/ACS that reveals several interesting morphological and broadband spectral features in this radio galaxy. In this section we attempt to construct a plausible and self-consistent story of the past, present, and future of TN J1338.

The host galaxy of TN J1338 appears to be forming stars at a high rate. None of the nonstellar processes known to produce the alignment effect in other galaxies can be dominant in this case. The ACS data presented here reveal a morphology that is consistent with most of the star formation being triggered by the passage of the radio jet. In Figure 12 we show a color-color diagram for the discrete regions within the radio galaxy. The color difference between regions 4 and 5 may be an age effect (region 4 is also bluer in $I_{775} - K_s$). We use the overplotted model colors in Figure 12 to derive an age difference between the two regions. The model has constant star formation with 0.4 solar metallicity and $E(B - V) = 0.1$, and the ages are labeled at time steps of 1, 10, 100, and 1000 Myr. We estimate from the comparison between the model points and the data that the age difference is between 25 and 200 Myr. This matches, within the (large) errors, the shock travel time from the radio core (in region 5) to the jet-cloud interaction in region 4 (a distance of $\sim$7 kpc with a 300 km s$^{-1}$ shock). We do not see very extended star formation, which may be triggered by the expanding radio cocoon. The energy injection from the AGN may be rather isolated to these few nodes along the radio jet itself. Therefore, we suspect that the large-scale Lyα gas has an origin apart from the AGN, namely, in the newly formed stars.

Once the prodigious star formation is initiated, the supernova explosions expel the ionized gas into the surrounding media by means of a superwind. In addition, ram pressure is stripping the gas from the star-forming regions as the radio galaxy moves through the ICM and IGM. This gas remains ionized primarily via shock excitation at the interface between the outflow and the ambient intergalactic gas. At a distance of approximately 20–30 kpc from the nucleus, the outflow reaches pressure equilibrium with the IGM. The gas rapidly cools at this interface, consistent with the boundary to the Lyα halo observed at this region. This cooling gas follows the density gradients in the IGM. The very low surface brightness line emission seen to the northeast of the radio galaxy, which is aligned with the radio axis, is probably gas that originated in the outflow, cooled, and is now being re-excited by low-luminosity shocks associated with the radio source.

The observed rest-frame $B$ magnitude of TN J1338 is approximately 1.5–2 mag brighter than that of the six BCGs at $z \sim 1$ observed with ACS (Postman et al. 2005). If we use the same star formation model as above (constant for 1 Gyr and 0.4 solar metallicity) and age the galaxy from 1 Gyr at $z = 4.1$ to 5.2 Gyr at $z = 1$, the galaxy fades by 3.3 mag. This would imply that some additional star formation or merging must occur during those 4.2 Gyr for TN J1338 to match the luminosity of the $z \sim 1$ BCGs. This is certainly not surprising. It is interesting to note as well that several of these BCGs have a nearby bright companion of almost equal luminosity ($\Delta M \lesssim 0.1$ mag), with which they seem to be destined to merge. The resulting increase in luminosity would nearly make up the 1 mag of “extra” fading seen for the 1 Gyr constant star formation model.

It is debatable whether one should attempt to draw conclusions for an entire population of sources (either BCGs or radio galaxies in this case) based on observations of a single example. TN J1338 may be a galaxy in a special phase of its evolution; alternatively, it may be a special source whose history cannot be generalized to describe other galaxies. However, studies of ensembles of radio galaxies, including their luminosity functions and duty cycles, suggest that the space density of radio source hosts at high $z$ are roughly in agreement with the density of
BCGs at low redshift and the density of non-RG overdensities at $z \sim 3$ (West 1994; Venemans et al. 2002).

5. CONCLUSIONS AND FUTURE

The host galaxy of the powerful radio source TN J1338–1942 shows signatures of several feedback processes that connect the black hole, the stellar host, and the intergalactic medium. The elongated and multicomponent ultraviolet continuum is aligned with the FR II radio axis and is likely to be due to emission from young stars being formed along the jet axis. Interpretation of this light in terms of jet-induced star formation is consistent with the observations. There is, however, also evidence for considerable star formation outside the highest surface brightness regions. If the current star formation rate has been constant over the jet travel time from the radio core to the site of the presumed jet-cloud interaction, this process could have produced in excess of $10^{11} M_\odot$ of stars. Data from the Spitzer Space Telescope will allow us to determine the total stellar mass of TN J1338 and help verify our hypothetical star formation history.

We interpret the ACS wedge of Ly$\alpha$ emission as a superwind driven by the winds and supernova explosions associated with prodigious star formation activity. This outflow connects with the larger scale Ly$\alpha$ halo. The initial source of the halo gas is then within the starburst and is possibly enriched. Deep spectrophotometry from the ground along the wedge axis would help us determine the ionization mechanism more definitively. In particular, covering the Ly$\alpha$, C iv, He ii, and C iii] emission lines may enable us to also measure the enrichment of the outflowing gas. An ongoing ACS program using the narrowband (ramp) filter (PI: W. van Breugel) to image several high-redshift radio galaxies in Ly$\alpha$ will discover how prevalent such wedge features are in this population.

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