HUBBLE SPACE TELESCOPE NEAR-INFRARED AND OPTICAL IMAGING OF FAINT RADIO SOURCES IN THE DISTANT CLUSTER CI 0939 + 4713

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ABSTRACT

We present deep Hubble Space Telescope Near-Infrared Camera and Multiobject Spectrograph (NICMOS) and Wide Field and Planetary Camera 2 (WFPC2) optical imaging of a small region in the core of the distant rich cluster CI 0939 + 4713 (z = 0.41). We compare the optical and near-infrared morphologies of cluster members and find apparent small-scale optical structures within the galaxies that are not present in the near-infrared. We conclude that strong dust obscuration is a common feature in the late-type galaxies in distant clusters. We then concentrate on a sample of 10 faint radio galaxies lying within our NICMOS field and selected from a very deep 1.4 GHz VLA map of the cluster with a 1 σ flux limit of 9 μJy. Using published data we focus on the spectral properties of the eight radio-selected cluster members and show that these comprise a large fraction of the poststarburst population in the cluster. The simplest interpretation of the radio emission from these galaxies is that they are currently forming massive stars, contradicting their classification as poststarburst systems based on the optical spectra. We suggest that this star formation is hidden from view in the optical by the same obscuring dust that is apparent in our comparison on the optical and near-infrared morphologies of these galaxies. We caution that even in the rest-frame optical the effects of dust cannot be ignored when comparing samples of distant galaxies to low-redshift systems, particularly if dust is as prevalent in distant galaxies as appears to be the case in our study.

Subject headings: galaxies: clusters: individual (CI 0939 + 4713) — galaxies: evolution — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

1. INTRODUCTION

The characteristics of the galaxy populations in the cores of rich clusters appear to vary strongly as a function of redshift, with an increasing fraction of blue galaxies in clusters at z > 0.2 (the Butcher-Oemler effect; Butcher & Oemler 1984). The search for the processes responsible for these rapid changes has become a vigorous field of research, and, at least for the blue cluster galaxies, a broad consensus has been reached about the nature of this population. The bulk are star-forming cluster members; they cover a wide range of luminosities, from a few L* downward, and they have emission-line strengths that indicate moderate to high star formation rates (Abraham et al. 1996; Balogh et al. 1999; Barger et al. 1996; Couch & Sharples 1987; Dressler & Gunn 1992; Dressler et al. 1999, hereafter D99; Fabricant, Bautz, & McClintock 1994; Fisher et al. 1998; Lavery & Henry 1988). The optical morphologies of these galaxies were investigated first with high-resolution ground-based imaging (Lavery et al. 1992) and more recently with Hubble Space Telescope (HST) imaging (Dressler et al. 1994a; Couch et al. 1994, 1998; Oemler, Dressler, & Butcher 1997; Smail et al. 1997, hereafter S97; Fabricant et al. 1999). These studies have shown that most of the blue star-forming galaxies have strong disk components, and a large fraction also appear to be disturbed, with structures suggesting mergers or tidal interactions. Thus the increasing proportion of blue galaxies within distant clusters is associated with an increasing number of active star-forming disk galaxies in these environments. The large fraction of apparently disturbed galaxies suggests that galaxy-galaxy interactions or the effects of the cluster tidal field on these disk galaxies could be responsible for the Butcher-Oemler effect (Moore, Lake, & Katz 1998).

The spectroscopic studies of distant clusters uncovered another population of luminous galaxies that is not seen in similar numbers in local clusters. These are galaxies with strong Balmer absorption (typically measured using the Hδ λ4104 line and coming predominantly from A stars) and no [O II] λ3727 emission. The large population of A stars is a sign that the galaxy was actively forming massive stars in the recent past (≤1 Gyr), while the lack of emission lines suggests that this star formation has now ceased. Together the spectral properties are interpreted as showing that the galaxy is in a poststarburst phase. Almost 20% of the luminous galaxies within the cores of distant clusters fall in this poststarburst class (e.g., D99, although see Balogh et al. 1999), and it has been suggested that this high fraction indicates that almost all cluster galaxies pass through this phase (Barger et al. 1996).

There is an increasing realization in the community of the importance of dust obscuration in defining the apparent properties of galaxies in the near-UV and optical, particularly at high redshifts. This issue has been highlighted by the disagreement over the form of the star formation history of the universe as estimated from the variation in the ultraviolet luminosity density with redshift (e.g., Lilly et al. 1996; Steidel et al. 1999) compared to star formation indicators at longer wavelengths, such as Hz emission (Yan et al. 1999) or reradiated starlight detected in the submillimeter (e.g., Blain et al. 1999). The longer wavelength tracers tend to find
higher star formation densities, a result that has been attributed to dust absorption in the UV and optical (Calzetti & Heckman 1999; Meurer et al. 1997; Pettini et al. 1998).

The issue of the effects of dust on the evolutionary cycle associated with the optical Butcher-Oemler effect has been disregarded by most investigations to date. However, the associated with the optical Butcher-Oemler effect has been studied in detail (e.g., Sanders & Mirabel 1996). The e(a) class is naturally identified as the progenitor of the e(a) galaxies. These galaxies have detectable [O II] emission and relatively strong Balmer absorption [EW(Hβ) ≥ 4]. These spectral features, along with other properties of the galaxies and of similar spectrally classified local systems (P99; Poggianti & Wu 1999), were interpreted by P99 as probably arising from a dust-obscured starburst, with the [O II] line strength suppressed by dust absorption. The e(a) class is naturally identified as the progenitor of the large population of poststarburst galaxies in the clusters.

To obtain a complete view of the star formation properties of cluster galaxies free from the effects of dust obscuration we need to complement the optical studies with observations at longer wavelengths, from the near-infrared to the submillimeter and radio. In particular, observations in the submillimeter and far-infrared can trace the amount of starlight absorbed by dust and reradiated at longer wavelengths. For the most extreme starburst galaxies in the local universe this reradiated emission dominates the bolometric luminosity of the galaxies (e.g., Sanders & Mirabel 1996). Unfortunately, current submillimeter and far-infrared surveys lack the sensitivity to study all but the most extreme starburst galaxies (M ≥ 100 M⊙ yr⁻¹) at moderate and high redshift. However, at radio wavelengths, the synchrotron radiation from electrons accelerated by supernovae leads to a tight correlation between the radio and far-infrared fluxes of star-forming galaxies across a wide range in luminosity (Condon 1992). This means that in the absence of a radio-loud active nucleus the radio flux of a star-forming galaxy can be used to estimate its current massive star formation rate.

By employing the huge collecting area of the VLA we can undertake a sensitive radio survey for star formation in obscured galaxies down to limits of M ∼ 5–10 M⊙ yr⁻¹ at z ∼ 0.5. To this end the VLA has been used in an ambitious survey to determine the evolution of the radio populations in a sample of very rich clusters out to z = 0.4 (Morrison et al. 1999). The survey contains 14 clusters at z = 0.10–0.18, 12 more between z = 0.20–0.25, and a further four at higher redshifts, z = 0.38–0.41 (the radio observations discussed in this paper are of the most distant cluster in this survey). Morrison et al. (1999) find that the population of radio galaxies with luminosities above 2 × 10²² W Hz⁻¹ in the most extreme clusters has increased by a factor of ∼ 5–6 out to z = 0.4. They conclude that the radio galaxy population in very rich clusters has evolved significantly over the last 5 Gyrs.

In this paper we report on high-resolution near-infrared imaging from HST and sensitive radio observations with the VLA of a small field in the core of the distant cluster Cl 0939+4713 (A851, z = 0.41) for which high-resolution optical HST images and extensive archival spectroscopic observations are available. We combine these data sets to study the characteristics of galaxies in distant clusters and to search for the signatures of dust obscuration on their apparent properties.

In § 2 we describe the HST optical and near-infrared imaging as well as the deep VLA 1.4 GHz map of this field. In § 3 we then present our results on the properties of the radio-selected galaxies within our HST field, drawing on published spectroscopy. We discuss these in § 4 and give our main conclusions in § 5. Throughout this paper we use H₀ = 50 km s⁻¹ Mpc⁻¹ and a Ω₀ = 1, Λ = 0 cosmology. In this geometry 1" corresponds to 6.5 kpc at z = 0.41.

2. OBSERVATIONS

2.1. NICMOS Imaging

The Near-infrared and Multiobject Spectrograph (NICMOS) observations of Cl 0939+4713 discussed here were obtained with camera 3 during the special campaign in 1998 January. Due to the distortion of the NICMOS dewar, the wide-field camera 3 (field-of-view 51.2 arcsec² sampling 0.20 pixel⁻¹) was not parfocal with the other instruments onboard HST, and to allow the diffraction-limited operation of this camera a special campaign was organized during which the main telescope optics were refoocused on the camera 3 focal plane.

The observations comprise a mosaic of four pointings through the F160W filter covering a combined field of around 100′ × 100′. Each pointing consists of four individual exposures of 1215 s, each spatially offset by 1/1 on a square grid to remove bad pixels and reduce the effects of flat field variations. The total integration time per pixel for the mosaic is thus 4.86 ks. The data were reduced in a standard manner using the NICMOS data pipeline (CALNICA) and the most recent calibration files taken from the archive. Any remaining features in the background were removed with the UNPEDESTAL software kindly provided by Dr. R. van der Marel, which worked well, and the final mosaicing was achieved using IMCOMBINE in IRAF. The mosaic was photometrically calibrated to give magnitudes on the H₁₆₀ Vega system. This image provides rest-frame J-band morphologies at a resolution of around 1.3 kpc for cluster members (Fig. 1).

To create a complete catalog of objects detected within the NICMOS mosaic we analyzed the frame using the SExtractor image analysis package (Bertin & Arnouts 1996). We adopted detection criteria of a minimum area of ≥ 0.4 arcsec² (10 pixels) above an μ₁₆₀ = 24.0 mag arcsec⁻² isophote, and using these we detect 303 sources brighter than the approximate 3 σ point-source flux limit of H₁₆₀ = 23.5.

2.2. Radio Data

The VLA observations of Cl 0939+4713 were obtained in B configuration at 1.4 GHz between 1996 January 06–08. The total integration time of the map is 60.7 ks at an effective resolution of 5.0′ (33 kpc at z = 0.41). The map was cleaned and analyzed using AIPS. Details of this complex procedure are given in Morrison et al. (1999). The map reaches a 1 σ noise level of 9 μJy beam⁻¹. We detect 10 sources above 27 μJy (3 σ) within the field defined by the overlap region of our NICMOS F160W mosaic and Wide Field and Planetary Camera 2 (WFPC2) F702W exposures (see Fig. 1). All 10 sources have bright optical/near-infrared counterparts in our HST images. The properties of these 10 sources are discussed in § 3. In Table 1 we report the positions, fluxes and rest-frame radio power (using the redshifts from Table 2 and assuming an S ∝ ν⁻⁰.7 spectrum). Unfortunately, owing to the modest resolution of the map only...
FIG. 1.—The VLA 1.4 GHz map overlaid as a contour plot on the HST NICMOS F160W mosaic. The radio sources are identified in large font using the numbering scheme of S97. The galaxies labeled with the smaller font represent other spectroscopically identified galaxies (with the exception of 333) from the catalog of Dressler et al. (1999); these are similarly numbered using the S97 identifications. The dashed line shows the overlap on this field of the WFPC2 F702W exposure from S97. The radio contours are at 12, 25, 50, 100, and 200 μJy per beam. North is at the top and east is on the left in this figure.

TABLE 1
PROPERTIES OF THE RADIO GALAXY SAMPLE

| Source Identification | R.A. (J2000) | Decl. (J2000) | S_{1.4} (μJy) | P_{1.4} (10^{22} W Hz^{-1}) | Comments |
|----------------------|-------------|--------------|----------------|----------------------------|----------|
| 36                   | 09 42 58.16 | +46 59 53.4  | 79 ± 9         | 5.9                        | Resolved?|
| 122                  | 09 42 57.62 | +46 59 45.3  | 204 ± 9        | 15.2                       |          |
| 224                  | 09 42 55.80 | +46 59 49.4  | 55 ± 9         | 4.0                        |          |
| 230                  | 09 43 02.32 | +46 59 55.3  | 52 ± 9         | 3.8                        |          |
| 296                  | 09 43 02.81 | +46 59 24.2  | 644 ± 9        | 47.6                       |          |
| 399                  | 09 42 57.84 | +46 59 13.3  | 43 ± 9         | 3.1                        |          |
| 426                  | 09 42 56.21 | +46 59 12.0  | 32 ± 9         | 2.4                        |          |
| 536                  | 09 43 00.03 | +46 58 53.4  | 196 ± 9        | 14.5                       |          |
| 610                  | 09 42 57.34 | +46 58 50.4  | 158 ± 9        | 11.7                       |          |
| 640                  | 09 42 55.08 | +46 58 41.7  | 57 ± 9         | 2.6                        |          |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
two sources, 122 and 296, appear to be resolved, and then only marginally. The radio and optical/near-IR images are aligned to an rms accuracy of 0.4 using the eight brightest radio sources in the NICMOS field.

The flux limit of the radio sample corresponds to a radio power of just $2 \times 10^{22}$ W Hz$^{-1}$ at the redshift of the cluster. Comparing this limit to those achieved by radio surveys of local clusters we note that Gavazzi & Boselli (1999) detect galaxies as faint as $3 \times 10^{20}$ W Hz$^{-1}$ in their analysis of the radio luminosity function in the Virgo cluster (a factor of roughly 100 times closer to us than Cl 0939+4713) using the NVSS 1.4 GHz survey (Condon et al. 1998).

2.3. WFPC2 Imaging

These observations were obtained as part of the early release observations during the science verification phase after the installation of the WFPC2 on board HST. The observations comprise a total of 21.0 ks of integration through the F702W filter (Dressler et al. 1994b). The exposures were dithered by integer pixels to allow the removal of defects and cosmic-ray events. The position of the corrective optics within WFPC2, to correct for the aberration of the primary mirror, was not optimal during these observations, and combined with a higher than ideal operating temperature for the CCDs, these images are not as cosmetically clean as later exposures with WFPC2. Nevertheless, they provide deep ($R \sim 26$) imaging of the core of the cluster at $0.1$–$0.2$ resolution in the rest-frame B band.

The reduction and analysis of the F702W exposure of this field is described in more detail in Smail et al. (1997), who provide a complete catalog of objects detected in the field with photometry calibrated to the $R_{702}$ passband described by Holtzman et al. (1995). Smail et al. (1997) also discuss visually classified morphologies on the revised Hubble scheme for the brighter galaxies within this field down to $R_{702} = 23.5$. There are a total of 123 galaxies with morphologies from S97 within the joint NICMOS/WFPC2 field. All 10 of the radio sources selected from the VLA map are included in the S97 catalog, and we list the Hubble type for each galaxy in Table 2. We also give the disturbance index ($D$), which is a measure of how disturbed the galaxy seemed compared to the typical appearance of a galaxy with its Hubble type locally, where $D = 0$ is “normal” and $D = 4$ is highly disturbed (S97). In addition to these objective measures, a subjective interpretation of the source of the disturbance was also given by S97 and is listed in the table (e.g., chaotic, tidal interaction, etc.). We note in particular that a galaxy would be classified as “merger” if two or more close nuclei were seen in a common envelope. These visual estimates were shown to correlate well with the machine-based asymmetry measurements (S97) and have been used to attempt to isolate and study the role of dynamical interactions in triggering the Butcher-Oemler effect (e.g., D99).

To investigate the optical-infrared colors of the galaxies in our sample we have aligned and resampled the WFPC2 image to the reference frame of the NICMOS exposure. A comparison of stars and compact galaxies in the resampled F702W exposure and the F160W image shows that they have very similar profiles in the two bands, which indicates that the resolution is dictated by the pixel sampling of the images. This suggests that point-spread function (PSF) variations should not strongly influence our analysis. To confirm this we have convolved the WFPC2 and NICMOS images with a model PSF for the other instrument generated using TINY TIM.  The colors determined from these convolved images show no systematic differences from those measured from the unsmoothed images, and hence we use the latter in the following analysis.

To measure colors from our F702W and F160W exposures we have used the IRAF task PHOT and apertures matched to the near-infrared extent of the galaxies. The diameter of the photometry apertures were taken as 2.5 times the FWHM of each source from the F160W catalog ($d_{phot}$ in Table 2). The color-magnitude diagram for the field is shown in Figure 2, with the radio sources and spectroscopically identified galaxies marked. We give total $H_{160}$ magnitudes and aperture ($R_{702} - H_{160}$) colors for the 10 radio sources in Table 2. We show the F160W and F702W images of this sample in Figure 3.

To study the color variations within the galaxies we have constructed $F702W-F160W$ color images for each galaxy in our spectroscopic sample. We show the color images for the relevant radio-detected galaxies in Figure 3 to illustrate the internal color variations within these galaxies. A comparison sample of confirmed cluster members that are not detected in the radio map is shown in Figure 4. We note that PSF-convolved versions of these images are qualitatively similar, in particular the blue cores at the centers of 296, 399, and 426 do not appear to result from differences in the PSF between the two passbands.
Fig. 3.—The groups of NICMOS F160W, F702W—F160W, and WFPC2 F702W images for each of the 10 galaxies selected from the VLA 1.4 GHz map of Cl 0939+4713. The F160W and F702W images provide rest-frame J- and B-band views of the galaxies, and these are shown with a linear intensity scale, while the color image is constructed from the difference of the log-scaled F160W and F702W images. In the F702W—F160W color image lighter regions represent redder areas of the galaxy, and the typical color range is roughly $R_{25} - I_{160} = 2.4 - 3.2$ (black to white). The panels are labeled with the catalog number, morphological type, spectral type, and disturbance index (from S97 and D99). Each panel is $10'' \times 10''$ (equivalent to 65 kpc$^2$ at the cluster redshift) with north at the top and east on the left, and the panels are ordered on morphology. Note that 640 lies in the extreme corner of the WFPC2 field and 230 falls on a chip-boundary in the F702W exposure. All of the galaxies are confirmed cluster members with the exception of 640, which is a foreground field galaxy, and 230, which has no spectroscopic identification.
Fig. 4—A comparison sample of spectroscopically confirmed cluster galaxies that show no detectable radio emission in the VLA map above a 1.4 GHz flux of $S_{1.4} = 27$ $\mu$Jy. This figure includes all the spectrally active members of this sample and again is ordered on morphology. The panels are labeled with the galaxy identification, morphology, and disturbance index, D, from S97 and the spectral classification from D99.
axies in the different spectroscopic classes is k (7/2), k + a (6/0), a + k (2/0), e(a) (5/1), e(b) (1/0), and e(c) (2/1). The spectrum of one field galaxy has a signal-to-noise ratio too low to allow a reliable classification.

For the 10 radio sources in the field, spectra and spectral classifications are available from D99 for nine galaxies (galaxy 230 lacks a spectroscopic identification), and we list these in Table 2. Of these nine galaxies, eight are cluster members and one is a field galaxy (the Sab galaxy 640).

3. RESULTS

With a small sample of galaxies our conclusions are by necessity fairly qualitative in nature and this paper should be seen as the prelude to the analysis of a larger sample of radio-selected galaxies in distant clusters by Morrison et al. (1999). Nevertheless, we will use our observations, and particularly the high-resolution near-infrared imaging with NICMOS, to illustrate the general characteristics of radio galaxies in distant clusters and to emphasize the effects of dust in galaxies on their perceived properties.

3.1. Radio-selected Sample

We have detected 10 galaxies above the 3 \( \sigma \) flux limit \((S_{1.4} \geq 27 \mu Jy)\) of the VLA map that lie within the joint NICMOS/WFPC2 field. The spectroscopic information available from D99 allows us to identify eight of these galaxies as cluster members (or 35% of the 22 cluster galaxies known within this field) and a further source as a foreground field galaxy (12% of the spectroscopically-confirmed field population within our image). Our field size corresponds to a region \( \sim 650 \times 650 \) kpc in extent at the cluster redshift and the equivalent radio power limit is \( 2 \times 10^{23} \) W Hz\(^{-1}\). A comparably deep survey of a similar region in the core of a rich local cluster would typically detect \( \leq 1 \) galaxy (e.g., Fig. 5), compared to the eight detected here. This suggests a substantial increase in the rate of occurrence of radio sources in high-density environments at moderate redshifts (Morrison et al. 1999).

The galaxies included in the radio-selected sample of cluster members are typically the brighter galaxies in our field (Fig. 2), including the brightest four galaxies (in the rest-frame \( B \) band). The whole sample spans a range of magnitudes \( R_{192} = 18.3 \pm 20.8 \) (\( L_B \sim 4 \pm 0.4L_\odot \)). The colors of the fainter radio-detected galaxies are slightly bluer than equivalently luminous, undetected cluster members, with the brighter radio-emitting galaxies having comparable (red) colors to the undetected population (Fig. 2). The fact that we detect only the optically brightest galaxies in the radio map may suggest that the majority of cluster galaxies would be detected if we could increase the sensitivity of the radio observations by a factor of a few (see Fig. 5).\(^8\)

In our analysis we will assume that the local relationship between star formation rate and radio emission (e.g., Condon 1992) holds for spiral galaxies detected in distant clusters. The validity of the local relationship at least for the distant field appears to be supported by recent observations (Georgakakis et al. 1999). However, we caution that the exact star formation rates derived from this analysis may

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\(^8\) We note that the radio population has similar dynamics to those cluster members undetected in the radio map: we calculate a rest-frame velocity dispersion of \( \sigma = (960 \pm 160) \) km s\(^{-1}\) for the eight radio-detected members compared to \( \sigma = (1110 \pm 140) \) km s\(^{-1}\) for the 12 undetected members lying within the same field.
# Table 2

**Optical/Near-infrared Properties of the Radio Sample**

| Source Identification | $z$   | $H_{160}$ | $(R_{702} - H_{160})$ | $d_{phot}$ (arcsec) | Morphological Type | Spectral Type | EW(H$\delta$) ($\AA$) | $D$ | Comments |
|-----------------------|-------|-----------|-----------------------|---------------------|-------------------|--------------|-----------------------|-----|----------|
| 36                    | 0.4119| 18.20     | 1.46 ± 0.10           | 5.6                 | Sd                | e(a)         | 10.2                  | 2   | EW([OII]) = −6.9 Å; Merger |
| 122                   | 0.4125| 17.96     | 2.30 ± 0.10           | 2.7                 | Sd                | a + k        | 11.6                  | 3   | Merger, H$\delta$ measurement uncertain. |
| 224                   | 0.4076| 15.85     | 2.33 ± 0.04           | 5.8                 | Sc/d?             | k + a        | 6.1                   | 2   | Merger |
| 230                   |       | 18.80     | 1.77 ± 0.14           | 2.2                 | Irr               | ...          | ...                   | 2   | No spectrum in D99 |
| 296                   | 0.4014| 16.87     | 2.49 ± 0.07           | 2.5                 | E                 | k + a        | 4.6                   | 0   |        |
| 399                   | 0.4109| 16.14     | 2.50 ± 0.05           | 2.5                 | E                 | k            | 0.0                   | 0   |        |
| 426                   | 0.4037| 16.18     | 2.55 ± 0.05           | 3.9                 | E                 | k            | 0.0                   | 0   |        |
| 536                   | 0.4111| 17.49     | 2.29 ± 0.08           | 4.0                 | Sc                | a + k        | 8.6                   | 3   | Tidal? |
| 610                   | 0.4007| 15.84     | 2.50 ± 0.05           | 3.4                 | Sa/S0             | k + a        | 4.2                   | 1   | Merger |
| 640                   | 0.3324| 16.27     | 3.21 ± 0.04           | 8.3                 | Sab               | k:           | 0.0                   | 1   | Field galaxy, low S/N spectrum—possible e(a)? |
have substantial systematic uncertainties. In particular, the claim that the radio to far-infrared correlation varies locally between galaxies in rich clusters and those in the field (Andersen & Owen 1995) may indicate an environmental influence in the conversion from radio luminosity to star formation rate (SFR) resulting from the compression of the galactic magnetic field by the galaxy’s motion through the intracluster medium (ICM). Without a fuller understanding of the state of the ICM in distant clusters it is difficult to quantify the extent of this bias on the radio-derived SFRs of distant cluster galaxies. We have chosen therefore to quote the SFRs determined using the local field relationship and also the correction that should be applied if the radio population in distant clusters shows the same behavior as is claimed for galaxies in rich clusters locally.

3.2. Optical Morphologies

Turning to the rest-frame B-band morphologies of the radio sources (Table 2 & Fig. 3), we see that they fall roughly equally into two broad classes: optically luminous early-type galaxies (E and S0/SA) and mid- to late-type spiral galaxies (Sc–Sd/Irr).

In their analysis of galaxies in the Virgo cluster detected in the NRAO VLA Sky Survey, Gavazzi & Boselli (1999) found that the most powerful radio sources in spirals were also in mid-type, Sb–Sc systems. To compare the optical and radio properties of the galaxies we plot the 1.4 GHz -band luminosity for galaxies in rich clusters locally.

3.3. Near-infrared Morphologies

We now discuss the internal structure of the cluster galaxies in our HST images (Figs. 3 and 4) and the important insights that our NICMOS near-infrared imaging has provided into the nature of these systems. Starting with the early-type galaxies we see relatively uniform optical–near-infrared colors (as shown by their lack of structure in the F702W–F160W images in Figs. 3 and 4). A few contain blue cores, which may be associated with central AGN, although the details of these features are sensitive to the exact form of the PSF in the F702W and F160W images and so we do not discuss them further here.

A comparison of the F702W and F160W morphologies for the late-type radio sources in Figure 3 shows that in these systems there are substantial differences in the appearance of these galaxies between the rest-frame B and J bands. The near-infrared morphologies are considerably more relaxed and symmetrical. However, the lack of a morphological classification scheme for local galaxies based on near-infrared imaging means that is not useful to attempt to reclassify the galaxies on the basis of the F160W images.

More interestingly, the F702W–F160W images in Figure 3 show that in a large number of cases the irregular structures seen in the rest-frame B band within the central regions of the late-type galaxies are replaced by a much more regular appearance in the near-infrared and so must be due to very red structures (visible as white regions in Fig. 3). These features are substantially redder than the outskirts of the galaxies (up to Δ(R–H) ~ 1.3–1.5) and could represent differences in the stellar populations within the galaxies or simply dust obscuration. To distinguish between these alternatives we concentrate on the large fraction of galaxies whose integrated spectra show poststarburst stellar populations. The lack of emission lines in the optical spectra indicates that there is no visible star-formation in the outskirts of these galaxies, which also show the red optical-infrared colors typical of an evolved stellar population (see the integrated colors in Fig. 2). In this situation it is very difficult to make the stellar population in the central regions of the galaxies substantially redder than the outskirts without invoking a contrived scenario. In contrast, dust obscuration can easily produce both the apparently red colors and its structured distribution. We propose therefore that large quantities of dust are probably a common feature of these galaxies.

The small-scale features seen in the optical images of these galaxies, which we claim are due to dust obscuration, have been previously interpreted as arising from dynamical disturbance of these galaxies, suggesting a dynamical origin for their star formation activity (S97). To understand the consequences of this change in interpretation of these galaxies we focus on those galaxies classified in the optical as showing signs of morphological disturbance by S97. There are a total of eight spectroscopically confirmed members in our sample with disturbance indices of Δz ≥ 2 that indicate abnormally disturbed morphologies; all of these are disk galaxies, and they are typically classified as mergers or...
tidally disturbed, and half of them are detected in our radio map. These galaxies exhibit substantially more regular morphologies in the near-infrared (Figs. 3 & 4); in particular, the apparently double structures seen in the F702W morphologies of the radio sources 36, 122, and 536 all disappear in the F160W passband.

We also see signs of dust obscuration in the disturbed galaxies that are not radio sources (171, 369, 497, and 622), although arguably not as extreme as the radio-selected sample. In a few cases there are other signatures of interactions in the F702W images apart from double nuclei, etc., such as low surface brightness tidal features or companion galaxies (e.g., 224 or 497), which indicate that these are true merging or interacting systems. But in the majority of the galaxies their high disturbance index was based upon the apparent presence of multiple nuclei in the central regions of the galaxies (see § 1). We suggest that in fact dust obscuration is the correct explanation for their irregular appearance in the rest-frame B band, which results in their classification as disturbed or merging. We estimate that of the eight confirmed members with \( D \geq 2 \) based on the F702W imaging, at least half (36, 122, 171, and 622) would have \( D < 2 \) if classified from the F160W images, suggesting that the occurrence of highly disturbed galaxies in the core of Cl 0939 + 4713 may have been overestimated by up to a factor of 2.

We conclude from our comparison of the near-infrared and optical morphologies of a small sample of confirmed cluster members that the frequency of galaxies showing small-scale signatures of disturbance or interaction is probably substantially less than has been suggested from optical studies (e.g., S97) owing to obscuration by dust. This effect acts in addition to the standard luminosity bias in optically selected samples toward actively star-forming galaxies (the usual justification given for undertaking near-infrared surveys of distant clusters; e.g., Barger et al. 1996). The expectation of previous optically-based studies was that dust obscuration would not be a significant bias when comparing the distant morphological samples with more local examples as they were comparing effective rest-frame B-band observations in both cases (S97). However, this expectation seems to have been misleading because of the wider prevalence of dust in cluster galaxies at \( z \sim 0.4 \), perhaps associated with the increased activity in galaxies at these epochs.

### 3.4. Spectral Properties

Looking now at the spectral properties of the radio-selected cluster members we see something striking: five of the galaxies have spectral features that class them as post-starburst (a + k/k + a) systems using the scheme of P99 (Table 2). Moreover, these five radio sources show the strongest Balmer absorption lines of the eight poststarburst galaxies in our cluster sample (they are also the brightest five poststarburst galaxies). There are no poststarburst field galaxies in our sample.

The detection of poststarburst galaxies in the radio wave band is surprising. These galaxies are selected to have no detectable [O II] emission and hence are expected to have no ongoing massive star formation (observations of the spectral region including any H\(_{\alpha}\) emission in these galaxies would make this statement more robust). In contrast, the radio emission is most easily explained as arising from massive star formation (although some contribution from an obscured radio-loud AGN cannot be ruled out with our present data). The expected lifetime of the radio emission after the starburst is \( \leq 0.1 \) Gyr; thus if they are poststarburst systems these galaxies must all be seen just after the cessation of their star formation. This seems very unlikely as the length of time in which the poststarburst signature (strong H\(_{\alpha}\) absorption) is visible is \( \sim 1 \) Gyr and we would thus expect to see an order of magnitude more radio-quiet k + a galaxies, where the radio emission had decayed but the Balmer absorption is still visible. This population is not observed. Therefore, we conclude that massive stars are currently being formed in these galaxies.

Where is the site of the active star formation in the a + k/k + a cluster galaxies? The optical spectra typically sample the whole of the bulge and disk of the galaxy (see D99), and thus it is unlikely that we are missing emission from the outskirts of the galaxy. We suggest instead that the star formation is occurring in the central regions of these galaxies but is hidden from view by the dust that we see there in our F702W - F160W images. This possibility was raised in P99, who stated that the most extreme e(a) galaxies might appear as poststarburst systems (a + k/k + a) owing to obscuration of the emission regions. The reddened regions lie in the central 5-10 kpc of the galaxies (Figs. 3 & 4) and have optical–near-infrared colors that are typically \( \Delta(A_{702}-H_{160}) \sim 1 \) magnitude redder than the outskirts of the galaxies. This would indicate optical extinctions of at least \( A_B \sim 2 \) mag to the population of disk stars (let alone the active sites of star formation), although this estimate is highly uncertain because of resolution effects.

Four of the five radio-selected poststarburst galaxies are disk galaxies, and we can estimate their star formation rates (SFR) from their radio power using the calibration of Condon (1992). We find that these galaxies are typically forming massive stars (\( M \geq 5 M_\odot \)) at rates of \( \sim 10 M_\odot \) yr\(^{-1} \), with the highest SFRs being \( 30 M_\odot \) yr\(^{-1} \) for 122 and 536. This assumes no boosting of the radio emission due to compression of the galactic magnetic fields by the ICM, which could amount to a factor of \( \sim 2 \) (Andersen & Owen 1995). Combining these SFRs with the B-band luminosities of the galaxies, using the relations given in Kennicutt (1992) we can predict their [O II] fluxes if the star formation regions are unobscured. We can then roughly estimate the amount of extinction needed for this line to be undetected in the optical spectra, \( EW ([\text{O II}]) \lesssim 5 \) \AA. We find that the star forming regions would need to suffer \( A_B \gtrsim 3 \) mag of extinction for the [O II] line to be undetected in the D99 spectra (\( A_B \gtrsim 2 \) mag if we assume the radio fluxes are artificially raised). This amount of obscuration is not unreasonable given the extent of the dust reddening seen in the F702 - F160W images (Figs. 3 & 4). We note that if we assume this dust is cold, \( T_d \sim 40 \) K, then the predicted submillimeter fluxes of these galaxies will be only \( S_{850} \sim 0.5 \) mJy at 850 \( \mu \)m. This is well below the confusion limit of current submillimeter instrumentation in blank fields.

There are also examples of proposed dusty galaxies within our sample that are not detected in the radio map. In particular, three of the cluster galaxies have e(a) spectral features and evidence for dust in their F702 - F160W images (Fig. 4: 177, 369, and 622). These galaxies are optically fainter than the e(a) galaxy that is detected in the radio, 36, and it is possible that their lower overall luminosities mean that their radio emission is below the limit of...
the VLA map. Interestingly, although the e(a) spectral class was interpreted as dusty starbursts in P99, the radio map places upper limits on the current rate of massive star formation in the undetected e(a) galaxies of \( M \lesssim 5 M_\odot \text{yr}^{-1} \), with similar limits applying to the galaxies with e(c) spectra in the field (e.g., 165 and 497 in Fig. 4). Taking the possible boosting of the radio emission due to compression of the galactic magnetic fields by the ICM (§ 3.1) into account these SFR limits could be dropped by a factor of two or more.

4. DISCUSSION

We see a combination of poststarburst spectral features, radio emission, and apparently large quantities of dust within the spiral galaxies in our sample. These characteristics can be most easily accommodated if they exist in spatially distinct regions of the galaxies, as suggested by our color maps. The radio emission would arise from massive star formation in the dust obscured center of the galaxy, while the A stars trace the remnants of an earlier (\( \lesssim 1 \) Gyr) strong star formation episode within the galactic disk. There is weak evidence in our sample for a correlation between H\( \alpha \) line strength and radio luminosity, which would suggest that there is a causal link between the numbers of A stars and the current (obscured) star formation rate, probably as a result of a single triggering mechanism.

This triggering mechanism could be a cluster-related phenomenon, a view that is supported by the lack of obvious poststarburst systems in samples of faint radio sources in the field (Hammer et al. 1995; L. L. Cowie 1999, private communication). Thus, we may be seeing a more dynamic situation including cluster-driven processes, whereby interactions between the ICM and the cold molecular gas within the galactic disks accelerates the collapse and evaporation of the star-forming regions. The effects of the ICM on the galactic disk are expected to be a function of the local density in the disk—with lower density regions in the outskirts of the disks being most severely affected, while star formation continues almost unaffected in the inner regions of the galaxy. Thus environmental processes could result in a combination of poststarburst and starburst within individual cluster galaxies. Studies of the spatial distribution and kinematics of larger samples of radio-selected galaxies may be able to discriminate between the different physical processes that could be operating (Morrison et al. 1999).

Alternatively, perhaps this activity may be triggered by a more general physical process that is unrelated to the cluster environment. Indeed, similar behavior is seen in the models of interacting field galaxies published by Mihos & Hernquist (1996) (although we have argued that a substantial fraction of apparently disturbed cluster spiral galaxies probably arise from dust obscuration, rather than true interactions). For a range of models for tidal interactions between galaxies Mihos & Hernquist predict that spatially extended enhanced star formation will first occur in the disk of the galaxy. This is followed on a timescale of \( \sim 0.1 \)–0.3 Gyr by funneling of any remaining gas into the center of the galaxy where it reaches very high densities and triggers an (obscured?) nuclear starburst. Again, more detailed investigation of the kinematics and internal dynamics of these galaxies may provide useful diagnostics to distinguish between the competing models.

The picture that is appearing is one in which galaxies that are visibly forming stars appear to have modest star formation rates, \( \lesssim 5 M_\odot \text{yr}^{-1} \) (\( M \gtrsim 5 M_\odot \)), while more vigorous star formation, \( \gtrsim 10 \)–30 \( M_\odot \text{yr}^{-1} \) is ongoing in highly obscured regions in the centers of what appear to be poststarburst galaxies. If the radio fluxes of these distant galaxies are increased by the same environmental effects that are claimed to boost the radio emission of local cluster galaxies, and to the same extent (Andersen & Owen 1995), then the quoted SFRs should be reduced by a factor of \( \sim 2 \). Sensitive observations to search for Hz emission (or emission lines further into the near-infrared) will provide a stronger test of the star formation rates in these galaxies, the extent of obscuration within them, and the degree to which their radio emission deviates from that seen in the distant field population owing to environmental processes. Finally, we note that by having poststarburst and starburst phases occurring in parallel within a single galaxy it is possible to reduce the high fraction of galaxies (\( \sim 100\% \), Barger et al. 1996) that must pass through this phase to explain the large numbers of poststarburst systems seen within distant clusters (Barger et al. 1996; P99).

5. CONCLUSIONS

In summary, we have highlighted the role that dust plays in obscuring our view of the morphologies and star formation properties of distant galaxies. We have shown that selection at faint radio fluxes provides a powerful technique for identifying spectrally classified poststarburst and starburst galaxies crucial to our understanding of the evolutionary cycle of galaxies in clusters (e.g., P99). Using this new tool we can undertake statistical studies to search for the mechanism responsible for triggering and/or quenching of this activity (P99; Morrison et al. 1999). The main conclusions of our study are the following:

1. We present optical and near-infrared imaging with HST of a region in the core of the distant rich cluster Cl 0939 + 4713 at \( z = 0.41 \).
2. We compare the high-resolution near-infrared and optical morphologies of a sample of 22 cluster members. This shows that while the broad morphological classifications are similar, the frequency of galaxies showing small-scale signatures of disturbance or interaction is substantially less when using the near-infrared imaging. We suggest that obscuration by dust has led optical studies to conclude that an anomalously high fraction of galaxies have suffered small-scale disturbances. This may point to a wider prevalence of dust in cluster galaxies at \( z \sim 0.4 \), perhaps as a result of the increased star formation activity at these epochs.
3. Using a very deep VLA 1.4 GHz map of this area we select a sample of 10 radio galaxies in our field above a flux limit of \( S_{1.4} = 27 \text{ \mu Jy} \), equivalent to a rest-frame 1.4 GHz power of \( 2 \times 10^{22} \text{ W Hz} \) at the cluster redshift. The faint radio sources are associated with two populations of cluster galaxies: luminous early-type galaxies, the radio emission of which originates from AGNs; and dusty galaxies with late-type spiral morphologies, the radio emission of which is expected to trace massive star formation (although the exact relationship between the radio luminosity and the SFR is uncertain as a result of environmental influences).
4. The optical spectral characteristics of the late-type radio members are highly unusual—they appear to be poststarburst systems. We suggest that these galaxies are not...
poststarburst but in fact host highly obscured star formation and starbursts. This is supported by our high-resolution optical–near-infrared imaging, which shows that the central regions of these galaxies are heavily dust enshrouded. If they continued for several 100 Myrs, these dust-enshrouded nuclear starbursts could build a substantial stellar bulge in the remnant of these luminous disk galaxies, possibly contributing to the formation of the S0 population in the clusters (Mihos & Hernquist 1996).

5. We emphasize that a lack of consideration of the effects of dust on the morphological and spectral properties of galaxies, even at the relatively modest redshifts discussed here, may lead to an incomplete understanding of the cycle of star formation in cluster galaxies. Further work on this subject is urgently required.

This paper is the prelude to a larger study of the HST morphologies and spectral properties of radio-selected galaxies in Cl 0939+4713 and other high-redshift clusters (Morrison et al. 1999). We expect that extensive studies with higher spatial resolution and wider wavelength coverage in the near future using the upgraded VLA and the next generation of millimeter interferometers will provide new insights into the prevalence and distribution of dust in distant galaxies.

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