Interferometric Followup of CO (1-0) Detections with the Zpectrometer

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Background

Why CO?

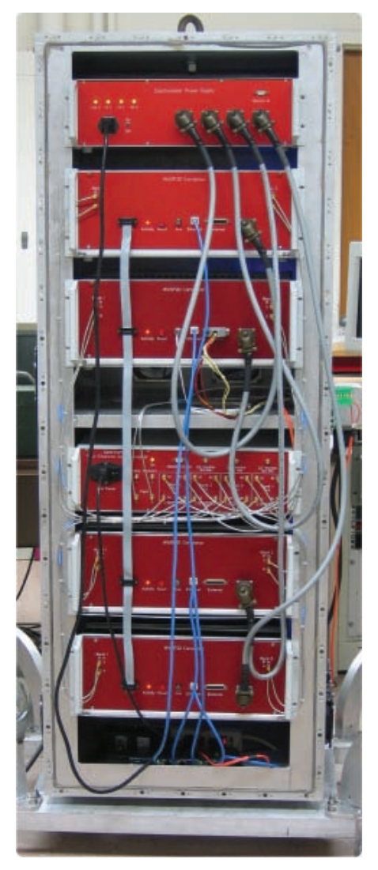
- CO is a stable and abundant tracer for molecular gas.
- Rotational transitions in CO are easily excited by collisions with H_2.
- Measurements of multiple rotational transitions can be used to create a CO sepctral line energy distribution (CO SLED), which when coupled with Large Velcocity Gradient (LVG) models can be used to determine properties of the gas such as temperature and number density (e.g., Weiss et al. 2005).

CO in Submillimeter Galaxies:

- Star formation in dusty, high-redshift submillimeter galaxies (SMGs) is fueled by molecular gas.
- Nearly all previous CO detections of SMGs have been in mid-*J* transitions.
- A prior CO (1–0) detection in an SMG (Hainline et al. 2006) had a broadened profile compared to mid-*J* lines, indicating a different dynamical state for the coldest gas component.
- This would be contrary to the single, thermalized component model advocated for SMGs based on the results of LVG models of CO SLEDs.

The Zpectrometer

The Zpectrometer is an ultra-wideband spectrometer for NRAO's Robert C. Byrd Green Bank Telescope (GBT) in West Virginia, optimized for the detection of low excitation CO lines at high redshifts (Harris et al. 2007).



The Zpectrometer opened up in lab at UMD.

Stats:

- 25.6–37.7 GHz range of the Ka band
- 20 MHz resolution
- CO (1–0) line within bandpass for sources at z = 2.2–3.6
- CO (2–1) line within bandpass for sources at z = 5.4–8.2

Designed to obtain flat, stable baselines:

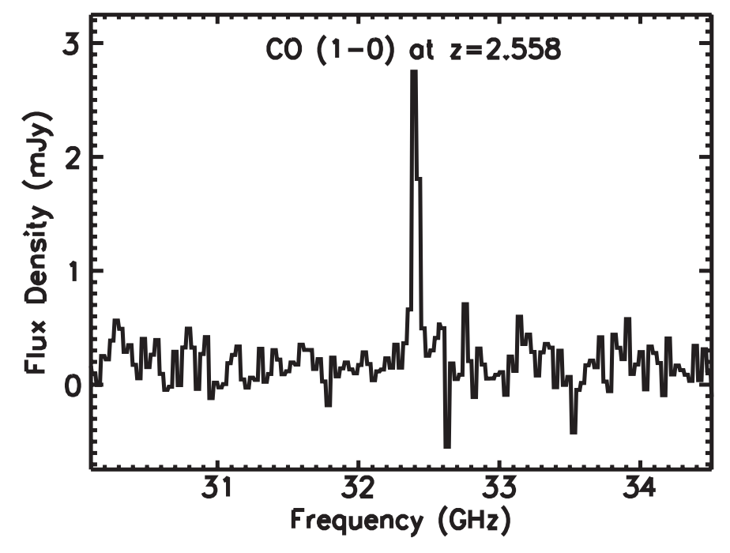
- 4x2 WASP2 analog lag cross-correlators (Harris & Zmuidzinas 2001) span the Ka band.
- Located in receiver cabin eliminating IF transport problems.
- Combination of subreflector nodding and position switching to a partner object results in the removal of nearly all baseline structure.

For more information, see: http://www.astro.umd.edu/~harris/kaband

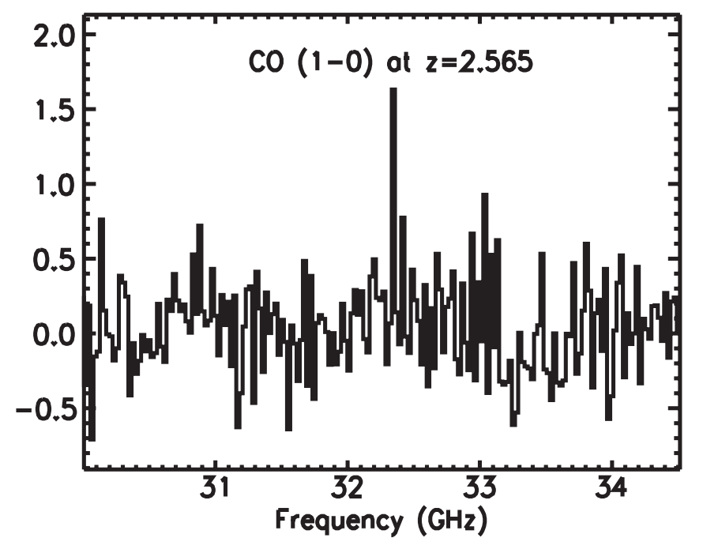
Zpectrometer Sources

- The initial survey sample of SMGs was meant to span a wide range of population characteristics: (1) objects with prior CO detections, (2) objects with approximate redshifts from PAH spectroscopy, and (3) objects without confirmed redshifts.
- The Zpectrometer has made positive detections of CO (1–0) lines in 3 SMGs of the orginal sample, plus an additional quasar (Harris et al. 2010): SMM J00266+1708, SMM J04431+0210, SMM J14011+0252, and HH1413+117 (the Cloverleaf).
- The Zpectrometer is an ideal tool for observing bright (>30 mJy) sources with unknown redshifts.

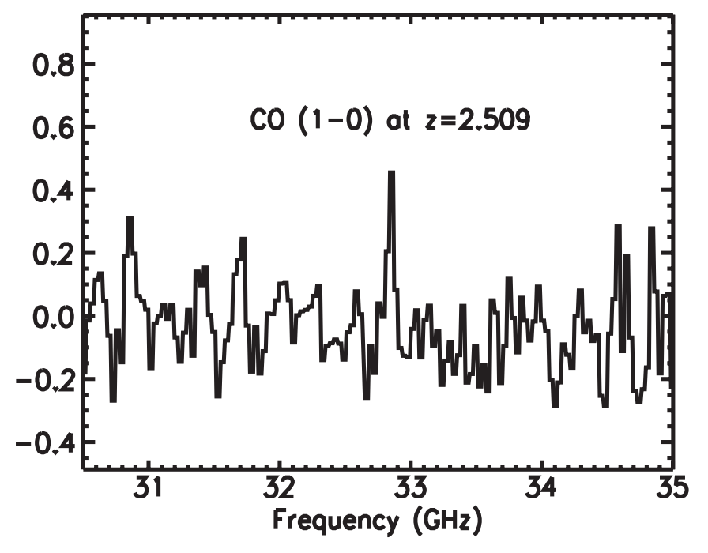
HH1413+117



SMM J14011+0252



SMM J04431+0210



Case Study: SMM J00266+1708

A Unique Opportunity:

- The uncommonly high obscuration of J00266 (as implied by its faint *J* and *K* magnitudes; Frayer et al. 2004) compared to other Plateau de Bure Interferometer (PdBI)-detected SMGs makes it an ideal candidate to probe the wide range of ISM geometries and/or physical conditions in these systems.
- As only one of two SMGs with CO detections of the lowest *J* level first, the CO spectral energy distribution can be built from the ground up, thus avoiding over-estimates of CO excitation from analyses possibly biased towards mid-*J* lines.
- Differing morphologies or line profiles between the lowest and mid-*J* transitions could indicate that the lines trace different gas volumes with a range in physical conditions; observations of multiple lines in J00266 could provide eveidence of a more complicated picture than the standard interpretation (Weiss et al. 2007) of thermalized, optically-thick CO emission.

Observations:

- J00266 was first detected in CO with the Zpectrometer in the winter of 2008 (see Fig.1; the prior Frayer et al. 2000 attempt to observe CO rotational lines failed due to an incorrect optical redshift and narrow OVRO bandwidth).
- We obtained 20 hours this fall on the PdBI in France to follow up our detecttion with mid-*J* observations of the *J* = 3–2 (Fig. 2–3) and *J* = 5–4 lines (Fig. 4).

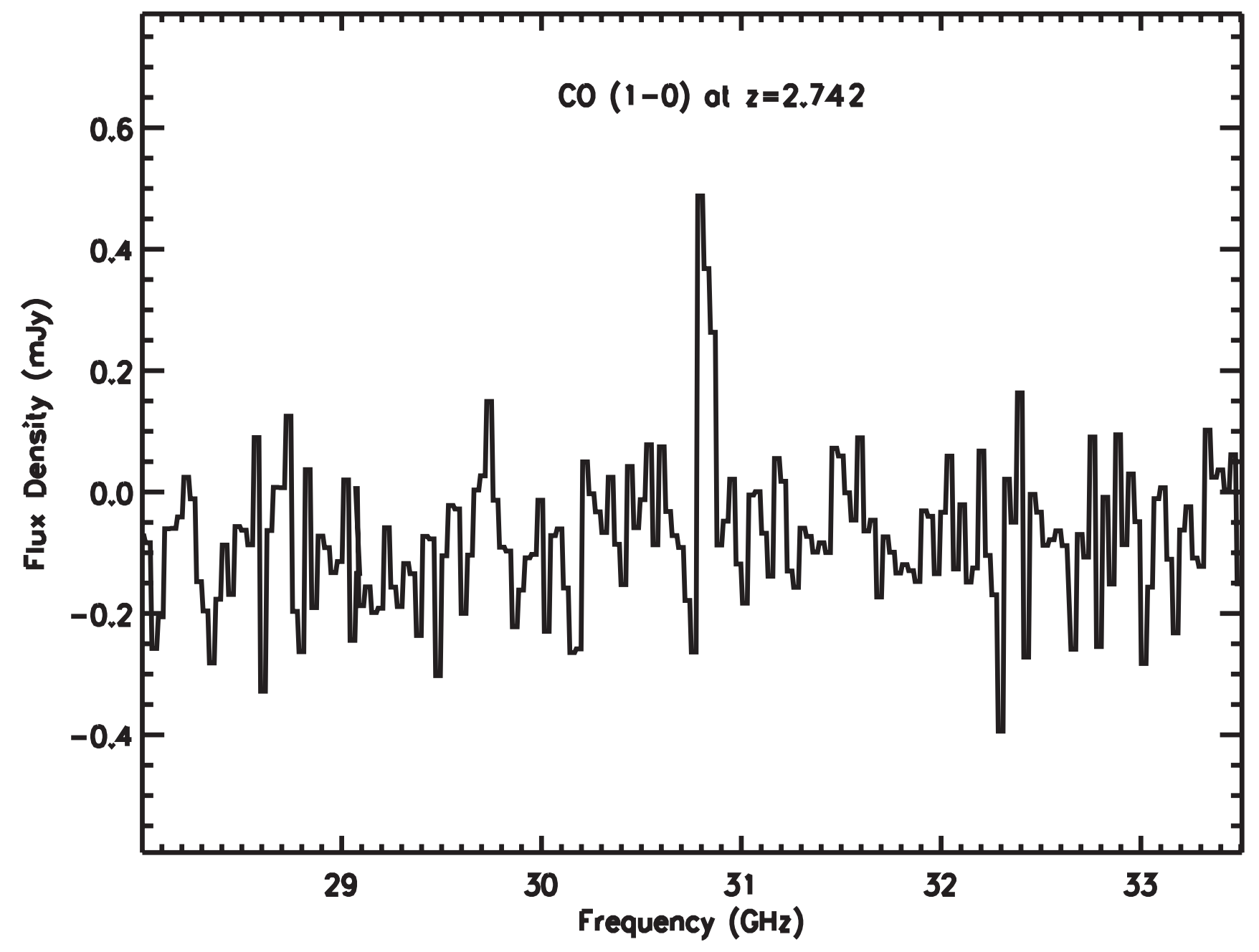


Fig. 1- CO (1–0) line as observed with the Zpectrometer. The line was measured to have a 0.095 ± 0.019 Jy km/s flux and FWHM = 334 ± 60 km/s (Baker et al. 2010).

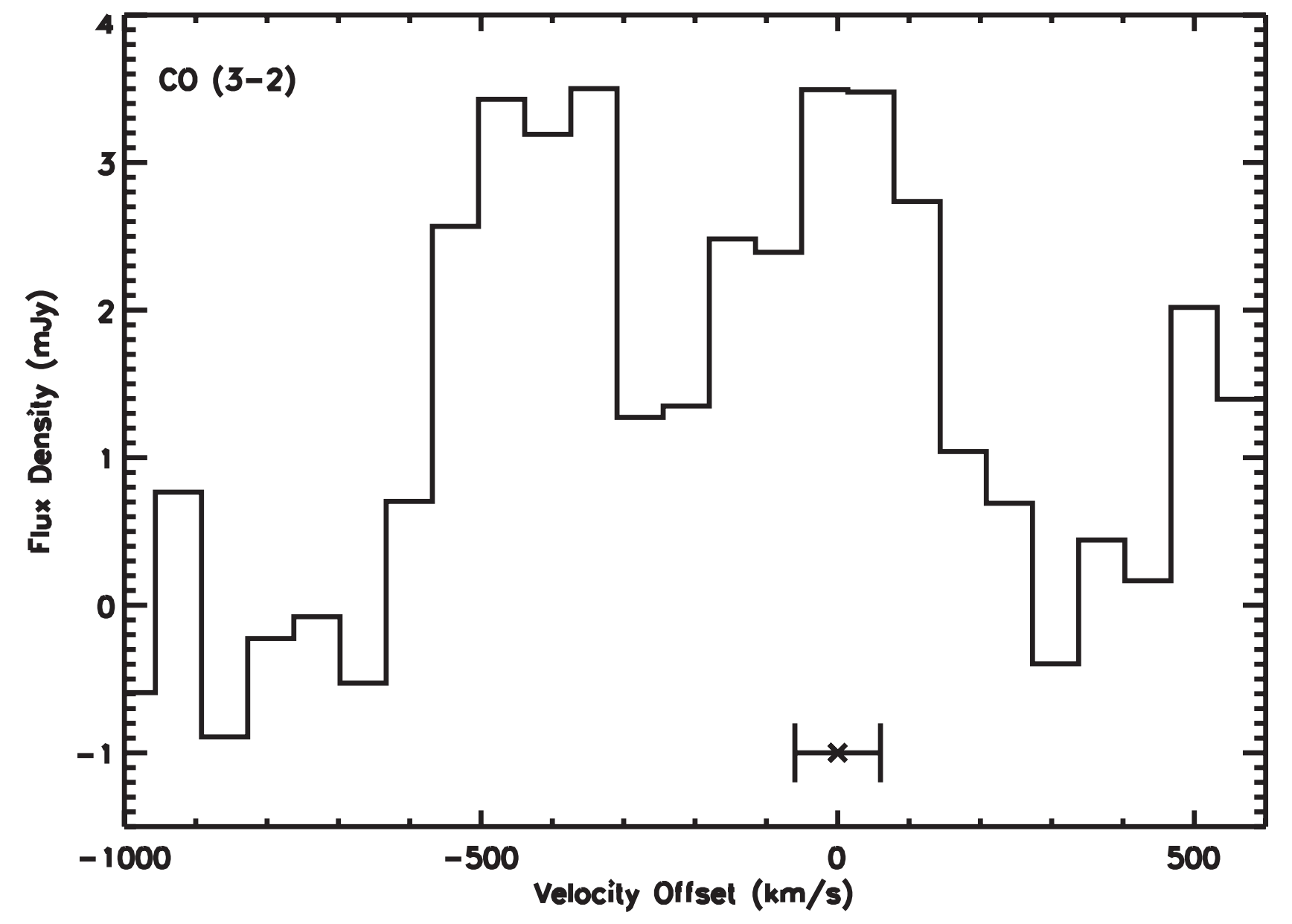


Fig. 2- CO (3–2) integrated spectrum as observed at the PdBI (velocity measured relative to CO (1–0) restframe; 1σ uncertainty shown). The initial estimate of the FWZI of the line is approximately 900 km/s, while the FWHMs of the blue and red peaks are 265 ± 36 km/s and 342 ± 38 km/s, respectively (Sharon et al. 2010).

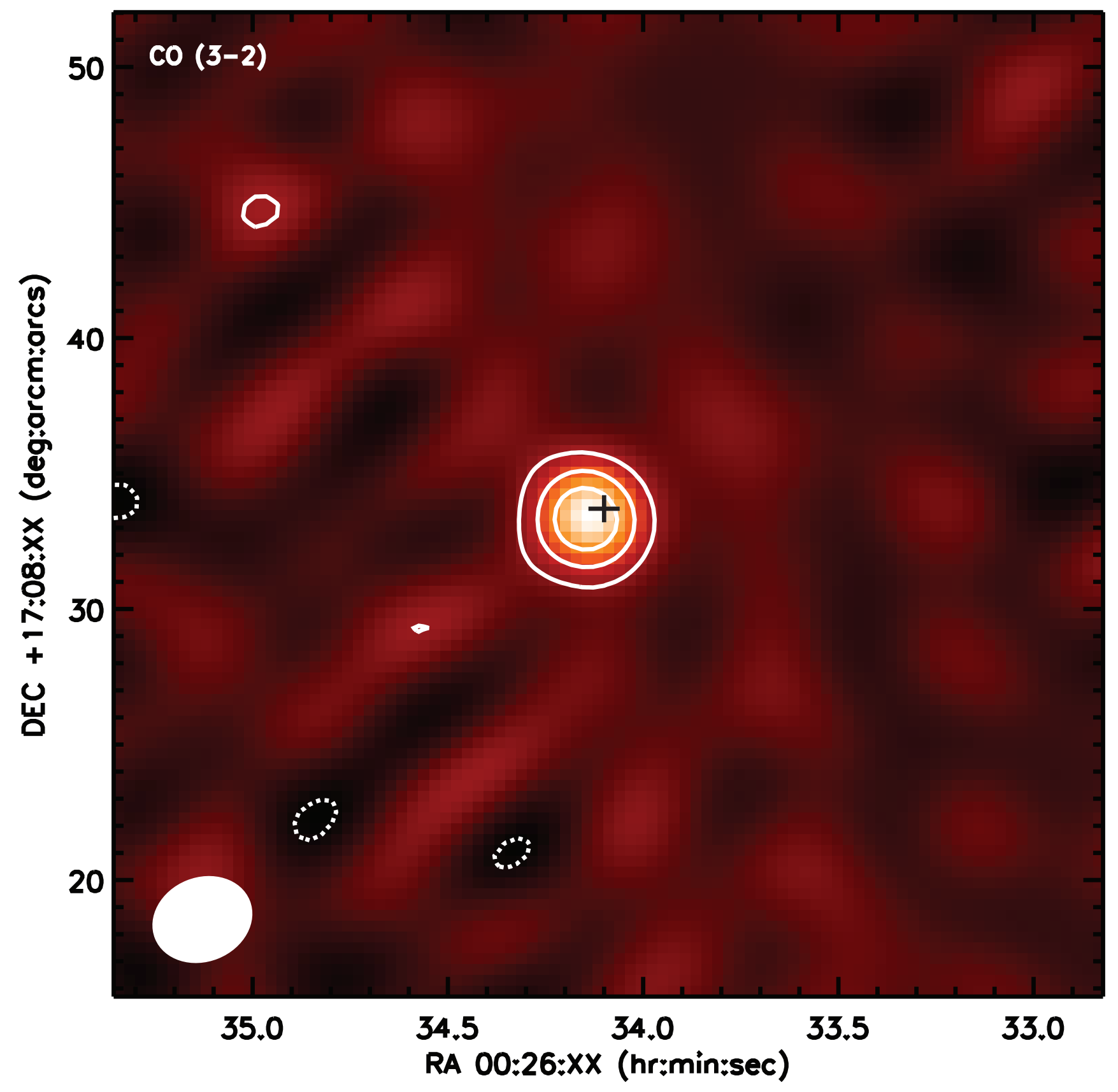


Fig. 3- Integrated CO (3–2) map as observed with the PdBI (contours are multiples of 3σ). The velocity-integrated line flux is 0.157 ± 0.012 Jy km/s. The black cross indicates the position and error of the OVRO 1.3 mm continuum detection (Frayer et al. 2000).

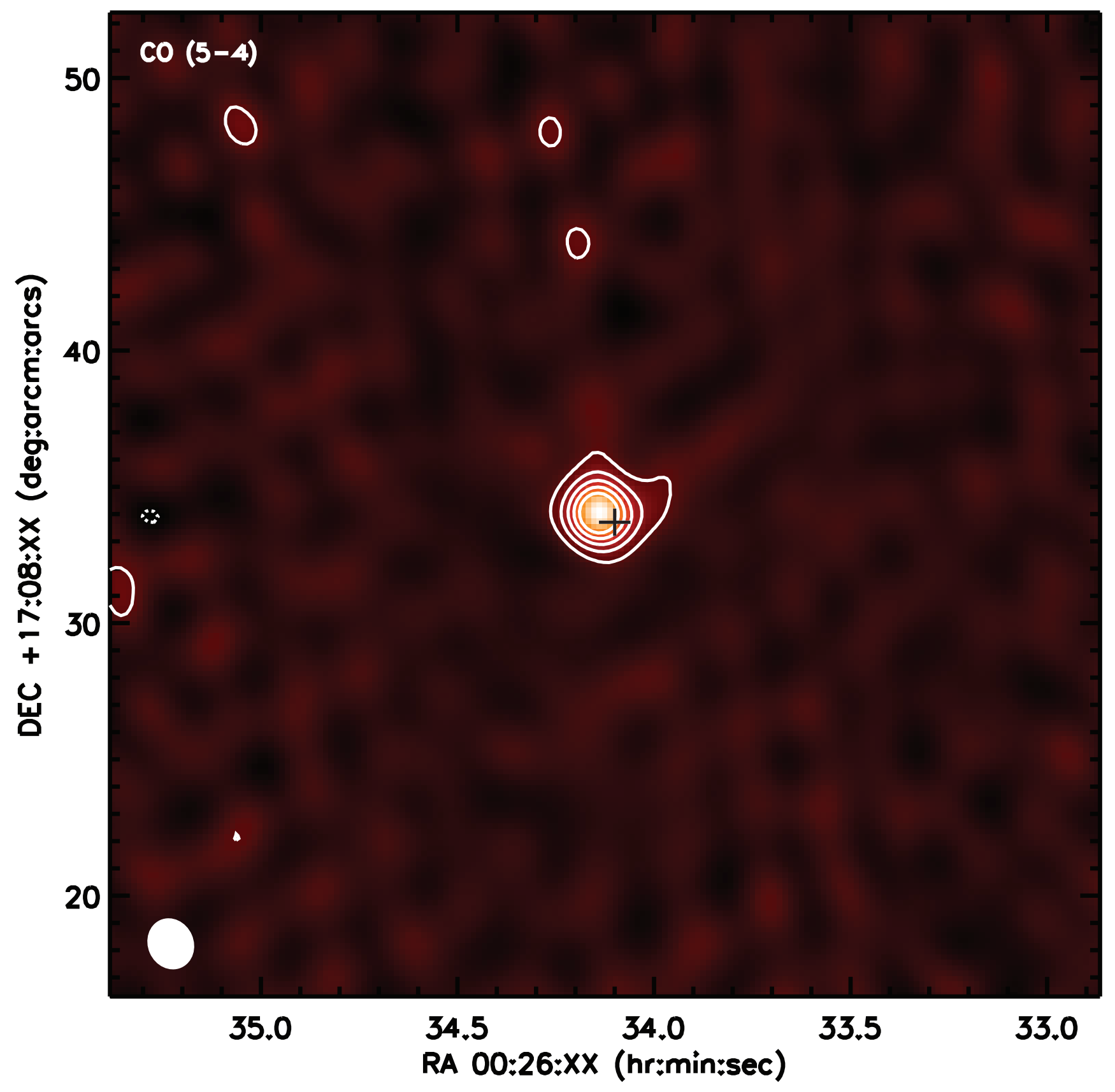


Fig. 4- Preliminary integrated CO (5–4) map as observed with the PdBI (contours are multiples of 3σ). The black cross indicates the position and error of the OVRO 1.3 mm continuum detection (Frayer et al. 2000).

Analysis

SMM J00266+1708 ($z = 2.742$, $\mu = 2.4^a$)

Transition	Peak	$S\Delta\nu^b$ (Jy km s^{-1})	FWHM (km s^{-1})	$L'_{\rm CO}{}^c$ (10^{10} K km s^{-1}pc^2)	$M_{\rm gas}{}^d$ ($10^{10}\ M_\odot$)
CO (1–0)		0.380 ± 0.074	334 ± 60	5.531 ± 1.079	4.425 ± 0.863
CO (3–2)	Total	1.445 ± 0.023	...	2.335 ± 0.036	2.448 ± 0.029
	Blue	0.660 ± 0.023	265 ± 36	1.067 ± 0.036	0.853 ± 0.029
	Red	0.785 ± 0.023	342 ± 38	1.269 ± 0.036	1.015 ± 0.029
CO (5–4)^e	Blue	1.329 ± 0.011	...	0.773 ± 0.006	0.619 ± 0.005

Note: Tabulated uncertainties do not include 10-20% flux calibration uncertainties.
[a] Lensing magnifcation from Frayer et al. 2000; [b] Measured, continuum corrected (0.7 mJy at 3 mm, and 1.2 mJy at 2 mm); [c] Magnification corrected; [d] Assumes ULIRG conversion factor $\alpha = 0.8\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$; [e] Analysis of the red peak is pending.

- From the integrated CO (5–4) map, the physical diameter of the blue component of J00266 is approximately 9 kpc. Assuming the system is dispersion dominated, $M_{\rm dyn} = 7 \times 10^{10}\ M_\odot$.
- The first moment map of the CO (5–4) line does show evidence of ordered rotation with $v_{\rm rot} = 30$ km/s. Based on this, $M_{\rm dyn} \sin^2 i = 9 \times 10^9\ M_\odot$.
- Assuming the CO (1–0) emission is associated with the red peak, and assigning a 3σ upper-limit to the blue peak, we can use an LVG analysis to compare the physical conditions of the gas in the two systems:
  - For the blue component, $T_{\rm kin} > 20$ K.
  - The blue component must have a higher column density than the red component for any temperature.
  - If we assume $T_{\rm kin} = 40$ K (reasonable for SMGs) for both components, the blue component is at least 10 times more dense than the red component.

Conclusions and Ongoing Work

- Our observations do show evidence that J00266 is a multi-component system with varying excitation conditions.
- The CO (1–0) emission is most likely associated with the red component in the CO (3–2) spectrum, which thus contains a large reservoir of cold gas.
- For thermalized optically thick CO emmision the line luminosities should be independent of the observed transitions; e.g., $L'_{\rm CO}(J = 1\text{–}0)$ should equal $L'_{\rm CO}(J = 3\text{–}2)$. This does not appear to be the case for either component.

CO (1-0) Maps:

- As most observations of dusty, high-redshift systems make use of amplification by gravitational lensing, interpretation of relative line luminosities is complicated by differential lensing.
- It is therefore crucial to map CO (1–0) lines to break degeneracies of coincidental agreement or disagreement with standard models of CO emission.
- In order to address this issue, we have attempted interferometric mapping of the CO (1–0) line in two highly-lensed Zpectrometer sources, HH 1413+117 (the Cloverleaf) and SMM J14011+0252, using the expanded frequency capabilities of the EVLA (data reduction is ongoing).

References: Baker, A. J. et al. 2010 (in preparation) • Frayer, D. T. et al. 2000, AJ, 120, 1668 • Frayer, D. T. et al. 2004, AJ, 127, 728 • Hainline, L. J. et al. 2006, ApJ, 650, 614 • Harris, A. I. & Zmuidzinas, J. 2001, Review of Scientific Instruments, 72, 1531 • Harris, A. I. et al. 2007, ASPCS, 375, 82 • Harris et al. 2010 (in preparation) • Sharon, C. E. et al. 2010 (in preparation) • Weiss, A. et al. 2005 A&A, 440, L45 • Weiss, A. et al. 2007 ASPCS, 440, 25

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