First detections of FIRBACK sources with SCUBA

Douglas Scott,[1][*] **Guilaine Lagache,**[2] **Colin Borys,**[1] **Scott C. Chapman,**[1][**] **Mark Halpern,**[1] **Anna Sajina,**[1] **Paolo Ciliegi,**[3] **David L. Clements,**[4] **Hervé Dole,**[2] **Sebastian Oliver,**[5] **Jean-Loup Puget,**[2] **William T. Reach**[6]**, and Michael Rowan-Robinson**[5]

[1] Department of Physics & Astronomy, University of British Columbia, Vancouver, B.C. V6T 1Z1, Canada
[2] Institut d'Astrophysique Spatiale, Bât. 121, Université Paris XI, F-91405 Orsay Cedex, France
[3] Observatories of the Carnegie Institute of Washington, Pasadena, CA 91101, U.S.A.
[4] Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy
[5] Department of Physics & Astronomy, Cardiff University, P.O. Box 913, Cardiff CF22 3YB, U.K.
[6] Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2BZ, U.K.
[7] Infrared Processing and Analysis Center, California Institute of Technology, Mail Stop 100-22, Pasadena, CA 91125, U.S.A.

Abstract. The FIRBACK (Far InfraRed BACKground) survey represents the deepest extensive $170\,\mu$m images obtained by the *ISO* satellite. The sources detected comprise about 10% of the Cosmic IR Background (CIB) seen by *COBE*, and, importantly, were observed at a wavelength near the peak of the CIB. Detailed follow-up of these sources should help pin down the redshifts, Hubble types, and other properties of the galaxies which constitute this background. We have used the Submillimetre Common-User Bolometer Array (SCUBA) instrument on the James Clerk Maxwell Telescope (JCMT) to search for sub-mm emission from a sample of 10 galaxies which are bright at $170\,\mu$m and for which we had accurate radio positions. Statistically we detect this sample at both $450\,\mu$m ($\sim 4\sigma$) and $850\,\mu$m ($\sim 7\sigma$); individual objects are convincingly detected in four cases at $850\,\mu$m, and one case at $450\,\mu$m. Fits to simple spectral energy distributions suggest a range of low to moderate redshifts, perhaps $z = 0$–1.5 for this FIRBACK sub-sample.

Key words: Cosmology: observations – Infrared: galaxies – Submillimeter – galaxies: evolution

1. Introduction

In the far-IR/sub-mm waveband there are currently two pressing (and related) cosmological mysteries:

1. what makes up the background detected by *COBE* (Puget et al. 1996, Fixsen et al. 1998, Hauser et al. 1998, Lagache et al. 1999)?

2. how do sources detected in the sub-mm (see e.g. Sanders 1999 and references therein) relate to galaxies at other wavelengths?

The study of both issues provides important diagnostics of galaxy formation models, and the answers should help illuminate the dark ages of how the first objects formed and subsequently evolved into present day galaxies. The first question is the main motivation behind the FIRBACK project (Clements et al. 1998, Lagache 1998, Reach et al. 1998, Puget et al. 1999, Dole et al. 1999), which made deep $170\,\mu$m images of the sky with *ISO*, to resolve the CIB into sources. The second question has been the main driving force behind the search for distant sources by several teams using SCUBA, as well as the large amount of follow-up work and comparison with other wavelengths (e.g. Smail, Ivison & Blain 1997, Barger et al. 1998, Blain, Ivison & Smail 1998, Holland et al. 1998, Hughes et al. 1998, Smail et al. 1998, Barger et al. 1999, Blain et al. 1999a, Chapman et al. 1999, Cowie et al. 1999, Eales et al. 1999, Lilly et al. 1999). These observational campaigns are untangling the problem of how obscuration by dust skews our optical view of the early Universe, unveiling the 'dark-side' of galaxy formation out to distant redshifts, and helping provide unbiased estimates of the global star formation history of the Universe.

In this letter we present the first results of a study at the interface between these two puzzles. Rather than trying to find new sources with SCUBA, we have carried out $450\,\mu$m and $850\,\mu$m photometry on sources already detected at $170\,\mu$m with ISOPHOT.

2. The FIRBACK Survey

The lifetime of the Infrared Space Observatory (*ISO*; Kessler et al. 1996) is long over, and we now have in hand the best information we will have from long-IR wavelengths until the launch of *SIRTF*. For SCUBA

observations, the smallest extrapolations come at the longest wavelengths attainable with the ISOPHOT instrument (Lemke et al. 1996). ISOPHOT is an imaging photo-polarimeter with 92 arcsec pixels and 1.6 arcmin FWHM at $170\,\mu m$; reasonably high signal-to-noise sources in 'dithered' images can be located with an accuracy of ~ 40 arcsec. Following the discovery of the CIB, *ISO* was in a unique position to investigate the sources which comprise this background. Consequently deep ISOPHOT images were obtained at $170\,\mu m$ of three separate ~ 1 square degree regions of the sky, selected for their low foreground emission – the FIRBACK Survey. One region, the 'Marano' fields, is only accessible from the southern hemisphere, while the other two coincide with the 'N1' and 'N2' fields of the ELAIS project (Oliver 1997), which used ISOCAM at $7\,\mu m$ and $15\,\mu m$ and ISOPHOT at $90\,\mu m$ (although only a fraction of the FIRBACK sources were detected at these other wavelengths). These northern regions have also been mapped with the VLA (Ciliegi et al. 1999). In addition an area towards the Lockman Hole is being studied by another group (Kawara et al. 1998).

Here we have concentrated on a sample of objects from the roughly two square degree 'N1' field, centred at $16^{\rm h}\,11^{\rm m}$, $+54°\,25^{\rm m}$. For this first attempt at JCMT follow-up we chose objects with secure, unconfused radio identifications, relatively strong $170\,\mu m$ emission, and additionally high $170\,\mu m$:21 cm flux density ratios (see Lagache et al., in preparation). This last criterion was aimed at biassing the sample away from the lowest redshift galaxies, and hence towards those which might have the highest $850\,\mu m$:$170\,\mu m$ flux density ratios. We expect that with the addition of more follow-up observations it should be possible to select future sub-samples with a higher likelihood of being strong SCUBA emitters.

3. JCMT Observations

The data were obtained on the nights of 18–23 March 1999 using the SCUBA instrument (Holland et al. 1999) on the JCMT. The short- and long-wavelength arrays were used simultaneously, at $450\,\mu m$ and $850\,\mu m$, respectively. We used 'photometry' mode, chopping at the standard $7.8125\,\mathrm{Hz}$, and also nodding every second by about 45 arcsec in coordinates fixed to the array (i.e. there was no sky rotation). This means that each measurement is a double-difference between the central bolometer and positions 45 arcsec each side, corresponding approximately to positions of other bolometers on both the long- and short-wavelength arrays. The data were analyzed using the SURF package (Jenness & Lightfoot 1998). The raw data for the two arrays were flat-fielded, corrected for extinction, had bad bolometers removed, and had the average sky removed at each time interval. The information from the off-beams was then added, assuming that one long wavelength bolometer had an efficiency of exactly 0.5, with the long wavelength bolometer on the other side,

Source	S_{170}	S_{450}	S_{850}	
	(mJy)	(mJy)	(mJy)	
N1-008	433	17.2 ± 10.8	3.3 ± 0.9	3.6σ
N1-015	219	2.8 ± 18.3	2.6 ± 1.4	< 4.9
N1-025B	200	40.5 ± 23.8	2.4 ± 1.2	< 4.4
N1-034	153	83.4 ± 25.8	-1.0 ± 1.2	< 1.8
N1-035	151	8.6 ± 21.0	0.8 ± 1.3	< 3.1
N1-038	148	22.8 ± 13.5	6.0 ± 1.1	5.4σ
N1-045	139	17.8 ± 22.7	2.1 ± 1.2	< 4.1
N1-061	121	32.3 ± 25.3	4.5 ± 1.3	3.4σ
N1-063	120	67.4 ± 24.2	4.8 ± 1.2	4.0σ
N1-087	93	8.3 ± 20.8	1.2 ± 1.2	< 3.3
Mean	178	23.8 ± 5.8	2.78 ± 0.37	

Table 1. FIRBACK identification (see Lagache et al., in preparation), together with $170\,\mu m$ flux density (with estimated systematic uncertainty of perhaps 30%). The $450\,\mu m$ and $850\,\mu m$ measurements are from our new SCUBA observations. The final column lists the SNR for the $>3\sigma$ detections, and the 95% Bayesian upper limits (in mJy) for the others.

as well as the two short wavelength off-beam bolometers, having slightly lower values (see Borys et al. 1999, Chapman et al. 1999, for more details). Adding the weighted off-beam signal always decreased the noise, and generally increased the signal to noise ratio (SNR), but we carried out the same procedure even when it slightly lowered the SNR.

Calibration was performed a few times per night using planets and other strong sub-mm sources, and the values we used were similar to the standard gains. The standard deviation of the calibrations was 10% at $850\,\mu m$ and 12% at $450\,\mu m$; these should be a reasonable estimate of the uncertainty in the calibration. At the low SNRs at which we are working, the calibration uncertainty is not a major contributor to the total uncertainty, and has essentially no effect on the SNR itself.

4. Individual Objects

At $850\,\mu m$ we detected one source at $>5\sigma$ and a further three at $>3\sigma$. While we would not claim detection of the other sources, they generally have positive flux density (see next section), and certainly there are good upper limits in each case. This last remark applies to the $450\,\mu m$ data, where there is only one detections above 3σ.

Bayesian 95% upper limits can be obtained for all our non-detections, by integrating a Gaussian probability, neglecting the unphysical negative flux density region. The $850\,\mu m$ upper limits for our six non-detections are given in the last column of Table 1. At $450\,\mu m$ the limits are generally less constraining for reasonable SEDs, being around $30\,\mathrm{mJy}$ in the best cases.

Using a combination of $170\,\mu m$, $450\,\mu m$ and $850\,\mu m$ data, we can place some constraints on the spectral en-

ergy distributions (SEDs) of these FIRBACK galaxies. Assuming a grey-body spectrum, we can obtain a limit on some combination of luminosity, temperature, spectral index and redshift. Here we choose to normalize the luminosity at $170\,\mu$m, and then use the SCUBA data to constrain the redshift. To do this we assume standard values for the dust temperature, $T_{\rm d} = 40\,$K (typical for sub-mm selected galaxies, e.g. Blain et al. 1999b, Dunne et al. 1999), and spectral index of the dust emissivity, $\beta = 1.5$. Because we do not know the absolute luminosity of any source, our results are degenerate in the ratio $T_{\rm d}/(1 + z)$, and so we are unable to tell apart cooler objects at lower redshift from hotter objects at higher redshift.

Assuming a uniform prior distribution of redshifts, we can obtain a Bayesian 95% confidence range on the redshift implied for each source by our $450\,\mu$m and $850\,\mu$m data, where it is understood that the redshifts can be scaled using a different dust temperature such that $(1 + z)/T_{\rm d}$ is held constant. We find that the objects with the highest $850\,\mu$m flux densities have the highest implied redshifts: e.g. $0.66 < z < 1.23$ for N1-038. Those with lower flux densities at $850\,\mu$m generally only yield upper limits to the redshift: e.g. $z < 0.55$ for N1-015. There are no objects for which we would infer $z > 2$. However, higher redshifts could be accommodated by adopting a higher dust temperature or a higher value of β (and lower redshifts by lowering these parameters).

The object in our sub-sample which is brightest at $170\,\mu$m, N1-008, is hard to fit with any reasonable SED; it has approximately half the $850\,\mu$m and $450\,\mu$m flux density expected from even a $z = 0$ source with the same $170\,\mu$m flux density. This suggests that there might be more than one source contributing to the ISOPHOT flux, which is not particularly unlikely, since the FIRBACK Survey is operating near the confusion limit. On the other hand, optical images show little in the error circle except for a very bright obvious spiral galaxy, and so from that point of view this is not a case where we expect more than one source in the ISOPHOT beam. Another possibility is that our JCMT beam did not include all the flux, since optically this object appears quite extended. However, we would expect the sub-mm emission to be more concentrated than the optical, and hence we are likely to have included most of the dust emission within the beam. This object will be discussed more extensively in Lagache et al. (in preparation).

Relatively poor values of χ^2 are also found for N1-034 and N1-063. These result either from low SCUBA flux densities relative to ISOPHOT, or somewhat high SCUBA $450\,\mu$m flux densities compared with $850\,\mu$m. Higher SNR data, or data at additional wavelengths are required to determine whether these flux densities come from multiple objects, complex SEDs, or simply the low SNRs of the current data for these objects.

Another way of estimating the redshift relies on the radio/far-IR correlation (e.g. Helou, Soifer & Rowan-
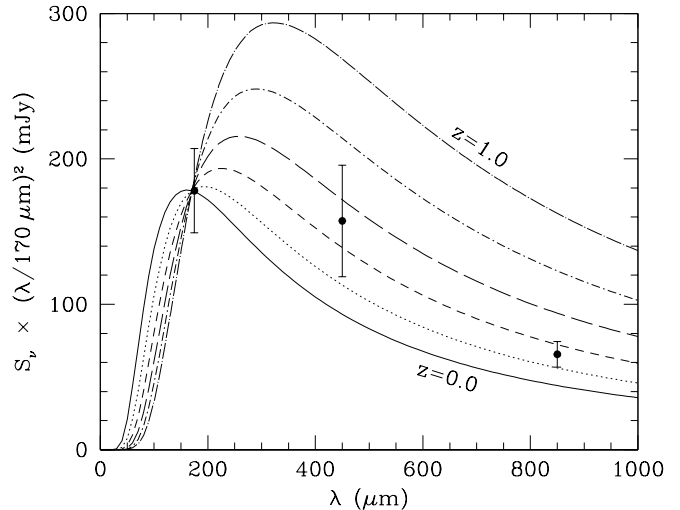

Fig. 1. Average spectral energy distribution for our FIR-BACK sub-sample. The $170\,\mu$m point is the average of our sub-sample of 10 FIRBACK sources, with the error-bar here being the standard error from the scatter among them. The $450\,\mu$m and $850\,\mu$m points are from our new SCUBA observations. For the sake of visual clarity we have multiplied the y-axis by x^2. The curves show emission from modified blackbodies, normalized to the $170\,\mu$m flux density, with $T_{\rm d} = 40\,$K and $\beta = 1.5$, and for $z = 0.0$ (solid line) up to $z = 1.0$ in steps of 0.2. Note that the shapes of these curves are degenerate in the combination $(1 + z)/T_{\rm d}$.

Robinson 1987, Carilli & Yun 1999, Barger, Cowie & Richards 1999, Smail et al. 1999). Using the $20\,$cm VLA data from Ciliegi et al. (1999) and the explicit correlation (using $\beta = 1.5$, $T_{\rm d} = 40\,$K) from Carilli & Yun (1999), we find $z = 0.6$, 1.2, 1.1 and 1.4 for N1-008, N1-038, N1-061 and N1-063, respectively (our four $850\,\mu$m detections). Except for N1-008 these are in broad agreement with the values obtained from the sub-mm and far-IR data alone.

5. Statistical Results

If we combine all the data together, then we can obtain a much more precise picture of the average galaxy in our FIRBACK sub-sample. The average flux densities are given in Table 1, and represent a 4.1σ detection at $450\,\mu$m and a 7.3σ detection at $850\,\mu$m. The average SED is shown in Figure 1. It is clear that for $T_{\rm d} = 40\,$K the best fitting redshift is around 0.3, with values as low as $z = 0$ or higher than $z \simeq 0.6$ providing relatively poor fits. However, we can certainly accommodate $z \sim 1$ galaxies for higher temperatures, and $z \sim 0$ galaxies for lower temperatures. Since higher dust temperature is seen in star-bursting galaxies, compared with more typical star-forming galaxies, then it is possible that a fraction of these sources are much more luminous and at higher redshift. However, it

would take unrealistically high temperatures, $T_d \gtrsim 100\,\mathrm{K}$, to push some of the objects up to say $z \simeq 3$ (although the possibility of gravitational lensing could complicate this).

Models of galaxy populations (e.g. Guiderdoni et al. 1998), designed to fit number counts at a range of wavelengths, as well as the CIB, predict that the average FIRBACK galaxy is indeed at $z \sim 1$. The other possibility is that we have uncovered a new population of relatively nearby star-forming galaxies, which do not show up clearly in surveys at other wavelengths. The degeneracy between $(1+z)$ and $1/T_d$ makes it impossible to decide between these possibilities using the far-IR and sub-mm data alone. Although it seems unlikely that all our objects can be at low redshift, this could obviously be resolved by obtaining optical redshifts. Once redshifts have been obtained, then the sub-mm data will be invaluable in measuring the properties of the dust in the various galaxy types: far-IR luminosities, dust temperatures and emissivities.

6. Conclusions

We have carried out the first SCUBA follow-up of FIR-BACK sources. We found that they are generally detectable in the sub-mm; those with somewhat higher $850\,\mu\mathrm{m}$ flux density may be at $z \sim 1$, while those which are fainter in the sub-mm may be more normal galaxies at $z \sim 0$. Models of evolving galaxy populations which provide a good fit to the $170\,\mu\mathrm{m}$ counts, as well as counts at other wavelengths (e.g. Guiderdoni et al. 1998) predict that the median redshift of the FIRBACK galaxies is around 1 (Puget et al. 1999). Our results are consistent with this, provided that the average galaxy in our sub-sample is a distant star-bursting galaxy with fairly hot dust temperature. The other possibility is that some could be from an otherwise unknown population of low redshift star-forming galaxies with relatively low dust temperature. Further observations at sub-mm and other wavelengths should decide this issue, and reveal the detailed properties of the galaxies which comprise the CIB.

References

Barger A.J., Cowie L.L., Sanders D.B., Taniguchi Y. 1998, Nature, 394, 248

Barger A.J., Cowie L.L., Smail I., Ivison R.J., Blain A.W., Kneib J.-P. 1999, AJ, 117, 265

Barger A.J., Cowie L.L., Richards E.A. 1999, in 'Photometric Redshifts and High Redshift Galaxies', in press [astro-ph/9907022]

Blain A.W., Ivison R.J., Smail I. 1998, MNRAS, 296, L29

Blain A.W., Kneib J.-P., Ivison R.J., Smail I., 1999a ApJ, 512, L87

Blain A.W., Smail I., Ivison R.J., Kneib J.-P. 1999b, in 'The Hy-redshift universe', ed. A. Bunker, W. van Breugel, in press [astro-ph/9908111]

Borys C., Chapman S.C., Scott D. 1999, MNRAS, 308, 527

Carilli C.L., Yun M.S. 1999, ApJ, 513, L13

Chapman S.C., et al. 1999, submitted to MNRAS [astro-ph/9909092]

Ciliegi, P., et al. 1999, MNRAS, 302, 222

Clements, D.L. et al. 1998, in 'Astrophysics with Infrared Surveys: A Prelude to *SIRTF*', ed. M. Bicay, in press [astro-ph/9809054]

Cowie L.L. Songaila A., Barger A.J. 1999, AJ, in press [astro-ph/990435]

Dole H., et al. 1999, 'The Universe as seen by *ISO*', ed. P. Cox, M.F. Kessler, UNESCO, Paris, ESA SP-427, in press [astro-ph/9902122]

Dunne L., Eales S., Edmunds M.G., Ivison R., Alexander P., Clements D.L. 1999, MNRAS, submitted

Eales S., Lilly S., Gear W., Dunne L., Bond J.R., Hammer F., Le Fevre O., Crampton D. 1999, ApJ, 515, 518

Fixsen D.J., Dwek E., Mather J.C., Bennett C.L., Shafer R.A. 1998, ApJ, 508, 123

Guiderdoni B., Hivon E., Bouchet F.R., Maffei B. 1998, MNRAS, in press [astro-ph/9710340]

Hauser M.G., et al. 1998, ApJ, 508, 25

Helou G., Soifer B.T., Rowan-Robinson, M. 1985, ApJ, 298, L7

Holland W.S., et al. 1998, Nature, 392, 788

Holland W.S., et al. 1999, MNRAS, 303, 659

Hughes D.H., et al. 1998, Nature, 394, 241

Jenness T., Lightfoot J.F. 1998, in ASP Conf. Ser. Vol. 145, 'Astronomical Data Analysis Systems and Software', ed. R. Albrecht, R.N. Hook, H.A. Bushouse, Astron. Soc. Pac., San Francisco, p. 216

Kawara K., et al. 1998, A&A, 336, L9

Kessler M.F., et al. 1996, A&A, 315, L27

Lagache G. 1998, Ph.D. thesis, Paris XI University

Lagache G., Abergel A, Boulanger F., Désert F. X., Puget J.-L. 1999, A&A, 344, 322

Lemke D., et al. 1996, A&A, 315, L64

Lilly S.J., et al. 1999, ApJ, 518, 641

Oliver S., et al. 1997, in IAU 179 'New Horizons from Multi-Wavelength Sky Surveys', ed. B. McLean, Kluwer

Puget J.-L., et al. 1996, A&A, 308, L5

Puget J.-L. 1999, A&A, 345, 29

Reach W.T., et al. 1998, in 'Astrophysics with Infrared Surveys: A Prelude to *SIRTF*', ed. M. Bicay, in press

Sanders D.B, 1999, in 'Space Infrared Telescopes and Related Science', 32nd COSPAR workshop, Nagoya, Japan, ed. T. Matsumoto, T. de Graauw, in press [astro-ph/9904292]

Smail I., Ivison R.J., Blain A.W. 1997, ApJ, 490, L5

Smail I., Ivison R.J., Owen F.N., Blain A.W., Kneib J.-P. 1999, ApJ, in press [astro-ph/9907083]