A CO EMISSION LINE FROM THE OPTICAL AND NEAR-IR UNDETECTED SUBMILLIMETER GALAXY GN10

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ABSTRACT

We report the detection of a CO emission line from the submillimeter galaxy (SMG) GN10 in the GOODS-N field. GN10 lacks any counterpart in extremely deep optical and near-IR imaging obtained with the Hubble Space Telescope and ground-based facilities. This is a prototypical case of a source that is extremely obscured by dust, for which it is practically impossible to derive a spectroscopic redshift in the optical/near-IR. Under the hypothesis that GN10 is part of a proto-cluster structure previously identified at \(z \approx 4.05\) in the same field, we searched for CO[4–3] at 91.4 GHz with the IRAM Plateau de Bure Interferometer, and successfully detected a line. We find that the most likely redshift identification is \(z = 4.0424 \pm 0.0013\), based on: (1) the very low chance that the CO line is actually serendipitous from a different redshift; (2) a radio–IR photometric redshift analysis; (3) the identical radio–IR spectral energy distribution, within a scaling factor of 2 other SMGs at the same redshift. The faintness at optical/near-IR wavelengths requires an attenuation of \(A_V \sim 5–7.5\) mag. This result supports the case that a substantial population of very high-z SMGs exists that has been missed by previous spectroscopic surveys. This is the first time that a CO emission line has been detected for an SMG that is invisible in the optical and near-IR. Our work demonstrates the power of existing and planned facilities for completing the census of star formation and stellar mass in the distant universe by measuring redshifts of the most obscured galaxies through millimeter spectroscopy.

Key words: cosmology: observations – galaxies: formation – galaxies: high-redshift – galaxies: starburst – infrared: galaxies – submillimeter

1. INTRODUCTION

Dust extinction at UV and optical rest-frame wavelengths is a major obstacle for obtaining a complete sampling of star formation in the distant universe. GN10 (also known as GOODS 850-5) is one of the most striking examples of an extremely obscured dusty galaxy. Discovered as a submillimeter emitting galaxy (SMG) by Wang et al. (2004; \(S(850 \mu m) = 12.9 \pm 2.1\) mJy), it was later confirmed as one of the brightest galaxies in the GOODS-N region at wavelengths between 850 \(\mu m\) and 1.25 mm (Pope et al. 2006; Dannerbauer et al. 2008; Greve et al. 2008; Perera et al. 2008). Its accurate position on the sky was obtained through interferometric observations of the dust continuum by Wang et al. (2007) with a submillimeter array (SMA) at 870 \(\mu m\) and by Dannerbauer et al. (2008) at 1.25 mm with the IRAM Plateau de Bure Interferometer (PdBI) as well as in the radio at 1.4 GHz with the Very Large Array. The dust continuum emission in the submillimeter and millimeter regime corresponds to an extreme luminosity of order \(10^{13} L_{\odot}\) and a star formation rate of the order of 1000 \(M_{\odot}\) yr\(^{-1}\), provided that it is at \(z > 1\). Despite its huge ongoing star formation activity, the galaxy is undetected in the highly sensitive Hubble Space Telescope (HST) ACS imaging of Giavalisco et al. (2004) down to limits of \(AB \sim 29\) mag, and the galaxy is also undetected to similar levels in the deep near-IR imaging with Subaru and HST+NICMOS of Wang et al. (2009), while a faint but significant emission is seen in the GOODS Spitzer+IRAC data (Pope et al. 2006; M. Dickinson et al. 2009, in preparation).

Dannerbauer et al. (2008) estimated a redshift of \(z \sim 4\) for this galaxy using spectral energy distribution (SED) fitting and employing the radio–IR relation, while Wang et al. (2007) suggested an even higher \(z \sim 6\), interpreting the very red \(K - 3.6 \mu m\) color as being due to a strong, redshifted Balmer\/4000 Å break from an evolved stellar population. Due to its faintness, it is practically impossible to measure the redshift of GN10 by ordinary means of optical or near-IR spectroscopy. A Multiband Imaging Photometer (MIPS) flux density of \(S(24 \mu m) = 30 \mu m Jy\) makes it impossible to obtain a redshift with the Spitzer Infrared Spectrograph (IRS), a technique that has been successfully used for SMGs (Menéndez-Delmestre et al. 2007; Pope et al. 2008). The search for CO emission lines, successfully detected in SMGs (review by Solomon & van den Bout 2005), seems to be the only way of measuring a redshift for GN10 before the launch of JWST or the realization of greater than 30 m optical/near-IR telescopes. However, the most sensitive radio and millimeter facilities have quite limited bandwidths, which complicate blind line searches. For example, 3 mm observations with the PdBI cover the range of \(\Delta z/(1+z) \sim 0.01\), requiring an accurate foreknowledge of the redshift for CO observations.

Daddi et al. (2009, henceforth D09) proposed a new radio–IR photometric redshift technique capable of obtaining accuracies of \(\Delta z/(1+z) \sim 0.1\) for SMGs. However, this accuracy is still not sufficient for blind CO follow-up. D09 also reported the discovery of a proto-cluster structure at \(z = 4.05\) in GOODS-N that includes two SMGs (GN20 and GN20.2a). GN10 has a radio–IR photometric redshift consistent with being part of this proto-cluster structure.

In this Letter, we report on IRAM PdBI observations of GN10, searching for a possible emission line of CO at \(z \sim 4.05\) based on the hypothesis that GN10 is indeed a part of the proto-cluster structure.
2. OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

We observed GN10 with the IRAM PdBI using the full array (with six antennas) for 4.0 hr on source on 2008 May 27th in D-configuration (synthesized beam of 6′6 × 5′4), for 3.8 hr on 2008 November 27th in the C-configuration (synthesized beam of 5′4 × 3′0), and for 6.8 hr on 2008 December 29 and 2009 January 5 in B-configuration (synthesized beam of 1′7 × 1′3). A tuning frequency of 91.375 GHz was used, with a correlator setup yielding a bandpass of 1 GHz with two polarizations. In the B- and D-configuration observations GN10 was 19′7 away from phase center, suffering a primary beam attenuation (PBA) of 30%. Those data were obtained while observing a galaxy at \( z = 1.52 \) as part of a CO survey of normal galaxies described in Daddi et al. (2008) and E. Daddi et al. (2009, in preparation). In the C-configuration observations the phase center was at 9′7 away from GN10, leading to a PBA of 8%.

We reduced the data with the GILDAS software packages CLIC and MAP, similarly to what is described in D09 and Daddi et al. (2008). The maps obtained using natural weights have noise levels (for the full 1 GHz bandpass) of 113 \( \mu Jy \) beam\(^{-1} \), 87 \( \mu Jy \) beam\(^{-1} \), and 63 \( \mu Jy \) beam\(^{-1} \) for the D-, C-, and B-configuration data, respectively.

We extracted spectra by independently fitting the reduced \( uv \) data of the D-, C-, and B-configuration observations sampled with 75 km s\(^{-1} \) spectral bins, using a point source model. We corrected each spectrum for the PBA and averaged them with weighting according to the different noise levels. Figure 1 shows the result: significant emission is detected, consistent with a CO emission line centered at \(-192 ± 70 \) km s\(^{-1} \) (all velocities are given relative to the tuning frequency) and with a velocity FWHM of 770 ± 200 km s\(^{-1} \). Integrating the spectrum from \(-812.5 \) km s\(^{-1} \) to 387.5 km s\(^{-1} \) (i.e., a total bandwidth of 1200 km s\(^{-1} \)) results in a detection with signal-to-noise ratio (S/N) > 7 and a flux density of 0.74 ± 0.10 mJy. Integrating the spectrum outside the detected emission line results in a continuum estimate of 0.02 ± 0.09 mJy. Assuming this value for the continuum emission, and accounting for its uncertainty, we derive an integrated flux of 0.86 ± 0.16 Jy km s\(^{-1} \) for the emission line, which is consistent with that found from the Gaussian fit shown in Figure 1.

Figure 2 shows the line (top) and continuum (bottom) maps obtained combining the data from all configurations using natural weighting (resulting in a synthesized beam of 2′6 × 1′9). The emission line is clearly detected, only 0′4 to the west of the 1.25 mm continuum position of GN10 measured by Dannerbauer et al. (2008; see the cross in Figure 2, top). The line does not appear to be significantly resolved. A fit to the combined B-, C-, and D-configuration visibilities with a circular Gaussian model results in an FWHM = 0′6 ± 0′3.
3. REDSHIFT IDENTIFICATION

The detection of our single CO emission line at 91.4 GHz fixes the redshift as one of $1 + z_{CO} \sim 1.261 \times n$, in the case that the observed transition is CO$(n) - (n - 1)$.

![Figure 3. Radio–IR photometric redshift of GN10, using the technique described in D09. The top panel shows $\chi^2$ vs. redshift and the bottom panel the implied total IR luminosity. The black solid line shows the results allowing for a renormalization of the CE01 models in the fitting, while the red solid line was obtained by preserving the intrinsic normalization of the CE01 models. The dashed horizontal lines correspond to the 99% confidence level ranges. The vertical dotted lines show the permitted redshifts, given the detection of a CO line at 91.4 GHz.](image)

First, this line is not serendipitously detected. We obtained these PdBI observations in order to verify if GN10 is part of the GOODS-N field. Our observations searched for possible SMGs with 1 at $z = 4.042$ which also includes two other CO-detected SMGs (GN20 at $z = 4.05$ (D09)). Scaling them down by a factor of 1.8, all the flux measurements for GN20 at radio–IR wavelengths agree with GN10 within the uncertainties, including the CO$(4-3)$ emission line flux. A similar picture holds for GN20.2a (the exception is its 1.4 GHz flux that is likely affected by active galactic nucleus (AGN) emission, see D09).

4. DISCUSSION

Identification of the line as CO$(4-3)$ at $z = 4.042$ implies a CO luminosity of $L'_{CO} = 3.4 \times 10^{10}$ K km s$^{-1}$ pc$^2$. The IR to
The radio flux of $34.4 \pm 4.2 \mu$Jy (Dannerbauer et al. 2008) corresponds to $L_{\text{1.4GHz}} = 3.8 \times 10^{24} \text{ W Hz}^{-1}$. Together with our estimate of $L_{\text{IR}} = 1.2 \times 10^{13} L_{\odot}$, GN10 lies on the local radio–IR correlation (e.g., Yun et al. 2001), as found also for GN20 (D09).

While the SEDs of GN10, GN20, and GN20.2a are very similar at radio–IR wavelengths, the galaxies are quite different at wavelengths shorter than 10 $\mu$m, where the light is dominated by the emission of stars. GN20 and GN20.2a are classified as $B$-band dropouts in the HST+ACS imaging, and both are relatively luminous and blue in the UV rest frame. This indicates a relatively low extinction by dust. Instead, GN10 is undetected at UV and optical rest-frame wavelengths, implying overall a very strong extinction of the stellar light by dust.

It seems likely that the dust extinction in these galaxies is not homogeneous. Among the few known SMGs with confirmed CO redshifts (Capak et al. 2008; see also Schinnerer et al. 2008) all have significant offsets of the order of 0.5 or more between the detected (and relatively blue) UV emission and the radio or CO positions. This suggests a complex dust distribution with “holes” that, in some cases, allow us to directly observe the emission from stars. In the case of GN10, however, the UV/ optical light seems to be wholly obscured along our line of sight.

We now discuss what levels of extinction and reddening are required to explain the observed properties of GN10. We can use the photometry comparison to GN20 and GN20.2a to derive a first guess of the amount of extinction present, assuming that to first order the stellar mass to IR continuum luminosity ratio is the same within these galaxies. Normalizing the galaxies SEDs at wavelengths longer than 10 $\mu$m, GN10 is found to be $1 \pm 0.2$ mag fainter in the Infrared Array Camera (IRAC) bands (observed 0.7–1.6 $\mu$m rest frame) than both GN20 and GN20.2a. For a Calzetti et al. (2000) attenuation law this corresponds to $A_V \sim 5$ mag. If we fit the UV rest frame to near-IR rest-frame SED with constant star formation models from the Maraston (2005) library, this requires an even larger $A_V \sim 7.5$ mag, mainly to be consistent with the very deep flux limit from the $K$-band observations of Wang et al. (2009).

Figure 4 shows this fit (the red curve in the top panel) and its residuals (bottom panel). The fit is redder than the trend suggested by the IRAC bands. Fitting only the IRAC bands would suggest again a reddening of $A_V \sim 5$ mag. The $K$-band flux density upper limit by Wang et al. (2009) shown in Figure 4 is derived for a 0.6 aperture, but the stellar light might be well distributed over a larger region. In such a case a less stringent $K$-band upper limit would be allowed, and solutions with less attenuation than $A_V \sim 7.5$ mag would become plausible. We conclude that there is evidence for extreme obscuration, likely at some level between $A_V \sim 5$–7.5 for a Calzetti law. The fits imply a stellar mass of about $1 \pm 0.5 \times 10^{11} M_{\odot}$ (Chabrier IMF) for GN10. Given the case for extreme obscuration, this stellar mass estimate should be treated with some caution.

We note that the large CO[4–3] line width of about 770 km s$^{-1}$ (very similar to those for GN20 and GN20.2a) suggests a large dynamical mass, assuming that the size of the CO emission is typical (e.g., a few kpc; Tacconi et al. 2006). This would be consistent with the stellar mass that we derive. That stellar mass for GN10 is three times larger than the nominal completeness limit for the IRAC-selected sample of massive galaxy candidates at $z > 3.5$ from Mancini et al. (2009). However, GN10 is absent from the Mancini sample because it is fainter.
than the adopted IRAC magnitude limit ($m_{4.5, μm} < 23$ AB), due to its extreme attenuation. This illustrates how dust obscuration can be a significant limitation for constructing complete samples of galaxies in the distant universe, even when using surveys based on Spitzer IRAC data.

On the basis of the identification of the line as CO[4–3] at $z = 4.042$, GN10 is now the third SMG in the $z = 4.05$ GOODS-N proto-cluster structure. Our finding also supports the suggestion that there is indeed a substantial population of SMGs at $z > 4$ (e.g., Dannerbauer et al., 2002, 2004, 2008; Dunlop et al. 2004; Wang et al. 2007, 2009; Younger et al. 2007; Capak et al. 2008; Coppin et al. 2009; D09), with several others awaiting to be spectroscopically confirmed in GOODS-N (D09). Contrarily to GN20 and GN20.2a, GN10 is not surrounded by an excess of $B$-band dropout Lyman break galaxies: only two such objects are present within $25''$ from GN10, while 14 are found within the same distance from GN20. Of these two $B$-band dropout galaxies one has an optical spectroscopic redshift of $z = 4.053$ (Stern et al., in preparation; based on the detection of Lyα emission with Keck+DEIMOS), placing it in the proto-cluster structure, while the other has no known spectroscopic redshift. The on-sky separation between GN10 and GN20 is $9''$, or 4.0 Mpc comoving. The velocity separation of $Δv = 3900 \pm 600$ km s$^{-1}$ (from $Δz = 0.013 \pm 0.002$) corresponds to a line-of-sight distance of $9.3 \pm 1.2$ Mpc comoving (this is likely an upper limit, as part of the velocity separation could be due to peculiar velocities within the structure). GN10 is closer to GN20.2a both in the sky and in velocity space. It appears that the proto-cluster structure is fairly extended on the sky, and presumably several other vigorous starburst galaxies could also be part of this structure, as also suggested by D09. More work and observations are required for a full characterization of this interesting high-$z$ overdensity of galaxies.

This is the first time that the redshift of a far-IR bright source that is undetected at optical and near-IR wavelengths has been derived through measurement of CO lines. Our result clearly demonstrates that this will be a very powerful technique to identify the earliest and most obscured star-forming galaxies, in particular once wider band and/or more sensitive instruments will be available, such as the upcoming 8 GHz receiver upgrade for PdBI, the Redshift Receiver for the Large Millimeter Telescope (LMT), and the Atacama Large Millimeter Array (ALMA).

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### Table 1

| R.A._CO (J2000) | Decl._CO (J2000) | z_C | I_CO (Jy km s$^{-1}$) | Δv_PWHM (km s$^{-1}$) | L_CO^CIX (K km s$^{-1}$ pc$^2$) | L_IR (L_☉) | M_dars (M_☉) | M_gas (M_☉) | A_V (mag) |
|-----------------|-----------------|-----|----------------------|----------------------|----------------------|------------|-------------|-------------|---------|
| 12:36:33.389    | 62:14:08.94     | 4.0424 ± 0.0013 | 0.86 ± 0.16 | 770 ± 200 | 3.4 ± 0.6 × 10$^{10}$ | 1.25 ± 0.5 × 10$^{13}$ | ≈ 10$^{11}$ | 2.7 ± 0.5 × 10$^{10}$ | 5.0–7.5 |

Notes. Coordinates are from the CO[4–3] emission. Their formal error is 0''1 for both R.A. and decl. All CO-related quantities are based on the measurement of the CO[4–3] emission. The molecular gas mass derivation assumes that the CO[1–0] and CO[4–3] transitions have the same brightness temperature and a conversion factor $α_{CO} = 0.8$ M_☉ (K km s$^{-1}$ pc$^2$)$^{-1}$. The stellar mass is fairly uncertain (see the text), given the extreme reddening of the source. A_V is given for a Calzetti et al. (2000) reddening law.