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A Search for CO ($J = 3$–2) Emission from the Host Galaxy of GRB 980425 with the Atacama Submillimeter Telescope Experiment

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Abstract

We report on a deep search for ^{12}CO (J = 3–2) line emission from the host galaxy of GRB 980425 with the Atacama Submillimeter Telescope Experiment (ASTE). We observed five points of the galaxy, covering the entire region. After combining all of the spectra, we obtained a global spectrum with a rms noise level of 3.3 mK in the $T_{\rm mb}$ scale at a velocity resolution of 10 $\mathrm{km\,s^{-1}}$. No significant emission was detected, though we found a marginal emission feature in the velocity range corresponding to the redshift of the galaxy. We derived 3 σ upper limits on the global properties: the velocity-integrated CO (3–2) intensity of $I_{\rm CO}$(3–2) < 0.26 K $\mathrm{km\,s^{-1}}$, by adopting a velocity width of 67 $\mathrm{km\,s^{-1}}$; an H_2 column density of $N(\mathrm{H_2}) < 3 \times 10^{20}\mathrm{cm^{-2}}$; a molecular gas mass of $M(\mathrm{H_2}) < 3 \times 10^8\ M_\odot$, by assuming a CO line luminosity to H_2 molecular gas mass conversion factor of $X_{\rm CO} = 5.0 \times 10^{20}\ \mathrm{cm^{-2}\ (K\ km\ s^{-1})^{-1}}$; and a star-formation rate of SFR $< 0.1\ M_\odot\ \mathrm{yr^{-1}}$, based on the Schmidt law. The SFR is consistent with the previous results of Hα and mid-IR observations, thereby suggesting that there is no significant obscured star formation in the host galaxy of GRB 980425. This result implies that there is a variety of GRB hosts with regard to the presence of obscured star formation.

Key words: galaxies: ISM — gamma rays: bursts — gamma rays: individual (GRB 980425)

1. Introduction

Long-duration gamma-ray bursts (GRBs)—the most energetic event in the universe—are considered to be due to the death of massive stars (e.g., Galama et al. 1998; Stanek et al. 2003). Therefore, GRBs are closely associated with the star formation of host galaxies. Since GRBs can be detected at cosmological distances (the current record is $z = 6.3$ for GRB 050904; Kawai et al. 2006), they are expected to be probes of the star-formation history of the universe (e.g., Totani 1997; Yonetoku et al. 2004). In order to determine the use of GRBs, it is essential to understand the star-formation activity of their hosts.

Multiwavelength observations have shown that GRB hosts are typically blue, sub-luminous dwarf galaxies (e.g., Le Floc'h et al. 2003) with low metallicity (e.g., Fynbo et al. 2003). The star-formation rates (SFRs) determined from optical/UV observations are $\sim$ 1–10 $M_\odot\ \mathrm{yr^{-1}}$. On the other hand, submillimeter and radio continuum observations indicate that some GRB hosts are dusty and have massively star-forming properties (SFR $\sim$ several 100 $M_\odot\ \mathrm{yr^{-1}}$) (Berger et al. 2003). There is a wide discrepancy between the SFRs derived from optical/UV and those from submillimeter/radio. Mid-IR observations further complicate the situation; only a small fraction of GRB hosts are detected at mid-IR wavelengths, in contrast with the image of submillimeter/radio observations (Le Floc'h et al. 2006). These methods for deriving the SFRs each have their own drawbacks. Because optical/UV bands are subject to dust extinction, the SFRs may be underestimated. Mid-IR, far-IR, and radio continuum are susceptible to contamination from active galactic nuclei (AGNs). The SFRs derived from the submillimeter continuum have uncertainties in the assumption of the dust temperature and the emission spectrum.

In order to solve these problems, it is necessary to derive the SFRs by a method that is independent of existing methods, and not affected by dust extinction and AGNs. For this purpose, an effective method is to observe the CO line. The CO line traces molecular gas, which is a fuel for star formation. Thus far, the search for CO (J = 1–0) emission from the host galaxy of GRB 030329 using the Nobeyama Millimeter Array

Table 1. Properties of the host galaxy of GRB 980425.*

RA (J2000.0) (1)	Decl (J2000.0) (2)	z (3)	i (deg) (4)	M_B (mag) (5)	$L(\mathrm{H}\alpha)$ ($\mathrm{erg\,s^{-1}}$) (6)	$L(\mathrm{IR})$ ($L_\odot$) (7)	$\log(\mathrm{O/H})+12$ (8)
$19^{\mathrm{h}}35^{\mathrm{m}}04\overset{\mathrm{s}}{.}4^{\dagger}$	$-52°50'38''^{\dagger}$	$0.0085 \pm 0.0002^{\ddagger}$	$30^{\dagger}$	$-17.65^{\S}$	$4.4 \times 10^{40}\ ^{\S}$	$2 \times 10^{9}\ ^{\|}$	$8.6^{\S}$

* (1) Right ascension. (2) Declination. (3) Redshift. (4) Inclination. (5) Absolute magnitude. (6) Hα luminosity. (7) IR luminosity determined by using the correlations between mid-IR luminosity and 8–1000 μm integrated emission. (8) Metallicity.
† 2MASS. ‡ Tinney et al.(1998). § Sollerman et al.(2005). ‖ Le Floc'h et al.(2006).

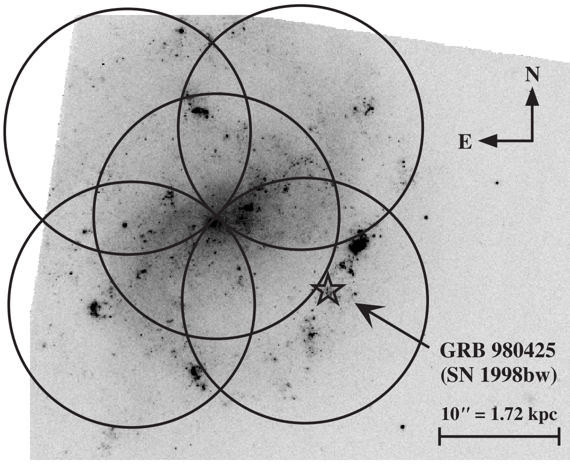

Fig. 1. Hubble Space Telescope image (Fynbo et al. 2000) and ASTE observation beams (circles). The HPBW of 22″ corresponds to 3.8 kpc at the distance of the galaxy. The position of the GRB is marked with a star.

(Kohno et al. 2005; Endo et al. 2007) has been reported as the only attempt in this regard. However, only upper limits of the molecular gas mass and SFR of the host galaxy have been obtained. Since current instruments have limitations, it appears that target selection is essential to detect CO line emission.

In this paper, we report on observations of the $J = 3$–2 transition line of ^{12}CO in the host galaxy of GRB 980425 using the Atacama Submillimeter Telescope Experiment (ASTE: Kohno et al. 2004; Ezawa et al. 2004). GRB 980425 emerged in an H II region in a spiral arm and was identified with SN 1998bw (type Ic supernova). Its isotropic γ-ray energy of $\sim 8 \times 10^{47}$ erg is significantly less than that of typical GRBs by several orders of magnitude (Galama et al. 1998). The host galaxy termed ESO 184-G82 (figure 1) is the nearest GRB host known to date. The redshift of $z = 0.0085 \pm 0.0002$ (Tinney et al. 1998) is extremely low among GRB hosts (the mean redshift is $z = 2.8$; Jakobsson et al. 2006). Due to the proximity, it is the best target to detect CO line emission. The host galaxy is a blue, sub-luminous, and low-metallicity star-forming galaxy (see table 1). SFR is derived from previous Hα, mid-IR, and hard X-ray observations as 0.35 $M_\odot\ \mathrm{yr}^{-1}$ (Sollerman et al. 2005), 0.4 $M_\odot\ \mathrm{yr}^{-1}$ (Le Floc'h et al. 2006), and $2.8 \pm 1.9\ M_\odot\ \mathrm{yr}^{-1}$ (Watson et al. 2004) respectively. The discrepancy between the SFRs derived from the X-ray and Hα observations implies that the host galaxy contains a large amount of molecular gas. The detection of CO line emission is simplified by the fact that the galaxy has one of the highest values of metallicity—[log(O/H)+12] = 8.6 (Sollerman et al. 2005)—among GRB hosts (e.g., Stanek et al. 2006).

We assume a cosmology with $H_0 = 71\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\mathrm{M}} = 0.27$, and $\Omega_\Lambda = 0.73$. The luminosity distance of GRB 980425 is $D_{\mathrm{L}} = 36.1$ Mpc and the angular distance is $D_{\mathrm{A}} = 35.5$ Mpc (1″ corresponds to 0.172 kpc).

2. Observations and Data Reduction

Observations of ^{12}CO ($J = 3$–2) were conducted using the ASTE on 2005 June 14–22. The ASTE is a single-dish 10 m submillimeter telescope at Pampa la Bola, Chile, equipped with a 4 K cooled superconductor-insulator-superconductor (SIS) mixer receiver (Sekimoto et al. 2001; Muraoka et al. 2007). The observations were carried out remotely from ASTE operation rooms in San Pedro de Atacama, Chile, and in Mitaka, Japan, by using the network observation system N-COSMOS3, developed by the National Astronomical Observatory of Japan (NAOJ) (Kamazaki et al. 2005). The observation frequency was set to the redshifted ^{12}CO ($J = 3$–2) line of 342.882 GHz at the upper side band (USB). The half-power beam width (HPBW) was 22″, corresponding to 3.8 kpc at the distance of the galaxy. We used 4 digital spectrometers (A1, A2, A3, and A4) with a bandwidth of 512 MHz and 1024 channels (Sorai et al. 2000). A1 and A2 were configured at the center of the USB, and A3 and A4 were moved from the center by ∓256 MHz respectively to cover a bandwidth of 1024 MHz ($\sim 900\ \mathrm{km\,s^{-1}}$). The weather was good during the observations and the system temperature was in the range of 250–750 K in DSB. In order to cover the entire region of the galaxy, we observed 5 points around the host galaxy center with a spacing of 11″, including the GRB position (see figure 1). The sky emission was subtracted by position switching. The pointing was checked every few hours using the CO (3–2) emission of W Aql and continuum emission of Mars, and the accuracy was within 3″. The intensity calibration was performed by the chopper wheel method. Absolute intensity calibration was performed by observing the CO (3–2) emission of M 17 SW and assuming that the velocity-integrated CO (3–2) intensity, $I_{\mathrm{CO}}(3$–$2)$, is 536.3 $\mathrm{K\ km\,s^{-1}}$ (Wang et al. 1994). The main beam efficiency was measured to be 0.59–0.64 during the observations, and we adopted a constant value of 0.62.

Data reduction was carried out using NEWSTAR GBASE developed by the Nobeyama Radio Observatory (NRO). We used only data when the system temperature was less than 500 K. The total integration time was about 3 hours at the host

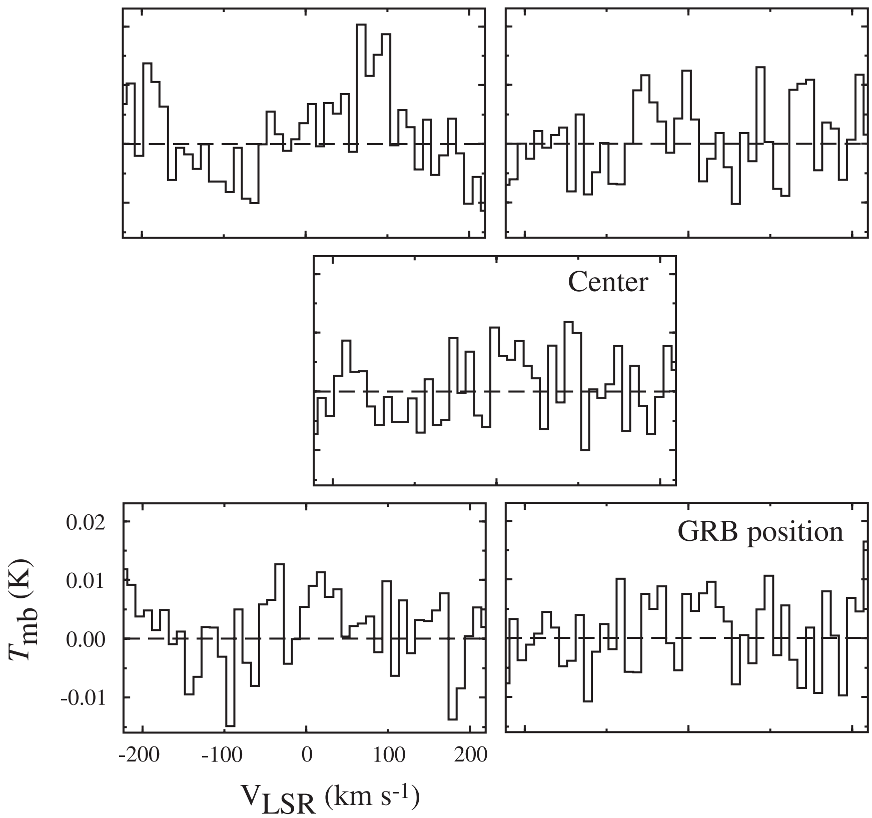

Fig. 2. Spectra of five observation points at a velocity resolution of $10\,\mathrm{km\,s^{-1}}$. The peak main beam temperatures are $\sim$ 13–20 mK. The rms noise levels are $\sim$ 6 mK in T_{mb} scale.

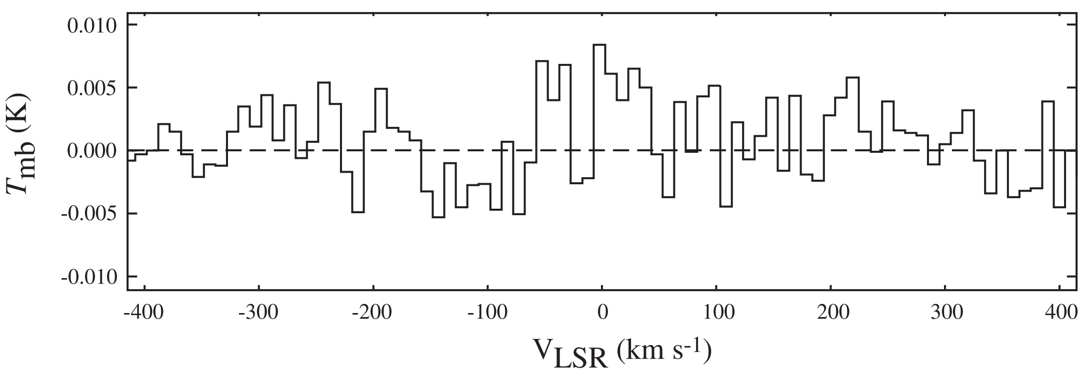

Fig. 3. Global spectrum at a velocity resolution of $10\,\mathrm{km\,s^{-1}}$. This exhibits the global property of the host galaxy of GRB 980425. The rms noise level is 3.3 mK in the T_{mb} scale.

galaxy center and about 1.5 hours at the other points. Linear baselines were subtracted from each spectrum. The rms noise level decreased with the square root of time, thereby indicating that the system was sufficiently stable for long integration.

3. Results

The spectra of 5 points using the data of spectrometers A1 and A2 are shown in figure 2. The rms noise levels are $\sim$ 6 mK in the scale of main beam temperature (T_{mb}) at a velocity resolution of $10\ \mathrm{km\,s^{-1}}$. By combining all spectra of 4 spectrometers, we obtained a global spectrum covering $\sim 800\,\mathrm{km\,s^{-1}}$ with the rms noise level of 3.3 mK in T_{mb} scale at a velocity resolution of $10\ \mathrm{km\,s^{-1}}$ (figure 3). When combining, we cut out 10% of the bandwidth of both ends, since the sensitivity is low. No significant emission was detected, although there seemed to be an emission feature at the center of the global spectrum. More observations are needed to confirm this possibility.

We now discuss the 3 σ upper limits on the global properties of the host galaxy. In order to estimate an upper limit of I_{CO}(3–2), we assume the velocity width of the galaxy.

Table 2. $3\,\sigma$ upper limits of the global properties of the host galaxy.*

$I_{\rm CO}$(3–2) (K km s^{-1}) (1)	N(H$_2$) (cm^{-2}) (2)	$\Sigma_{\rm H_2}$ ($M_\odot$ pc^{-2}) (3)	M(H$_2$) ($M_\odot$) (4)	SFR ($M_\odot$ yr^{-1}) (5)
0.26	3×10^{20}	5	3×10^{8}	0.1

* (1) Velocity-integrated CO(3–2) line intensity. (2) H_2 column density. (3) H_2 surface density. (4) Molecular gas mass. (5) Star formation rate.

In the sample of Leroy et al. (2005), rotation velocities of 115 dwarf galaxies ($M_B \gtrsim -18$) are in the range 21–150 $\mathrm{km\,s^{-1}}$ and the average is 67 $\mathrm{km\,s^{-1}}$. Correcting for the inclination of the host galaxy multiplying the velocity by 2, we assume a velocity width of 67 $\mathrm{km\,s^{-1}}$. The rms of the global spectrum at this velocity resolution is 1.3 mK, and therefore the $3\,\sigma$ upper limit of $I_{\rm CO}$(3–2) is 0.26 $\mathrm{K\,km\,s^{-1}}$.

4. Discussion

4.1. H_2 Column Density

The $3\,\sigma$ upper limit of the H_2 column density is calculated to be $3\times10^{20}\,\mathrm{cm^{-2}}$ as follows:

$$N(\mathrm{H_2}) = X_{\rm CO}\cdot I_{\rm CO}(3\text{–}2)\cdot R_{32/10}^{-1}\cdot \cos i, \tag{1}$$

where $X_{\rm CO}$ is a CO luminosity to the H_2 molecular gas mass conversion factor in units of $\mathrm{cm^{-2}}$ $(\mathrm{K\,km\,s^{-1}})^{-1}$, $R_{32/10}$ is the CO (3–2)/CO (1–0) integrated line intensity ratio, and i is the inclination of the disk. A conversion factor, $X_{\rm CO}$, is derived using the correlation between $X_{\rm CO}$ and the metallicity (Arimoto et al. 1996). By using the metallicity of the host galaxy of $[12+\log(\mathrm{O/H})] = 8.6$, $X_{\rm CO}$ is estimated to be $5.0\times 10^{20}\,\mathrm{cm^{-2}}$ $(\mathrm{K\,km\,s^{-1}})^{-1}$. $R_{32/10}$ is in the range of 0.2–1.2, depending on the type of the galaxy, such as nearby dwarf starburst galaxies, early-type galaxies, starburst spiral galaxies, luminous infrared galaxies (LIRGs), and ultraluminous infrared galaxies (ULIRGs) (Meier et al. 2001; Devereux et al. 1994; Mauersberger et al. 1999; Vila-Vilaró et al. 2003; Yao et al. 2003; Narayanan et al. 2005). In this paper we adopt $R_{32/10} = 0.4$, the typical value of the Galactic disk (Sanders et al. 1993).

4.2. Molecular Gas Mass

The $3\,\sigma$ upper limit of molecular gas mass of $M(\mathrm{H_2}) < 3\times10^{8}\,M_\odot$ is obtained from

$$M(\mathrm{H_2}) = \Sigma_{\rm H_2}\cdot S\cdot(\cos i)^{-1} \tag{2}$$

where $\Sigma_{\rm H_2}$ is the H_2 surface density, and S is the area of the total beam, which is subtended by the 5 observation beams. This is consistent with those of dwarf galaxies (Leroy et al. 2005; Meier et al. 2001).

4.3. Star Formation Rate

We derive the $3\,\sigma$ upper limit of star formation rate of 0.1 $M_\odot\,\mathrm{yr^{-1}}$ by applying the Schmidt law (Kennicutt 1998):

$$\mathrm{SFR} = 2.5\times10^{-4}\cdot(\Sigma_{\rm H_2})^{1.4}\cdot S\cdot(\cos i)^{-1}\ M_\odot\,\mathrm{yr^{-1}}. \tag{3}$$

This is consistent with the results of previous Hα observations (SFR = 0.35 $M_\odot\,\mathrm{yr^{-1}}$, Sollerman et al. 2005), considering the uncertainties stated above. This indicates that the host galaxy has no significant obscured star formation. This is also consistent with the value of mid-IR observations—SFR = 0.4 $M_\odot\,\mathrm{yr^{-1}}$ (Le Floc'h et al. 2006).

Figure 4 shows the SFRs of GRB hosts derived by several methods (see Endo et al. 2007 and references therein). The ordinate is the SFR determined from extinction-free wavelengths, such as the CO line, radio continuum, submillimeter continuum, infrared continuum, and X-rays. The abscissa is the SFR determined from optical lines (recombination and forbidden lines) and UV continuum. The diagonal indicates that the values of both axes are equal. The majority of the GRB hosts are located above this line, implying that they have a large amount of molecular gas and massive star formation obscured by dust. This tendency is observed in LIRGs, ULIRGs, and submillimeter galaxies but not in normal spiral galaxies (e.g., Young et al. 1996; Berger et al. 2003). On the other hand, our study shows that the host galaxy of GRB 980425 shows a different trend. This suggests that various GRB hosts exist in terms of the presence of obscured star formation.

5. Summary

We searched for ^{12}CO (J = 3–2) line emission from the host galaxy of GRB 980425 with the ASTE. Five points were observed around the host galaxy center covering the whole area. The results are as follows:

1. No significant emission was detected, but there seems to be a marginal emission feature in the velocity range corresponding to the redshift of the galaxy. After combining all spectra, we obtained a global spectrum with a rms noise level of 3.3 mK in the $T_{\rm mb}$ scale at a velocity resolution of $10\,\mathrm{km\,s^{-1}}$.
2. The $3\,\sigma$ upper limit of velocity-integrated CO (3–2) intensity is $I_{\rm CO}(3\text{–}2) < 0.26\,\mathrm{K\,km\,s^{-1}}$ by assuming a velocity width of $67\,\mathrm{km\,s^{-1}}$.
3. The $3\,\sigma$ upper limits of H_2 column density and molecular gas mass are $N(\mathrm{H_2}) < 3\times10^{20}\,\mathrm{cm^{-2}}$ and $M(\mathrm{H_2}) < 3\times10^{8}\,M_\odot$ respectively by adopting a CO (3–2)/CO (1–0) integrated line intensity ratio of $R_{32/10} = 0.4$ and a CO luminosity to H_2 molecular gas mass conversion factor of $X_{\rm CO} = 5.0\times10^{20}\,\mathrm{cm^{-2}}$ $(\mathrm{K\,km\,s^{-1}})^{-1}$. These are consistent with the values of nearby dwarf galaxies.
4. The $3\,\sigma$ upper limit of the star-formation rate is SFR $< 0.1\,M_\odot\,\mathrm{yr^{-1}}$, based on the Schmidt law. This is consistent with the results of Hα and mid-IR observations, suggesting that there is no significant obscured star formation in the host galaxy of GRB 980425. This result

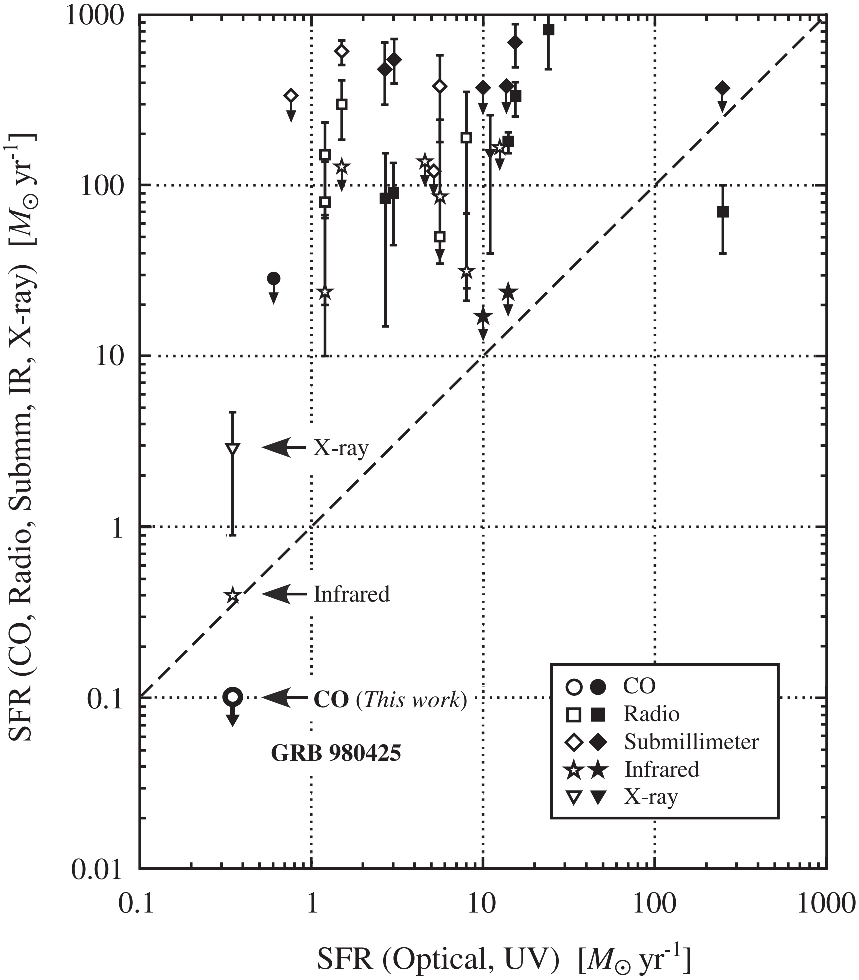

Fig. 4. Comparison of the SFRs of GRB hosts determined by various observational methods. The ordinate is the SFR derived by extinction-free methods such as the CO line, radio continuum, submillimeter continuum, infrared continuum, and X-rays. The abscissa is the SFR from optical (recombination and forbidden lines) and UV continuum. The data are based on Endo et al. (2007). The open symbols are the SFRs that are corrected for extinction in the host galaxies, and the solid symbols are those that are not corrected. The down-pointing arrows represent upper limits. The diagonal indicates equal values for both axes. It is clear that most of the GRB hosts are above this line, that is, the SFRs from the extinction-free methods are higher than those from the optical/UV bands even after extinction correction. On the other hand, the host galaxy of GRB 980425 show a different trend.

implies that various GRB hosts exist in terms of the presence of obscured star formation.

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