CO OBSERVATIONS OF THE HOST GALAXY OF GRB 000418 AT $Z = 1.1$

B. Hatsukade,[1] K. Kohno,[2,3] A. Endo,[4] K. Nakanishi,[5] and K. Ohta[1]
Accepted for publication in the Astrophysical Journal

ABSTRACT

We performed CO ($J = 2$–1) observations of the host galaxy of GRB 000418 at $z = 1.1181$ with the Plateau de Bure Interferometer. Previous studies show that the host galaxy has properties similar to those of an ultraluminous infrared galaxy (ULIRG). The star-formation rate (SFR) of the host galaxy as derived from submillimeter and radio continuum emission is a few 100 $M_\odot$ yr^{-1}, which is an order of magnitude greater than the SFR derived from optical line emission. The large discrepancy between the SFRs derived from different observing wavelengths indicates the presence of a bulk of dust-obscured star formation and molecular gas that is enough to sustain the intense star formation. We failed to detect CO emission and derived 2σ upper limits on the velocity integrated CO (2–1) luminosity of $L'_{\rm CO} < 6.9 \times 10^9$ K km s^{-1} pc^2 and the molecular gas mass of $M_{\rm H_2} < 5.5 \times 10^9$ $M_\odot$ by adopting a velocity width of 300 km s^{-1} and a CO-to-H$_2$ conversion factor of $\alpha_{\rm CO} = 0.8$ $M_\odot$ (K km s^{-1} pc^2)$^{-1}$, which are standard values for ULIRGs. The lower limit on the ratio of far-infrared luminosity to CO luminosity, a measure of the star-formation efficiency, is higher compared to that of other gamma-ray burst hosts and other galaxy populations, which is consistent with active star formation taking place in this galaxy.

Subject headings: cosmology: observations — galaxies: high-redshift — galaxies: ISM — gamma rays: bursts — gamma rays: individual (GRB 000418) — radio lines: galaxies

1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs)—the most energetic events in the universe—are considered to be effective indicators for star-formation activity in the distant universe (e.g., Totani 1997; Wijers et al. 1998) because (1) GRBs are considered to occur because of the deaths of massive stars, and therefore, they are closely associated with star formation in host galaxies (e.g., Stanek et al. 2003; Hjorth et al. 2003), and (2) GRBs can be detected at cosmological distances (the current record is $z = 8.2$ for GRB 090423; Tanvir et al. 2009; Salvaterra et al. 2009). The majority of GRB hosts are blue, subluminous, low-metal, dwarf star-forming galaxies (e.g., Fynbo et al. 2003; Le Floc'h et al. 2003; Fruchter et al. 2006) and their star-formation rates (SFRs) as derived from UV/optical/near-infrared (NIR) observations are typically ∼0.1–10 $M_\odot$ yr^{-1} (e.g., Savaglio et al. 2009; Levesque et al. 2010; Svensson et al. 2010). However, if the production rate of GRBs traces the star formation in their hosts, a large fraction of GRBs should occur in star-forming regions obscured by dust. There are reports that some GRB hosts have a large amount of dust and obscured star formation: (1) There is a discrepancy between the SFRs derived from different observing wavelengths. SFRs derived from mid-infrared, submillimeter (submm), and radio wave-

lengths are much larger (by an order of magnitude in some cases) than SFRs derived from UV, optical, NIR wavelengths (e.g., Berger et al. 2003; Le Floc'h et al. 2006). (2) Large hydrogen column densities ($N_{\rm H} \gtrsim 10^{22}$ cm^{-2}) are observed along the line of sight to GRBs (e.g., Jakobsson et al. 2006; Schady et al. 2007; Zheng et al. 2009). (3) About 25–40% of GRBs are "dark GRBs" (e.g., Fynbo et al. 2001; Djorgovski et al. 2001; Fynbo et al. 2009; Greiner et al. 2011). The nature of dark GRBs, which are characterized by the faintness of their optical afterglow compared to their X-ray afterglow (Jakobsson et al. 2004; van der Horst et al. 2009), is not yet well understood and one possible explanation is due to the large dust extinction along the line of sight to GRBs (e.g., Perley et al. 2009). So far, only a small fraction of GRB hosts have been studied for which high obscured star formation is indicated (e.g., Tanvir et al. 2004; Priddey et al. 2006). Whether GRB hosts have obscured star formation is still uncertain because it is difficult to identify them when their optical afterglows are extincted by dust.

An alternative approach for understanding star-formation activity in GRB hosts is to measure the amount of molecular gas, which is the ingredient for star formation. The CO emission line observations provide the information of molecular gas mass, dynamical mass, and star-formation efficiency in GRB hosts without being affected by dust extinction. Thus far, only a few efforts have been made to search for molecular gas in GRB hosts (Table 1): CO (1–0) observations of the GRB 030329 host (Kohno et al. 2005; Endo et al. 2007), CO (3–2) observations of the GRB 980425 host (Hatsukade et al. 2007), and CO (3–2) observations of the GRB 090423 host (Stanway et al. 2011). No CO emission has been detected from GRB hosts and whether GRB hosts have sufficient molecular gas to maintain their star formation

[1] Department of Astronomy, Kyoto University, Kyoto 606-8502
[2] Institute of Astronomy, the University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015
[3] Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
[4] Kavli Institute of NanoScience, Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
[5] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588

remains unknown.

In this paper, we report a search for CO line emission toward the host galaxy of GRB 000418 using the Plateau de Bure Interferometer (PdBI; Guilloteau et al. 1992). § 2 describes the host galaxy of GRB 000418. § 3 outlines the observations and data reduction, and the results are presented in § 4. In § 5, we derive constraints on physical quantities of the host galaxy and discuss the nature of the galaxy. A summary is presented in § 6.

Throughout the paper, we adopt a cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. HOST GALAXY OF GRB 000418

UV/optical/NIR observations show that the host galaxy is a blue, compact, subluminous galaxy ($M_B = -20.6$; Gorosabel et al. 2003) at $z = 1.1181 \pm 0.0001$ (Bloom et al. 2003). The extinction-corrected SFR derived from the [O II] line luminosity is 15.4 $M_\odot$ yr^{-1} (Bloom et al. 2003; Gorosabel et al. 2003). SED fits to the UV/optical/NIR data show that the host is a young star-forming galaxy with an SFR of ∼10–20 $M_\odot$ yr^{-1} (Gorosabel et al. 2003; Christensen et al. 2004; Savaglio et al. 2009; Svensson et al. 2010). Submm and radio observations with the Submillimetre Common-User Bolometer Array (SCUBA) and the Very Large Array (VLA) detected a source at the position of the host galaxy with fluxes of $S(850\mu m) = 3.2 \pm 0.9$ mJy, $S(1.43\text{GHz}) = 69 \pm 15$ μJy, $S(4.86\text{GHz}) = 46 \pm 13$ μJy, and $S(8.46\text{GHz}) = 51 \pm 12$ μJy (Berger et al. 2003). The SFRs derived from the submm and radio emissions are SFR(submm) = 690 ± 195 $M_\odot$ yr^{-1} and SFR(radio) = 330 ± 75 $M_\odot$ yr^{-1} (Berger et al. 2003). The SED fit of Michałowski et al. (2008) ranging from UV to radio wavelengths shows that the host galaxy is a young star-forming galaxy with $L_{IR} = 4.6 \times 10^{12}$ $L_\odot$ and SFR = 288 $M_\odot$ yr^{-1}. The IR luminosity classifies the host galaxy as an ultraluminous infrared galaxy (ULIRG). The large discrepancy between the SFR based on UV/optical/NIR observations and the SFR based on submm/radio observations indicates that the bulk of the star formation is obscured by dust.

3. OBSERVATIONS AND DATA REDUCTION

The PdBI observations were conducted on August 6 and 7, 2006 using the D configuration with five antennas and on March 13, 2007 using the B configuration with six antennas. The phase center was positioned at α(J2000) = $12^h 25^m 19.3^s$ and δ(J2000) = +20° 06′ 11″.0. The redshifted CO (2–1) and CO (4–3) lines were simultaneously observed at 3-mm and 1.3-mm bands, respectively. Receiver 1 was tuned to 108.842 GHz (3-mm band) for the upper sideband and the receiver 2 was tuned to 217.667 GHz (1.3-mm band) for the lower sideband. The correlator was equipped with 580-MHz bandwidth in each sideband in the 2006 observations and 1-GHz bandwidth in each sideband in the 2007 observations. The system temperature of receiver 1 was $T_{\rm sys} \sim 200$–300 K in 2006 and $T_{\rm sys} \sim 100$–200 K in 2007 (SSB). Because the atmospheric conditions in the 1.3-mm band for the CO (4–3) line were unfavorable ($T_{\rm sys} \gtrsim 1000$ K), we use only 3-mm data for the CO (2–1) line in what follows.

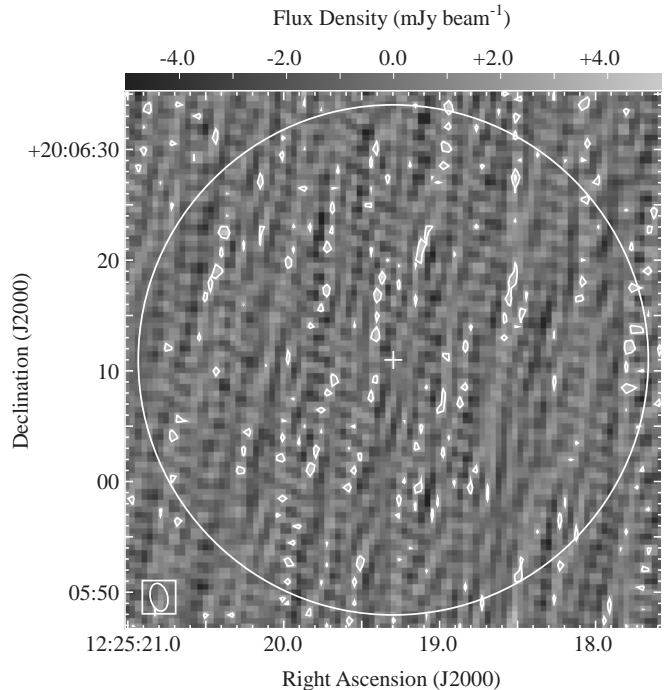Data reduction and imaging were carried out using the CLIC program in the GILDAS package

Flux Density (mJy beam^{-1})

Fig. 1.— Map around the position of GRB 000418 (cross) at 108.83 GHz with a velocity resolution of 100 km s^{-1} (36.3 MHz). Contours are $+2\sigma$ ($1\sigma = 1.3$ mJy beam^{-1}). The large circle represents the field of view (46″ diameter). The synthesized beam is shown on the bottom left.

(Guilloteau & Lucas 2000). Passband calibrations were performed using bright QSOs observed during the track. Flux calibrations were performed using standard calibrators. Maximum sensitivity was achieved by adopting natural weighting, which gave a final synthesized beam size of 2″.54 × 1″.56 (position angle = 13°).

4. RESULTS

Neither CO line emission nor continuum emission is detected (Fig. 1). The rms noise level is 1.3 mJy beam^{-1} with 100 km s^{-1} resolution. Summing the signals within the bandwidth, we obtained an rms noise level of 0.15 mJy beam^{-1} for the 3-mm continuum (rest frame 1.3 mm). The 2σ upper limits on the CO flux and continuum flux at the position of the host are 2.4 mJy beam^{-1} (100 km s^{-1} resolution) and 0.62 mJy beam^{-1}, respectively. This upper limit on continuum flux is consistent with the SED model of Michałowski et al. (2008).

The CO line luminosity ($L'_{\rm CO}$) is given as follows (Solomon et al. 1992):

$$L'_{\rm CO} = 3.25 \times 10^7 S_{\rm CO} \Delta v \nu_{\rm obs}^{-2} D_L^2 (1+z)^{-3}, \qquad (1)$$

where $L'_{\rm CO}$ is measured in K km s^{-1} pc^2, $S_{\rm CO}$ is the observed CO flux in Jy, Δv is the velocity width in km s^{-1}, and D_L is the luminosity distance in Mpc. Assuming a velocity width of 300 km s^{-1}, which is the typical value for local ULIRGs (Solomon et al. 1997), the 2σ upper limit of CO (2–1) line luminosity is $L'_{\rm CO}(2$–$1)$ $< 6.9 \times 10^9$ K km s^{-1} pc^2.

5. DISCUSSION

5.1. *Constraints on Physical Quantities*

GRB	z	Transition	L'_{CO} (K km s^{-1} pc^2)	$M_{\mathrm{H_2}}$ ($M_\odot$)	Reference
GRB 980425	0.0085	CO (3–2)	$< 2.3 \times 10^7$	$< 1.8 \times 10^8$ [a]	Hatsukade et al. (2007)
GRB 000418	1.1181	CO (2–1)	$< 6.9 \times 10^9$	$< 5.5 \times 10^9$	*This work*
GRB 030329	0.1685	CO (1–0)	$< 4.6 \times 10^8$	$< 1.9 \times 10^{10}$ [b]	Kohno et al. (2005); Endo et al. (2007)
GRB 090423	8.23	CO (3–2)	$< 3.6 \times 10^9$	$< 2.9 \times 10^9$ [c]	Stanway et al. (2011)

NOTE. — Upper limits are 2σ.
[a] $\alpha_{\mathrm{CO}} = 8.0\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$ is adopted. [b] $\alpha_{\mathrm{CO}} = 40\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$ is adopted. [c] $\alpha_{\mathrm{CO}} = 0.8\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$ is adopted.

5.1.1. *Molecular Gas Mass*

Molecular gas mass is given by

$$M_{\mathrm{H_2}} = \alpha_{\mathrm{CO}} L'_{\mathrm{CO}}, \qquad (2)$$

where α_{CO} is the CO-to-H$_2$ conversion factor in $M_\odot$ (K km s^{-1} pc^2)$^{-1}$. We assume that the gas is optically thick and thermalized and has a CO (2–1)/CO (1–0) luminosity ratio of unity. The 2σ upper limit on molecular gas mass is $M_{\mathrm{H_2}} < 5.5 \times 10^9\ M_\odot$, and it is obtained by adopting a conversion factor of $\alpha_{\mathrm{CO}} = 0.8\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$, which is the standard value for ULIRGs (Downes & Solomon 1998). This is lower than the median value of $(3.0 \pm 1.6) \times 10^{10}\ M_\odot$ obtained for a sample of submillimeter galaxies (SMGs; Greve et al. 2005). Note that if we adopt a Galactic conversion factor of $\alpha_{\mathrm{CO}} = 4.6\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$ (Solomon & Barrett 1991), the 2σ upper limit would increase by about a factor of 6.

5.1.2. *Dust Mass*

The dust mass can be derived from submm flux,

$$M_d = \frac{S_{\mathrm{obs}} D_L^2}{(1+z)\kappa_d(\nu_{\mathrm{rest}}) B(\nu_{\mathrm{rest}}, T_d)}, \qquad (3)$$

where S_{obs} is the observed flux density, ν_{rest} is the rest frequency, $\kappa_d(\nu_{\mathrm{rest}})$ is the rest-frequency dust mass absorption coefficient, T_d is the dust temperature, and $B(\nu_{\mathrm{rest}}, T_d)$ is the Planck blackbody function (Hughes et al. 1997). It is believed that the absorption coefficient varies with frequency as $\kappa_d \propto \nu^\beta$, where β lies between 1 and 2 (e.g, Hildebrand 1983). We assume $\kappa_d(125\mu m) = 1.875$ m^2 kg^{-1} (Hildebrand 1983). T_d and β depend on the properties of the dust, and hence, on the type of galaxy being considered. Because the submm flux is detected only at 850 μm (Berger et al. 2003), T_d and β cannot be uniquely determined. We adopt $T_d = 30$–50 K and $\beta = 1.5$, the typical values for local ULIRGs and SMGs (e.g., Yang et al. 2007; Kovács et al. 2006; Coppin et al. 2008; Michałowski et al. 2010). The dust mass is calculated to be $M_d = (4\text{–}10) \times 10^8\ M_\odot$. This is consistent with $M_d = 8.2 \times 10^8\ M_\odot$ derived from SED model fit of Michałowski et al. (2008), where they assume $T_d = 50$ K.

From the 2σ upper limit of molecular gas mass derived in § 5.1.1, the 2σ upper limit of molecular gas-to-dust mass ratio is estimated to be $\sim$10–20. This is lower than that of other galaxy samples, such as 100–200 of our Galaxy (e.g., Hildebrand 1983) and $\sim$50–a few 100 for spiral galaxies and star-forming galaxies at local

to high-redshift (e.g., Dunne et al. 2000; Stevens et al. 2005; Kovács et al. 2006; Michałowski et al. 2010). We note that the derived molecular gas-to-dust ratio relies on the estimates of both gas mass and dust mass that are themselves quite uncertain. If we adopt a Galactic CO-to-H$_2$ conversion factor for deriving molecular gas mass, the upper limit on molecular gas-to-dust ratio would increase by about a factor of 6.

5.1.3. *Star-formation Efficiency*

The CO luminosity and the far-infrared (FIR) luminosity are measures of the molecular gas mass and SFR, respectively. Therefore, the ratio of $L_{\mathrm{FIR}}/L'_{\mathrm{CO}}$ indicates how efficiently stars are formed from molecular gas and is used as an indicator of star-formation efficiency (SFE; Young et al. 1986). The 2σ lower limit is $L_{\mathrm{FIR}}/L'_{\mathrm{CO}} > 6.7 \times 10^2\ L_\odot$ (K km s^{-1} pc^2)$^{-1}$ and is obtained using the FIR luminosity derived by Michałowski et al. (2008). This is higher than that of local spiral galaxies ($\sim$10–100; Young et al. 1996), LIRGs, and ULIRGs ($\sim$a few hundred; Sanders et al. 1991; Solomon et al. 1997) and is located at the higher end of SMGs and QSOs (see Solomon & Vanden Bout 2005, and references therein), indicating that active star formation occurs in the host galaxy. This is shown in terms of a specific star-formation rate (SSFR; SFR per unit stellar mass). SSFR is considered to be an indicator of current star-forming activity, and its inverse is related to the mass doubling time. The SSFR of 12–15 Gyr^{-1} derived in previous studies (Christensen et al. 2004; Michałowski et al. 2008; Svensson et al. 2010) is higher than that of other galaxy populations in the local to high-redshift universe (e.g., Castro Cerón et al. 2006). It is known that GRB hosts have higher SSFRs compared to field galaxies (e.g., Chary et al. 2002; Christensen et al. 2004; Castro Cerón et al. 2006; Savaglio et al. 2009). The high SFE of this host galaxy is consistent with the typical properties of GRB hosts.

The high SFE could be due to the uncertainty of the CO luminosity derived in this work and/or the FIR luminosity derived from submm emission, and we discuss this issue in the next section.

5.2. *Nondetection of CO*

There are some possible reasons for the nondetection of CO emission. One is that the amount of molecular gas in this galaxy is actually small. Optical observations show that the galaxy is compact and subluminous (Bloom et al. 2003). However, in order to sustain the large SFR inferred from submm and radio observations,

a large amount of molecular gas is essential. It is possible that the submm flux is overestimated. When dealing with a low S/N map, we must account for the boosting of flux densities of low S/N sources to above detection thresholds (Murdoch et al. 1973; Hogg & Turner 1998). In surveys at submm wavelengths, flux densities of low S/N sources ($\sim 3.5\sigma$) are corrected downward by $\sim$10–30% (e.g., Coppin et al. 2006; Hatsukade et al. 2011). In addition, some of the detections in flux-limited submm surveys are spurious, having been caused by positive noise fluctuations. Because the submm observations of Berger et al. (2003), where S/N ~ 3.5 for the submm source, do not take into account these effects, the submm derived SFR is possibly overestimated. It is also possible that the radio flux is overestimated. Berger et al. (2003) pointed out that the contribution from the afterglow to the radio flux is expected to be 10, 5, and 10 μJy at 1.43, 4.86, and 8.46 GHz, respectively, suggesting that the intrinsic radio flux of the host galaxy could decrease by about 10–20%.

Another possibility is that the CO emission per unit molecular gas mass is low. Some authors suggest that the CO-to-H_2 conversion factor depends on the oxygen abundance; the CO-to-H_2 conversion factor increases as the metallicity of the host galaxy decreases (e.g., Wilson 1995; Arimoto et al. 1996). CO observations of local low-metal dwarf galaxies suggest a higher CO-to-H_2 conversion factor (e.g., Taylor et al. 1998; Leroy et al. 2005; Komugi et al. 2011). GRB hosts typically have subsolar metallicity (e.g., Fynbo et al. 2003; Stanek et al. 2006; Levesque et al. 2010), and theoretical models support the low-metal environment of GRB progenitors (e.g., Woosley & Heger 2006). The metallicity of the host galaxy of GRB 000418, $[12 + \log(\text{O/H})] = 8.43$, was derived by Svensson et al. (2010) based on the stellar mass-metallicity relation of Savaglio et al. (2005). The correlation between α_{CO} and metallicity obtained by Arimoto et al. (1996) yields $\alpha_{\text{CO}} = 12\ M_\odot\ (\text{K km s}^{-1}\ \text{pc}^2)^{-1}$. This is 15 times higher than that of the ULIRGs we adopt in this work. Therefore, it is possible that the nondetection of CO is due to the low metallicity of the host galaxy.

6. SUMMARY

We carried out observations of redshifted CO ($J = 2$–1) line toward the host galaxy of GRB 000418 at $z = 1.1181$ using the PdBI. Neither CO line emission nor continuum emission were detected. We derived 2σ upper limits on the velocity integrated CO luminosity $L'_{\text{CO}} < 6.9 \times 10^9$ K km s^{-1} pc^2 and the molecular gas mass $M_{\text{H}_2} < 5.5 \times 10^9\ M_\odot$, by assuming a velocity width of 300 km s^{-1} and a CO-to-H_2 conversion factor of 0.8 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$, which are standard values for local ULIRGs. The upper limit of molecular gas-to-dust mass ratio was lower than that of other galaxy populations, although it must be noted that the derived molecular gas mass and dust mass were uncertain. The lower limit on the ratio of FIR luminosity to CO luminosity, a measure of the star-formation efficiency, was higher compared to that of other GRB hosts and other galaxy populations, indicating that active star formation is taking place in this galaxy.

No CO line emission has been detected in GRB hosts so far. Previous studies show that a CO detection itself is difficult in low-metal systems. We expect that the Atacama Large Millimeter/submillimeter Array (ALMA) will enable us to detect CO lines in such challenging conditions and to examine gas properties of GRB hosts.

REFERENCES

Arimoto, N., Sofue, Y., & Tsujimoto, T. 1996, PASJ, 48, 275
Berger, E., Cowie, L. L., Kulkarni, S. R., Frail, D. A., Aussel, H., & Barger, A. J. 2003, ApJ, 588, 99
Bloom, J. S., Berger, E., Kulkarni, S. R., Djorgovski, S. G., & Frail, D. A. 2003, AJ, 125, 999
Castro Cerón, J. M., Michałowski, M. J., Hjorth, J., Watson, D., Fynbo, J. P. U., & Gorosabel, J. 2006, ApJ, 653, L85
Chary, R., Becklin, E. E., & Armus, L. 2002, ApJ, 566, 229
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Coppin, K., et al. 2006, MNRAS, 372, 1621
Coppin, K., et al. 2008, MNRAS, 384, 1597
Djorgovski, S. G., Frail, D. A., Kulkarni, S. R., Bloom, J. S., Odewahn, S. C., & Diercks, A. 2001, ApJ, 562, 654
Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615
Dunne, L., Eales, S., Edmunds, M., Ivison, R., Alexander, P., & Clements, D. L. 2000, MNRAS, 315, 115
Endo, A., et al. 2007, ApJ, 659, 1431
Fruchter, A. S., et al. 2006, Nature, 441, 463
Fynbo, J. P. U., et al. 2003, A&A, 406, L63
Fynbo, J. P. U., et al. 2009, ApJS, 185, 526
Fynbo, J. U., et al. 2001, A&A, 369, 373

Gorosabel, J., et al. 2003, A&A, 409, 123
Greiner, J., et al. 2011, A&A, 526, A30
Greve, T. R., et al. 2005, MNRAS, 359, 1165
Guilloteau, S., & Lucas, R. 2000, Imaging at Radio through Submillimeter Wavelengths, 217, 299
Guilloteau, S., et al. 1992, A&A, 262, 624
Hatsukade, B., et al. 2007, PASJ, 59, 67
Hatsukade, B., et al. 2011, MNRAS, 411, 102
Hildebrand, R. H. 1983, QJRAS, 24, 267
Hjorth, J., et al. 2003, Nature, 423, 847
Hogg, D. W., & Turner, E. L. 1998, PASP, 110, 727
Hughes, D. H., Dunlop, J. S., & Rawlings, S. 1997, MNRAS, 289, 766
Jakobsson, P., Hjorth, J., Fynbo, J. P. U., Watson, D., Pedersen, K., Björnsson, G., & Gorosabel, J. 2004, ApJ, 617, L21
Jakobsson, P., et al. 2006, A&A, 460, L13
Kohno, K., et al. 2005, PASJ, 57, 147
Komugi, S., Yasui, C., Kobayashi, N., Hatsukade, B., Kohno, K., Sofue, Y., & Kyu, S. 2011, PASJ, in press
Kovács, A., Chapman, S. C., Dowell, C. D., Blain, A. W., Ivison, R. J., Smail, I., & Phillips, T. G. 2006, ApJ, 650, 592

Le Floc'h, E., Charmandaris, V., Forrest, W. J., Mirabel, I. F., Armus, L., & Devost, D. 2006, ApJ, 642, 636
Le Floc'h, E., et al. 2003, A&A, 400, 499
Leroy, A., Bolatto, A. D., Simon, J. D., & Blitz, L. 2005, ApJ, 625, 763
Levesque, E. M., Berger, E., Kewley, L. J., & Bagley, M. M. 2010, AJ, 139, 694
Michałowski, M. J., Hjorth, J., Castro Cerón, J. M., & Watson, D. 2008, ApJ, 672, 817
Michałowski, M., Hjorth, J., & Watson, D. 2010, A&A, 514, A67
Murdoch, H. S., Crawford, D. F., & Jauncey, D. L. 1973, ApJ, 183, 1
Perley, D. A., et al. 2009, AJ, 138, 1690
Priddey, R. S., Tanvir, N. R., Levan, A. J., Fruchter, A. S., Kouveliotou, C., Smith, I. A., & Wijers, R. A. M. J. 2006, MNRAS, 369, 1189
Salvaterra, R., et al. 2009, Nature, 461, 1258
Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1991, ApJ, 370, 158
Savaglio, S., et al. 2005, ApJ, 635, 260
Savaglio, S., Glazebrook, K., & Le Borgne, D. 2009, ApJ, 691, 182
Schady, P., et al. 2007, MNRAS, 377, 273
Solomon, P. M., & Vanden Bout, P. A. 2005, ARA&A, 43, 677
Solomon, P. M., & Barrett, J. W. 1991, Dynamics of Galaxies and Their Molecular Cloud Distributions, 146, 235
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, 398, L29
Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, ApJ, 478, 144
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Stanek, K. Z., et al. 2006, Acta Astron., 56, 333
Stanway, E. R., Bremer, M. N., Tanvir, N. R., Levan, A. J., & Davies, L. J. M. 2011, MNRAS, 410, 1496

Stevens, J. A., Amure, M., & Gear, W. K. 2005, MNRAS, 357, 361
Svensson, K. M., Levan, A. J., Tanvir, N. R., Fruchter, A. S., & Strolger, L.-G. 2010, MNRAS, 405, 57
Tacconi, L. J., et al. 2008, ApJ, 680, 246
Tacconi, L. J., Genzel, R., Lutz, D., Rigopoulou, D., Baker, A. J., Iserlohe, C., & Tecza, M. 2002, ApJ, 580, 73
Tanvir, N. R., et al. 2004, MNRAS, 352, 1073
Tanvir, N. R., et al. 2009, Nature, 461, 1254
Taylor, C. L., Kobulnicky, H. A., & Skillman, E. D. 1998, AJ, 116, 2746
Totani, T. 1997, ApJ, 486, L71
van der Horst, A. J., Kouveliotou, C., Gehrels, N., Rol, E., Wijers, R. A. M. J., Cannizzo, J. K., Racusin, J., & Burrows, D. N. 2009, ApJ, 699, 1087
Wijers, R. A. M. J., Bloom, J. S., Bagla, J. S., & Natarajan, P. 1998, MNRAS, 294, L13
Wilson, C. D. 1995, ApJ, 448, L97
Woosley, S. E., & Heger, A. 2006, ApJ, 637, 914
Yang, M., Greve, T. R., Dowell, C. D., & Borys, C. 2007, ApJ, 660, 1198
Young, J. S., Schloerb, F. P., Kenney, J. D., & Lord, S. D. 1986, ApJ, 304, 443
Young, J. S., Allen, L., Kenney, J. D. P., Lesser, A., & Rownd, B. 1996, AJ, 112, 1903
Zheng, W.-K., Deng, J.-S., & Wang, J. 2009, Research in Astronomy and Astrophysics, 9, 1103