Cold molecular gas in 3 massive star-forming galaxies discovered in the SXDF

Science Justification

The discovery of massive star-forming galaxies in blank-field extragalactic submm/mm-wavelength continuum surveys has opened a new window on the study of galaxy and large-scale structure formation at high-redshift (Smail, Ivison & Blain 1997; Hughes et al. 1998; Barger et al. 1998). The bulk of this population lies at $z > 2$, meaning that their FIR luminosities are $\gtrsim 10^{13}$ which, if powered mainly by star-formation would imply star-formation rates in excess of $1000 M_{\odot}$/yr, sufficient to build up the stellar mass of a giant elliptical galaxy in about 1 Gyr. In order to sustain such high rates of star-formation requires that large reservoirs of molecular gas be present in these (sub)mm galaxies (hereafter SMGs). The most powerful means of measuring the total molecular (and dynamical) mass of any FIR luminous object at high-redshift is through observations of the molecular CO line luminosity, which is known to be a robust tracer of molecular gas in the local Universe (Downes & Solomon 1998). Here, we propose to observe CO $J=1-0$ in 3 newly discovered SMGs, in order to determine if these objects do indeed contain very large masses of cold molecular gas.

To date, only 16 SMGs at $z > 1$ have been detected in CO line emission (see review by Solomon & Vanden Bout 2005), where most have been detected in either the $J=4-3$ or the $J=3-2$ transitions of CO in the 3 mm band (e.g. Neri et al. 2003; Greve et al. 2005). These observations have shown that the molecular gas masses for the SMGs are $\sim 10^{10} M_{\odot}$, while the typical dynamical masses are $\sim 10^{11} M_{\odot}$. Of those detected in high-$J$ CO line emission, only one of these has also been detected in CO $J=1-0$ line emission, namely SMM J13120+4242 at $z=3.408$, which was detected using the GBT (Figure 1; Hainline et al. 2006). Indeed, only 6 objects at $z > 2$ have been detected in CO $J=1-0$ line emission (Papadopoulos et al. 2001; Greve et al. 2004; Klamer et al. 2005; Riechers et al. 2006), and the GBT has been responsible for 3 of these detections. The selection criteria that these SMGs (and other high-z galaxy samples) are first observed in high-$J$ CO line emission before attempts are made to detect the much weaker CO $J=1-0$ line, may introduce a selection bias towards objects whose interstellar medium is warmer and denser than that of an ‘average’ SMG, so that the high-$J$ lines are more strongly excited.

As such, it is crucial that surveys of low-$J$ CO line emission in larger SMG samples be conducted, in order to provide unbiased mass estimates for the cold, possibly subthermal gas, which could constitute most of the total gas reservoir fueling the enormous starbursts, yet be virtually undetectable in the high-$J$ CO line transitions.

Prior to 2006, roughly 400 SMGs had been identified in small-area ($\lesssim 100$ sq. arcmins) blank-field submm/mm-wavelength surveys, and only $\sim 25\%$ of those had optical/infrared spectroscopic redshifts (e.g. Chapman et al. 2003; 2005). Originally motivated by this need for a larger sample of bright SMGs identified in a single wide-area survey, the largest 850 $\mu$m extragalactic survey to date has been the SCUBA Half Degree Extragalactic Survey (SHADES), a JCMT/SCUBA survey of the Lockman Hole and Subaru/XMM Deep Field. SHADES was intended to map a total area of 0.5 square degree down to an 850 $\mu$m rms of $\sim 2.2$ mJy (Mortier et al. 2005, hereafter M05). In addition, observations over a wide wavelength range (from the X-ray to the radio) exist for the SHADES survey fields (e.g. Ivison et al. 2007). One of the main goals is to determine whether SMGs are indeed the progenitors of present-day massive ellipticals. To achieve this goal, one could potentially measure the angular clustering strength of the SHADES sources, however the retirement of SCUBA in late 2005 meant that SHADES was only $\sim 40\%$ completed (Coppin et al. 2006), and the number of objects (120) is not sufficient to obtain a high significance measurement of the clustering amplitude. Thus, the most desirable means of testing whether these new SHADES sources will indeed evolve into massive, present-day ellipticals, is to measure their dynamical and molecular masses through observations of redshifted molecular CO line emission.

Given the early stage of the spectroscopic redshift follow-up efforts, only a small fraction of the SHADES optical/infrared counterparts currently have spectroscopic redshifts. As such, although a
large CO emission line survey of the SHADES sources is desirable, here we propose to observe the CO $J=1-0$ line in only 3 SMGs discovered in the SHADES 850\(\mu\)m survey of the SXDF. Of the 7 SXDF sources which have spectroscopic redshifts, only 3 of these have redshifts for which the CO $J=1-0$ line is redshifted into a frequency window that is accessible to the GBT receivers. These observations will provide

- unbiased estimates of their total molecular (=\(^2\)H\(_2\)) gas masses,
- estimates of their dynamical masses, and
- robust redshifts for the molecular emission line regions in these 3 SMGs, which would enable searches for weaker molecular and atomic species over narrower frequency intervals with other facilities such as the VLA.

**Technical Considerations**

The redshifts of our 3 targets require that we use the GBT K and Q-band receivers to detect CO $J=1-0$ line emission. We estimate the far-infrared luminosities for our three targets from their deboosted 850\(\mu\)m flux densities (table 1; Coppin et al. 2006). These FIR luminosities are estimated to be in the range, (6.4 – 14.0)\(\times\)10\(^{12}\) \(L_\odot\), so that by assuming the FIR to CO line luminosity relation observed in high-redshift objects (e.g. Riechers et al. 2006), we may estimate the expected CO $J=1-0$ line luminosities and peak fluxes for a 500 km/s line (Table 1). We note that these estimates could represent a lower limit to the true intensity in the CO $J=1-0$ line, as some of the SMGs may in fact have larger masses of cold molecular gas than is expected from their FIR luminosities (e.g. SMM J13120+4242; Hainline et al. 2006). The GBT is the only facility in the world with the combination of both spectral line sensitivity at Ka and Q-band and broad bandwidth capabilities required to achieve these science goals. The RA of our target sources (2\textdegree18\textquoteright) means that these proposed high frequency observations are ideally carried out during the winter semester, when they would transit at night while the dish surface is most likely to be stable.

The typical uncertainty in the CO redshift with respect to that of \(^{\prime}\La\) and H\(\alpha\) in high-redshift SMGs (~500 km s\(^{-1}\); Greve et al. 2005) means that the large bandwidth afforded by the GBT receivers is required in order to ensure that the CO $J=1-0$ lines are detected in our targets. We therefore propose to use 800 MHz of bandwidth, which allows for redshift uncertainties of ±3000 km s\(^{-1}\). Accurate CO redshifts are critical before follow-up observations of rest-frame (sub)mm wavelength transitions of additional molecular and atomic line species can be conducted using instruments with narrower available bandwidth. The optical spectroscopic redshifts for our 3 targets are 1.625, 3.0 and 3.3, meaning that the 115.2712 GHz CO $J=1-0$ line is redshifted to Q and K-band frequencies. Although the nominal K-band frequency range should be limited to frequencies below 26.5 GHz, while for two of our sources the CO $J=1-0$ line is redshifted to ~26.8 GHz, the HCN $J=1-0$ line in F10214+4724 (Vanden Bout, Solomon & Maddalena 2004) was detected at ~27 GHz and the receiver was found to perform well here. From the online GBT sensitivity estimator we can estimate the expected sensitivity of these proposed standard position switched observations. We assume $T_{sys}=80$ and 40 K (for the Q and K-bands, respectively) so that for $t_{on} = t_{off}=12600$ s, $N_{pol}=2$, the rms per 11.0 and 6.7 MHz (75 km/s) channel would be ~160 and 60 \(\mu\)Jy, respectively (3.5-\(\sigma\) detection in the peak channel). In the case of SXDF850.56, we would spend an additional 3 hours on-source in order to achieve the required rms of 50 \(\mu\)Jy per 100 km/s channel. If it were available at the time of these observations, we would use subreflector nodding in order to gain an additional ~15–20\% increase in sensitivity and flatter spectral baselines.

To detect CO $J=1-0$ in our 3 sources we request a total of 24 hours of on-source integration time, while an additional 3 hours per object is required to account for overhead costs (pointing, focus, and flux calibration), so that a total of 35 hours would be necessary to achieve our science goals. The
observing and data analysis (using gbtidl) will be conducted by Wagg and Greve, who have well over 100 hours of GBT observing experience through related projects (02A066, 02C025, 05A032, 05B041 05C047, 03C028, 05A032, 05B041 and 06C105; Greve et al. 2006; Wagg et al. 2007).

References


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Figure 1: GBT detection of CO $J=1-0$ line emission in the SMG; SMM J13120+4242 at z=3.4 (Hainline et al. 2006). The rms per 94 km/s channel is 0.16 mJy.
Figure 2: Simulated CO $J=1-0$ spectra of the 3 SMGs in our sample; SXDF850.28, SXDF850.7 and SXDF850.56 (from top to bottom). We have assumed 7 hours of on-source integration time (10 hours total) for each of the first two objects, and 10 hours of integration time (15 hours total) for SXDF850.56. We note that these are conservative estimates for the total line intensity in these objects, as previous observations of CO $J=1-0$ in a single SMG indicates that there may be an excess of cold gas in these systems above that which is indicated by the FIR luminosity.