The Astrophysical Journal, 659:1431–1437, 2007 April 20

A REVISED ESTIMATE OF THE CO $J = 1{-}0$ EMISSION FROM THE HOST GALAXY OF GRB 030329 USING THE NOBEYAMA MILLIMETER ARRAY

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Received 2006 June 21; accepted 2007 January 15

ABSTRACT

A sensitive observation of the CO $J = 1{-}0$ molecular line emission in the host galaxy of GRB 030329 ($z = 0.1685$) has been performed using the Nobeyama Millimeter Array to detect molecular gas and hidden star formation. No sign of CO emission was found, which invalidates our previous report of the presence of molecular gas. The 3 σ upper limit on the CO line luminosity ($L'_{\rm CO}$) of the host galaxy is 6.9×10^8 K km s^{-1} pc^2. The lower limit to the host galaxy's metallicity is estimated to be $12 + \log({\rm O/H}) \sim 7.9$, which yields a conversion factor from CO line luminosity to H$_2$ of $\alpha_{\rm CO} = 40\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$. Assuming this factor, the 3 σ upper limit on the molecular gas mass of the host galaxy is $2.8 \times 10^{10}\ M_\odot$. Based on the Schmidt law, the 3 σ upper limit on the total star formation rate (SFR) of the host galaxy is estimated to be 38 $M_\odot$ yr^{-1}. These results independently confirm inferences from previous observations in the optical, submillimeter, and X-ray bands, which regard this host galaxy as a compact dwarf and not a massive, aggressively star-forming galaxy. Finally, the SFRs of GRB host galaxies, estimated using various techniques immune to dust obscuration, including our CO luminosity measurements, are compared with the SFRs of the same galaxies estimated using extinction-corrected optical/UV tracers. We show that most of the SFRs measured in extinction-free wavelengths, including positive detections and upper limits, are larger by from 1 to a few orders of magnitude compared with the SFRs of the same galaxies measured by optical/UV tracers.

Subject headings: galaxies: ISM — gamma rays: bursts — radio lines: galaxies

1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs) provide a new and powerful means to detect distant galaxies and star formation. Because of their extremely energetic ($\sim 10^{53}$ ergs), dust-transparent gamma-ray emission, GRBs can be detected from cosmological distances. It is now widely believed that GRBs accompany the core collapse of massive stars (e.g., Stanek et al. 2003; Hjorth et al. 2003), and many GRBs have been found in star-forming galaxies (e.g., Bloom et al. 2003; Berger et al. 2003; Sollerman et al. 2005). This implies that the GRB formation rate (GFR) within a certain redshift bin is probably correlated with the star formation rate at that epoch (Totani 1997; Wijers et al. 1998; Blain & Natarajan 2000). If so, GRBs hold the potential to become extremely powerful tracers of distant star formation, extending the Madau diagram (Madau et al. 1996) up to $z \gtrsim 20$ (Lamb & Reichart 2000). However, there is no guarantee that the GFR is correlated only with the global SFR. The evolution of metallicity (Stanek et al. 2006; Fynbo et al. 2006) or the stellar initial mass function in galaxies (Ramirez-Ruiz et al. 2002) could indeed influence the GFR. Of course, being able to track any of these parameters to cosmological distances would be very fruitful. Studying the basic properties of the GRB host galaxies is essential to a precise understanding of the type of evolution we are tracking by counting the GRBs.

GRB host galaxies often appear to be blue, subluminous, and low-metallicity dwarf galaxies in the optical/UV band, with a moderate SFR of 0.01–10 $M_\odot$ yr^{-1} (Fynbo et al. 2003; Christensen et al. 2004; Sollerman et al. 2005). On the other hand, Berger et al. (2003) have reported that some GRB host galaxies emit strongly in the submillimeter continuum, corresponding to SFRs higher by a few orders of magnitude compared with those measured in the optical/UV band, and thus resemble active star-forming galaxies enshrouded in heavy clouds of dust, commonly found at similar redshifts (Blain et al. 1999; Franceschini et al. 2001; Chary & Elbaz 2001). However, these GRB host galaxies have not been detected by subsequent sensitive observations in the near-/mid-infrared window using the *Spitzer Space Telescope* (Le Floc'h et al. 2006), which renders the conversion between the observed submillimeter fluxes and SFR suspect. Clearly, confirmatory measurements in these wavelengths, as well as more observations based on other, independent methods, are necessary for understanding this discrepancy.

Measurements of the CO line luminosity ($L'_{\rm CO}$) of GRB host galaxies may be able to resolve this discrepancy. The correlation between a galaxy's $L'_{\rm CO}$ and its total molecular gas mass ($M_{\rm H_2}$) is well known (Solomon & Vanden Bout 2005). Once $M_{\rm H_2}$ and, subsequently, the molecular gas surface density ($\Sigma_{\rm H_2}$) are known, the total SFR can be estimated using the global Schmidt law (Kennicutt 1998). Since millimeter waves penetrate through dust, the total SFR of a galaxy measured in this manner is influenced by neither its dustiness nor its dust temperature. However, to date, no CO measurements of the $M_{\rm H_2}$ of GRB host galaxies have been performed. This is mainly because GRBs are found at cosmological distances ($z_{\rm mean} \sim 2.7$ for GRBs detected by *Swift*; Jakobsson et al. 2006), and their CO emission is too faint to be detected by existing millimeter-wave telescopes.

Here we present the results of an observation of the CO $J = 1{-}0$ molecular line emission in the host galaxy of GRB 030329 using the Nobeyama Millimeter Array (NMA). This is one of the GRBs that occurred closest to Earth ($z = 0.1685$; Greiner et al. 2003; Caldwell et al. 2003) and was the third-closest to us at the

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TABLE 1
NOBEYAMA MILLIMETER ARRAY OBSERVATIONS OF GRB 030329

UT Date (1)	Duration (hr) (2)	$f_{\rm USB}$ (GHz) (3)	$T_{\rm sys}$ (K) (4)	Seeing (5)
2004:				
Dec 8	8.8	98.905	157	
Dec 9	10.3	98.905	174	
Dec 10	10.3	98.905	158	
Dec 11	8.8	98.825	194	Bad
Dec 12	10.8	98.825	184	Bad
Dec 13	8.7	98.825	156	
2005:				
Apr 22	7.0	98.905	139	
Apr 23	9.1	98.825	152	
Apr 24	9.1	98.825	258	
Apr 25	7.0	98.825	197	Bad
Apr 26	7.5	98.905	176	
Apr 27	5.5	98.905	180	
Apr 28	8.0	98.905	163	

NOTES.—Col. (1): Observation date. Col. (2): Observation duration. The net on-source integration time is typically about half this. Col. (3): Center of the USB frequency. Col. (4): System noise temperature in double sideband. Col. (5): Atmospheric stability. "Bad" implies that a large fraction of the visibility data ($\gtrsim$50%) were discarded because of significant phase noise.

time of observation.[7] In the optical, the host galaxy appears to be a dwarf galaxy resembling the Small Magellanic Cloud (SMC) ($M_V \sim -16.5$; Fruchter et al. 2003), with a moderate extinction-corrected SFR of $\sim$0.5 $M_\odot$ yr^{-1} (Matheson et al. 2003). However, Kohno et al. (2005, hereafter K05) found a possible feature of CO $J = 1-0$ emission in the millimeter-wave spectrum during an afterglow observation using the NMA, suggesting that the host galaxy might possess an enormous amount of molecular gas, $M_{\rm H_2} > 10^9\ M_\odot$. This is substantially more than what would be expected from the optical faintness of the host galaxy. For example, the total molecular gas mass of the SMC is only $\gtrsim 4 \times 10^6\ M_\odot$ (Mizuno et al. 2001). If this line actually exists, then it would imply that a large amount of star formation in this galaxy is obscured by heavy dust clouds. This would certainly support the relationship between GRBs and star formation. Therefore, the host galaxy of GRB 030329 was considered to be the best target to conduct the first ever deep CO $J = 1-0$ observation.

Assuming a cosmology with $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$, the luminosity distance of GRB 030329 is $d_L = 802$ Mpc, and the angular distance is $d_A = 587$ Mpc ($1''$ corresponds to 2.85 kpc).

2. OBSERVATIONS AND DATA ANALYSIS

We conducted a set of sensitive observations of the CO $J = 1-0$ emission in the host galaxy of GRB 030329 using the NMA. The observation log is presented in Table 1. The observations were performed over two periods separated by 4 months. The first period was from 2004 December 9 to 14, and the second one was from 2005 April 22 to 29. The most compact configuration (D array; baseline lengths ranging from 13 to 82 m) was used for the observations. The tracking frequency was set at 98.824 or 98.905 GHz to observe the redshifted CO $J = 1-0$ line ($\sim$98.65 GHz) at the upper sideband (USB). The center frequency was shifted to ensure that the detected line feature is actually due to molecular emission and not to any unexpected correlator bandpass characteristics. The lower sideband (LSB) was centered at 86.825 and 86.905 GHz, respectively. Each band was separated by a 90° phase switching of the reference signal. The Ultra–Wide Band Correlator (Okumura et al. 2000) was configured to cover a bandwidth of 1024 MHz per sideband with a resolution of 8 MHz.

[7] See http://www.mpe.mpg.de/jcg/grbgen.html.

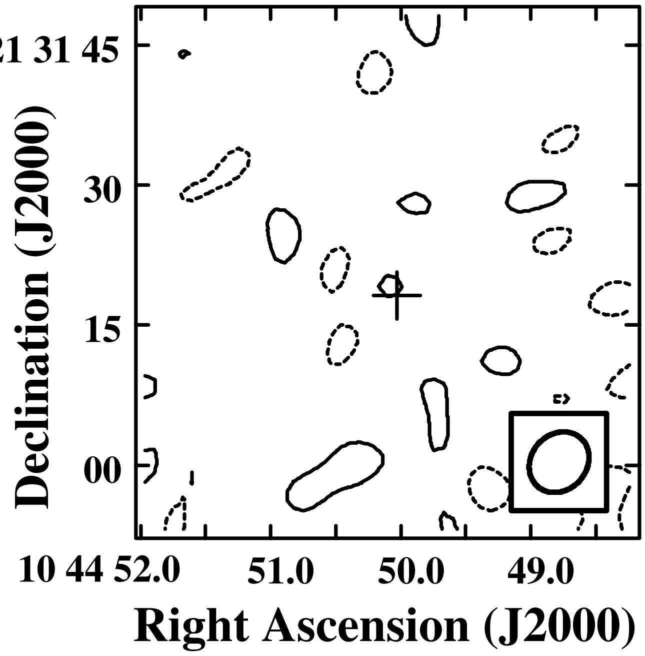

FIG. 1.—Intensity map in the direction of GRB 030329 obtained after combining our data with those from Kohno et al. (2005). The intensity is integrated over a velocity width of 220 km s^{-1}, to allow direct comparison with Fig. 3 of Kohno et al. (2005). The synthesized beam, shown at bottom right, is $6.95'' \times 5.94''$ (position angle $-43°$). The contour interval is 0.46 Jy beam^{-1} km s^{-1} (1.5 σ). Solid contours indicate positive fluxes, and dashed contours indicate negative fluxes. The crosshair at the center coincides with the position of the GRB 030329 optical afterglow ($\alpha = 10^{\rm h}44^{\rm m}50.03^{\rm s}$, $\delta = +21°31'18.15''$; J2000). The emission feature at the center has almost disappeared ($\lesssim 1.5\ \sigma$), and its significance could not be improved by increasing the spectral resolution.

The radio sources B1741$-$038 and 3C 84 were observed every $\sim$20 minutes for amplitude and phase calibration, and the passband shape of the system was determined based on observations of strong continuum sources—3C 84 or 3C 279. We also observed B1040+244 and B0953+254 several times during each observation run to verify the consistency of the amplitude calibration. The flux densities of B1040+244 and B0953+254 were determined several times during the observation runs; the flux density of B1040+244 ranged from 0.92 to 0.97 Jy, and that of B0953+254 was 0.93 Jy. In this study, we adopt a constant flux value of 1.0 Jy for both these sources throughout the observation runs.

The raw visibilities were edited and calibrated using the UVPROC-II package (Tsutsumi et al. 1997) of the Nobeyama Radio Observatory (NRO). Images were produced using the NRAO AIPS task IMAGR. By applying different levels of smoothing to the observed data, with a native spectral resolution of 8 MHz (24.3 km s^{-1}), we produced a series of intensity maps and spectra with various spectral resolutions. The upper limits on the CO flux, discussed in subsequent sections, are based on the rms noise level measured over these intensity maps.

3. RESULTS

Although we carefully examined the produced spectra and intensity maps, no sign of CO emission from the host galaxy of GRB 030329 could be found, either in the data that were newly acquired from our observation or from these data combined with those reported in K05. As the significance of the possible emission

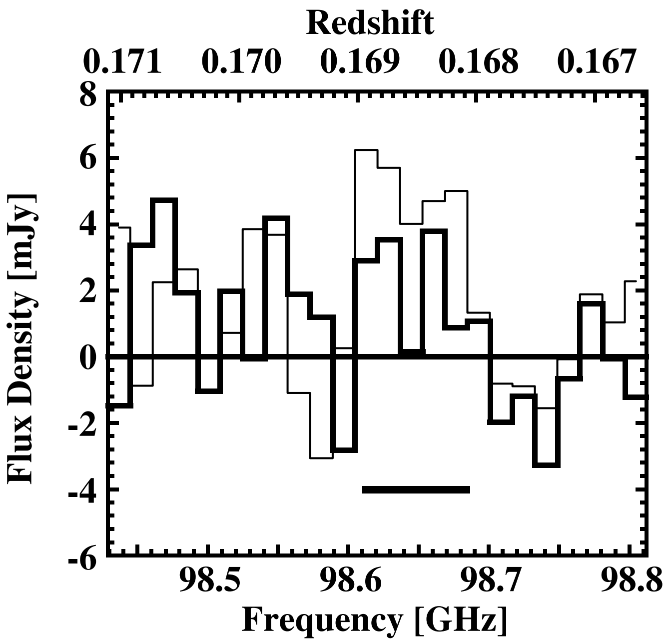

FIG. 2.—Spectrum observed in the 98 GHz band toward GRB 030329. The thin line represents the spectrum presented in Kohno et al. (2005), and the thick line shows the spectrum produced by combining our data with those of Kohno et al. (2005). The spectrum is smoothed to a resolution of 16 MHz, or 48.6 km s^{-1}. The horizontal bar indicates the velocity range where a possible emission feature was visible in the old spectrum centered on the redshifted CO $J = 1-0$ emission frequency (98.65 GHz) of GRB 030329 ($z = 0.1685$). The rms noise level has improved from 3.8 to 2.0 mJy beam^{-1}, and the emission feature has lost its significance. The significance could not be improved by changing the smoothing factor.

feature reported earlier in K05 was merely 2 σ, we believe that in all likelihood it was purely noise. In this section, we present the upper limits placed on the total CO $J = 1-0$ flux of the host galaxy of GRB 030329.

3.1. *New Data*

Prior to adding our data to those of K05, we analyzed our data alone. This was for two reasons: (1) Our observation was conducted more than a year after the burst; thus, the possibility of contamination from the emission of the burst is excluded, although the continuum component of the emission was properly subtracted in K05 as well. (2) Further, the bandpass characteristics of the instruments used for observation drift over the years, and the two sets of data can be regarded as being obtained from two independent instruments, at least to some extent. Therefore, the separate analyses of the data enable a cross-check for any instrumental errors.

Because the velocity width (Δv) of the CO line could not be measured, we assumed two different velocity widths to estimate the upper limit of the velocity-integrated CO line flux ($I_{\rm CO} = \int S_{\rm CO}\, dv$, where $S_{\rm CO}$ denotes the CO flux density per beam). First, we adopted $\Delta v = 220$ km s^{-1}, which was the velocity width of the emission feature reported in K05. In this case, a 3 σ upper limit of $3\delta I_{\rm CO}$ = 0.96 Jy km s^{-1} can be set on the host galaxy. This is less than half the upper limit attained in K05.

Since the CO $J = 1-0$ emission line was not detected, the host galaxy of GRB 030329 is most likely to be a dwarf galaxy, as observed in the optical band (Fruchter et al. 2003; Matheson et al. 2003; Gorosabel et al. 2005; Sollerman et al. 2005). For this reason, we next adopted $\Delta v = 95$ km s^{-1} as a more realistic estimate of the velocity width of the host galaxy. This is the average of the 115 dwarf galaxies selected by Leroy et al. (2005) with rotation velocities of $v_{\rm rot} = 67$ km s^{-1}, multiplied by sin 45° assuming an inclination angle of 45°. In this case, we derive $3\delta I_{\rm CO}$ = 0.60 Jy km s^{-1}.

3.2. *Combined with Data from Kohno et al.* (*2005*)

Since no CO line emission features were detected in our data, we combined our data with those of K05 in order to obtain the lowest possible upper limit on the total flux. Figure 1 shows the intensity map in the direction of GRB 030329 integrated over $\Delta v = 220$ km s^{-1}. Figure 2 shows the spectrum in the 98 GHz band toward GRB 030329. The significance of the emission feature reported in K05 has been reduced to near the rms noise level ($\sim$1.5 σ). We again place an upper limit on the velocity-integrated flux density of the CO emission from the host galaxy using the above two candidate line velocity widths. Assuming Δv = 220 km s^{-1}, the 3 σ upper limit of $I_{\rm CO}$ is $3\delta I_{\rm CO}$ = 0.89 Jy km s^{-1}. Likewise, $\Delta v = 95$ km s^{-1} yields an upper limit on $3\delta I_{\rm CO}$ = 0.51 Jy km s^{-1}. We adopt $3I_{\rm CO}$ = 0.51 Jy km s^{-1} in what follows, assuming that the host galaxy is an average dwarf galaxy.

4. DISCUSSION

4.1. *Molecular Gas Mass*

The total molecular gas mass ($M_{\rm H_2}$) of a galaxy is proportional to its CO line luminosity ($L'_{\rm CO}$): $M_{\rm H_2} = \alpha_{\rm CO} L'_{\rm CO}$, where $\alpha_{\rm CO}$ is the conversion factor from CO line luminosity to H_2 molecular gas mass. Here we make an attempt to set an upper limit on the molecular gas mass of the host galaxy of GRB 030329.

The 3 σ upper limit on $L'_{\rm CO}$ can be calculated from the obtained $\delta I_{\rm CO}$, using the following formula:

$$\begin{aligned} 3\delta L'_{\rm CO} &= \left(\frac{c^2}{2k}\right)(3\delta I_{\rm CO}) d_L^2 \nu_{\rm rest}^{-2}(1+z)^{-1} \\ &= 6.9 \times 10^8 \left(\frac{3\delta I_{\rm CO}}{0.51\ {\rm Jy\ km\ s^{-1}}}\right)\left(\frac{\nu_{\rm rest}}{115\ {\rm GHz}}\right)^{-1} \\ &\quad \times \left(\frac{d_L}{802\ {\rm Mpc}}\right)^2 \left(\frac{1+z}{1.1685}\right)^{-1} {\rm K\ km\ s^{-1}\ pc^2} \quad (1) \end{aligned}$$

TABLE 2

INFLUENCE OF DIFFERENT VALUES OF HOST GALAXY METALLICITY ON THE RESULTS

12 + log (O/H) (1)	$\alpha_{\rm CO}$ ($M_\odot$ [K km s^{-1} pc^2]$^{-1}$) (2)	$3\delta M_{\rm H_2}$ (10^{10} $M_\odot$) (3)	$3\delta\Sigma_{\rm H_2}$ ($M_\odot$ pc^{-2}) (4)	3δSFR ($M_\odot$ yr^{-1}) (5)
7.9	40	2.8	72	38
8.3	16	1.1	29	11
8.6	7.9	0.55	14	4.0

NOTES.—Col. (1): Possible values of the host galaxy's metallicity. Col. (2): The CO line luminosity–to–H_2 molecular gas mass conversion factor, calculated using eq. (2). Col. (3): The 3 σ upper limit on the total molecular gas mass, calculated using eq. (3). Col. (4): The 3 σ upper limit on the molecular gas mass column density. Col. (5): The 3 σ upper limit on the total SFR of the host galaxy, calculated using eq. (4).

TABLE 3
CONSTRAINTS ON THE MOLECULAR GAS MASS OF THE HOST GALAXY OF GRB 030329

Source	δS_{CO} (mJy beam^{-1}) (2)	$3\delta L'_{CO}$ (10^8 K km s^{-1} pc^2) (3)	$3\delta M_{H_2}$ (10^{10} $M_\odot$) (4)	$3\delta\Sigma_{H_2}$ ($M_\odot$ pc^{-2}) (5)	Reference (6)
First run	4.0	15	6.1	1.6×10^2	1
Second run	2.1	8.1	3.2	85	This study
Total	1.8	6.9	2.8	72	This study
From OH absorption	...	...	...	112	2

NOTES.—Col. (2): The rms noise level (1 σ) of the flux density per beam. The spectral resolution is 32 MHz, which corresponds to a velocity width of 97 km s^{-1}. Col. (3): The 3 σ upper limit on the CO $J = 1-0$ line luminosity, assuming a line velocity width of Δv = 95 km s^{-1}. Col. (4): The 3 σ upper limit on the total molecular gas mass, assuming α_{CO} = 40 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$. Col. (5): The 3 σ upper limit on the molecular gas mass column density. The values derived from the CO line observation are averaged within the synthesized beam. The value derived from OH absorption is the density within the line of sight toward the GRB, assuming a Galactic OH/H_2 abundance value.

REFERENCES.—(1) Kohno et al. 2005; (2) Taylor et al. 2005.

(Solomon & Vanden Bout 2005). The uncertainty in α_{CO} is one of the largest error sources for the CO-measured molecular gas mass. There is a large variation, of about 2 orders of magnitude, in the global values of α_{CO} among galaxies. Dwarf galaxies, which have low metallicity, tend to have large α_{CO} factors [e.g., α_{CO} = 40 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ for the SMC; Mizuno et al. 2001] as compared with the Galactic value [α_{CO} = 2.9 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$; Dame et al. 2001]. On the other hand, the nearby metal-rich ultraluminous infrared galaxies typically have $\alpha_{CO} \lesssim 1$ $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ (Downes & Solomon 1998).

Although the α_{CO} factor of the GRB 030329 host galaxy is unknown, we can estimate it by using the following correlation between the metallicity and α_{CO}, which holds for nearby dwarf and spiral galaxies:

$$\log \alpha_{CO} = -1.0[12 + \log(O/H)] + 9.5 \qquad (2)$$

(Arimoto et al. 1996). Sollerman et al. (2005) conducted a series of optical photometric and spectroscopic measurements of the host galaxy of GRB 030329 and successfully measured the R_{23} = ([O II] λ3727 + [O III] $\lambda\lambda$4959, 5007)/Hβ emission-line ratio (see also Gorosabel et al. 2005). This allowed them to employ the standard R_{23} diagnostic (Kewley & Dopita 2002) and estimate the metallicity of the host galaxy. However, the R_{23} ratio has a maximum value at 12 + log (O/H) $\sim$ 8.5, and the result is two-valued. According to Sollerman et al., the lower and upper solution branch values of 12 + log (O/H) are 7.9 and 8.6, respectively. Though it is customary to break this degeneracy using other line ratios such as [N II] λ6584/[O II] λ3727, they were not able to do so because, unfortunately, none of these pairs appeared above their detection limit. Instead, they used the metallicity-luminosity relation presented by Lee et al. (2003) and the host galaxy's absolute B magnitude ($M_B \sim -16.5$; Gorosabel et al. 2005). This yields a host galaxy metallicity closer to the lower branch value, that is, 12 + log (O/H) $\sim$ 8.1. Therefore, Sollerman et al. (2005) state that the lower branch value is more plausible. Recently, a stronger upper limit on [N II] λ6586 has been reported by Thoene et al. (2006), which also supports the lower value.

However, a recent update of the metallicity-luminosity relation using $\sim$53,000 star-forming galaxies in the Sloan Digital Sky Survey yields a metallicity $\sim$0.2 dex higher than the relation reported by Lee et al. (2003) for a given M_B (Tremonti et al. 2004). Adopting this relation, the host galaxy's metallicity is estimated to be 12 + log (O/H) = 8.3 $\pm$ 0.16, which falls equally close to the two R_{23} solutions. Moreover, it should be noted that the R_{23} method rapidly loses sensitivity near its local maximum at 12 + log (O/H) $\sim$ 8.5. For example, applying R_{23} = 6.1 and [O III] $\lambda\lambda$4950, 5008/[O II] λ3727 = 2.8 (Sollerman et al. 2005) to the calibration diagram presented by Kobulnicky et al. (1999; their Fig. 8) yields two closely neighboring solutions at around 12 + log (O/H) $\sim$ 8.3–8.6 with errors of $\pm$0.25 dex each. Therefore, we must say that there is quite a large ambiguity in the host galaxy's metallicity, in the range 12 + log (O/H) $\sim$ 7.9–8.6. This difference has a considerable effect on the upper limits for the molecular gas mass and SFR of the host galaxy, as summarized in Table 2. We adopt 12 + log (O/H) = 7.9 in the subsequent discussion, which yields the most conservative upper limits for both these values. Substituting this into equation (2) yields α_{CO} = 40 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$.

Applying the aforementioned values of $3\delta L'_{CO}$ and α_{CO}, the 3 σ upper limit on the total molecular gas mass of the host galaxy of GRB 030329 can be derived as follows:

$$\begin{aligned} 3\delta M_{H_2} &= \alpha_{CO}(3\delta L'_{CO}) \\ &= 2.8 \times 10^{10} \left[\frac{\alpha_{CO}}{40\ M_\odot\ (\mathrm{K\ km\ s^{-1}\ pc^2})^{-1}} \right] \\ &\quad \times \left(\frac{3\delta L'_{CO}}{6.9 \times 10^8\ \mathrm{K\ km\ s^{-1}\ pc^2}} \right) M_\odot. \end{aligned} \qquad (3)$$

Assuming a Gaussian profile, the synthesized beam (6.95″ $\times$ 5.94″ FWHM) corresponds to a surface area of $S = 3.8 \times 10^2$ kpc^2 at z = 0.1685. After adopting this value, the 3 σ upper limit on the

TABLE 4
STAR FORMATION RATE OF THE HOST GALAXY OF GRB 030329

Observational Method (1)	SFR ($M_\odot$ yr^{-1}) (2)	Reference (3)
CO $J = 1-0$	<38[a]	This study
[O II] λ3727 and Balmer lines	$\sim$0.6[b]	1
Photometric SED	$\sim$0.54[b]	1
Submillimeter continuum	<200[c]	2
X-ray luminosity	$\lesssim$200 $\pm$ 80	3

NOTES.—Col. (1), observed emission feature; col. (2), measured SFR.

[a] Adopting α_{CO} = 8.6 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ leads to a more rigid upper limit of 4.0 $M_\odot$ yr^{-1}.

[b] Assuming the SMC extinction law ($A_V \sim 0.6$).

[c] We calculated the SFR based on the reported 3 σ upper limit on the submillimeter flux density, using the relation between submillimeter flux density and SFR (Carilli & Yun 1999).

REFERENCES.—(1) Gorosabel et al. 2005; (2) Smith et al. 2005; (3) Watson et al. 2004.

TABLE 5
Star Formation Rate of GRB Host Galaxies

Source (1)	Unobscured SFR ($M_\odot$ yr^{-1}) (2)	Tracer (3)	Ref. (4)	Optical SFR ($M_\odot$ yr^{-1}) (5)	Tracer (6)	Extinction Corrected? (7)	Refs. (8)
GRB 970228	<335	Sub-mm	1	~0.76	[O II]	No	5
GRB 970508	<380	Sub-mm	1	~10	[O II]	Yes	6
	<17	IR	2	...	...	...	
GRB 970828	80 ± 60	Radio	1	~1.1	[O II]	No	7
	24^{+43}_{-14}	IR	2	...	...	...	
GRB 971214	120 ± 275	Sub-mm	1	~5.2	UV	No	8
GRB 980425	0.4	IR	2	~0.35	Hα	No	9
	<2.8 ± 1.9	X-ray	3	...	...	...	
GRB 980613	380 ± 200	Sub-mm	1	~5.6	[O II]	No	10
	50 ± 140	Radio	1	...	...	...	
	87^{+156}_{-52}	IR	2	...	...	...	
GRB 980703	<380	Sub-mm	1	~14	Hβ	Yes	6
	180 ± 25	Radio	1	...	...	...	
	<24	IR	2	...	...	...	
GRB 981226	150 ± 85	Radio	1	1.2 ± 0.3	UV	No	11
GRB 990123	<140	IR	2	~3.6–4.6	UV	No	12
GRB 990506	<170	IR	2	~12.6	[O II]	No	13
GRB 990705	190 ± 165	Radio	1	~5–8	UV	No	14
	32^{+37}_{-11}	IR	2	...	...	...	
GRB 991208	<370	Sub-mm	1	~156–249	Hβ	Yes	6
	70 ± 30	Radio	1	...	...	...	
GRB 000210	560 ± 165	Sub-mm	1	~3	[O II]	Yes	15, 16
	90 ± 45	Radio	1	...	...	...	
GRB 000418	690 ± 195	Sub-mm	1	~15.4	[O II]	Yes	17
	330 ± 75	Radio	1	...	...	...	
GRB 000911	495 ± 195	Sub-mm	1	~2.7	UV	Yes	18
	85 ± 70	Radio	1	...	...	...	
GRB 000926	820 ± 340	Radio	1	~24	UV	Yes	19
GRB 010222	610 ± 100	Sub-mm	1	1.5	...	No	1
	300 ± 115	Radio	1	...	...	...	
	<130	IR	2	...	...	...	
GRB 030329	<4.0–38	CO	4	~0.6	[O II]	Yes	20
GRB 031203	<150 ± 110	X-ray	3	>11	Hα	Yes	21

Notes.—Col. (1): Source name. Col. (2): SFR derived from tracers free from dust extinction. Col. (3): SFR tracer of col. (2). Col. (4): References for col. (2). Col. (5): SFR derived from optical tracers. Col. (6): SFR tracer of col. (5); [O II] is the 3727 Å doublet. Col. (7): Whether the SFR in col. (5) is corrected for both local and Galactic dust extinction. Col. (8): References for col. (5).

References.—(1) Berger et al. 2003; (2) Le Floc'h et al. 2006; (3) Watson et al. 2004; (4) this work; (5) Bloom et al. 2001; (6) Sokolov et al. 2001; (7) Djorgovski et al. 2001; (8) Kulkarni et al. 1998; (9) Sollerman et al. 2005; (10) Djorgovski et al. 2003; (11) Christensen et al. 2005; (12) Bloom et al. 1999; (13) Bloom et al. 2003; (14) Le Floc'h et al. 2002; (15) Piro et al. 2002; (16) Gorosabel et al. 2003a; (17) Gorosabel et al. 2003b; (18) Masetti et al. 2005; (19) Fynbo et al. 2001; (20) Gorosabel et al. 2005; (21) Prochaska et al. 2004.

average molecular gas mass surface density ($\Sigma_{\rm H_2}$) within the beam can be calculated as 72 $M_\odot$ pc^{-2}.

Taylor et al. (2005) measured the OH main line opacity of the host galaxy of GRB 030329 and set an upper limit of $3\delta\Sigma_{\rm H_2}$ = 112 $M_\odot$ pc^{-2} using the relation $N_{\rm OH}/N_{\rm H_2} \approx 1 \times 10^{-7}$. However, so far this relation holds only for Galactic dark clouds (Liszt & Lucas 1999) and four intermediate-redshift molecular absorption systems (Kanekar & Chengalur 2002). This ratio may be lower in a galaxy with a low metallicity, thereby resulting in an even higher upper limit on $\Sigma_{\rm H_2}$. Nevertheless, the upper limit we have set on the $\Sigma_{\rm H_2}$ of the host galaxy of GRB 030329 is the lowest ever, to our knowledge.

4.2. *Star Formation Rate*

We can place a constraint on the total SFR of the host galaxy of GRB 030329, using the upper limit on $\Sigma_{\rm H_2}$ derived above. Using the global Schmidt law (Kennicutt 1998), which holds for spiral and dwarf galaxies on a large scale (e.g., Komugi et al. 2005; Leroy et al. 2005), the 3 σ upper limit of the total SFR of the host galaxy can be deduced as follows:

$$3\delta{\rm SFR} = 38\left(\frac{3\delta\,\Sigma_{\rm gas}}{72\ M_\odot\ {\rm pc}^{-2}}\right)^{1.4}\left(\frac{S}{3.8\times10^{2}\ {\rm kpc}^{2}}\right)\ M_\odot\ {\rm yr}^{-1}. \tag{4}$$

Note that adopting a smaller $\alpha_{\rm CO}$ factor of 7.9 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ leads to a considerably more rigid upper limit of 3δSFR = 4.0 $M_\odot$ yr^{-1}. The influence of different possible values of the host galaxy's metallicity is presented in Table 2, while a summary of results from several studies is presented in Table 3.

Recently, there have been reports on submillimeter (Smith et al. 2005) and X-ray (Watson et al. 2004) observations of the host galaxy of GRB 030329, as well as optical observations corrected for extinction (Gorosabel et al. 2005). Table 4 lists the SFRs of the host galaxy as measured with various star formation tracers.

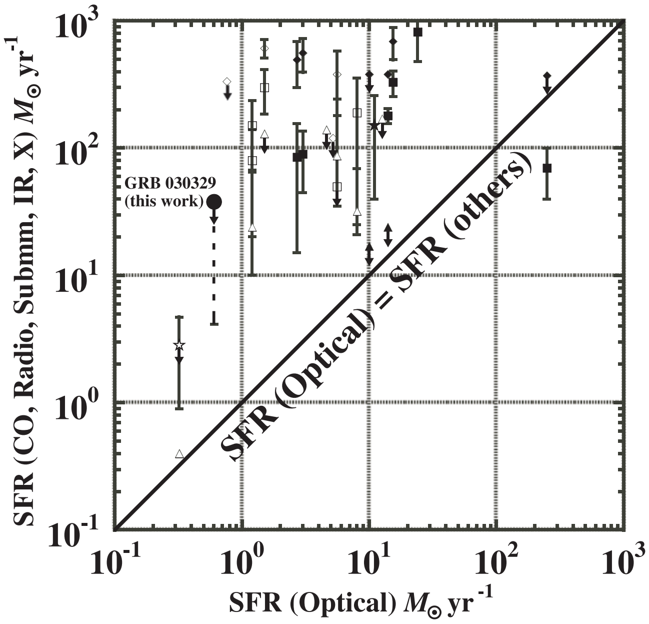

FIG. 3.— Comparison between the SFRs of GRB host galaxies measured by optical methods and other methods that are free of dust extinction. References are listed in Table 5. The abscissa is the SFR measured by optical methods, namely, [O II] λ3727 and Balmer line luminosities, and UV continuum luminosity. The ordinate is the SFR measured by various tracers in wavelengths other than those belonging to the optical/UV band, namely, CO line luminosity (*circles*; this study), radio (*squares*), submillimeter continuum luminosity (*diamonds*), mid-/far-infrared continuum luminosity (*triangles*), and X-ray luminosity (*stars*). Filled symbols have optical SFRs corrected for dust extinction, and the open ones are not corrected for extinction in the host galaxy. The symbols with arrows are upper limits for the host galaxies without any significant detection in the extinction-free wavelength. The solid line indicates a one-to-one correspondence between the two SFRs. The dashed vertical line indicates the uncertainty of the upper limit measured by the CO line luminosity, which originates from the uncertainty in the metallicity and the $\alpha_{\rm CO}$ factor. It can be seen that SFRs measured using optical/UV wavelengths are significantly smaller compared with other methods, even after correction for dust extinction.

The upper limits derived from nondetections are included. Our upper limit, which is derived from the molecular gas mass measured by the CO line luminosity, is the most rigid among the observational methods that are intrinsically free of dust extinction, even when the uncertainty in the $\alpha_{\rm CO}$ factor is considered. This result confirms the moderate SFR ($\ll 100\ M_\odot$ yr^{-1}) of the host galaxy.

4.3. *What Is the True SFR of GRB Host Galaxies?*

Many observations of GRB host galaxies in the optical/UV range suggest that GRB host galaxies are blue, subluminous dwarf galaxies with only a moderate SFR. However, SFR measurements in the optical/UV can underestimate the true SFR if severe extinction by dust is present. Recently, there have been more such studies that make an attempt to correct for dust extinction, mostly using optical spectral energy distribution (SED) fits (e.g., Sokolov et al. 2001). Such corrections are useful to an extent, but they lose effectiveness when the clouds of dust are so thick that the optical emission is completely obscured from view.

Recently, many groups have begun to measure the SFRs of GRB host galaxies using various methods that are immune to dust extinction, in order to confirm the optical/UV results. These include the present study, using the molecular gas mass measured from the CO emission line. In Table 5, we present a list of GRB host galaxies whose SFRs have been measured in the optical/UV band and with at least one other extinction-free method. As can be seen, these results do not necessarily coincide with each other.

Figure 3 shows how the SFRs of GRB host galaxies in Table 5 measured by extinction-free methods appear when compared with the corresponding SFRs measured in the optical/UV band. As can be seen, most of the results (positive detections as well as upper limits) from extinction-free methods demonstrate SFRs that are greater than the optical results by from 1 to a few orders of magnitude. The "positive detections" that are especially above the one-to-one correspondence line are the results of submillimeter and radio observations by Berger et al. (2003); some of these are called into question by the much lower "upper limits" set by the nondetection in mid-infrared observations (Le Floc'h et al. 2006). In order to confirm whether GRB host galaxies are actually subluminous dwarf galaxies, as they appear in the optical view, or dusty active star-forming galaxies, as they seem to be in the submillimeter band, measurements with sensitivity to star formation activity as high as that of the optical/UV methods must also be performed in other wavelengths. CO measurements have the potential to become one such method, especially by virtue of future instruments with higher sensitivity, such as the Atacama Large Millimeter/Submillimeter Array (ALMA).

5. CONCLUSION

No CO $J = 1{-}0$ emission was detected from the GRB 030329 host galaxy. The 3 σ upper limit on the CO $J = 1{-}0$ line luminosity of the host galaxy is $3\delta L'_{\rm CO} = 6.9 \times 10^8$ K km s^{-1} pc^2. The lower limit to the host galaxy's metallicity is estimated to be $12 + \log({\rm O/H}) \sim 7.9$, which yields a CO line luminosity–to–H_2 conversion factor of $\alpha_{\rm CO} = 40\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$. Assuming this $\alpha_{\rm CO}$ factor, the 3 σ upper limit on the molecular gas mass of the host galaxy is $3\delta M_{\rm H_2} = 2.8 \times 10^{10}\ M_\odot$. Using the Schmidt law, the 3 σ upper limit on the total star formation rate of the host galaxy is estimated to be $3\delta{\rm SFR} = 38\ M_\odot$ yr^{-1}. Though the host galaxy of GRB 030329 is most likely a compact dwarf galaxy as seen in the optical band, multiwavelength observations of GRB host galaxies are still essential to estimating their SFRs accurately, in order to reveal the nature of their star formation activity. The CO line observations will play an important role as an independent SFR estimator, free from dust extinction and ambiguity in dust temperature.

We would like to acknowledge the referee for invaluable comments. We wish to thank the NRO staff for operating the telescopes and for their continuous efforts to improve the performance of the instruments. NRO is a branch of the National Astronomical Observatory, National Institute of Natural Sciences, Japan. This study was financially supported by a MEXT Grant-in-Aid for Scientific Research on Priority Areas (No. 15071202). A. E., T. O., and K. M. were financially supported by Japan Society for the Promotion of Science (JSPS) Research Fellowships for Young Scientists.

Facilities: NoMA

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