The discovery of ERO counterparts to faint submillimetre galaxies

Ian Smail,1 R. J. Ivison,2 J.-P. Kneib,3 L. L. Cowie,4 A. W. Blain,5 A. J. Barger,4 F. N. Owen6 and G. Morrison6

1Department of Physics, University of Durham, South Road, Durham DH1 3LE
2Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT
3Observatoire Midi-Pyrénées, CNRS-UMR5572, 14 Avenue E. Belin, 31400 Toulouse, France
4Institute of Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii, HI 96822, USA
5Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE
6NRAO, PO Box 0, 1003 Lopezville Road, Socorro, NM 87801, USA

Accepted 1999 May 4. Received 1999 May 4; in original form 1999 March 8

ABSTRACT

We have used deep ground-based imaging in the near-infrared (near-IR) to search for counterparts to the luminous submillimetre (submm) sources in the catalogue of Smail et al. For the majority of the submm sources the near-IR imaging supports the counterparts originally selected from deep optical images. However, in two cases (10 per cent of the sample) we find a relatively bright near-IR source close to the submm position, sources that were unidentified in the deep Hubble Space Telescope (HST) and ground-based R-band images used by Smail et al. We place limits on colours of these sources from deep high-resolution Keck II imaging and find they have 2σ limits of $(I - K) \approx 6.8$ and $(I - K) \approx 6.0$, respectively. Both sources thus class as extremely red objects (EROs). Using the spectral properties of the submm source in the radio and submm we argue that these EROs are probably the source of the submm emission, rather than the bright spiral galaxies previously identified by Smail et al. This connection provides important insights into the nature of the enigmatic ERO population and faint submm galaxies in general. From the estimated surface density of these submm-bright EROs we suggest that this class accounts for the majority of the reddest members of the ERO population, in good agreement with the preliminary conclusions of pointed submm observations of individual EROs. We conclude that the most extreme EROs represent a population of dusty, ultraluminous galaxies at high redshifts; further study of these will provide useful insights into the nature of star formation in obscured galaxies in the early Universe. The identification of similar counterparts in blank-field submm surveys will be extremely difficult owing to their faintness $(K, I \approx 26.5)$. Finally, we discuss the radio and submm properties of the two submm-bright EROs discovered here and suggest that both galaxies lie at $z \approx 2$.

Key words: galaxies: evolution – galaxies: formation – cosmology: observations – infrared: galaxies.

1 INTRODUCTION

The nature of the population of extremely red objects (dubbed ‘EROs’, Elston, Rieke & Rieke 1988; Hu & Ridgway 1994; Barger et al. 1999a; Cowie et al., in preparation) uncovered in deep near-IR surveys remains elusive. Their extreme colours, $(R - K) \approx 6$ or $(I - K) \approx 5$, could be produced by a number of diverse factors: an evolved stellar population in a high-redshift galaxy; a substantial contribution to the K-band flux from a strong emission line; a very high-redshift galaxy ($z > 6$–8) with strong absorption from the Ly$\alpha$ forest shortward of the K band, or a dust-obscured, highly reddened galaxy. These explanations suggest that a wide range of galaxies may belong to this class.

The surface density of the ERO population is $\approx 0.01$ arcmin$^{-2}$ at $K \approx 19$ in blank fields, roughly similar to that of quasi-stellar objects (QSOs) (Hu & Ridgway 1994). The exact surface density of sources depends upon the passbands and colours used to define an ERO as well as the magnitude limit of the sample, reaching $\sim 0.1$ sources per square arcmin redder than $(I - K) > 5$ at $K = 21$ (Cowie et al., in preparation). EROs also appear to have higher surface densities, $\times 10$–100, in the vicinity of high-redshift active galactic nuclei (AGN) compared with the general field (Elston...
eros discovered in the field of the binary quasar PC 1643. Dey et al. (1999) have presented new optical, near-IR and submm observations of ERO J164502. Working in this manner, Cimatti et al. (1998) and many others have been testing using SCUBA, with observations of around 20 EROs now completed at 850 μm (Cimatti et al. 1998; Dey et al. 1999; Andreani et al. 1999; Thommes et al., in preparation). The picture that is emerging is of a bimodal population – roughly two thirds of the K ≲ 20 EROs are undetected in the submm, indicating that they are neither strongly star forming nor contain large quantities of cold dust and thus are probably red because of old stellar populations. The remainder, which are typically redder, do show submm emission and have extreme colours because of reddening by dust (these include HR 10). The surface density of these dust-rich EROs, while highly uncertain, is such that they could be a moderate fraction of the SCUBA sources brighter than a few mJy at 850 μm. The confirmation of such a connection between EROs and the SCUBA sources would provide important insights into the nature of both of these populations.

In this paper we present multiwavelength observations of two luminous submm sources selected from the SCUBA Lens Survey of Smail et al. (1998, hereafter S98). These sources were initially identified with bright spiral galaxies at z = 0.18 and z = 0.33. Subsequent near-IR imaging uncovered relatively bright galaxies close to the submm positions, sources that were invisible on the original deep optical images. Sensitive radio mapping with the Very Large Array (VLA) has strengthened the identification of one of these red galaxies with the submm emission. We begin in Section 2 by presenting the near-IR and radio observations of these fields, along with new deep high-resolution optical imaging to provide more stringent and uniform limits on the colours of the galaxies. We then discuss in Section 3 the spectral energy distributions (SEDs) of these two galaxies and compare these with what is known of other EROs. We give our conclusions in Section 4. Throughout this paper we adopt H₀ = 50 km s⁻¹ Mpc⁻¹ and a Ω₀ = 1, Λ₀ = 0 cosmogony.

### 2 OBSERVATIONS

The two submm sources discussed here were discovered in deep 850-μm maps taken with the SCUBA bolometer array on the

---

**Table 1. Log of observations.**

| Telescope | Instrument | Date          | Band     | FWHM (arcsec) | Comments               |
|-----------|------------|---------------|----------|---------------|------------------------|
| SMM J09429+4658 | SCUBA | 1998 Mar 12–13 | 850 μm | 30.1           | mapping mode           |
| JCMT      | SCUBA     | 1999 Feb 17   | 850 μm  | 1.8            | photometry mode        |
| JCMT      | SCUBA     | 1999 Jan 06-08| 850 μm  | 7.8            | photometry mode, simultaneous with 850 μm |
| VLA       | UFTI      | 1998 Oct 19   | K       | 3.2            | non-photometric        |
| UKIRT     | IRCAM3    | 1999 Feb 10   | K       | 8.1            | photometric            |
| UKIRT     | IRCAM3    | 1999 Feb 11   | H       | 3.2            | photometric            |
| Keck II   | LRIS      | 1998 Nov 01   | I       | 3.6            | photometric            |
| P200      | COSMIC    | 1993 Nov 06   | r       | 3.0            | photometric            |
| SMM J04431+0210 | SCUBA | 1997 Aug–1998 Sep | 850 μm | 35.8           | mapping mode           |
| JCMT      | SCUBA     | 1998 Sep 10   | K       | 3.2            | photometric            |
| VLA       | IRCAM3    | 1999 Apr 19   | K       | 28.0           | A configuration        |
| UKIRT     | UFTI      | 1998 Oct 19   | K       | 3.2            | non-photometric        |
| UKIRT     | IRCAM3    | 1999 Feb 12   | H       | 3.2            | photometric            |
| Keck II   | LRIS      | 1998 Nov 01   | I       | 6.5            | photometric            |
| HST       | WFPC2     | 1994 Oct 06   | F702W   | 6.5            | photometric            |
ERO counterparts to faint submm galaxies

Figure 1. Four different views of the field of SMM J09429+4658 from the optical and near-IR, through the submm to the radio. These four panels show the 850-µm map; the original Hale 5-m Gunn-r image used by S98 with the 850-µm map overlaid; the 0.6° resolution, deep Keck II I-band image of the same field with the VLA 1.4-GHz map overlayed (the faintest sources visible in the I-band exposure have I ∼ 25.5); the UKIRT K-band image with the original candidate counterpart, H1, and new ERO candidate, H5, both marked. Each panel is 30-arcsec square and is centred on the nominal position of the 850-µm peak (absolute accuracy of ± 3 arcsec), with north top and east to the left. The relative radio-optical astrometry for objects in the field is better than 0.4° and hence the radio source close to the bright galaxy at the top of the frame is not coincident with that galaxy.

Figure 2. The similar four views shown in Fig. 1, but here for the field of SMM J04431+0210. The four panels show from left to right, the 850-µm map; the original HST F702W identification image used by S98 with the 850-µm map overlaid; the deep Keck II I-band image of the same field with the VLA 1.4-GHz map overlayed (the faintest sources visible in the I-band exposure have I ∼ 26); the UKIRT K-band image with the original candidate counterpart, N1, and new ERO candidate, N4, both marked. Faint emission coincident with N4 is just visible in the F702W images, however, aperture photometry does not confirm this as a formal detection and hence we have instead quoted a 2σ upper limit for N4 in these passbands. Each panel is 30-arcsec square and is centred on the nominal position of the 850-µm peak (absolute accuracy of ± 3 arcsec), with north top and east to the left. The relative radio-optical astrometry in the field is better than 0.4° arcsec.

JCMT during the Lens Survey of S98. They are SMM J09429+4658 in the field of the cluster Cl 0939+4713 (A851) and SMM J04431+0210 in the MS 0440+02 field. The log of the observations is given in Table 1. The maps of SMM J09429+4658 were supplemented with data obtained using SCUBA's photometry mode during the night of 1999 Feb 17. Details of the data reduction can be found in Ivison et al. (1998a,b).

Analysis of deep optical imaging data for the fields indicated that the most probable counterparts (on the basis of optical magnitudes and relative positions) for the two sources were both bright spiral galaxies, H1 and N1 (Figs 1 and 2), 4.5 and 2.3 arcsec from the SMM J09429+4658 and SMM J04431+0210, respectively (S98). H1 has a prominent dust lane in HST Wide Field Planetary Camera 2 (WFPC2) and Near-IR Camera and Multi-Object Spectrometer (NICMOS) images (see also Smail et al. 1999). Spectroscopy of these galaxies identified N1 as a z = 0.18 cluster member with relatively strong [O II]λ3727 and Hα emission (Barger et al. 1999b), while the redshift of H1 is z = 0.33, which places it in the foreground of the cluster in that field. H1 shows no strong emission lines in its relatively low signal-to-noise spectrum (Dressler et al. 1999).

Until the next generation of millimetre interferometers becomes available the combination of radio and near-IR data is the cleanest route to identify reliable counterparts for the submm sources. Therefore, as part of the identification procedure for the S98 submm survey, we have obtained sensitive 1.4-GHz maps from the VLA and deep near-IR imaging of all of the sources (Smail et al. 2000; Ivison et al., in preparation). The radio maps are sensitive to the same starburst (or AGN activity in any radio-loud cases) which is powering the submm emission, while at the same time providing substantially higher astrometric precision and resolution – both crucial for correctly identifying the counterparts to the submm sources. Combined with the submm fluxes, the radio maps can also provide crude redshift information on these galaxies (Carilli & Yun 1999). In addition, near-IR imaging, described later, offers an opportunity to identify the dusty, luminous submm galaxies through their unusual colours.

The VLA observations of MS 0440+02 and Cl 0939+4713 were obtained in the A and B configurations, respectively, at 1.4 GHz. Relevant details are listed in Table 1. The maps were cleaned and analysed using AIPS. Details of this complex procedure are given by Ivison et al. (in preparation). The Cl 0939+4713 map reaches a 1σ noise level of 9 µJy beam⁻¹. The

---

1 The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.
We aimed to reach $K_{\text{lim}}$-band limits from P200/HST data to correct the science frames. The science and standard star frames were dithered on a 3 arcsec grid to minimize correlated noise and create identical exposures dithered on a 3 arcsec grid to minimize correlated noise and create identical exposures. Integrating any residual noise into total exposure time was $1.7\times 10^4$ s per target.

The lack of radio emission within the submm error box of SMM J04431+0210 was taken with IRCAM3 in photometric and good-seeing conditions on the night of 1998 September 10. The original observations of SMM J09429+4658 were obtained in non-photometric conditions on 1998 October 19 using the new 10242 InSb imager UFTI (Leggett et al., 1999), along with further $K$-band observations of SMM J04431+0210. Each of these exposures consists of a total of 3.2 ks of on-source integration, with the UFTI images being slightly shallower owing to the poor transparency and seeing encountered. Nevertheless, the UFTI exposure of SMM J04431+0210 provides an independent confirmation of the reality of the source N4. To check the reliability of the detection of H5 and to improve our photometry we repeated the observations of SMM J09429+4658 using IRCAM3 in much better conditions on the nights of 1999 February 10±11, obtaining a total of 8.1-ks integration in $K$ and 3.2-ks integration in $H$. These observations confirm that H5 is indeed an extremely red source, with only a marginal detection of the source in the $H$-band image giving $(H - K) \approx 2.4$.

All of the near-IR observations were broken into subsets of nine exposures dithered on a 3 x 3 grid. Each of these sets of subexposures was also spatially offset. The dithering allows us to construct sky frames from the science exposures and use these to correct the science frames. The science and standard star frames were linearized, reduced and calibrated on to the Cousin's $I$-band in a standard manner. The colour term results in an uncertainty in the final $I$-band photometry of +0.15 for sources as red as $(R - I) = 3$.

After modelling and removing contaminating light from nearby galaxies, the magnitudes of the two sources were measured in 3.0-arcsec diameter apertures. These were converted to total
magnitudes using aperture corrections measured from bright compact objects in each field (Table 2, Fig. 3). The uncertainties quoted on this photometry includes a contribution due to removal of the contaminating light.

Optical imaging of the two fields was obtained with the LRIS imaging spectrograph (Oke et al. 1995) on the 10-m Keck II telescope, Mauna Kea. These images were taken to constrain the \((I - K)\) colours of the two near-IR sources that we identified from the UKIRT imaging. The observations were obtained in good conditions during bright time (Table 1) and consist of multiple 200-s exposures of the two fields dithered on a non-redundant grid. The science frames were processed in a standard manner and flat-fielded with twilight flat-fields. To remove fringing from the frames, subsets of the science exposures were stacked to construct flat-fielded images. This procedure worked well and the final frames reach 2\(\sigma\) sensitivities of \(I \approx 25.5-26\) within 3.0-arcsec diameter apertures. Notwithstanding the depth of these images, neither of the near-IR sources N4 or H5 is reliably detected. Faint emission is just visible in the \(I\), and perhaps \(F702W\), images of N4 coincident with the near-IR source; our aperture photometry does not confirm this as a formal detection and so instead we have chosen to quote a conservative limit. We therefore give the 2\(\sigma\) limiting \(I\)-band magnitudes for both counterparts in Table 2 and Fig. 3, along with the equivalent limits from the original R-band data of S98.

3 Discussion

Our deep \(K\)-band imaging of the submm sources from S98 has turned up two objects with relatively bright near-IR emission which were invisible on the deep optical imaging used by S98. We estimate 2\(\sigma\) limits of \((I - K) \approx 6.8\) and \((I - K) \approx 6.0\) for N4 and H5, respectively. This puts both N4 and H5 firmly into the class of EROs, with N4 possibly an extreme example. Moreover, both objects exhibit sufficiently red optical to near-IR colours that the probability of randomly detecting such a source within the submm error boxes is slight, \(P \approx 0.01\). We now discuss the properties of the submm sources in more detail and argue that the EROs, rather than the bright spirals N1 and H1, are the most likely counterparts of the submm sources.

We begin by discussing the spectral indices for the two submm sources between the submm and radio regimes using our 850-\(\mu m\) and 1.4-GHz flux densities or limits. Carilli & Yun (1999) have shown that the spectral index, \(\alpha_{1.4}^{850} = 0.42 \times \log_{10}(S_{850}/S_{1.4})\), can be used to obtain a crude redshift estimate for a range of starburst- and AGN-dominated SEDs. We find \(\alpha_{1.4}^{850} = 1.02 \pm 0.07\) for SMM J09429+4658 using the radio flux for H1 or \(\alpha_{1.4}^{850} = 1.10 \pm 0.08\) using the radio flux of H5 and \(\alpha_{1.4}^{850} \approx 0.84\) for SMM J04431+0210. These values are at the upper end of the distribution for high-redshift sources discussed in Carilli & Yun (1999), with SMM J09429+4658 having the highest \(\alpha_{1.4}^{850}\) index of any source currently known.

Using the various empirical and model curves in Carilli & Yun (1999), we translate the \(\alpha_{1.4}^{850}\) indices into redshift limits of \(z \approx 4\) for SMM J09429+4658 and \(z \approx 2\) for SMM J04431+0210. This indicates that both submm sources lie at high redshifts and are not associated with the bright spiral galaxies H1 or N1. The expected submm–radio spectral index for \(z = 0.2-0.3\) star-forming galaxies such as H1 or N1 would be in the range \(\alpha_{1.4}^{850} \approx -0.2\) to 0.3, far lower than the observed values. The predicted submm fluxes for these two galaxies adopting the observed radio limits/detections and the range of \(\alpha_{1.4}^{850} = 0.2-0.3\) from SMM J04431+0210 might also suggest that AGN-based emission is unlikely to dominate the radio power of these sources (Carilli & Yun 1999).

Another independent redshift estimate for the submm sources is available to us: the ratio of 450- to 850-\(\mu m\) flux densities. For SMM J09429+4658, \(S_{850}/S_{450} = 4.0 \pm 1.0\), which indicates \(1.5 \leq z \leq 5.0\) according to Hughes et al. (1998). For SMM J04431+0210, \(S_{850}/S_{450} \leq 8.3\), which suggests that \(z \approx 0.3\) -- a weak but useful constraint. The expected ratio of 450- to 850-\(\mu m\) flux densities for star-forming galaxies at \(z = 0.2-0.3\) is \(S_{850}/S_{450} \approx 8\). Again, the spectral properties of the submm sources appear to be incompatible with the bright galaxies H1.
and N1 being the counterparts of the submm emission and suggest instead that the source lies at substantially higher redshifts.

Data at submm and radio wavelengths thus appear to rule out the identification of the two spiral galaxies, H1 and N1, as counterparts of the submm sources (S98). Therefore we now discuss the properties of the EROs H5 and N4 to determine if these could be the true counterparts to the submm sources.

The modest resolution and signal-to-noise ratio of our K-band imaging means we can make no strong statements about the morphologies of the near-infrared sources H5 and H4. However, both show signs of being extended in our 0.5-arcsec-seeing UKIRT images indicating that they are likely to be a galaxies.

As we have shown, both submm sources probably lie at high redshifts. They, therefore, have bolometric luminosities of \( \geq 10^{12} L_\odot \) and their counterparts will class as ULIRGs. We can thus compare our limits on the colours of the two EROs with the predicted \((I-K)\) colours of ULIRGs at high redshift from Trentham, Kormendy & Sanders (1999). They use ultraviolet observations of low-redshift ULIRGs from \( HST \) to model the expected colours of similar systems at high redshift. The only galaxy of which the colours exceed \((I-K) = 6.0\) (our limit for H5) is VII Zw031, the reddest galaxy in their sample. This would have \((I-K) \geq 6.0\) at \( z \geq 2 \) and \((I-K) \geq 6.8\) at \( z \geq 2.5 \). Less extreme galaxies only become as red as \((I-K) \sim 5.3\) at \( z \geq 3 \) but tend to become bluer again after that. With few observations to compare with (and a wide range in the possible galaxy colours) this comparison is necessarily of only limited scope. Nevertheless, the colours of N4 and H5 would suggest that N4 may be a highly obscured galaxy at \( z \geq 2.5 \), while H5 could be a similarly obscured galaxy at \( z \geq 2 \).

The various constraints on the redshifts of the submm sources and the possible ERO counterparts are summarized in Table 3. In each case the constraints provide a consistent picture suggesting that both the submm sources and the EROs lie at high redshifts, \( z \geq 2 \). Taken together with the low likelihood of a chance spatial coincidence between a submm source and an ERO (neither class being particularly numerous), and the highly obscured nature suggested by the extreme colours of the ERO, we propose that the EROs H5 and N4 are the most likely counterparts of the submm sources SMM J09429+4658 and SMM J04431+0210.

We now discuss the consequences of the identification of ERO counterparts to the submm sources for our understanding of the nature of these two galaxies, as well as for ERO and submm galaxies in general. To simplify the discussion below we adopt redshifts of \( z \sim 4 \) for H5 and \( z \sim 3 \) for N4 which are representative of the results in Table 3.

Before investigating the intrinsic properties of the two galaxies H5 and N2, we must first estimate their lens magnifications. We use our robust mass models for both cluster lenses (Blain et al. 1999b) and include mass components for not only the main cluster potential but also the galaxies near the ERO positions using the scaling relations of Natarajan et al. (1998) to estimate their relative contributions. We assume redshifts of \( z \sim 4 \) for H5 and \( z \sim 3 \) for N4 and estimate an amplification factor of 2.0 for H5, with a range of 1.5–2.1 for \( z = 1–5 \); N4 has an amplification of 4.4 at \( z \sim 3 \), with a range of 3.1–4.8 across \( z = 1–5 \). These magnifications are achromatic and have typical errors of around 20 per cent, comparable to the absolute calibration errors of the SCUBA maps. Taking the appropriate amplifications, we correct the observed 850-\( \mu \)m flux densities and estimate intrinsic apparent fluxes of 7.7 \pm 1.0 mJy for H5 and 1.6 \pm 0.4 mJy for N4 (where the errors do not include any systematic components owing to the unknown redshifts of the galaxies). The corrected K-magnitudes are 20.1 for H5 and 20.7 for N4, while the equivalent I-band limits for these galaxies if they had been found in a blank-field survey would be very faint, \( I \geq 26.3 \) and \( I \geq 27.6 \).

Assuming that the far-IR spectral energy distributions (Fig. 3) of the two EROs are roughly similar to that of HR 10 (Dey et al. 1999), then their intrinsic submm fluxes, assuming \( T_{\text{dust}} = 47 K \), correspond to bolometric luminosities of \( 19 \times 10^{13} L_\odot \) and \( 5 \times 10^{13} L_\odot \) for H5 and N4 at \( z \sim 4 \) and \( z \sim 3 \), respectively (or a range of \( 35-18 \times 10^{12} \) and \( 8-3 \times 10^{12} \) for \( z = 1-5 \)). Thus both galaxies class as ULIRGs. If we assume that the far-IR emission from these galaxies is purely the result of star formation, the star formation rates (SFRs) that we derive are of the order of \( 1000 M_\odot \) year\(^{-1} \) for stars above \( 10 M_\odot \) for N4 and \( 4000 M_\odot \) year\(^{-1} \) for H5 [assuming SFR (\( M \geq 10 M_\odot \) year\(^{-1} \)) = \( L_{850}/0.5 \times 10^{10} L_\odot \); see Ivison et al. 1998a; Thronson & Telesco 1986]. However, in the local Universe, the majority of galaxies as luminous as H5/N4 show signs of AGN activity (Sanders & Mirabel 1996) and hence it is probable that this galaxy is a composite starburst/AGN, an obscured system akin to SMM J02399–0136 (Ivison et al. 1998a). We next compare the characteristics of H5 and N4 with those of HR 10, the submm-bright ERO at \( z = 1.44 \). HR 10 has an \((I-K)\) colour of 5.8, with \( K = 18.4 \), a flux density of 4.9 mJy at 850 \( \mu \)m and a bolometric luminosity of \( 7 \times 10^{12} L_\odot \) (Dey et al. 1999; c.f. Cimatti et al. 1998). Thus, HR 10 has a comparable bolometric luminosity to N4 and is \( \sim 3 \) times fainter than H5; in contrast, HR 10 is nearly an order of magnitude brighter than either N4 or H5 in the K-band. Assuming similar rest-frame optical/far-IR ratios for all three galaxies, their relative K-band magnitudes are compatible with N4 and H5 lying at higher redshifts than HR 10, as suggested by their \( \alpha_{1.4}^{850} \) indices (HR 10 has \( \alpha_{1.4}^{850} = 0.5 \), which is consistent with the models of Carilli & Yun (1999) for \( z = 1.44 \)) as well as their 450- to 850-\( \mu \)m flux density ratios. We plot the multiwavelength SED of HR 10 along with the available observations of H5 and N4 in Fig. 3.

The similarly extreme optical/near-IR colours and luminosities for N4, H5 and HR 10, as shown in Fig. 3, support the suggestion that N4 and H5 are more distant analogues of HR 10. The identification of ERO counterparts to two of the submm sources from S98 indicates that at least 10 per cent of the faint submm population down to 850-\( \mu \)m flux levels of a few mJy could be EROs. This estimate would rise to 20 per cent if the optical blank-field sources in S98 turn out to be faint EROs, which is entirely plausible. Taking the 10 per cent estimate and the surface density of 850-\( \mu \)m sources detected in the SCUBA Lens Survey (Blain et al. 1999b) of \( 2.5-4 \times 10^{4} \) deg\(^{-2} \) brighter than 2 mJy, we would expect a surface density of submm-selected EROs of around 0.1 arcmin\(^{-2} \). The K-band magnitudes of these galaxies are \( K \sim 20.5 \) in the absence of lensing and hence they would also account for all of the reddest objects in the ERO population at this limit (Cowie et al., in preparation).

Our conclusion that all of the most extreme ERO population are

Table 3. Redshift constraints for the EROs.

| Constraint   | H5       | N4       |
|--------------|----------|----------|
| \((I-K)\)    | \(\geq 2\) | \(\geq 2.5\) |
| \(\alpha_{1.4}^{850}\) | \(\geq 4\) | \(\geq 2\) |
| \(S_{850}/S_{50}\) | \(1.5-5\) | \(\geq 0.3\) |
| SED fit      | \(\sim 2.5\) | \(\sim 3\) |
likely to be submm emitters agrees well with the results from pointed SCUBA observations of extreme EROs (see Section 1). These programs are also detecting such sources at flux densities of $S_{250} \approx 2$ mJy. We therefore suggest that the most extreme EROs, $(I-K) \approx 6$, comprise a population of dusty ultraluminous starbursts in the distant Universe. While this population produces only a minor component of the background, $\lesssim 10$ per cent of the far-infrared background (see Blain et al. 1999a), the study of these sources will be an important step in understanding the formation and evolution of dust within the most luminous and obscured galaxies at high redshifts.

We stress that the whole ERO population [defined as those objects redder than $(I-K) \approx 5$] is not dominated by submm-bright sources. This is not particularly surprising given the wide range of characteristics which can place a galaxy in that class (see Section 1). However, the extreme colours of H5 and N4 and the spread of optical to near-IR colours that they indicate in the submm-selected sample (cf. Ivison et al. 1998a) is more puzzling and suggests a relatively inhomogeneous population with a wide range of line-of-sight dust obscuration. Similar behaviour is seen in samples of low-redshift ULIRGs (Trentaham et al. 1999) and these are therefore likely to be the best laboratories for unravelling the cause of these widely varying optical properties.

We also note that relatively bright ERO counterparts $(K \lesssim 20.5)$ such as those discussed here are not seen for the bulk of the submm sources in our survey. Moreover, in at least two cases, we have submm sources with bright and blue optical counterparts, two galaxies at $z = 2.80$ and $z = 2.56$ (Ivison et al. 1998a; Ivison et al., 1999), and in both instances we have confirmed the identifications with CO observations at mm wavelengths (Frayer et al. 1998, 1999). Hence, while the SCUBA population contains some near-IR bright EROs, these do not appear to dominate the sample. It is possible that some of the remaining SCUBA sources have counterparts with ERO-like characteristics that are fainter than $K \sim 21$ (equivalent to $K \geq 22$ for a blank-field survey). Such objects would be exceedingly difficult to identify and their further study would be almost completely confined to what could be learnt at millimetre and radio wavelengths.

The similarities between the properties of H5, N4 and HR 10 along with the identification of the latter as a massive, dust-shrouded starburst galaxy at $z = 1.44$ (Dey et al. 1999) suggests that these two galaxies represent similar systems lying at even higher redshifts and hence earlier times in the Universe. The redshift constraints from our multiwavelength observations are summarized in Table 3. These massive star-forming galaxies will provide particularly stringent tests of hierarchical galaxy-formation models (Baugh et al. 1998) if it can be shown that a large fraction of their bolometric luminosity is powered by star formation.

4 CONCLUSIONS

(i) In the course of a near-IR survey of counterparts to faint submm sources we have uncovered two extremely red galaxies, H5 and N4, which were undetected in the deep optical images used originally to select likely counterparts by Smail et al. (1998). Follow-up deep optical imaging of both fields with Keck II puts $2\sigma$ limits of $(I-K) \approx 6.0$ and $(I-K) \approx 6.8$ on the colours of H5 and N4, respectively. Both galaxies therefore class as EROs.

(ii) Using the submm and radio spectral properties of the submm sources we argue that the EROs are probably the source of the submm emission, not the bright spiral galaxies previously identified as such by Smail et al. (1998). The identification of two ERO counterparts to submm sources indicates that at least 10 per cent of the submm population down to 850-μm flux levels of a few mJy could be EROs. The equivalent surface density of submm-selected EROs would be around 0.1 arcmin$^{-2}$ at $K \leq 20.5$. This density would account for all of the reddest EROs detected in near-IR surveys at this depth.

(iii) A comparison of the submm and radio emission from H5 and N4 with the models of Carilli & Yun (1999) and a study of their optical and far-IR SEDs suggests that both galaxies are likely to be dusty ultraluminous starbursts at high redshifts, probably at $z \approx 2$.

ACKNOWLEDGMENTS

We thank referee Neil Trentham for his thorough report on this paper as well as for kindly providing the predicted $(I-K)$ colours of high redshift ULIRGs. We acknowledge useful conversations with Arjun Dey, James Graham and Katherine Gunn. We thank Sandy Leggett for help and support during our UFTI observations. IRS acknowledges support from the Royal Society and RJI and AWB from PPARC.

REFERENCES

Andreon P., Cimatti A., Rottgering H., Tilanus R., 1999, Ap&SS, in press
Aragon-Salamanca A., Ellis R. S., Schwartzzenberg J. M., Bergeron J. A., 1994, ApJ, 421, 27
Barger A. J., Cowie L. L., Trentam N., Fulton E., Hu E. M., Songaila A., Hall D., 1999a, AJ, 117, 102
Barger A. J., Cowie L. L., Smail I., Ivison R. J., Blain A. W., N. Kneib J., 1999b, ApJ, in press
Blain A. W., Cole S., Frenk C. S., Lacey C. G., 1998, ApJ, 498, 504
Blain A. W., Smail I., Ivison R. J., Kneib J. P., 1999a, MNRAS, 302, 632
Blain A. W., Kneib J. P., Ivison R. J., Smail I., 1999b, ApJ, 512, L87
Carilli C. L., Yun M. S., 1999, ApJ, 513, L13
Cimatti A., Andreen P., Rottgering H., Tilanus R., 1998, Nat, 392, 895
Cowie L. L., Gardner J. P., Hu E. M., Songaila A., Hodapp K. W., Wainscoat R. J., 1994, ApJ, 434, 114
Dey A., Spinrad H., Dickinson M. E., 1995, ApJ, 440, 515
Dey A., Graham J., Ivison R. J., Smail I., Wright G. S., Liu M., 1999, ApJ, in press
Dressler A., Smail I., Poggianti B. M., Butcher H., Couch W. J., Ellis R. S., Oemler A., 1999, ApJS, in press
Elston R., Rieke G. H., Rieke M. J., 1988, ApJ, 331, L77
Frayer D. T., Ivison R. J., Scoville N. Z., Yun M., Evans A. S., Smail I., Blain A. W., Kneib J. P., 1998, ApJ, 506, L7
Frayer D. T., Ivison R. J., Scoville N. Z., Yun M., Evans A. S., Smail I., Barger A. J., Blain A. W., Kneib J. P., 1999, ApJL, 514, L13
Graham J. R., Dey A., 1996, ApJ, 471, 720
Graham J. R. et al., 1994, ApJ, 420, L5
Hu E. M., Ridgway S., 1994, AJ, 107, 156
Hughes D. H., Serjeant S., Lawrence A., Longair M., Goldschmidt P., Jenness T., 1998, Nat, 394, 241
Ivison R. J., Smail I., Le Borgne J. F., Blain A. W., Kneib J. P., Beazecourt J., Kerr T. H., Davies J. K., 1998a, MNRAS, 298, 583
Ivison R. J. et al., 1998b, ApJ, 494, 211
Ivison R. J., Smail I., Barger A., Kneib J. P., Blain A. W., Owen F. N., Kerr T. H., Cowie L. L., 1999, MNRAS, submitted
Leggett S. K., 1999, http://www.jach.hawaii.edu/UKIRT/new/instruments/ufit
Natarajan P., Kneib J. P., Smail I., Ellis R. S., 1998, ApJ, 499, 600

© 1999 RAS, MNRAS 308, 1061–1068
Oke J. B., Cohen J. G., Carr M., Cromer J., Dingizian A., Harris F. H., Labrecque S., Lucinio R., Schaal W., Epps H., Miller J., 1995, PASP, 107, 375
Sanders D. B., Mirabel I. F., 1996, ARA&A, 34, 749
Smail I., Ivison R. J., Blain A. W., Kneib J.-P., 1998, ApJ, 507, L21 (S98)
Smail I., Morrison G., Gray M. E., Owen F. N., Ivison R. J., Kneib J.-P., Ellis R. S., 1999, ApJ, in press
Smail I., Ivison R. J., Owen F. N., Blain A. W., Kneib J.-P., 2000, ApJL, submitted
Soifer B. T., Neugebauer G., Matthews K., Lawrence C., Mazzarella J., 1992, ApJ, 399, L55
Trentham N., Kormendy J., Sanders D., 1999, AJ, 117, 2152
Thronson H., Telesco C., 1986, ApJ, 311, 98
Yamada T., Tanaka I., Aragon-Salamanca A., Kodama T., Ohta K., Arimoto N., 1997, ApJ, 487, L125

This paper has been typeset from a \TeX/LaTeX file prepared by the author.