1999), and conclusions drawn solely from optical studies are observations of moderate redshift clusters (Smail et al. 1999; Best et al. 2002). As in the field, much of this and more active systems (e.g., Butcher & Oemler 1984; cant differences from their local descendants, indicative of young the level of individual objects. complex physical details of hierarchical structure formation at galaxy evolution will be a major step toward clarifying the which may continue to significantly lower redshifts than the orig- merging and accretion of groups. Understanding this process, rem-ained elusive. In a hierarchical universe clusters begin to the influence of the local environment on galaxy evolution. of cosmology, from the determination of fundamental constants to the study of galaxy clusters encompasses almost every aspect of cosmology, from the determination of fundamental constants to the influence of the local environment on galaxy evolution. Yet a solid understanding of the process of cluster evolution has remained elusive. In a hierarchical universe clusters begin to form at very high redshift, then grow and evolve through cluster merging and accretion of groups. Understanding this process, which may continue to significantly lower redshifts than the original epoch of formation, and its importance in driving cluster galaxy evolution will be a major step toward clarifying the complex physical details of hierarchical structure formation at the level of individual objects. By a redshift of $z \sim 1$ galaxy clusters already show significant differences from their local descendants, indicative of younger and more active systems (e.g., Butcher & Oemler 1984; van Dokkum et al. 1999, 2001; Dwarkanath & Owen 1999; Smail et al. 1999; Best et al. 2002). As in the field, much of this activity is dust enshrouded (Poggiati et al. 1999; Smail et al. 1999), and conclusions drawn solely from optical studies are potentially misleading or at best incomplete. Indeed, recent observations of moderate redshift clusters ($z \sim 0.2–0.4$) at 15 $\mu$m with the Infrared Space Observatory (ISO), which directly measures hot dust, have detected dusty starbursts (Fadda et al. 2000; Duc et al. 2002; Coia et al. 2005), and it is estimated for one cluster that perhaps 90% of the star formation is dust enshrouded and undetected in optical studies (Duc et al. 2002). The ISO results are particularly interesting, since at least one cluster, A1689 (Fadda et al. 2000), the fraction of dusty galaxies is greater than that in the field, implying that the cluster environment is somehow responsible for triggering the intense star formation. Thus far, extreme star formation activity in clusters (such as that seen in ultraluminous infrared galaxies [ULIRGs] at high and low redshift) has not been unambiguously detected; even the systems seen by ISO are limited to rates of a few tens of solar masses per year (assuming no contribution from active galactic nuclei [AGNs]). The exception to this is the handful of central D galaxies detected at 850 $\mu$m primarily during surveys for faint background sources (Edge et al. 1999; Smail et al. 2002; Cowie et al. 2002, K. K. Knudsen et al. 2005, in preparation). Best (2002) reported an excess number of submillimeter luminous galaxies (SMGs), detected at 850 $\mu$m, in $z \sim 1$ cluster fields and, based on lensing considerations, argued that they were associated with the clusters rather than with a background population. If the SMGs are indeed cluster members, they represent by far the most intense starbursts seen in clusters to date, with rates of $\sim 100 M_\odot$ yr$^{-1}$. Still, since none of the systems have been verified to lie at the cluster redshifts, they could be background objects, perhaps lensed by the cluster potential. Lensing effects have been exploited by many groups in order to overcome the blank-field confusion limitations and detect faint SMGs ($S_{850 \mu m} < 2$ mJy) at high redshift (Smail et al. 1997; Cowie et al. 2002; Chapman et al. 2002), but these surveys have employed lower redshift clusters ($z \leq 0.5$), since massive, relaxed clusters at low redshift are more efficient lenses than high-redshift clusters. Recent results from the RCS (Gladders & Yee 2005), however, indicate that this is not always the case, and some higher redshift clusters appear to be excellent lenses. Gladders et al. (2003) have found that the number of strong multiple optical arcs for $z > 0.6$ clusters seen in the RCS is larger than expected. This, along with the fact that the number of arcs in other medium- to high-redshift cluster surveys is several times larger than that expected from standard $\Lambda$CDM cosmology (Bartelmann et al. 1998; Zaritsky & Gonzalez 2003; Dalal

### ABSTRACT

We present deep 850 $\mu$m imaging of the $z = 0.773$ strong lensing galaxy cluster RCS J022434−0002.5 from the Red-Sequence Cluster Survey (RCS). These data are part of a larger submillimeter survey of RCS clusters with SCUBA on the JCMT. We find five objects at 850 $\mu$m, all of which are also detected at either 1.4 GHz or 450 $\mu$m, or both. The number density of objects in this field is in general agreement with the blank-field source counts; however, when combined with other cluster surveys a general tendency of cluster fields toward higher submillimeter number densities is seen, which may be the result of unrecognized submillimeter luminous cluster galaxies. Primarily employing optical photometric redshifts, we show that two of the five submillimeter galaxies in this field are consistent with being cluster members, while two are more likely background systems.

### Subject headings: dust, extinction — galaxies: clusters: individual (RCS J022434−0002.5) — galaxies: evolution — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

## 1. INTRODUCTION

The study of galaxy clusters encompasses almost every aspect of cosmology, from the determination of fundamental constants to the influence of the local environment on galaxy evolution. Yet a solid understanding of the process of cluster evolution has remained elusive. In a hierarchical universe clusters begin to form at very high redshift, then grow and evolve through cluster merging and accretion of groups. Understanding this process, which may continue to significantly lower redshifts than the original epoch of formation, and its importance in driving cluster galaxy evolution will be a major step toward clarifying the complex physical details of hierarchical structure formation at the level of individual objects.

By a redshift of $z \sim 1$ galaxy clusters already show significant differences from their local descendants, indicative of younger and more active systems (e.g., Butcher & Oemler 1984; van Dokkum et al. 1999, 2001; Dwarkanath & Owen 1999; Smail et al. 1999; Best et al. 2002). As in the field, much of this activity is dust enshrouded (Poggiati et al. 1999; Smail et al. 1999), and conclusions drawn solely from optical studies are potentially misleading or at best incomplete. Indeed, recent observations of moderate redshift clusters ($z \sim 0.2–0.4$) at 15 $\mu$m with the Infrared Space Observatory (ISO), which directly measures hot dust, have detected dusty starbursts (Fadda et al. 2000; Duc et al. 2002; Coia et al. 2005), and it is estimated for one cluster that perhaps 90% of the star formation is dust enshrouded and undetected in optical studies (Duc et al. 2002). The ISO results are particularly interesting, since at least one cluster, A1689 (Fadda et al. 2000), the fraction of dusty galaxies is greater than that in the field, implying that the cluster environment is somehow responsible for triggering the intense star formation. Thus far, extreme star formation activity in clusters (such as that seen in ultraluminous infrared galaxies [ULIRGs] at high and low redshift) has not been unambiguously detected; even the systems seen by ISO are limited to rates of a few tens of solar masses per year (assuming no contribution from active galactic nuclei [AGNs]). The exception to this is the handful of central D galaxies detected at 850 $\mu$m primarily during surveys for faint background sources (Edge et al. 1999; Smail et al. 2002; Cowie et al. 2002, K. K. Knudsen et al. 2005, in preparation). Best (2002) reported an excess number of submillimeter luminous galaxies (SMGs), detected at 850 $\mu$m, in $z \sim 1$ cluster fields and, based on lensing considerations, argued that they were associated with the clusters rather than with a background population. If the SMGs are indeed cluster members, they represent by far the most intense starbursts seen in clusters to date, with rates of $\sim 100 M_\odot$ yr$^{-1}$. Still, since none of the systems have been verified to lie at the cluster redshifts, they could be background objects, perhaps lensed by the cluster potential.

Lensing effects have been exploited by many groups in order to overcome the blank-field confusion limitations and detect faint SMGs ($S_{850 \mu m} < 2$ mJy) at high redshift (Smail et al. 1997; Cowie et al. 2002; Chapman et al. 2002), but these surveys have employed lower redshift clusters ($z \leq 0.5$), since massive, relaxed clusters at low redshift are more efficient lenses than high-redshift clusters. Recent results from the RCS (Gladders & Yee 2005), however, indicate that this is not always the case, and some higher redshift clusters appear to be excellent lenses. Gladders et al. (2003) have found that the number of strong multiple optical arcs for $z > 0.6$ clusters seen in the RCS is larger than expected. This, along with the fact that the number of arcs in other medium- to high-redshift cluster surveys is several times larger than that expected from standard $\Lambda$CDM cosmology (Bartelmann et al. 1998; Zaritsky & Gonzalez 2003; Dalal...
et al. 2004), leads to the interpretation that at least at high redshift, there may be a subset of rich clusters that have much higher lensing cross sections than predicted (but see Wambganss et al. 2004 for an alternative explanation). These “superlenses” could be due, for example, to an increase in cluster substructure with redshift, when clusters are observed in a younger and less relaxed state.

To examine the issues of both superlensing and possible excess SMGs in high-redshift clusters, we have begun a survey at 850 μm of high-redshift (0.6 < z < 1.1) galaxy clusters from the RCS with the Submillimeter Common-User Bolometric Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT). The survey consists of two subsamples: (1) five clusters that show strong optical arcs and (2) five control clusters of similar richness and redshift, without strong optical arcs. Here we present the submillimeter data and follow-up imaging from a single superlensing cluster field, RCS J022434−0002.5 (hereafter RCS 0224); the entire submillimeter program, when complete, will be presented in a later paper (T. M. A. Webb et al. 2005, in preparation). This paper is organized as follows. In §2 we outline the submillimeter and supplementary observations and data analysis; §3 presents the object catalog. In §4 we discuss the properties of the counterparts to the submillimeter emission; §5 contains a discussion of the results. A flat, ΩΛ = 0.7 universe, with H0 = 72 km s⁻¹ Mpc⁻¹ is assumed throughout.

2. OBSERVATIONS AND DATA REDUCTION

2.1. RCS 0224

RCS 0224 (Gladders et al. 2002, 2003) was discovered within the RCS, a 90 square degree optical imaging survey designed to find galaxy clusters up to z = 1.4. It is the most spectacular example of the RCS’s superlensing clusters, with two strong optical arcs originating from different background objects, one with z = 4.9; a third arc was discovered in a deep Hubble Space Telescope (HST) image. Subsequent spectroscopic follow-up has confirmed the cluster redshift to be z = 0.773.

2.2. Submillimeter Data

2.2.1. Observations and Reduction

The cluster was simultaneously observed at 450 and 850 μm, using SCUBA (Holland et al. 1998) on JCMT over two observing runs in 2001 and 2002. We employed the jiggle-map mode of SCUBA, which fills in the undersampled sky by stepping the secondary mirror through a 64 point pattern in each nod position throughout each 128 s integration. With AC-coupled bolometers, chopping and nodding is still required in the submillimeter range for proper sky removal, and we chopped in bolometers, chopping and nodding is still required in the subposition throughout each 128 s integration. With AC-coupled mode of SCUBA, which fills in the undersampled sky by step-serving runs in 2001 and 2002. We employed the jiggle-map lenses’ could be due, for example, to an increase in cluster subet al. [2004] for an alternative explanation). These “superlensing cross sections than predicted (but see Wambsganss shift, there may be a subset of rich clusters that have much higher is produced by convolving the raw map with the beam template, which includes the off beams produced by the chop. This technique is similar to the template fitting used by other groups.

The data reduction was complicated by the presence of a strong correlated noise signal that occurred at the jiggle-map frequency (16 s; C. Borys 2004, private communication). This signal appears in the 2002 data and affects between 1/5 and 1/3 of the bolometers at any given time. We reduced its effect in the following way. After the standard flat-fielding and extinction corrections, noise-corrupted bolometers were identified through the presence of power in their Fourier spectrum at the characteristic scale. Residual sky flux was removed from all the bolometers by subtracting the median sky level at each second, determined using only the noncorrupted bolometers. Because the noise on the remaining corrupted bolometers is correlated, it is possible to reduce its effect through the subtraction of this correlated signal. This was done through simple multiple linear regression techniques in which the expected noise signal in a given bolometer was predicted using all other corrupted bolometers and then removed. As a final step, noise spikes at >3 σ were iteratively removed from all bolometers, and the bolometer time streams were rebinned to produce the final map. The removal of the correlated noise from the corrupted bolometers results in an overall reduction of the noise in the final map of ~30%. A comparison of the noncorrupted 2001 data with the corrupted data from 2002, both corrected and noncorrected, shows that the presence of point sources in this map is robust, with no sources lost and no new sources introduced other than what is expected from an improved signal-to-noise ratio (S/N). We note, however, that this is not the case for shallower surveys in which this noise signal can lead to significant changes in the number of real and spurious sources detected (Sawicki & Webb 2005).

2.2.2. Source Detection

Because of strongly varying noise properties (spatial and temporal), and the fact that one is generally working at the detection limit of the data, deep imaging with SCUBA requires careful noise analysis in order to assign significance to each detection and to minimize spurious sources. To estimate the noise as a function of position on the image, we employed two related techniques. First, following the method outlined in Eales et al. (2000) and Webb et al. (2003), we generated 500 Monte Carlo simulations of each bolometer time stream, assuming Gaussian noise statistics and uncorrelated bolometers, and without introducing any signal. The reduction procedure was repeated on these simulated data, resulting in a set of final rebinned maps with no sources, but with noise characteristics similar to the real data. A noise map is then simply the variance of the individual simulations. Second, using the real bolometer time streams, we employed a bootstrap algorithm to generate a variance map from 500 realizations. The two techniques produced similar variance maps: the mean ratio between the two maps was ~1.0 and varied by <20% over the entire field. The significance levels quoted in Table 1 refer to the first method.

Source extraction was performed using an iterative cleaning technique (Eales et al. 2000). An initial list of source positions was produced by convolving the raw map with the beam template, which includes the off beams produced by the chop. This technique is similar to the template fitting used by other groups.
and is advantageous over simple smoothing, since it incorporates information (position and flux) from the two negative off-sources associated with each real source. Beginning with an initial list of S/N $>$ 3 detections, the map was iteratively cleaned of sources in 10% flux steps. Using these cleaned results, for each source all other sources were removed from the raw, unconvolved map, and the isolated source was again convolved with the beam template. This provides improved flux densities, positions, and detection significances for each source, since contamination from nearby confused sources is reduced (see Fig. 1 and $\chi$ 3.1).

The 450 $\mu$m observations, which are taken simultaneously by exploiting a dichroic beam splitter, suffer from a greatly increased sky opacity and a very unstable beam, and are therefore much more difficult to work with. Instead of generating a separate source catalog from the 450 $\mu$m data, we simply searched for 450 $\mu$m emission from the previously detected 850 $\mu$m sources. We adopted a search radius of 10$^\prime$ around each 850 $\mu$m position, allowing for a combination of the expected positional uncertainties at both wavelengths, and we take as the flux measurement the nearest 450 $\mu$m peak above 2.5 $\sigma$ within this radius.

### 2.3. Supplementary Data

#### 2.3.1. Radio Imaging

Approximately 5 hr of data were obtained on each of 3 days during 2003 December, using the National Radio Astronomy Observatory’s (NRAO)$^8$ Very Large Array in B configuration, exploiting a pseudocontinuum correlator mode to minimize bandwidth smearing. Data were recorded every 5 s in 3.25 MHz channels, 28 in total, centered at 1.4 GHz, taking both left-circular and right-circular polarizations. 0137+331 was used for

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**TABLE 1**

| Positions and Flux Densities of Submillimeter Sources |
|-----------------------------------------------|

| Name            | R.A. (J2000.0) | Decl. (J2000.0) | $S_{850 \mu m}$ (mJy) | $S_{850 \mu m}$/S/N | $S_{450 \mu m}$ (mJy) | $S_{450 \mu m}$/S/N | Offset: 850 and 450 $\mu$m Position (arcsec) | Lensing Magnification$^a$ |
|-----------------|---------------|----------------|----------------------|----------------------|----------------------|-------------------|----------------------------------|--------------------------|
| SMM RCS 0224.1 | 02 24 34.29   | 00 03 28       | 6.4                  | 7.0                  | 14.4                 | 3.5               | 5.2                             | 1.10–1.17                |
| SMM RCS 0224.2 | 02 24 33.56   | 00 03 58       | 5.3                  | 4.6                  | >66$^b$              | ...               | ...                             | ...                     |
| SMM RCS 0224.3 | 02 24 29.79   | 00 03 01       | 4.0                  | 3.3                  | 15.8                 | 3.0               | 6.4                             | 1.05–1.09               |
| SMM RCS 0224.4 | 02 24 32.69   | 00 03 46       | 3.2                  | 3.1                  | 18.7                 | 2.5               | 1.6                             | 1.06–1.11               |
| SMM RCS 0224.5 | 02 24 33.00   | 00 03 35       | 3.2                  | 4.1                  | 13.2                 | 3.0               | 9.0                             | 1.61–2.59               |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ For all sources but SMM RCS 0224.4, the lensing magnification was determined using the radio position (see Table 2). Two possible magnifications are listed: the first assumes a source redshift of $z = 1.5$, and the second assumes $z = 4.0$. Note that this is simply the lensing calculated at the source position and that none of these sources are confirmed as lensed objects.

$^b$ A 3 $\sigma$ upper limit on the flux; the object lies at the edge of the usable 450 $\mu$m field.

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$^8$ NRAO is operated by the Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

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Fig. 1.—**Left**: The 850 $\mu$m map of RCS 0224, smoothed with a 14$''$ Gaussian, with white indicating positive flux. Overlaid are the S/N contours (before cleaning) in 0.5 steps, beginning with 3.0 $\sigma$, and 1.0 steps above 4 $\sigma$. The five sources listed in Table 1 are marked. Sources 2 and 4 are confused and separate into two sources during the 850 $\mu$m cleaning process. This is more easily apparent in the 450 $\mu$m map in which source 4 has been detected. **Right**: The gray-scale 850 $\mu$m map of RCS 0224, with the 450 $\mu$m flux contours overlaid. The contours have been smoothed with an 8$''$ Gaussian and are shown in steps of 1 mJy, starting at 12 mJy. Note that the 450 $\mu$m FOV (denoted by the ellipse) is smaller than at 850 $\mu$m such that the outer $\sim$20$''$ of the 850 $\mu$m map does not have useful 450 $\mu$m coverage, including the southernmost 850 $\mu$m.

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**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
flux calibration, and 0239+42 (0.72 Jy) was observed every hour for local phase/amplitude/bandpass calibration.

Initial calibration and mapping were performed using standard AIPS tasks. The initial calibration was good on most baselines, although we were able to improve the fidelity of the final image by running a series of self-calibration/imaging tasks, with a model comprising the central 820"×820" field plus 11 noncontiguous fields containing bright sources. The final image has a series of north-south stripes near the brightest sources, typical of equatorial fields, but in clean regions of the map the noise is around 15 μJy beam⁻¹, where the beam is near-circular with FWHM ~ 4.5".

2.3.2. Optical and Near-Infrared Imaging

Multifilter optical images of the field are available from various sources. The original discovery data from the RCS provide data in z' and R_C using the CFH12K camera (Gladders et al. 2002). Additional images in V and B have been obtained, also with the CFH12K, as part of the four-color photometry follow-up of the CFHT (Canada-France-Hawaii Telescope) part of the RCS survey. The details of the observations and photometric reduction techniques are provided in Gladders & Yee (2005) for the z' and R_C data, and in Hsieh et al. (2005) for the V and B images.

J and K'-band images of the central ~2'×2' were obtained using PANIC (Persson’s Auxiliary Nasmyth Infrared Camera; Martini et al. 2004) on the Magellan Baade 6.5 m telescope. PANIC is a 1024×1024 pixel near-IR camera with a pixel scale of 0″125 pixel⁻¹. Integrations totaling 54 minutes in K were obtained on 2003 December 21, and integrations of 52 minutes in J were obtained on 2004 October 24, both under moderately good seeing and photometric conditions. Object finding and photometry in the K' image were performed using the program PPP (Yee 1991). The R_C−K' colors were measured using identical angular aperture sizes based on the magnitude growth curve (see Yee [1991] for details). The (J−K') colors, discussed in § 5, were measured for the two brightest SMGs in a similar manner.

3. SUBMILLIMETER RESULTS

3.1. The Detected Sources

The 850 μm map is shown in Figure 1, and the detected sources are listed in Table 1. We detect five SMGs at 850 μm above S/N > 3.0. Because the use of chopping to remove the sky level results in a map with a mean flux level of zero, the noise will be symmetric around zero, and the number of spurious sources on a SCUBA map may be estimated through the number of sources detected in an inverted map. After first removing all positive sources and their associated negative off-sources, we searched for negative sources at a >3.0 σ level on the inverted map. Only one negative source was found, at 3.0 σ near the northern edge of the map, indicating that our source list is reliable at this level.

To quantify the uncertainties in the submillimeter position and flux measurement, we placed and recovered point sources of varying flux levels and positions into the image. Working with the real map produces more realistic results than working with the simulated data, since the effects of confusion are included through the presence of the unresolved background. In order to avoid overestimating the effects of confusion, the five bright real sources (i.e., S/N > 3) were removed from the map before this analysis. Given our small field size and the high number of sources, the addition of even a single object leads to an unrealistically large source density. On the other hand, moving all the detected sources leads to an underestimate of the positional uncertainties, since only confusion with sources below the confusion limit is considered.

The 95th percentiles for the positional offsets for S/Ns of 3.5, 4.5, 5.5, and 6.5 σ are 9″2, 8″4, 7″6, and 7″6, respectively. The distributions in each bin are all centered at ~4″5 and skewed strongly to larger offsets, particularly in the lowest S/N bins. We note that these offsets are in good agreement with Ivison (2005), who find a positional accuracy (1 σ) of 1.5×FWHM/(S/N) for 5 σ sources, determined from the distribution of offsets from the objects to radio positions. The error on the flux measurement may be estimated from the S/N map or through a comparison of the input flux to recovered flux in the simulations described above (more correctly, from the output flux to the range in input fluxes that produce such a measured flux). It was found that these two methods compare well, indicating that the Monte Carlo simulations reasonably reproduce the noise statistics of the data.

In Figure 1 (right) we show the 450 μm flux contours, overlaid on the 850 μm map, and a correlation between the two wavelengths is apparent. Four of the five 850 μm sources have usable 450 μm coverage (the southernmost 850 μm source lies in the unreliable edge region of the 450 μm map). Three of these are detected at 450 μm with ≥3.0 σ, and the fourth with 2.5 σ. Using the 450 μm number density on the map at these levels of significance, we can estimate the probability that a 450 μm detection is randomly aligned within 10″ of an 850 μm source. For the 450 μm sources with S/N ≥ 3 this probability is 8%, while the single S/N = 2.5 σ has a probability of 16%. Given the actual measured offsets (which, barring one, are ≤6″), the probability of chance alignments for all four sources is <6%. Thus, for these four sources we would expect less than one chance alignment and regard the 450 μm detections as reliable counterparts to the 850 μm emission. The detection of these four objects in both submillimeter bands is strong evidence that they are real and not spurious detections.

In principle, because of the smaller beam size, the 450 μm detection should provide a better measure of the true source position than the one at 850 μm; in practice, the poorer quality of the 450 μm data does not make this so. Simulations of the positional uncertainty at 450 μm, similar to those discussed above for 850 μm, indicate that at ≤4 σ (the significance of these detections) the median positional uncertainty is roughly equal to that at 850 μm, but with higher dispersion and skewed heavily to large offsets (the 95th percentile is ~13″).

3.2. Gravitational Lensing

The magnifications were computed using a model that was derived to reproduce the strong lensing features observed for the cluster. The model consists of a smooth cluster component that was modeled as an isothermal ellipsoid with a core. The free model parameters are the central velocity dispersion, core radius, ellipticity, position angle, and the position of the smooth halo. In addition, we included truncated isothermal spheres at the positions of galaxies on the cluster R_C = z′ color-magnitude relation. For these, we assumed a Faber-Jackson relation and used the velocity dispersion of an L′ galaxy as a free parameter in the model.

We used deep optical HST observations to model the lensing, but found that the model cannot reproduce all strong

9 Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. These observations are associated with program 9135.
Fig. 2.—$K'$ images of the region surrounding each SMG. The images are centered on the SMG position with the approximate positional error indicated by the plus sign ($8', \sim 95\%$). Overlaid are the 1.4 GHz contours showing the radio detections. Source SMM RCS 0224.4 does not have a radio identification. The offset between the radio and optical positions for source SMM RCS 0224.2 is likely due to the low S/N of this object in the radio. North is up, and east is to the left. 1.4 GHz contours start at 40 $\mu$Jy and increase in 20 $\mu$Jy steps up to 100 $\mu$Jy, and then in 100 $\mu$Jy steps.
lensing features to great accuracy. The $L^*$ velocity is not well constrained, but the best fit value of 180 km s$^{-1}$ is quite reasonable based on other studies (e.g., Hoekstra et al. 2000). The models prefer a small core radius. Despite the problems of reproducing all detailed lensing features, we found that the results for the mass, ellipticity, and position angle of the smooth cluster component are robust. This is not surprising because these are well constrained by the high-redshift arc system, for which we have confirmed the counterimage spectroscopically. The orientation based on the strong lensing model agrees well with that of the X-ray emission (Hicks et al. 2004). The resulting mass estimate is also in good agreement with that determined from a weak lensing analysis of the HST image.

Given the fact that most of the SMGs are found at relatively large distances from the cluster center, the derived strong lensing model is sufficiently accurate to derive their magnifications. In Table 1 we list the lensing magnifications these objects would experience, assuming they lie behind the cluster. The magnifications are calculated assuming source plane redshifts of $z = 1.5 - 4.0$, although in Table 1 we list only the two extremes. Four of the five objects lie at large angular distances from the cluster center and therefore suffer very small magnifications of $\sim 1.1$ for all plausible redshifts. Even source SMM RCS 0224.5, which lies close to the cluster center, has a magnification of only 2.3 in the most extreme case. In conclusion, simple but accurate analysis shows that on average we do not expect the SMGs to be significantly magnified.

4. THE RADIO AND NIR COUNTERPARTS AND REDSHIFT ESTIMATES

To identify counterparts to the SMGs we employed the empirical correlation between the radio and far-infrared flux (Condon 1992) observed in the local universe. Using the deep 1.4 GHz maps, we searched for a radio detection within the

| Name                  | R.A. (J2000.0) (1.4 GHz) | Decl. (J2000.0) (1.4 GHz) | 1.4 GHz Flux (µJy) | Offset from 850 µm (arcsec) | $z_{\text{est}}$ | $K$ | $(R_C - K)$ | $z_{\text{phot}}$ |
|-----------------------|--------------------------|---------------------------|-------------------|-----------------------------|-----------------|----|-------------|-----------------|
| SMM RCS 0224.1........ | 02 24 33.815             | -00 03 33.00              | 1652 ± 41         | 8.7                         | <0              | 16.92 ± 0.01 | 4.63 ± 0.02   | 0.66 ± 0.11     |
| SMM RCS 0224.2........ | 02 24 33.332             | -00 04 05.53              | 68.4 ± 29         | 8.3$^a$                      | 1.9 ± 1.0      | 18.22 ± 0.04 | 4.11 ± 0.05   | 0.72 ± 0.08     |
| SMM RCS 0224.3........ | 02 24 29.972             | -00 03 04.10              | 97.4 ± 29         | 4.1                         | 0.85 ± 1.0     | 20.81 ± 0.14 | ~6.1 ± 0.7    | ...            |
| SMM RCS 0224.4........ | ...                      | ...                       | <48$^a$           | ...                         | >1.6$^e$        | ...          | ...          | ...            |
| SMM RCS 0224.5........ | 02 24 32.867             | -00 02 31.34              | 94.3 ± 28         | 4.1                         | 0.65 ± 1.0     | 19.38 ± 0.06 | 4.6 ± 0.12    | ...            |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ Using the empirical 1.4 GHz–850 µm relation for high-redshift submillimeter-selected galaxies from Chapman et al. (2004). All estimates have uncertainties of $\Delta z \sim 1$.

$^b$ The substantial radio emission of this source, and the compact nature of the optical counterpart, leads us to conclude that this object contains an AGN. As discussed in the text, this will result in an underestimation of the redshift and, in this case, a completely nonphysical estimate of $z < 0$. The photometric redshift is determined using the $\epsilon R_C - YB$ empirical training set technique presented in Hsieh et al. (2005). Sources without a photometric redshift have not been detected in enough filters to enable an estimate.

$^c$ A 3 $\sigma$ upper limit on the flux.

$^d$ The large positional offset could be due, in part, to blending with SMM RCS 0224.4.
submillimeter error radius (§ 3.1). Statistically this is also one of the least ambiguous methods of identifying counterparts, since the number density of radio sources on the sky is low enough that chance alignments between submillimeter and radio galaxies are almost negligible. In Figures 2 and 3 we show the $K'$ images surrounding each submillimeter detection, with 1.4 GHz flux contours overlaid. Four of the five 850 $\mu$m sources have radio detections within the submillimeter search radius (§ 3.1), and all four have $K'$ counterparts. The fifth source, SMM RCS 0224.4, does not have a secure counterpart at radio or optical/near-infrared wavelengths.

The $z/R_{C}/V$ four-filter photometry data were used to generate photometric redshifts using an empirical training set technique, providing photometric redshifts with typical accuracy of $\sim 10\%$ for galaxies with $R_{C} \leq 23.0$ (see Hsieh et al. [2005] for details). Two of the four radio-detected objects (SMM RCS 0224.1 and SMM RCS 0224.2) have sufficiently accurate optical measurements to allow photometric redshift estimates. We were not able to obtain photometric redshifts for the other two sources with radio counterparts. The source SMM RCS 0224.3 is undetected in all our optical bands, while SMM RCS 0224.5 is detected only marginally in the $R_{C}$ image. The redshift estimates are listed in Table 2 along with the $K'$ magnitude and $R_{C} - K'$ colors.

A detection at radio wavelengths has the added advantage of providing a redshift constraint from the radio-submillimeter spectral index (Dunne et al. 2000; Yun & Carilli 2002). This method draws on the tight correlation between FIR and radio flux for low-redshift star-forming galaxies and the steep slope of the submillimeter side of the thermal dust spectrum (e.g., Eales et al. 2000; Ivison et al. 2002). There are, however, a number of substantial uncertainties in this technique, including the assumed temperature of the dust and contamination of the radio flux by an AGN. Until recently the small number of SMGs with spectroscopically determined redshifts made it difficult to verify the extension of this relationship to the high-redshift 850 $\mu$m–selected population. In Figure 4 we show the 1.4 GHz–850 $\mu$m spectral index for the SMGs with spectroscopic redshifts from Chapman et al. (2004), with two empirically determined relations from local starbursts overlaid. It is clear that the SMG spectral indices are not well described by the empirical low-redshift relations at $z \leq 1.4$, and therefore we adopt the average relation from the high-redshift SMGs (Chapman et al. 2004) to estimate redshifts for the four radio-detected sources in the RCS 0224 field (and a lower limit for the fifth). These are listed in Table 2 and shown in Figure 4. We note that all have a substantial uncertainty of $\Delta z \sim 1$.

Source SMM RCS 0224.1 is particularly interesting. It is the brightest submillimeter detection in the RCS 0224 field and is identified with a bright and extended radio source with a large positional offset of 8.7. Since the positional error analysis outlined in § 3.1 indicates that roughly 5% of the detected sources should be recovered at $>8''$ from their true positions, it is worrisome that this is one of two radio identifications with $>8''$ in this field. However, given the extreme observed luminosity of the radio source, it is statistically very unlikely that the radio source and submillimeter source are not related (0.1% assuming the 1.4 GHz counts of Bondi et al. 2003), and we reiterate that the positional uncertainty may be underestimated (§ 3.1).

The radio counterpart is asymmetrically extended over $7''\times 4''$ and centered on a highly compact, although resolved, galaxy in the optical and NIR images. The 450 $\mu$m emission (which should be resolved given the smaller 450 $\mu$m beam) shows hints of extension along the same position angle (see Fig. 1). The extreme radio flux of the source indicates the presence of an AGN; assuming the cluster redshift and a radio spectral index of $S \propto \nu^{-0.7}$ yields a rest-frame luminosity of $1.9 \times 10^{24}$ W Hz$^{-1}$, well within the radio power regime dominated by AGNs (Condon et al. 2002). The asymmetric extended emission is suggestive of the morphology of a head-tail radio source, specifically, a narrow-angle tail galaxy (e.g., Sijbrin & de Bruyn 1998): a single or parallel radio jet, bent by bulk flows in the intercluster medium. The presence of a strong AGN can introduce uncertainties to the photometric redshift; however, this is unlikely to be significant in this case, since the object is resolved optically.

5. DISCUSSION

5.1. SMG Source Counts

A main goal of our submillimeter survey of RCS clusters is to determine whether some, or possibly all, $z \sim 1$ galaxy cluster fields show an excess number of SMGs compared to that expected from the blank-field counts and simple lensing estimates. If so, this could be due either to enhanced gravitational lensing as explained in § 1 or to source-count contamination by submillimeter-bright cluster members.
In Figure 5 we show the cumulative source counts toward RCS 0224 with no correction made for lensing effects, which we calculate to be negligible, but account for the varying depths within the submillimeter map. The results from this single cluster field are consistent with the blank-field counts and indicate an excess of sources due to either lensing or submillimeter-luminous cluster members only at the 1σ level. It is interesting to note that the source counts are similar to those from other cluster surveys of Smail et al. (2002) and Best (2002), which also lie systematically above the blank-field counts at the 1σ level (the exception to this is Cowie et al. [2002], which is also a cluster program). The Smail et al. counts do not include two cluster members (cD galaxies) and have been corrected for lensing, which can be substantial for low-redshift clusters, whereas the higher redshift cluster fields of Best (and RCS 0224) suffer a reduction in the radio flux, in addition to the usual uncertainties. Two of the radio-detected SMGs, SMM RCS 0224.1, which is almost certainly due to the AGN contribution, and SMM RCS 0224.3 and SMM RCS 0224.5, have measured ratios that are consistent with the redshift z ≳ 1 and indeed with the counterparts of the z ≥ 2 blank-field SMGs, which are often faint and red. Source SMM RCS 0224.4, however, has a more moderate R_C – K′ color, similar to SMM RCS 0224.1 and SMM RCS 0224.2.

Redshifts estimated from radio-submillimeter spectral indices have substantial uncertainties (Δz ≳ 1) and provide much poorer redshift constraints than the photometric redshifts. Nevertheless, since this is a frequently applied technique in the absence of spectroscopy, we discuss such estimates here. This method implies an unphysical redshift of z < 0 for SMM RCS 0224.1, which is almost certainly due to the AGN contribution to the radio flux, in addition to the usual uncertainties. Two sources, SMM RCS 0224.3 and SMM RCS 0224.5, have measured ratios that are consistent with z < 1 objects. As discussed above, however, the optical/NIR properties of SMM RCS 0224.3 do not support cluster membership, but rather are similar to the background SMG population. Source SMM RCS 0224.5, on the other hand, has a more moderate color and thus, while not ruling out a background source, is in general agreement with the radio estimate. The radio-to-submillimeter redshift estimate of SMM RCS 0224.2 is z = 1.9, substantially higher than the optical/NIR estimate, and while the radio-submillimeter estimate is uncertain, this raises the interesting possibility that the radio-submillimeter galaxy and the optical counterpart may represent different galaxies, as there is a small offset (∼1′) between the radio and optical positions.

In principle the 450–850 μm flux ratios may also be used to isolate low-redshift SMGs, but the large uncertainties on the 450 μm flux measurement and the flatness of the observed ratio with redshift out to z ∼ 2 (e.g., Webb et al. 2003) makes this method of little use in our case. Three of the four 450 μm–detected SMGs are consistent with essentially all redshifts below z ∼ 3, given a reasonable thermal spectral energy distribution.
(SED). The fourth source, the strong radio source SMM RCS 0224.1, has a ratio that appears to place it at $z > 3$; however, in this case it is likely that the 850 $\mu$m flux is also boosted by the AGNs, although to a lesser extent than the radio flux, and therefore the 450–850 $\mu$m flux ratio cannot be described by a simple thermal SED.

To summarize, sources SMM RCS 0224.1 and SMM RCS 0224.2 are likely cluster members, based on their optical photometric redshifts, $K$ magnitudes, and optical/NIR colors. Sources SMM RCS 0224.3 and SMM RCS 0224.4 are more consistent with belonging to the background population of SMGs, although they are not highly lensed by the cluster. Very little constraint can be placed on the redshift of SMM RCS 0224.5; there are not enough data for an optical photometric redshift estimate, and while its radio-submillimeter ratio suggests a $z < 1$ galaxy, there is substantial uncertainty in this technique, as shown by Figure 4. Spectroscopic redshift measurements are clearly required to resolve this issue as well as improve positional information for the SMGs with large offsets to their radio identifications. The latter is particularly important to rule out the possibility of single-galaxy, or cluster-substructure, lensing.

If two of the SMGs in the RCS 0224 field are indeed dusty starbursts and/or AGNs within the cluster, this has interesting implications for the evolution of galaxy clusters. Thus far, star formation rates and dust levels great enough to produce strong enough submillimeter emission to be seen by SCUBA ($\sim$100 $M_\odot$ yr$^{-1}$, but very dependent on temperature) have not been unambiguously detected in clusters. This could, in part, be a selection effect; in addition to the fact that very few high-redshift galaxy clusters have been searched for star formation, such objects may be so obscured that they go unrecognized in optical studies, as was the case in the field until recently. Submillimeter surveys are sensitive to much colder dust than mid-IR observations with the ISO and thus may detect fundamentally different objects. In fact, a deep SCUBA image has been obtained for A1689, but none of the ISO sources are coincident with the 850 $\mu$m–selected objects (K. K. Knudsen et al. 2005, in preparation).

We can estimate the star formation rate such systems would have if they lie at $z = 0.773$, through an extrapolation from $S_{850\mu m}$ to $L_{\text{FIR}}$ and using the relation of Kennicutt (1998). We adopt a temperature of 40 K and dust emissivity $\beta = 1.3$ (Dunne et al. 2000). Ignoring SMM RCS 0224.1, which is likely AGN-dominated, we find a range in star formation rates (SFRs) of $\sim$250–430 $M_\odot$ yr$^{-1}$ for our range in 850 $\mu$m flux levels. We note, however, that this estimate is highly dependent on temperature (see Eales et al. [2000] for a discussion), and varying the dust temperature from 30 to 50 K (a relatively modest range) results in SFR estimates from 90 to 900 $M_\odot$ yr$^{-1}$.

We note that both of the clusters in the literature with substantial 15 $\mu$m emission (Fadda et al. 2000; Duc et al. 2002) show signs of recent or ongoing cluster mergers, as do many of the clusters with excess radio sources at high redshift and within the local universe (Smail et al. 1999; Miller & Owen 2003; Giacintucci et al. 2004). Currently there is no evidence that RCS 0224 is undergoing a merger or large accretion, other than a shallow X-ray map showing hints of substructure (Hicks et al. 2004), but this is simply a reflection of the limited amount of data acquired for this cluster so far. It is interesting to note that an increase in cluster merging at $z \sim 1$ also provides an explanation for the superlensing phenomenon, of which RCS 0224 is an example. Torri et al. (2004) show that during a merger the lensing cross section of a cluster is temporarily enhanced to such a degree that this process may account for the excess multiple arcs seen in optical surveys. In such a picture, the presence of strong optical arcs may mark merging clusters in which we may also find enhanced star formation and AGN activity.

### 6. CONCLUSIONS

We undertake an 850 $\mu$m imaging survey of $z \sim 1$ galaxy clusters selected from the Red-Sequence Cluster Survey. Here we present the submillimeter data on the first completed cluster, RCS 0224, and follow-up imaging for counterpart determination. We detect five SMGs within the field, which our mass model shows are not strongly lensed, and measure cumulative number counts that are in general agreement with that expected from other blank-field surveys. It is interesting to note that this field and two of the three other cluster surveys lie systematically above the blank-field counts, all at roughly 1 $\sigma$, and taken together suggest that SMG counts in cluster fields may be enhanced by unrecognized submillimeter luminous cluster members. A larger sample of clusters would provide tighter statistics.

All five SMGs in the RCS 0224 field are detected at 1.4 GHz or 450 $\mu$m, or both, and we have located NIR counterparts for all the radio detections. Based on accurate optical photometric redshifts, and magnitude and color considerations, we find that two of the five SMGs (SMM RCS 0224.1 and SMM RCS 0224.2) are likely cluster members, while another two objects are more likely background objects. The redshift of the last source (SMM RCS 0224.5) is poorly constrained; while its radio-submillimeter flux ratio is consistent with the cluster redshift, the large uncertainty in this technique makes this measurement unreliable. Further data, such as spectroscopic redshifts and improved submillimeter positions, would verify this picture.

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