ALMA SUBMILLIMETER CONTINUUM IMAGING OF THE HOST GALAXIES OF GRB 021004 AND GRB 080607

WEI-HAO WANG1, HSIAO-WEN CHEN2, AND KUI-YUN HUANG1

ABSTRACT

We report 345 GHz continuum observations of the host galaxies of gamma-ray bursts (GRBs) 021004 and 080607 at \( z > 2 \) using the Atacama Large Millimeter/Submillimeter Array (ALMA) in Cycle 0. Of the two bursts, GRB 021004 is one of the few GRBs that originates in a Lyman limit host, while GRB 080607 is classified as a “dark burst” and its host galaxy is a candidate of dusty star forming galaxy at \( z \sim 3 \). With an order of magnitude improvement in the sensitivities of the new imaging searches, we detect the host galaxy of GRB 080607 with a flux of \( S_{345} = 0.31 \pm 0.09 \) mJy and a corresponding infrared luminosity of \( L_{IR} = (2.4 - 4.5) \times 10^{11} L_\odot \). However, the host galaxy of GRB 021004 remains undetected and the ALMA observations allow us to place a 3-\( \sigma \) upper limit of \( L_{IR} < 3.1 \times 10^{11} L_\odot \) for the host galaxy. The continuum imaging observations show that the two galaxies are not ultraluminous infrared galaxies but are at the faintest end of the dusty galaxy population that gives rise to the submillimeter extragalactic background light. The derived star formation rates of the two GRB host galaxies are less than 100 \( M_\odot \) yr\(^{-1} \), which are broadly consistent with optical measurements. The result suggests that the large extinction (\( A_V \sim 3 \)) in the afterglow of GRB 080607 is confined along its particularly dusty sightline, and not representative of the global properties of the host galaxy.

Subject headings: galaxies: high-redshift — submillimeter: galaxies — Gamma-ray burst: individual (021004, 080607)

1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs) are believed to originate in the death of massive stars (see Woosley & Heger 2006 for a recent review), and are thus expected to trace star formation in galaxies (e.g., Wijers et al. 1998; Totani 1999). Because of the extreme luminosity of the prompt emission and the afterglow, GRBs are a powerful probe of star formation in early times (e.g., Tanvir et al. 2009; Salvaterra et al. 2009). In order to establish the link between GRBs and the cosmic star formation, it is important to understand the properties of the GRB host galaxies (Hjorth et al. 2012). A critical measurement is the star formation rates (SFRs) of the host galaxies.

There exist various SFR indicators for high-redshift galaxies in different spectral windows. One key concern is the effect of dust extinction. Even with arguably good extinction corrections in optical data, highly obscured components may still exist and would only appear at the far-infrared and radio wavelengths. The presence of such components would indicate a significant spatial variation in dust content in which case a global extinction correction would not apply. For GRB host galaxies, systematic surveys were carried out to observe continuum emission in the radio (Michałowski et al. 2012) and submillimeter (Berger et al. 2003; Tanvir et al. 2004; Priddey et al. 2006) frequency ranges for constraining dust enshrouded SFR. Because of the synchrotron spectral slope, radio observations are only effective in detecting GRB host galaxies at \( z \lesssim 1 \) (e.g., Michałowski et al. 2012). Dust continuum emission in the submillimeter has a spectral slope that can nearly cancel the effect of luminosity distance from \( z \sim 1 \) to \( z \sim 10 \), making the submillimeter wavebands an effective window for detecting faint galaxies at high redshifts (Blain & Longair 1993). However, the 850 \( \mu \)m survey of 21 GRB host galaxies at \( z < 3.5 \) by Tanvir et al. (2004) using the James Clerk Maxwell Telescope (JCMT) only uncovered three host galaxies at \( z > 3 \sigma \) confidence levels, and all three hosts are at \( z < 1.5 \). Submillimeter single-dish telescopes are confusion limited at roughly a few mJy at 850 \( \mu \)m, and therefore can only detect galaxies with infrared luminosities of \( L_{IR} > 8 \) to 1000 \( M_\odot \) \( \mu \)m, or SFR \( > 1000 M_\odot \) yr\(^{-1} \). This SFR limit is much larger than the typical SFR of GRB host galaxies measured in the optical (Christensen, Hjorth, & Gorosabel 2004; Savaglio, Glazebrook, & Le Borgne 2009). Deeper submillimeter measurements are thus required to better constrain their infrared luminosity and the underlying SFR.

A particularly interesting class of GRB is “dark GRBs” (Djorgovski et al. 2001; Jakobsson et al. 2005), defined by their faint optical afterglow, relative to the bright X-ray emission. A definition for dark bursts is those with the optical-to-X-ray spectral index of \( \beta_{OX} < 0.5 \) (Jakobsson et al. 2004), which is physically motivated based on theoretical predictions of the synchrotron model. Approximately 30%–50% of long-duration GRBs have suppressed optical fluxes relative to their X-ray emission (Melandri et al. 2009; Cenko et al. 2009; Melandri et al. 2012). The weaker optical emission can be caused by either intergalactic medium absorption at \( z > 6 \) (Kawai et al. 2006; Greiner et al. 2009; Tanvir et al. 2009; Salvaterra et al. 2009) or dust extinction in their host galaxies (Perley et al. 2009). In the latter case, dark GRBs may serve as a tracer of dust enshrouded star formation across cosmic time. However, uncertainty remains regarding whether the observed dust obscuration is representative of the global properties of the host galaxies or merely local to the progenitor site. This uncertainty can be addressed by comparing the rest-frame infrared luminosities between dark GRB host galaxies and the rest of the host galaxy population.

In this letter, we present initial results from a pilot study of GRB host galaxies in the submillimeter frequency range using the Atacama Large Millimeter/Submillimeter Array (ALMA). In Cycle 0, we observed the host galaxies of GRB 021004 (\( z = 2.330 \)) and GRB 080607 (\( z = 3.036 \)) at 345 GHz. The GRB fields were selected to have early-time afterglow spectra
available for constraining the ISM absorption properties of the host galaxies (e.g., Fynbo et al. 2005; Prochaska et al. 2009; Sheffer et al. 2009). They are among the best studied events and they represent two extremes in the integrated total ISM column density alone the afterglow line of sight. GRB 021004 is one of a few GRBs arising in a Lyman limit absorber with $N_{\text{HI}} = 10^{19.5\pm0.3}$ cm$^{-2}$, and the host of GRB 080607 is a damped Ly$\alpha$ absorber with an unprecedentedly high gas density of $N_{\text{HI}} = 10^{22.7\pm0.15}$ cm$^{-2}$. GRB 080607 is a dark burst with highly extinguished afterglow ($A_V \sim 3.2$, Prochaska et al. 2009; Perley et al. 2011), and the extinction suggests that the host galaxy may have detectable submillimeter dust emission. The host galaxies of the two GRBs are found to have optical SFRs of $10^{-4} - 10^{-3} M_{\odot}$ yr$^{-1}$ (Jakobsson et al. 2005; Castro-Tirado et al. 2010; Chen, Perley, & Wilson et al. 2011), consistent with normal star forming galaxies at $z > 2$. Here we use the ALMA results to estimate the infrared luminosities of the two host galaxies, and to examine whether there exist highly obscured star-forming regions that are not revealed by optical observations. We describe our ALMA observations and data reduction in Section 2, and the results and estimate the infrared luminosities and the SFRs of the host galaxies in Section 3. The implication of our observations is discussed in Section 4. We adopt cosmological parameters of $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$, and we convert the previous results to this set of cosmology.

2. OBSERVATION AND DATA REDUCTION

Observations of the continuum emission at 345 GHz from the host galaxies of GRB 021004 and GRB 080607 were obtained using the ALMA 12-m array. Four spectral windows were tuned to center at 338, 340, 350, and 352 GHz, each with a 2 GHz bandwidth. Bandpass calibrators and flux calibrators were observed prior to the observations of the science targets. Bright quasars near the GRB fields were observed every $\sim 11$ minutes for phase and amplitude calibrations. For each science target, a total of 0.7–0.8 hr of on-target integration was collected. Table 1 summarizes the basic observing parameters and the various calibrators.

We received the data from the Joint ALMA Observatory (JAO) a few weeks after the observations. The delivered data were already bandpass, flux, and gain (phase and amplitude) calibrated by JAO, and reference images were also provided. All the above calibration and imaging were carried out using Common Astronomy Software Applications (CASA, McMullin et al. 2007). We further inspected the JAO calibration in CASA, and Fourier-transformed the complex visibility to make our own images. To obtain the highest S/N, we gave all visibility data equal weights regardless of their density distribution in the $uv$ plane (i.e., “natural weighting”). The resulting synthesized beams and sensitivities are summarized in Table 1. We do not detect the host galaxy of GRB 021004, and thus the imaging remains in the “dirty” stage. We detect the host galaxy of GRB 080607, and therefore “CLEANed” the sidelobes of the detected object in CASA.

3. RESULTS

3.1. GRB 021004

We do not detect the host galaxy of GRB 021004 (Figure 1). The 345 GHz point-source flux measured at the location of the host galaxy is $0.17 \pm 0.11$ mJy. Tanvir et al. (2004) measured an 850 µm flux of $0.77 \pm 1.25$ mJy using SCUBA on JCMT. Smith et al. (2005) improved the previous SCUBA result slightly to $-1.4 \pm 1.0$ mJy. Our measurement is $10 \times$ deeper than these previous observations but the host galaxy remains undetected.

Given the redshift of $z = 2.330$ and adopting the 3-$\sigma$ upper limit of 0.33 mJy, we can estimate the upper limits of its rest-frame infrared luminosity and SFR. To do so with single-band photometry, we need to assume a dust temperature, and this can be done using the infrared spectral energy distribution (SED) library of Chary & Elbaz (2001, hereafter CE01). The SEDs in CE01 are luminosity dependent (based on a locally calibrated luminosity—dust temperature relation) and do not allow for scaling of the SEDs. The library contains a broad range of infrared luminosity, from $2 \times 10^8$ to $4 \times 10^{13} L_{\odot}$, and each template has its unique dust temperature. We thus redshift the CE01 SEDs to $z = 2.330$ and look for those with observed 345 GHz fluxes below our upper limit. Of the 105 templates provided by CE01, 65 have 345 GHz fluxes lower than 0.33 mJy (Figure 2), with corresponding infrared luminosities between $2.6 \times 10^8$ and $3.1 \times 10^{11} L_{\odot}$.

![Image](image-url)
An ultraluminous infrared galaxy (ULIRG, $L_{IR} > 10^{12} L_\odot$) is clearly ruled out for the host of GRB 021004, which can be at most a modest infrared luminous galaxy of $L_{IR} \sim 3 \times 10^{11} L_\odot$. Combining available optical photometric measurements (open squares in Figure 2) with the ALMA upper limit further reveals a blue SED that is inconsistent with any of the CE01 templates, suggesting that the host of GRB 021004 contains primarily young stars with little dust (e.g., Chen et al. 2009) and that the infrared luminosity may be substantially lower than the observed limit. If we adopt the SFR conversion of star-forming galaxies, SFR ($M_\odot$ yr$^{-1}$) $= 1.7 \times 10^{-10} L_{IR}/L_\odot$ (Kennicutt 1998), then the 3-$\sigma$ upper limit of the SFR of the host galaxy is 53 $M_\odot$ yr$^{-1}$. These results are summarized in Table 2.

Castro-Tirado et al. (2010) obtained an optical spectrum of the early-time afterglow of GRB 021004. The authors estimated an unobscured SFR of $\sim 40 M_\odot$ yr$^{-1}$ based on the observed H$\alpha$ flux. Jakobsson et al. (2005) obtained a Ly$\alpha$ spectrum of the host galaxy and estimated an SFR of $\sim 11 M_\odot$ yr$^{-1}$, but this is uncertain because of the complex radiative transfer of Ly$\alpha$. Both results are within our 3-$\sigma$ upper limit. The ALMA imaging observation confirms the low SFR of the host galaxy, and also shows that more sensitive, multiwavelength ALMA submillimeter imaging is needed to constrain the infrared luminosity and dust SED of this object.

3.2. GRB 080607

A significant 345 GHz flux is detected at the location of GRB 080607. Figure 1 shows our ALMA image of the field around GRB 080607, and its 345 GHz flux contours overlaid on an HST WFC3 F160W image. The rms noise is measured to be 0.094 mJy beam$^{-1}$ within the primary beam. There exists a peak of 345 GHz emission at the location of the host galaxy, with a peak flux of 0.27 mJy beam$^{-1}$. We measure a flux of 0.31 mJy by fitting the emission with a point-source model. On the other hand, the contours in Figure 1 suggest that the emission is elongated, and the elongation is similar to that observed in the HST image. We therefore also fit the emission with an extended 2-D Gaussian, and obtain a slightly higher integrated flux of 0.32 mJy. However, the fitted Gaussian is still consistent with a point source, which is not surprising given the low S/N. In the subsequent analyses, we adopt the more conservative measurement of 0.31 mJy with a statistical significance of 3.3 $\sigma$. Approximately 3″5 south of the GRB host galaxy, a marginal ($\sim 3\sigma$) submillimeter emission is also detected at an optically bright Mg II absorber at $z = 1.3399$ (H.-W. Chen et al. 2012, in preparation). We do not give further consideration to this object in this paper, but we note that this Mg II absorber could also be a faint submillimeter source.

The key question here is whether we can consider the $\sim 3.3\sigma$ emission as a detection of the GRB host galaxy. First, the fitted 345 GHz peak in both the point-source and the Gaussian cases has an offset of 0″08 from the centroid of the optical emission. This offset is negligible given the S/N and the synthesized beam size of 1″56 × 0″38. Thus the confidence of the detection is enhanced by its coincident position with the GRB host galaxy.

Second, we consider the probability for this peak to be spurious. Figure 3 shows the histogram of pixel brightness in the primary beam. The distribution can be well fitted with a Gaussian with $\sigma = 0.096$ mJy beam$^{-1}$ (solid curve), consistent with our measured noise of 0.094 mJy beam$^{-1}$ (dotted curve). Following the Gaussian distribution function, the probability of finding a $> 3.3\sigma$ noise spike is $5 \times 10^{-4}$. However, there are hints of a non-Gaussian noise. The histogram in Figure 3 suggests an excess of positive pixels (at $> 0.2$ mJy). In the image (Figure 1), additional to the GRB host galaxy, there is a
second $>3.3\sigma$ spike to the north-east of the GRB host, which has no known optical counterpart. Within the ALMA primary beam (FWHM = 17\,′′4), there are approximately 220 independent resolution elements. This additional $>3.3\sigma$ spike suggests a probability of $1/220 = 5 \times 10^{-3}$, which is $10 \times$ higher than the Gaussian probability. This is an upper limit, since we cannot rule out this spike as a real submillimeter source. Thus the probability of finding a $>3.3\sigma$ spike at the location of our target is between $5 \times 10^{-4}$ (assuming a Gaussian noise) and $5 \times 10^{-3}$ (assuming that the second $3\sigma$ spike is due to noise). Both these values are sufficiently small. Therefore, the fact that the observed emission coincides with the position of the GRB host substantially increases the confidence level of the detection of the host. In this paper, we consider this a detection, but we also point out that it will be worthwhile to confirm this with ALMA in future larger GRB host galaxy surveys.

With the above measured flux and the redshift of $z = 3.036$, we then estimate the infrared luminosity of the host galaxy of GRB 080607, using the CE01 library. We redshift the CE01 templates to $z = 3.036$ and find seven of the 105 templates fall in the observed range of $0.313 \pm 0.094\,\text{mJy}$ (Figure 2), with $L_{\text{IR}} = 2.4 \times 10^{11}$ to $4.5 \times 10^{11} \, L_{\odot}$. Including available optical and near-infrared photometric measurements, the bottom panel of Figure 2 further shows that the SED is well represented by known dusty templates of local galaxies across the full spectral range. The agreement strongly supports the conclusion that the host galaxy of GRB 080607 is similar to a luminous infrared galaxy (LIRG, $L > 10^{11} \, L_{\odot}$) in the local universe. The inferred SFR is between 41 and $77 \, M_{\odot} \, \text{yr}^{-1}$. The above results are summarized in Table 2.

Chen, Perley, & Wilson et al. (2011) presented SED fitting for the host of GRB 080607 at $\lambda_{\text{host}} \sim 0.4$–$4\,\mu\text{m}$. Adopting a Milky-Way-type dust extinction law, they found $A_V = 1.24$ and an extinction corrected SFR of $\sim 16$–$24 \, M_{\odot} \, \text{yr}^{-1}$, roughly $3 \times$ lower than the submillimeter SFR. Given known uncertainties in both the optical extinction correction and the infrared SED of galaxies and possible variation in the distribution of dust content, the factor of three difference between the optical and submillimeter SFRs only suggests a modest amount of dust enshrouded star formation.

### Table 2: Properties of the GRB Host Galaxies

| Target       | Redshift | $S_{345}$ (mJy) | $L_{\text{IR}} (10^{11} \, L_{\odot})$ | SFR ($M_{\odot} \, \text{yr}^{-1}$) |
|--------------|----------|-----------------|-------------------------------------|-----------------------------------|
| GRB 021004*  | 2.330    | $< 0.33$        | $< 3.1$                             | $< 53$                            |
| GRB 080607   | 3.036    | 0.31 $\pm$ 0.09 | 2.4–4.5                             | 41–77                             |

*The upper limits for GRB 021004 are all $3\sigma$.

4. DISCUSSION

With the pilot ALMA imaging program of two GRB host galaxies at $z > 2$, we attempt to constrain the far-infrared properties of GRB host galaxies. In our sample, GRB 021004 has a very bright afterglow, but the host galaxy does not appear to show unusual dust content. On the other hand, GRB 080607 is a dark GRB with large extinction along the line of sight. Their host galaxies have measured 345 GHz fluxes of $0.17 \pm 0.11$ and $0.31 \pm 0.09\,\text{mJy}$, respectively. Statistically, we cannot rule out the possibility that the two host galaxies have comparable submillimeter fluxes. Despite that we had already pushed the sensitivities to roughly an order of magnitude deeper than previous measurements, deeper ALMA observations (and a larger sample) are clearly needed to tell the difference between the host galaxies of typical and dark GRBs.

On the other hand, the ALMA sensitivity limit is deep enough to probe beyond the ULIRG regime. Chen et al. (2010) suggest that the high-redshift infrared luminous galaxy population contributes to the GRB host galaxy population. The ALMA sensitivity thus allows us to examine whether the two host galaxies are similar to typical dusty galaxies selected by submillimeter telescopes (submillimeter galaxies, hereafter SMGs). First, it is established that bright 345 GHz selected SMGs primarily reside in the redshift range of $z = 1.5$–3.5 (Barger, Cowie, & Richards 2000; Chapman et al. 2003, 2005; Wardlow et al. 2011). The host galaxies of GRB 021004 and GRB 080607 have redshifts in the range of these bright SMGs. The integrated source counts indicate that bright SMGs of $S_{345} > 2\,\text{mJy}$ contribute to $\sim 30\%$ of the extragalactic background light in this wavelength range (e.g., Coppin et al. 2006). Faint-end counts derived from lensing cluster surveys indicate that approximately $50\%$ of the background arises from fainter sources in the flux range of $S_{345} = 0.5$–2\,mJy (Cowie, Barger, & Kneib 2002; Knudsen, van der Werf, & Kneib 2008; Chen, Cowie, & Wang et al. 2011). Our ALMA detection and tight upper limit on the host galaxies of GRB 021004 and GRB 080607 thus put them at the still fainter end of the 345 GHz population.

We further compare the two GRB host galaxies with normal star forming galaxies at high redshift. There exists a correlation between SFR and stellar mass of star forming galaxies at high redshift (e.g., Daddi et al. 2007; Pannella et al. 2009; Karim et al. 2011; Rodighiero et al. 2011). This correlation is often referred to as the star formation “main sequence” of galaxies. Galaxies at the main sequence are suggested to be disks that undergo quasi-steady star formation, and outliers are suggested to be starbursts with star formation boosted by gas-rich mergers (Daddi et al. 2010; Genzel et al. 2010). For $z \sim 2$, Daddi et al. (2007) found SFR $= 200 \, M_{\odot} \, \text{yr}^{-1}$ for main-sequence galaxies, where $M_{11}$ is stellar mass in units of $10^{11} M_{\odot}$. The host galaxy of GRB 021004 has estimated stellar masses of $1.6 \times 10^{10} M_{\odot}$ (Savaglio, Glazebrook, & Le Borgne 2009) and $2.6 \times 10^{10} M_{\odot}$ (Chen et al. 2009). With our ALMA SFR upper limit ($3\sigma$) of $53 \, M_{\odot} \, \text{yr}^{-1}$, its SFR/$M_{11}^{0.9}$ has values of $< 280$ or $< 1400$, depending on the adopted stellar mass. The former is consistent with main-sequence galaxies, while the latter is close to a starburst. However, both values are $3\sigma$ upper limits. The host galaxy of GRB 080607 has a better constrained stellar mass of $1 \times 10^{10} M_{\odot}$ (Chen, Perley, & Wilson et al. 2011). If we adopt our ALMA SFR of 41–77\,M_{\odot} \, \text{yr}^{-1}, then it has SFR/$M_{11}^{0.9} = 100–600$. This exercise shows that both GRB host galaxies are consistent with being main-sequence star-forming galaxies.

Finally, the afterglow spectrum of GRB 080607 shows a fairly large dust extinction of $A_V = 3.2$, and unprecedentedly high gas densities of $N_{\text{HII}} = 10^{22.70 \pm 0.15} \, \text{cm}^{-2}$ and $N_{\text{CO}} = 10^{16.53 \pm 0.3} \, \text{cm}^{-2}$, with a warm CO excitation temperature of $T_{\text{ex}}^{\text{CO}} > 100\,\text{K}$ (Prochaska et al. 2009). However, Prochaska et al. also suggest that the intervening molecular cloud is not the birth place of the GRB. The extinction in the afterglow is significantly larger than that for the host galaxy ($A_V = 1.2$, Chen, Perley, & Wilson et al. 2011). All the above, together with our ALMA result of a relatively normal SFR, indicates that GRB 080607 is not in a rare dusty galaxy, but the sightline happens to pass through a molecular cloud in its host galaxy.
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