Completing the Molecular Gas Census at High Resolution in High-z Galaxies

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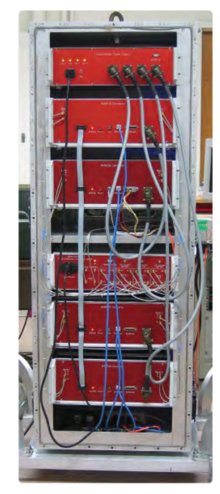
CO in High-z Galaxies

• Observations of CO rotational lines can be used to determine the physical conditions of the molecular gas that fuels star formation.

• Recent CO observations show that submillimeter galaxies (SMGs) have a common CO(3-2)/CO(1-0) line ratio of $r_{3,1}\approx0.6$ (in brightness temperature units; e.g., Swinbank et al. 2010; Harris et al. 2010; Ivison et al. 2011; Danielson et al. 2011) indicating the presence of multi-phase molecular gas, including a substantial cold gas reservoir.

• Quasar host galaxies have $r_{3,1}$ closer to unity, indicating they lack the cold molecular gas seen in SMGs, and are well-described by a single-phase molecular ISM (Riechers et al. 2011).

• These results highlight the need for CO spectral line energy distributions (CO SLEDs) to be complete down to the lowest-J transition (using instruments like the Zpectrometer; Harris et al. 2007) if we wish to determine high-z galaxies' star formation potential and their likely z~0 descendents.



The Zpectrometer opened up in lab at UMD.

Resolution Effects

• While $r_{3,1}$ is a powerful diagnostic for the presence of a multi-phase molecular ISM, more detailed characterizations of the gas physical conditions require full radiative transfer modeling (e.g., using the Large Velocity Gradient (LVG) approximation; Ward et al. 2003; Weiß et al. 2007).

• In order to be confident about radiative transfer results, we must be certain that the different CO lines are being emitted from the same gas clouds, which may not be the case in complicated sources like major mergers.

• Many studies of high-z sources also utilize the magnification provided by a gravitational lens; differential lensing (the variation in magnification factors across an extended source) could affect observed line ratios.

• Since low spatial and spectroscopic resolution observations can hide complicated source structures, interferometric mapping of the CO SLEDs at high resolution is necessary if we are to determine the gas conditions that accompany the large star formation rates seen in high-z galaxies.

SMM J00266+1708

• J00266 was first detected in the SCUBA Lens Survey (Smail et al. 2002).

• Initial CO observations failed due to an incorrect optically-determined redshift (Frayer et al. 2000).

• Observations of the CO(1-0) line with the Zpectrometer on the Robert C. Byrd Green Bank Telescope confirmed a *Spitzer* PAH redshift estimate (Valiante et al. 2007) of z = 2.742 (Baker et al. in prep.).

• We followed up with observations at the Jansky Very Large Array (JVLA) in CO(1-0), at the Plateau de Bure Interferometer (PdBI) in CO(3-2) and CO(5-4), and at the Submillimeter Array in CO(7-6) (Sharon et al. in prep.).

• We discovered a second component in the mid-J lines that was undetected by the Zpectrometer (Fig. 1).

• J00266 is likely comprised of two merging galaxies (Fig. 2): a blue component with dispersion-dominated kinematics and a single-phase molecular ISM, and a red component with a velocity gradient and a multi-phase molecular ISM (Fig. 3).

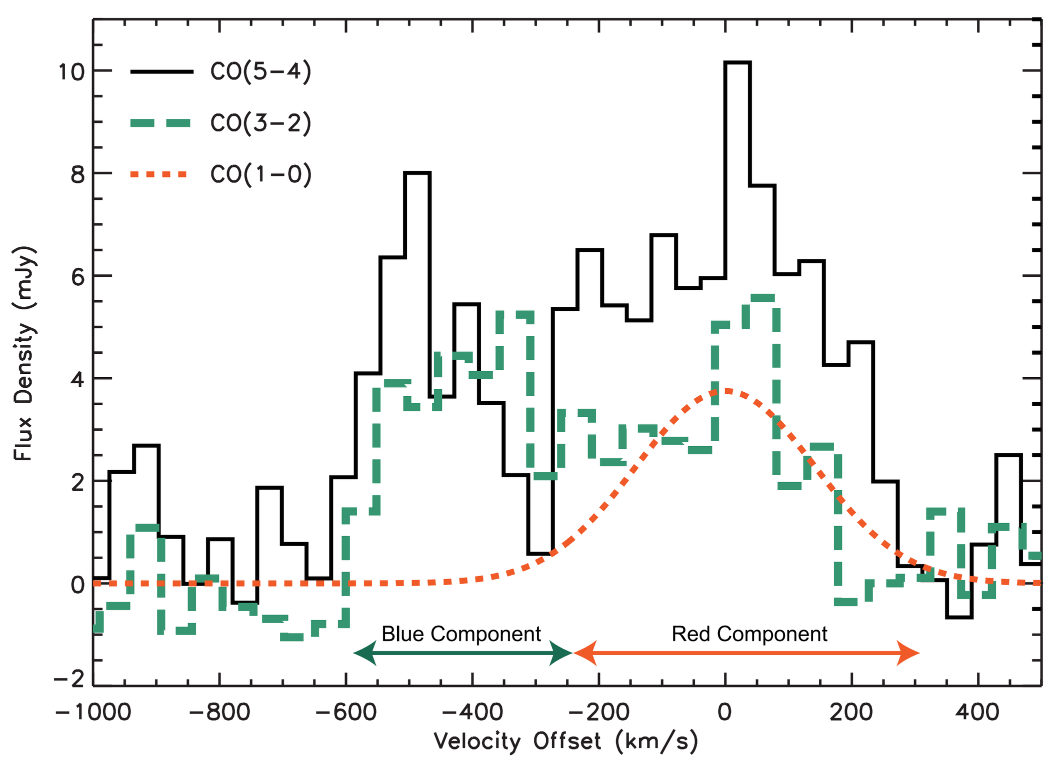


Figure 1- The CO(5-4) (solid/black) and CO(3-2) (dashed/green) spectral lines, shifted to match the rest frame velocity of the CO(1-0) line (Gaussian fit to GBT observation shown in dotted orange line; multiplied by a factor of five for clarity).

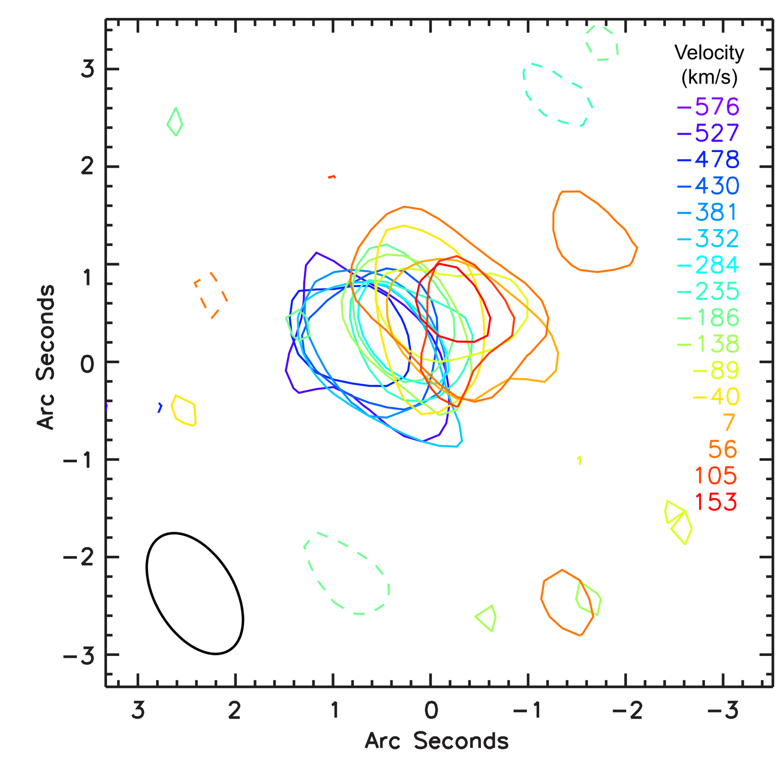


Figure 2- Overlaid contours of the CO(3-2) channel maps, colorized by the channels' relative velocities. The beam size is shown in the lower left corner. Only the positive (solid) and negative (dashed) 3σ contours are shown (1σ = 3.6 mJy beam⁻¹).

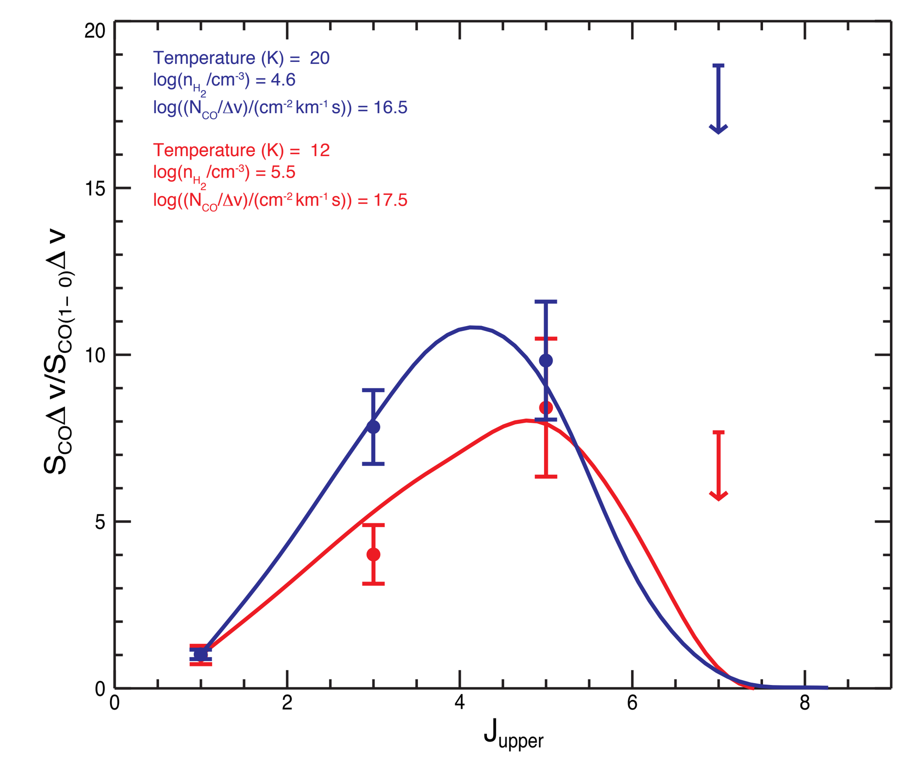


Figure 3- Best fit single-phase CO SLEDs for the blue and red components (solid lines) and the measured line ratios (points; not in brightness temperature units).

SMM J14011+0252

• J14011 (z = 2.5652) was detected in the SCUBA Lens Survey (Smail et al. 2002) and was the first SMG to be detected in any CO line (Frayer et al. 1999).

• J14011 has been followed up extensively at optical wavelengths, including Hα integral field spectroscopy (e.g., Barger et al. 1999, Tecza et al. 2004).

• Our CO(1-0) detection with the Zpectrometer gave $r_{3,1}$= 0.76 ± 0.12 (Harris et al. 2010).

• We followed up with mapping of the CO(1-0) line at the JVLA (Fig. 4; Sharon et al. in prep.).

• The line ratio maps indicate the presence of an excitation gradient parallel to the lensing shear (Fig. 5).

• Acceptable single-phase LVG models (Fig. 6) exist for a range of conditions (though C I observations prefer lower temperature models; Walter et al. 2011) and require measurements of J_{upper}=4-6 lines to break the degeneracies.

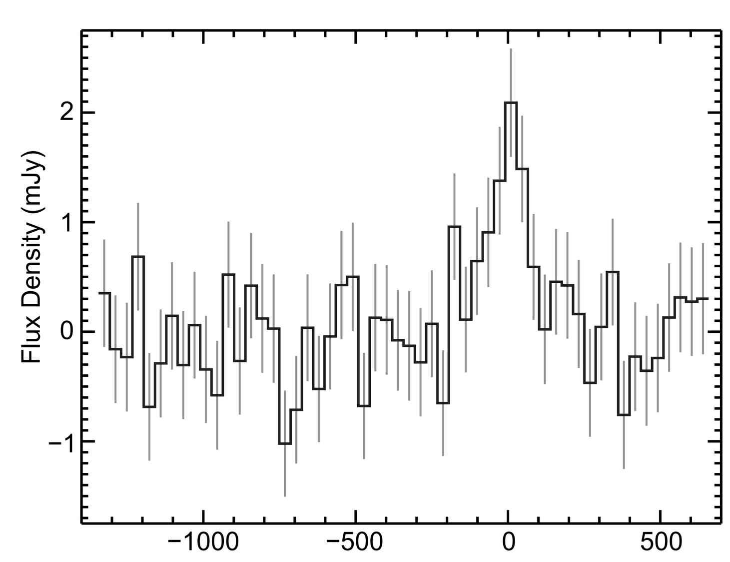


Figure 4- The 37 km s⁻¹ resolution JVLA spectrum plotted relative to the expected CO(1-0) systemic redshift. Vertical lines indicate statistical uncertainties.

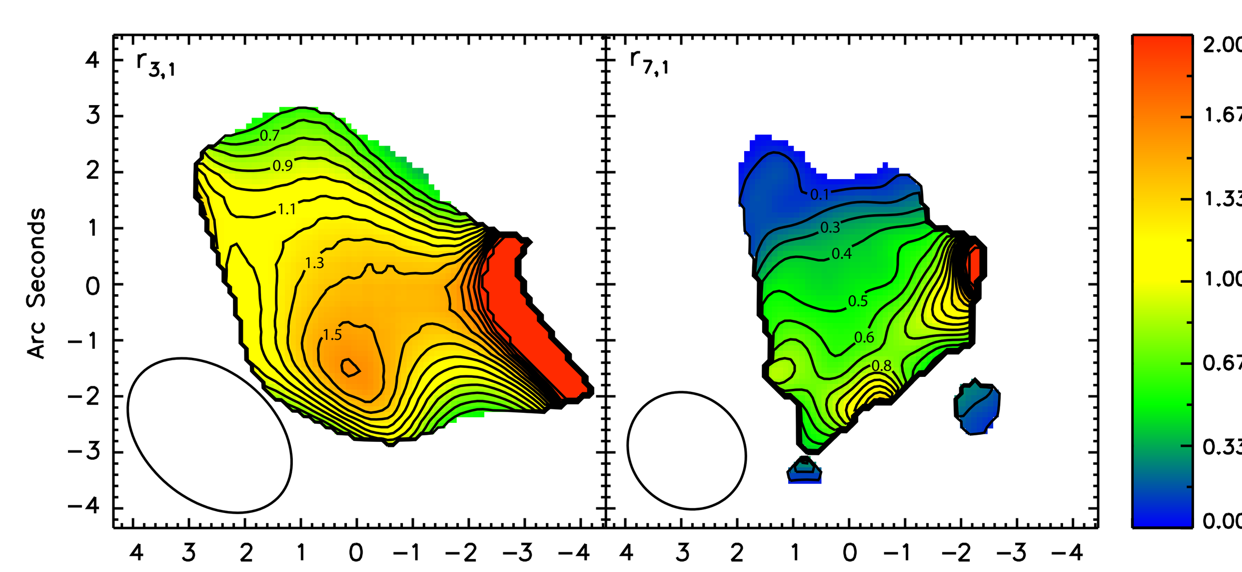


Figure 5- Maps of the CO(3-2)/CO(1-0) (left) and CO(7-6)/CO(1-0) (right) line ratios in units of brightness temperature centered at α (J2000) = 14ʰ01ᵐ04.93ˢ and δ (J2000) = +02°52′24.1″. For each panel the CO(1-0) map was first convolved with a Gaussian to give the same resolution as the higher-J map (beam sizes are shown in the lower left corners). Pixels with negative line ratios have been blanked out, as are pixels that are not at least 2σ significance in the CO intensity maps. Contours are in steps of 0.1. The color mapping is saturated (and the contouring stopped) at $r_{J,1}$ = 2 for clarity.

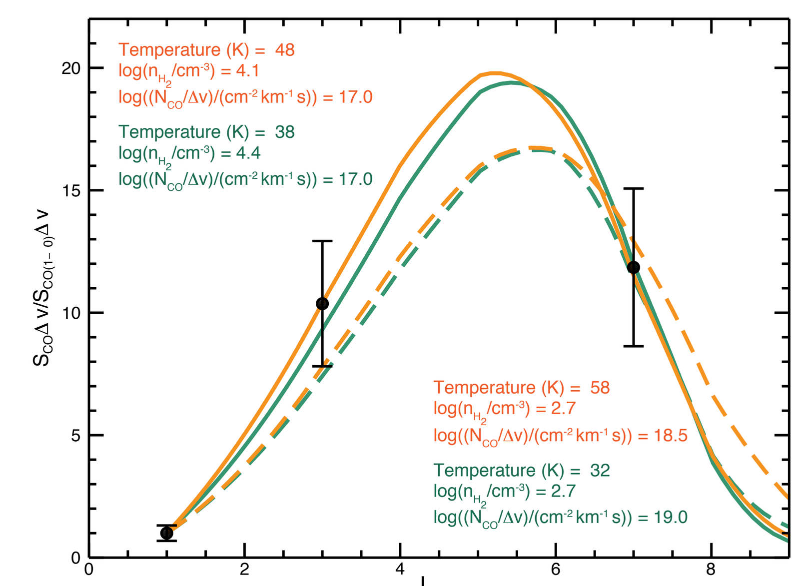


Figure 6- Example CO SLEDs that span the range of acceptable single-phase models for J14011. Warm models are in orange and cool models are in green. The upper set of labels/curves (solid lines) are for the higher H_2 density models, while the lower set of labels/curves (dashed lines) are for the lower density H_2 models.

SDSSJ0901+1814

• J0901 is a strongly lensed star-forming galaxy (z = 2.2597) discovered in a systematic Sloan Digital Sky Survey search (Diehl et al. 2009).

• It is luminous in both rest-UV and dust emission (i.e., J0901 is similar to both Lyman break galaxies and SMGs).

• We observed the CO(3-2) line at the PdBI (Baker et al. in prep.) and the CO(1-0) line at the JVLA (Sharon et al. in prep.).

• Clear velocity gradients across the three images (Fig. 7) and preliminary lens models indicate that J0901 is a disk galaxy, making it a valuable source for testing the Schmidt-Kennicutt relation at high-z (Hα data is in hand).

• Differences in the line shape and strengths between the three images indicate that differential lensing may be affecting the source (Fig. 8).

• The CO(3-2)/CO(1-0) line ratio map (Fig. 9) indicates that the lower excitation gas is more spatially extended than the higher excitation gas.

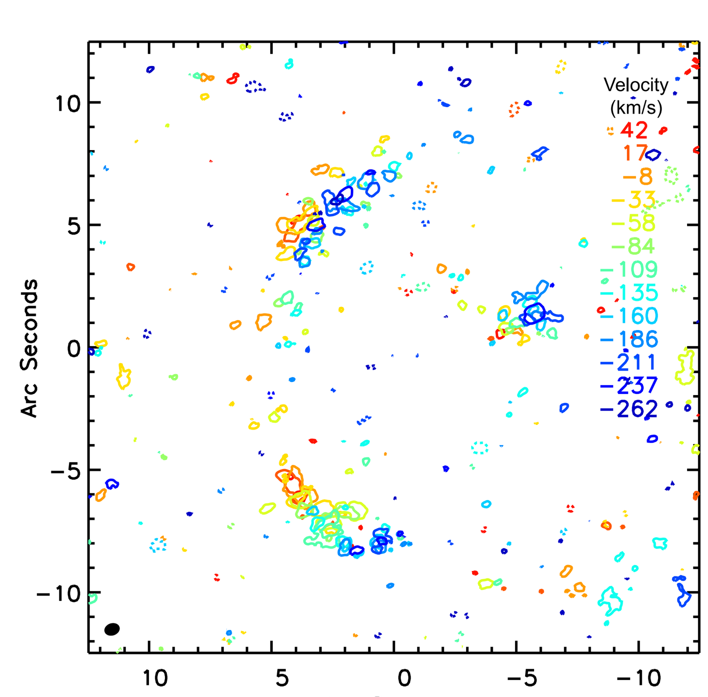


Figure 7- Overlaid contours of the CO(1-0) channel maps (Δv=3 MHz), colorized by the channels' relative velocities. The beam size is shown in the lower left corner. Only the positive (solid) and negative (dashed) 3σ contours are shown (1σ = 0.1 mJy beam⁻¹).

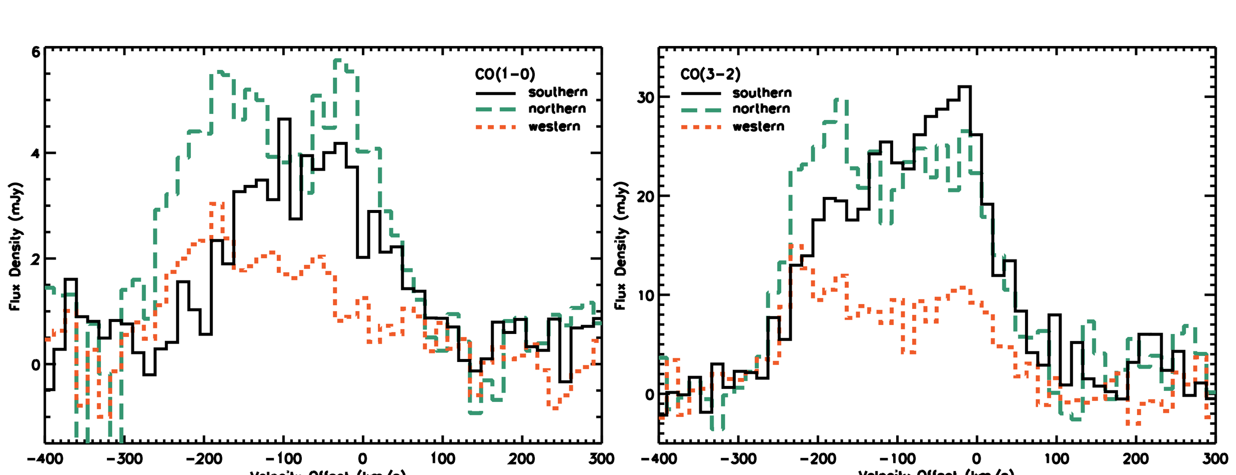


Figure 8- JVLA CO(1-0) spectra (left) and PdBI CO(3-2) spectra (right) of the southern (black/solid), northern (green/dashed), and western (orange/dotted) images of SDSSJ0901+1814, relative to a nebular emission-line redshift measured at Keck (Hainline et al. 2009).

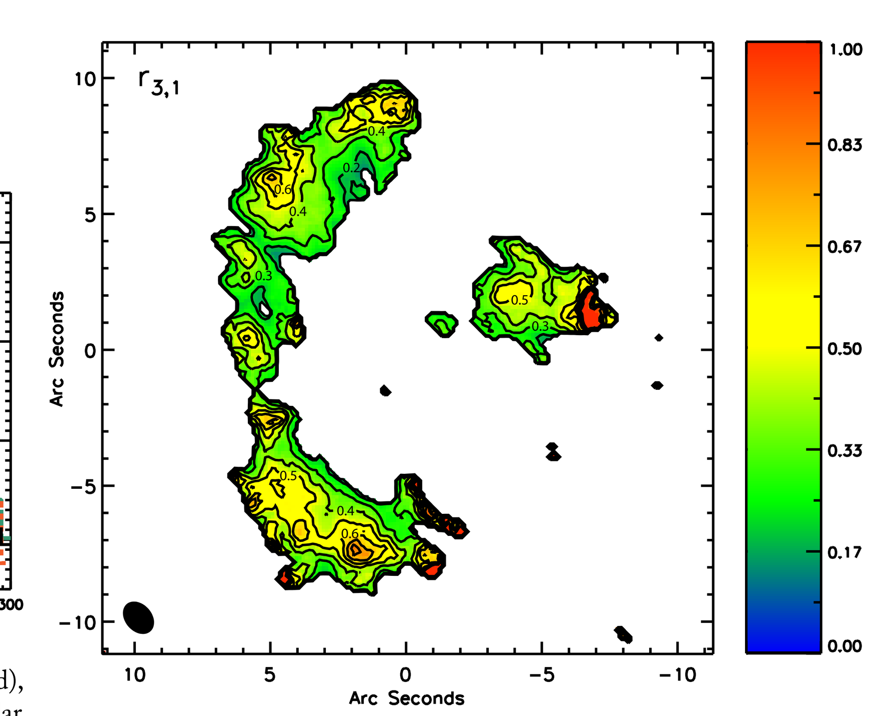


Figure 9- Map of the CO(3-2)/CO(1-0) line ratio in units of brightness temperature. The higher resolution CO(1-0) map was made using a Gaussian restoring beam that matched the CO(3-2) data (shown in lower left corner). Like Fig. 5, negative and <1σ significance pixels have been blanked out, contours are in steps of 0.1, and the color saturation is $r_{3,1}$=1.

Conclusions

• Observations of the complete CO excitation ladder, including a cold gas tracer like CO(1-0), are necessary in order to obtain an accurate picture of the molecular gas conditions in high-redshift galaxies.

• In addition, it is crutial that observations be made at high spectral and spatial resolution to ensure that peculiar galaxy structures or gravitational lensing are not affecting the excitation analysis.

• High-resolution mapping of mid- and low-J transitions have revealed:

  • A SMG that is a clear example of a major merger, where the two components have different kinematic structures and different excitation conditions.

  • A SMG with an internal excitation gradient that is only apparent using high-resolution mapping of CO(1-0), and benefits from the coincidental alignment of the gravitational lensing shear.

  • A strongly-lensed, UV-selected disk galaxy with a clear spatially extended cold gas phase.

• Similar observations are necessary for a larger number of sources in order to establish how common these structures are in high-z galaxy populations.

References

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