

# SCUBA sub-millimeter observations of gamma-ray bursters

## I. GRB 970508, 971214, 980326, 980329, 980519, 980703, 981220, 981226

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**Abstract.** We discuss our ongoing program of Target of Opportunity observations of gamma-ray bursts (GRBs) using the SCUBA instrument on the James Clerk Maxwell Telescope. We present observations of GRB 970508, 971214, 980326, 980329, 980519, 980703, 981220, and 981226.

Our most important result to date is the detection of a fading counterpart to GRB 980329 at 850  $\mu\text{m}$ . Although it proved to be difficult to find the infrared counterpart to this burst, the sub-millimeter flux was relatively bright. This indicates that the brightness of this counterpart (corrected for absorption) was very similar to GRB 970508. The radio through sub-millimeter spectrum of GRB 980329 is well fit by a power law with index  $\alpha = +0.9$ . However, we cannot exclude a  $\nu^{1/3}$  power law attenuated by synchrotron self-absorption. An  $\alpha \sim +1$  VLA-SCUBA power law spectrum is definitely ruled out for GRB 980703, and possibly also for GRB 980519.

We cannot rule out that part of the sub-millimeter flux from GRB 980329 comes from a dusty star-forming galaxy at high redshift, such as the ones recently discovered by SCUBA. Any quiescent dust contribution will be much larger at sub-millimeter than at radio wavelengths. Both a high redshift and large dust extinction would help explain the reddening of the counterpart to GRB 980329. The large intensity of this burst might then indicate that beaming is important.

**Key words:** gamma rays: bursts – radio continuum: general – infrared: general

### 1. Introduction

An important reason for the long-standing mysteries surrounding the gamma-ray burst (GRB) sources has been the lack of

prompt accurate locations to look for quiescent or fading counterparts. This situation changed dramatically in 1997 with the rapid and accurate location of X-ray emission detected during GRBs using the wide-field camera on the *Satellite per Astronomia X (BeppoSAX)*, the All Sky Monitor on the *Rossi X-ray Timing Explorer (RXTE)*, and from the detection of X-ray afterglow in scans of BATSE GRB error boxes with the PCA on *RXTE*.

These localized X-ray counterparts have led to intense multiwavelength campaigns. Optical transients have been found to some but not all of the bursts with fading X-ray counterparts. The reason optical transients have not been discovered for the other bursts with X-ray counterparts (some of which are much brighter during the gamma-ray burst itself) is that the searches have not always been sensitive enough, particularly given the possibility of absorption local to the source (Groot et al. 1998a).

In spite of detailed searches, radio emission has only been detected for  $\sim 1/2$  of the bursts. The first detection of a variable radio source was GRB 970508 (Frail et al. 1997; Taylor et al. 1997; Galama et al. 1998a). This  $\sim \text{mJy}$  source had a rising spectral index, and its rapid radio variability was most likely caused by interstellar scintillation. The combined observations of GRB 970508 showed that the peak of the spectrum was in the sub-millimeter region  $\sim 12$  days after the burst (Galama et al. 1998b) with the radio, millimeter, and optical emission peaking days to weeks after the burst (Frail et al. 1997; Galama et al. 1998a; Gruendl et al. 1998; Bremer et al. 1998; Pian et al. 1998; Pedersen et al. 1998; Castro-Tirado et al. 1998a). Even before any counterparts were found, two completely separate classes of models had suggested this would be the case: (1) cosmological fireball models (e.g. Paczyński & Rhoads 1993; Katz 1994; Mészáros & Rees 1997), and (2) Compton scattering models (e.g. Liang et al. 1997; Liang 1997).

For GRB 970508 there are at least two breaks in the spectrum between  $10^{11}$  and  $10^{14}$  Hz (Galama et al. 1998b) making this a

crucial region for the models. To obtain a complete picture of the nature of the burst counterparts, it is clear that one needs to cover the entire spectrum, and sub-millimeter observations with a  $\sim$  mJy sensitivity are needed. This is particularly important since the optical emission can be suppressed by local absorption, and the radio emission at frequencies below 20 GHz can be self absorbed as well as scrambled by interstellar scintillation (Walker 1998), while “clean” observations ought to be possible at sub-millimeter wavelengths (the radio interstellar scintillation frequency depends on the Galactic latitude of the source, and can be well below 20 GHz; D. Frail, private communication).

In this paper we discuss our ongoing program of Target of Opportunity observations using SCUBA on the James Clerk Maxwell Telescope. In Sect. 2 we discuss some of the technical features of SCUBA that make it well suited for performing counterpart searches. In Sect. 3 we present the results of our observations to date on GRBs 970508 (which was a limited trial run), 971214, 980326, 980329, 980519, 980703, 981220, and 981226. Our SCUBA observations of GRB 990123 are presented elsewhere (Galama et al. 1999). In Sect. 4 we give a brief discussion.

## 2. SCUBA details

SCUBA is the new sub-millimeter continuum instrument for the James Clerk Maxwell Telescope on Mauna Kea, Hawaii (for a review see Holland et al. 1999). It uses two arrays of bolometers to simultaneously observe the same region of sky,  $\sim 2.3'$  in diameter. The arrays are optimized for operations at 850 and 450  $\mu\text{m}$ . Fully sampled maps of the  $2.3'$  region can be made by “jiggling” the array. Thus this mode is appropriate for mapping the better localized GRB error boxes as well as those of the X-ray transients. This mode can also be used to look for extended quiescent counterparts.

Deeper photometry can be performed using any pixel of these arrays. There are also dedicated photometry pixels for 1100, 1350, and 2000  $\mu\text{m}$  observations (that cannot be used at the same time as the arrays). This photometry mode is appropriate for well localized radio or optical transients.

Scan mapping of larger GRB error boxes using the 450:850 filters is also possible. While this mode is ideal for mapping the long thin GRB error boxes that are obtained using triangulation between satellites, e.g.  $5' \times 0.5'$  (Hurley et al. 1997), the sensitivity is greatly reduced.

Given the rapid dissemination of candidate optical and radio transients, the photometry mode is the one that we use most often. Except for the 1997 Dec 16 map of GRB 971214, all the results presented in this paper use the photometry mode. In principle, the most sensitive measurements can be made at 1350  $\mu\text{m}$ , though the 850  $\mu\text{m}$  array has an advantage because the multiple bolometers permit a good sky noise subtraction. In photometry mode, for an integration time of 2 hours, we would expect to achieve an rms  $\sim 1$  mJy at 1350  $\mu\text{m}$ ,  $\sim 1.5$  mJy at 850  $\mu\text{m}$ , and  $\sim 5$ –20 mJy at 450  $\mu\text{m}$ . The sensitivities depend significantly on the weather, particularly at the shorter wavelengths. The jiggle maps at full resolution give an rms that is a factor  $\sim 4$  times higher.

To ensure a homogeneous sample we used a similar calibration and reduction procedure for all the observations. The main steps during the data reduction were the application of the flat-field, removal of systematically noisy bolometers, despiking, and sky-noise removal. The flat-field corrects each bolometer both for a systematic relative gain factor and for its exact position on the sky. In photometry observations of a point source with an array, one pixel, typically the central one, is always used to measure the source while all the other bolometers monitor the surrounding sky. Excluding the noisy bolometers and after despiking, the median value of these sky bolometers for each 18-sec integration is adopted as the instantaneous local sky level and this is subtracted from all the data in that integration. Sky-noise removal thus attempts to best account for the absolute sky level as seen by the central pixel during each integration. No systematic effects were observed associated with the exact choice of sky bolometers i.e. whether the whole array was used or only the inner ring around the central bolometer.

During an observation the secondary is chopped between the source and sky at 7 Hz. This is done mainly to take out small relative DC drifts between the bolometers, and also to remove any large-scale sky variations. Thus sky subtraction also happens for observations using the single-bolometer photometric pixels, but it is not as accurate as for the arrays. The term “integration” time in this paper always refers to the “on+off” time, including the amount of time spent while chopped off-source. An 18 sec integration thus amounts to a 9 sec on-source observation time.

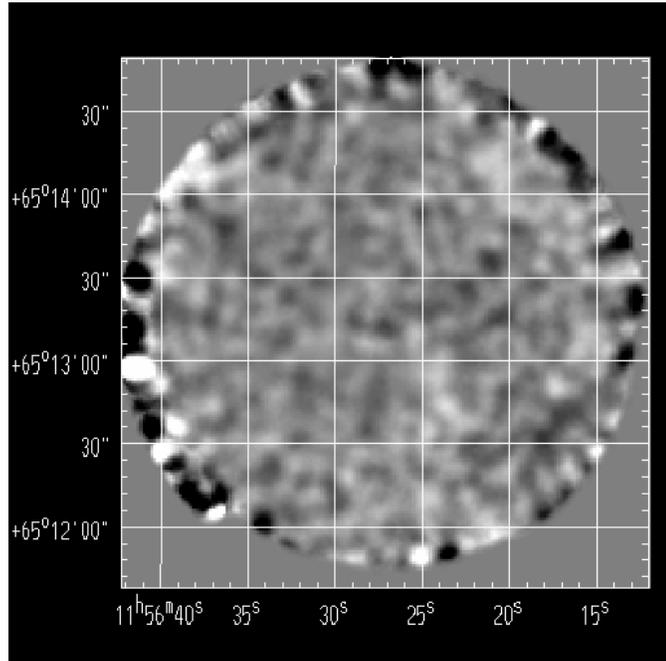
A typical measurement consisted of 50 integrations of 18 seconds. Each observation of a source in general consists of several such measurements with pointing and calibration observations in between. Calibration involves establishing both the opacity and the gain for each observation. The opacities at 850 and 450  $\mu\text{m}$  were measured from skydips while using the continuously monitored 1.3 mm opacity as a guideline for any trends between the skydips. For the absolute flux calibration the gain was measured using planets or standard SCUBA secondary calibrators. The dominant uncertainties in the flux calibrations are transient effects such as thermal relaxation of the dish during the night, the weather, and pointing errors resulting from an inaccurate track model. Based on observed variations of the gain factor and signal levels we estimate typical systematic uncertainties in the absolute flux calibrations of 10% at 850  $\mu\text{m}$  and 20% at 450  $\mu\text{m}$ . In general the rms errors of the observations presented here are larger than this uncertainty.

The reduction of map observations is similar to the photometry ones, except that care is taken that no low-level extended emission is subtracted by the sky-noise removal algorithm. As a final step the data is gridded onto a rectangular grid.

## 3. Results of SCUBA observations

### 3.1. GRB 970508

As a limited trial run, a 30 minute SCUBA observation of GRB 970508 was made on 1997 May 26 using the 1350  $\mu\text{m}$  photometry pixel. The weather conditions were very poor. No source was detected with an rms  $\sim 10$  mJy. This result is consistent with



**Fig. 1.** SCUBA 850  $\mu\text{m}$  jiggle map of the  $\sim 1'$  radius error box to 1SAX J1156.4+6513 on UT 1997 December 16.53. The beam size is  $14.7''$ . None of the fluctuations in this map are significant.

the other millimeter observations of GRB 970508 (Gruendl et al. 1998; Bremer et al. 1998; Shepherd et al. 1998).

### 3.2. GRB 971214

Our preliminary SCUBA results on GRB 971214 were originally reported in Smith et al. (1997).

The *BeppoSAX* GRB Monitor was triggered on 1997 December 14.97 UT (Heise et al. 1997). A previously unknown fading X-ray source (1SAX J1156.4+6513) was found inside the burst error circle (Antonelli et al. 1997). Consistent with this X-ray source an optical transient was found (e.g. Halpern et al. 1998; Kulkarni et al. 1998; Ramaprakash et al. 1998; Gorosabel et al. 1998; Diercks et al. 1998). A possible quiescent host to the transient was found with a redshift  $z = 3.418$  (Kulkarni et al. 1998; Odewahn et al. 1998). No radio counterpart has so far been seen (Ramaprakash et al. 1998).

We began our series of SCUBA observations on UT 1997 December 16.53, before the optical transient was reported, and when the error box of 1SAX J1156.4+6513 had a radius  $\sim 1'$  (L. Piro, private communication). We performed a 450:850 jiggle map of the whole error box. Fig. 1 shows the whole 850  $\mu\text{m}$  map, which illustrates a typical SCUBA jiggle map. At 850  $\mu\text{m}$ , the rms was 2.2 mJy in the central region of the map and the beam size was  $14.7''$ . The optical transient was near the edge of this map at RA(J2000) = 11:56:26.4, DEC(J2000) = +65:12:00.5, where the rms is approximately 3 mJy. No sources were detected by SCUBA anywhere in the map.

The remainder of our SCUBA observations were performed on the optical transient using the photometric mode with the

**Table 1.** SCUBA 850  $\mu\text{m}$  observations of the optical transient to GRB 971214.

Observing date (UT 1997)	Integration time (sec)	850 $\mu\text{m}$ opacity	850 $\mu\text{m}$ rms (mJy)
Dec 16.53	14080 <sup>a</sup>	0.13	3.0
Dec 17.68	3600	0.13	1.2
Dec 19.73	2700	0.19	1.5
Dec 22.65	3600	0.14	1.3

<sup>a</sup> This is the total integration time for the map, which corresponds to  $\sim 900$  sec in photometry mode, but suffers additional noise because the position of the source was at the edge of our map.

450:850 arrays. The results are given in Table 1. We did not detect a sub-millimeter continuum source at the location of the optical transient. Combining all our photometric observations gives an rms of 1.0 mJy at 850  $\mu\text{m}$ .

The decay of the optical flux followed a power law  $\propto t^{-\delta}$  with slope  $\delta \sim 1.2$ . In the simple adiabatic piston model, a fireball produced by a one time impulsive injection of energy in which only the forward blast wave efficiently accelerates particles predicts a power law spectrum  $S_\nu \propto \nu^{-\beta}$  with energy spectral index  $\beta = 2\delta/3$  (Wijers et al. 1997). For GRB 971214, this would imply  $\beta = 0.8$ . This is in general agreement with the optical to X-ray slope. Extrapolating this power law gives a flux density  $\lesssim 1$  mJy at 850  $\mu\text{m}$  on December 17. However, the optical spectrum alone has a much steeper spectrum, indicating that there is significant extinction local to the source (Halpern et al. 1998; Ramaprakash et al. 1998). The required correction is several magnitudes in the I-band, which similarly raises the prediction at 850  $\mu\text{m}$ . Our SCUBA limits then imply that there is a break between the optical and sub-millimeter bands, as was found in GRB 970508. Infrared observations of GRB 971214 suggest that this break was at  $\sim 1 \mu\text{m}$  in the first few hours after the burst (Ramaprakash et al. 1998; Gorosabel et al. 1998).

### 3.3. GRB 980326

The *BeppoSAX* GRB Monitor was triggered on 1998 March 26.888 UT (Celidonio et al. 1998). Although *BeppoSAX* was unable to make an observation with the Narrow Field Instruments and *RXTE* did not see any X-ray emission from the GRB error box (Marshall & Takeshima 1998), a candidate optical transient was found (Groot et al. 1998b). This transient was notable for its unusually rapid optical fade, with a power law decay index  $\delta = 2.10 \pm 0.13$  (Eichelberger et al. 1998; Groot et al. 1998b). Although initial observations suggested there was a constant underlying source with  $R_c = 25.5 \pm 0.5$  (Grossan et al. 1998; Djorgovski et al. 1998a; Groot et al. 1998b), this was not confirmed by observations long after the burst, with a limit of  $R \sim 27.3$  (Bloom & Kulkarni 1998). This burst was also interesting in that the gamma-ray spectrum during the burst was quite soft.

We used SCUBA to make a short photometry observation of the optical transient to GRB 980326 on 1998 March 29.36. The

**Table 2.** SCUBA 850  $\mu\text{m}$  observations of VLA J070238.0+385044, the counterpart to GRB 980329.

Observing date (UT 1998)	Integration time (sec)	850 $\mu\text{m}$ opacity	850 $\mu\text{m}$ flux density (mJy)
Apr 05.2	2700	0.135	$5.0 \pm 1.5$
Apr 06.2	3600	0.125	$4.0 \pm 1.2$
Apr 07.2	6300	0.14	$2.1 \pm 0.9$
Apr 08.2	4500	0.13	$2.0 \pm 1.0$
Apr 11.2	5400	0.10	$0.8 \pm 0.9$

source was not detected, with rms 2.7 mJy at 850  $\mu\text{m}$  and 30 mJy at 450  $\mu\text{m}$ . Since there was no report of a radio counterpart, and the much more interesting GRB 980329 occurred at this time, we did not try to make any further observations of GRB 980326.

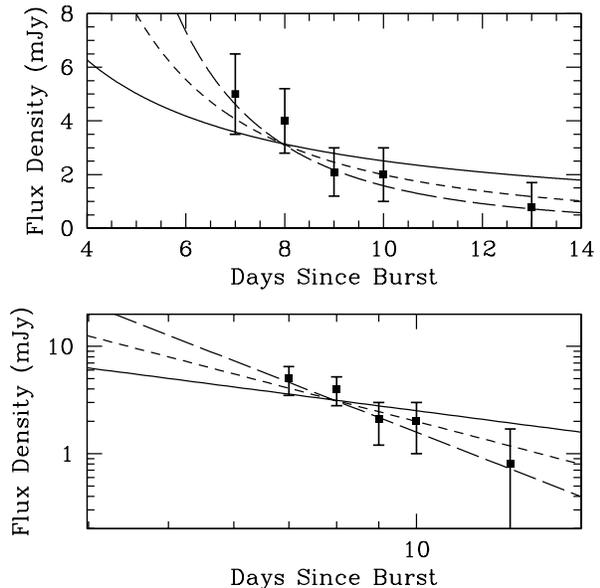
On 1998 March 29 the counterpart had  $R_c = 24.5$ , and the optical spectrum was poorly determined, with  $\beta = 0.66 \pm 0.70$  (Groot et al. 1998b). Extrapolating with  $\beta = 0.66$  would give a flux density of 0.06 mJy at 850  $\mu\text{m}$ , while using the  $1\sigma$  value of  $\beta = 1.36$  gives 8.8 mJy at 850  $\mu\text{m}$ . The difficulty in determining the extinction corrections adds to the uncertainty in the counterpart spectrum. Thus we are currently unable to make any statements about breaks in the optical to sub-millimeter spectrum for GRB 980326.

### 3.4. GRB 980329

Our preliminary SCUBA results on GRB 980329 were originally reported in Smith & Tilanus (1998).

The *BeppoSAX* GRB Monitor was triggered on 1998 March 29.156 UT (Frontera et al. 1998a). This was the brightest burst that had been seen simultaneously by the *BeppoSAX* Wide Field Camera, with a peak flux  $\sim 6$  Crab in the 2–26 keV band. A fading X-ray source 1SAX J0702.6+3850 was found using the *BeppoSAX* Narrow Field Instruments (in’t Zand et al. 1998). Inside this X-ray error box, a variable radio source VLA J070238.0+385044 was found that was similar to GRB 970508 (Taylor et al. 1998a, 1998b). It was not until after the variable radio source was discovered that infrared observations found a fading counterpart (Klose et al. 1998; Palazzi et al. 1998; Metzger 1998): this indicated that the optical extinction was significant for this source (Larkin et al. 1998; Taylor et al. 1998b), and/or the redshift was large (Fruchter 1999).

Starting on 1998 April 5, we made a series of photometry observations of VLA J070238.0+385044 using SCUBA. The results are summarized in Table 2. On April 5.2 UT, we detected the source at 850  $\mu\text{m}$  with a flux density of  $5 \pm 1.5$  mJy. This source was confirmed on April 6.2 with a flux density of  $4 \pm 1.2$  mJy, resulting in an average of  $4.5 \pm 1$  mJy over the two days. The source was not detected at 450  $\mu\text{m}$ , with an rms of 10.0 mJy averaged over these two days. The 850  $\mu\text{m}$  source was present in all our separate integrations, making us confident that it was real. A hint of a fading trend was confirmed by observations on April 7.2, when the 850  $\mu\text{m}$  flux density was  $2.1 \pm 0.9$  mJy. Observations on April 8.2 gave  $2.0 \pm 1.0$  mJy at 850  $\mu\text{m}$ , with no



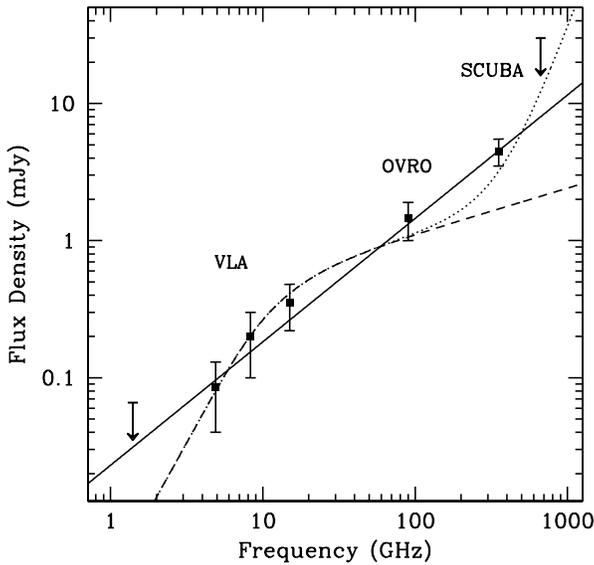
**Fig. 2.** Evolution of the 850  $\mu\text{m}$  flux seen by SCUBA for the counterpart VLA J070238.0+385044 to GRB 980329. The two plots show the same data plotted on linear-linear and log-log axes. The curves plot flux density  $\propto t^{-m}$  where  $t$  is the time since the burst and  $m = 1$  (solid),  $m = 2$  (short dashed), and  $m = 3$  (long dashed).

detection at 1350  $\mu\text{m}$  (the rms was 1.2 mJy). Finally, the signal was  $0.8 \pm 0.9$  mJy at 850  $\mu\text{m}$  on April 11.2.

Assuming the sub-millimeter fluxes are due to the burst counterpart, they should represent “clean” measures of its intensity, unaffected by scintillation and extinction. Although the optical emission was significantly reduced in this burst, the radio and sub-millimeter observations show that the brightness of this counterpart (before absorption) was similar to GRB 970508 (e.g. see Fig. 2 of Palazzi et al. 1998).

Fig. 2 plots the evolution of the 850  $\mu\text{m}$  SCUBA flux. For a power law decay with the flux density  $\propto t^{-m}$  where  $t$  is the time since the burst, the best fit power law index is  $m = 3.0$ . However,  $m$  is not tightly constrained: the 90% confidence interval is  $m = 1.2$  to  $m = 5.3$ .

Fig. 3 adds the SCUBA results to the VLA-OVRO results presented in Fig. 2 of Taylor et al. (1998b). Because of the averaging of the rapidly varying radio data over several days, some caution is required in using this figure. Taylor et al. found that a power law  $S_\nu \propto \nu^\alpha$  with  $\alpha = +0.9$  gave the best fit to the VLA-OVRO data alone. The solid curve shows that this extends very well to the SCUBA results. The dashed curve shows that the popular  $\nu^{1/3}$  power law (e.g. Katz 1994; Waxman 1997) attenuated by a synchrotron self-absorption component gives a much worse description of the shorter wavelength emission for GRB 980329. However, the reduced  $\chi^2_\nu = 2.6$  for this fit, and the probability that a random set of data points would give a value of  $\chi^2_\nu$  as large or larger than this is  $Q = 0.034$ . It is therefore not possible to exclude this model, and it will be important to study more bursts to determine whether there is a range of power law indices for  $\alpha$ .



**Fig. 3.** The radio through sub-millimeter spectrum of GRB 980329. The time-averaged VLA and OVRO points are taken from Fig. 2 of Taylor et al. (1998b). The  $3\sigma$  SCUBA upper limit at  $450 \mu\text{m}$  has been included. The solid curve is a power law  $S_\nu \propto \nu^\alpha$  with  $\alpha = +0.9$ . The dashed curve is a  $\nu^{1/3}$  power law attenuated by a synchrotron self-absorption with  $\nu_0 = 13 \text{ GHz}$  at  $\tau_0 = 1$ . The dotted curve adds a  $\nu^3$  power law to the synchrotron curve.

One way to slightly reduce the sub-millimeter flux of the counterpart in Fig. 3 would be if part of the flux comes from an underlying quiescent sub-millimeter source. An instrument more sensitive than SCUBA will be required to see if such a quiescent source is present for GRB 980329. SCUBA has recently discovered several dusty star-forming galaxies at high redshifts (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Smail et al. 1998). Both a high redshift and large dust extinction would help explain the reddening of the counterpart to GRB 980329, and a redshift of  $z \sim 5$  has been suggested (Fruchter 1999). Recent studies of the star formation history have concluded that the star formation rate does not drop rapidly beyond  $z \sim 1$  (e.g. Blain et al. 1999), and so seeing GRBs at large redshifts may not be surprising if they are related to active star forming regions. The large intensity of GRB 980329 might then indicate that beaming is important.

In dust models, one expects  $S_\nu \propto \nu^3$  or  $\nu^4$  (e.g. Dwek & Werner 1981). Thus any quiescent dust contribution is very much larger at sub-millimeter than at radio wavelengths. For illustrative purposes the dotted curve in Fig. 3 adds a quiescent  $S_\nu \propto \nu^3$  component to the synchrotron curve. In this example, the quiescent flux density at 8.3 GHz is only  $0.02 \mu\text{Jy}$ .

### 3.5. GRB 980519

The *BeppoSAX* GRB Monitor was triggered on 1998 May 19.514 UT (Muller et al. 1998). A fading X-ray counterpart 1SAX J2322.3+7716 was found, although the X-ray decay was not monotonic (Nicastrò et al. 1998). A fading optical counterpart was also found, whose power law decay was steep  $\delta \sim 2$

(e.g. Jaunsen et al. 1998, Djorgovski et al. 1998b). A very faint quiescent optical source was eventually detected (Sokolov et al. 1998, Bloom et al. 1998a). A variable radio source was found at the same location (Frail et al. 1998a).

This source was not in an ideal location for SCUBA observations, with the elevation never rising above  $35^\circ$ . Also, the weather conditions were very poor at this time, and the JCMT was locked into using a different instrument. This meant we were only able to make one photometry observation of GRB 980519 with SCUBA on UT 1998 May 27.71. The source was not detected, with flux density  $0.9 \pm 1.8 \text{ mJy}$  at  $850 \mu\text{m}$  and an rms of  $80 \text{ mJy}$  at  $450 \mu\text{m}$ .

The radio flux uncorrected for scintillation at the time of our SCUBA observation is not currently available. On May 22.3, the 8.3 GHz flux measured by the VLA was  $0.1 \text{ mJy}$ . Extrapolating from this using  $\alpha = +1/3$  predicts a flux density of  $0.35 \text{ mJy}$  at  $850 \mu\text{m}$ . On the other hand, extrapolating using  $\alpha = +1$  predicts a flux density of  $4.3 \text{ mJy}$  at  $850 \mu\text{m}$ . When the final radio results are available, it may be possible to determine whether this steeper slope is unacceptable for GRB 980519.

It is believed that the optical extinction is small for this burst (Gal et al. 1998). Assuming the optical flux continued to decay with a power law of index  $\delta = 1.98$ , and extrapolating the optical spectrum assuming a power law index of  $\beta = 1.26$  (Gal et al. 1998) would predict a flux of  $1.6 \text{ mJy}$  at  $850 \mu\text{m}$  at the time of our SCUBA observation. Unfortunately, our observation was made too late to determine if there was a break between the optical and millimeter bands in GRB 980519.

### 3.6. GRB 980703

BATSE trigger 6891 (Kippen et al. 1998) was also detected by the *RXTE* ASM on 1998 July 3.182 UT (Levine et al. 1998). *BeppoSAX* NFI observations of the *RXTE* ASM error box located a fading X-ray source 1SAX J2359.1+0835 (Galama et al. 1998c, 1998d). A variable radio, infrared, and optical counterpart was found, as well as an underlying galaxy with  $R = 22.6$  and a redshift of 0.966 (e.g. Bloom et al. 1998b; Djorgovski et al. 1998c; Castro-Tirado et al. 1999).

SCUBA performed a photometry observation of the radio counterpart on 1998 July 10.5 UT. The source was not detected, with an rms of  $2.6 \text{ mJy}$  at  $1350 \mu\text{m}$ . A second observation was performed on 1998 July 15.6 UT. Again the source was not detected with an rms of  $1.6 \text{ mJy}$  at  $850 \mu\text{m}$  and  $20 \text{ mJy}$  at  $450 \mu\text{m}$ . Another observation was tried on July 16, but the weather conditions were too poor to produce any useful results.

While the 4.86 GHz flux suffered from large variations, the 8.46 GHz flux was steadier, with a mean of  $0.94 \text{ mJy}$  (Frail et al. 1998b). Extrapolating from this using  $\alpha = +1$  predicts flux densities of 39 and  $25 \text{ mJy}$  at 850 and  $1350 \mu\text{m}$  respectively. Our SCUBA results can definitely rule out this simple power law for GRB 980703. Extrapolating from the radio using  $\alpha = +1/3$  predicts flux densities of 3.3 and  $2.8 \text{ mJy}$  at 850 and  $1350 \mu\text{m}$  respectively. While we would expect to have detected  $1-2\sigma$  signals in our SCUBA observations, the lack of detections are not inconsistent with this model for GRB 980703.

### 3.7. GRB 981220

The *RXTE* ASM, the *BeppoSAX* GRBM, *Ulysses*, and *KONUS* were all triggered on 1998 December 20.91 UT (Smith et al. 1998; Feroci et al. 1998; Hurley et al. 1998; Frontera et al. 1998b). No obviously variable optical sources were found in the burst error box (e.g. Vrba et al. 1999), but an unusual variable radio source J034228.94+170914.6 was found in this region (Galama et al. 1998e; Frail et al. 1998c; Frail et al. 1999a). A faint, slowly variable optical source was associated with J034228.94+170914.6 (Bloom et al. 1999). However, this radio source lies outside the refined IPN error box from triangulating between *Ulysses* and *BeppoSAX* (Hurley et al. 1999), and it is extended (Taylor et al. 1999), so it is presumably unrelated to GRB 981220.

SCUBA performed a photometry observation of the variable radio source J034228.94+170914.6 starting 1998 Dec 30.24 UT for 3.8 hours (Smith, Tilanus, & Baas 1999a). The observation was performed in mediocre weather, and no source was detected at this location: the 850  $\mu\text{m}$  flux density was  $0.1 \pm 1.6$  mJy.

### 3.8. GRB 981226

The *BeppoSAX* GRBM and WFC were triggered on 1998 December 26.41 UT (Di Ciolo et al. 1998). A previously unknown fading X-ray source 1SAX J2329.6–2356 was found (Frontera et al. 1998c). A couple of candidate optical sources were suggested, but no conclusive fading counterparts were found inside the X-ray error box. There was no radio emission associated with these optical counterparts (Frail et al. 1998d; Galama et al. 1998f), but there was a separate faint variable radio source in the NFI error box that likely was the counterpart (Frail et al. 1999b).

Given the poor location of the GRB in a direction towards the Sun, we only attempted one short photometry observation with SCUBA (Smith et al. 1999b). We observed the candidate optical source (23:29:35.0, –23:55:42, J2000) suggested by Castro-Tirado et al. (1998b). The observation, performed in mediocre weather, started 1998 Dec 30.15 UT and lasted 44 minutes. No source was detected at this location: the 850  $\mu\text{m}$  flux density was  $0.6 \pm 3.8$  mJy.

## 4. Discussion

The sub-millimeter is an important band for GRB studies because it is where the emission peaks in some bursts in the days to weeks following the burst. The sub-millimeter emission is not affected by extinction local to the source or interstellar scintillation. We have shown that sub-millimeter observations are important to:

- Determine the breaks in the radio to sub-millimeter to optical spectrum so that the spectral shape can be compared to the synchrotron models.
- Determine the evolution of the sub-millimeter flux.
- Look for underlying quiescent sources that may be dusty star-forming galaxies at high redshifts.

To obtain a detailed understanding of the GRB counterpart behaviors will require observations of many bursters. To this end our program of Target of Opportunity observations using SCUBA is ongoing.

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