Follow-up of lensed submillimeter galaxies with Z-Spec and ALMA

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Recent theoretical and observational studies show that most of the extremely bright submillimeter galaxies (SMGs) at wavelengths larger than 500 µm are lensed by foreground objects (Negrello et al., 2010). Large area surveys, such as the Herschel H-ATLAS, HerMES, and the South Pole Telescope (SPT) survey, have uncovered a large number of such sources. This makes it possible for ground based instruments to obtain data on typical star forming galaxies at high redshifts that would otherwise be inaccessible.

Our instrument Z-Spec, a grating spectrograph with simultaneous coverage over the 190-308 GHz bandpass, can detect multiple CO lines for redshifts greater than ~0.6. Z-Spec has proven to be an efficient redshift machine, measuring ^{12}CO redshifts for some of the brightest sources found in the large area surveys, circumventing the need for optical or radio counterpart identification. However, the derivation of the physical properties of the gas (density, temperature, CO abundance) from Z-Spec data alone is limited by the unknown source size and the small number of CO lines measured.

With ALMA, we can resolve the source morphology and the line profiles, and derive the source sizes, lensing magnification factors, bulk motions of the gas, and constrain the dynamical masses. In addition, the precise redshift determination from Z-Spec together with the large sensitivity of ALMA will allow us to measure fainter lines from high density tracers, such as HCN, HNC, HCO$^+$, and ^{13}CO, as well as to look for a number of excited water lines. In combination with other multi-wavelength follow-ups, these data will enable a detailed study of the processes governing dust-obscured star forming galaxies at high redshifts.

THE Z-SPEC INSTRUMENT

The Z-Spec instrument at the CSO.

Z-Spec is a grating spectrometer with 160 silicon-nitride micro-mesh bolometer detectors (i.e. channels) operating from 190 to 308 GHz, and illuminated by a single feedhorn (Naylor et al. 2003; Earle et al. 2006; Bradford et al. 2009). It has been operating at the Caltech Submillimeter Observatory (CSO), and the Atacama Pathfinder Experiment (APEX).

- Using multiple CO lines detected simultaneously by Z-Spec, we can efficiently determine redshifts for submillimeter galaxies, especially for 1<z<3
- Limited to the brightest galaxies, $L_{obs} > 10^{13}\ L_{\odot}$
- Redshift desert ~3.7<z<5.3. Beyond z > 3.7, the excitation of the CO lines for typical ISM conditions becomes faint in the Z-Spec bandpass, and no strong lines are present again until [CII] appears at z = 5.3.

ALMA

ALMA with 8 antennas, Fall 2010.

- ALMA will be capable of a faster redshift survey, to lower luminosities, and over a larger redshift range.
- The follow-up of lensed sources with ALMA can provide a comprehensive census of fainter lines, rarely detected at high redshifts (e.g., HCN, HNC, HCO$^+$,^{13}CO).

CO EXCITATION

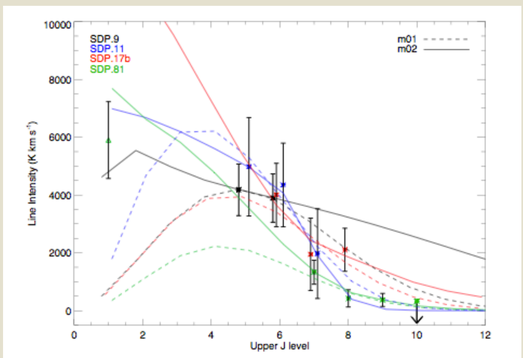


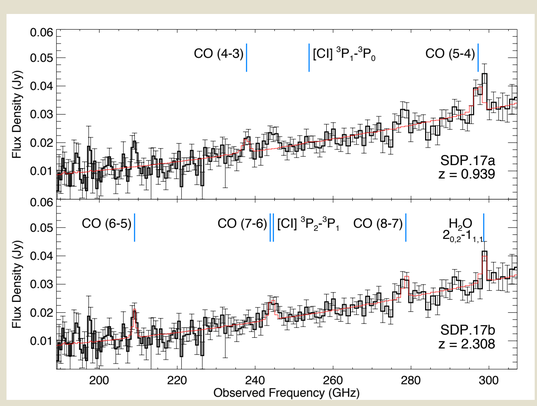
Fig. 12.— $W(J)$ as a function of transition for four of the galaxies in our sample. For clarity, the values for the same transition in different galaxies have been slightly offset around the position of the upper J level. The triangle point represents the intensity of the CO(1-0) line for SDP.81 measured by Frayer et al. (2010). The $W(J)$ distributions predicted by the RADEX models m01 and m02 are shown with a dashed and continuous line, respectively. These lines emphasize the constraints on the allowed parameter space that can be gained by having measurements of both higher and lower J transitions.

- The partial SLEDs for the CO molecule constructed from the lines observed by Z-Spec cannot distinguish between different models of CO excitation (m01 corresponds to the cold and dense LTE solution, and m02 to the maximum likelihood non-LTE solution, generally hot and diffuse).
- Degeneracies: gas density/ kinetic temperature
  CO column density / source size
- Measurements of the lower rotational transitions, especially the CO(1-0) line, are essential in selecting between such models.

Using ALMA, we can perform a comprehensive analysis of the CO excitation:

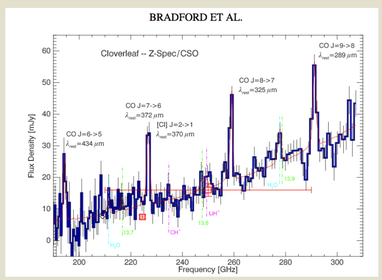
- Measure multiple CO lines and construct full CO SLEDs. However, for the CO(1-0) line we need to use other facilities, making it more difficult to obtain for southern hemisphere targets.
- Well sampled CO SLEDs can reveal a multi-component gas, with distinct temperatures and densities (e.g., Scott et al., in prep., Danielson et al., 2010).
- Measure directly the source sizes, breaking the degeneracy between CO column density and source size.
- Measure CO line profiles and identify multiple velocity components, estimate the dynamical masses.
- Resolve spatial structure and derive gravitational lensing magnification factors, inferring the spatial distribution of the CO gas components.

WATER

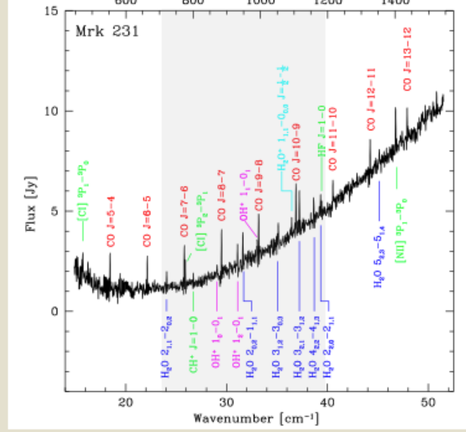


Z-Spec spectra of SDP.17 (H-ATLAS) and the Cloverleaf quasar (Lupu et al., 2010, Bradford et al., 2009).

The spectrum of SDP.17 is consistent with a superposition of two independent redshifts, z=2.308 and z=0.942.
The water line at z=2.308 has recently been confirmed by IRAM/PdBI.



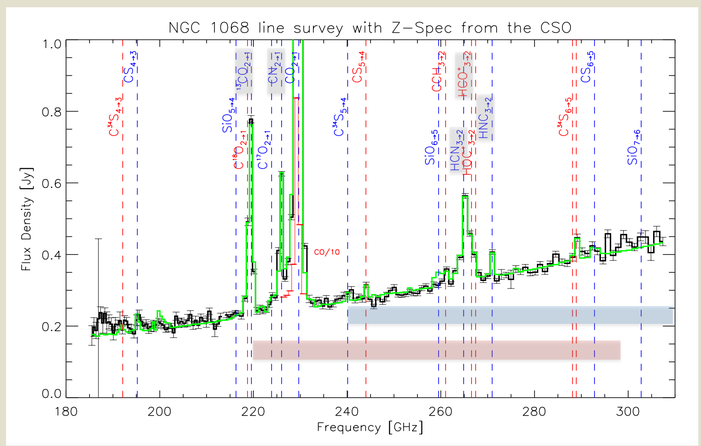
Quasar spectra also show indications of water lines.



SPIRE/FTS, Van der Werf et al., 2010.

- Water can be an important coolant in the warm interstellar medium.
- Measuring both the water and CO lines, we can determine the relationship between the water and CO excitation.
- For 1<z<4.8, most of the bright water lines (in the grey region) will fall in ALMA bands 6 and 7.
- ALMA can not only confirm the lines identified by Z-Spec, but also detect additional transitions, allowing a detailed modeling of the water excitation in these galaxies.

DENSE GAS TRACERS



NGC 1068, Kamenetzky et al., submitted.

- Z-Spec can measure lines from a number of dense gas tracers in local galaxies (e.g., Naylor et al., 2010, Kamenetzky et al., submitted).
- Some of the same lines can be observed by ALMA at higher redshifts, allowing a direct comparison between low- and high-z galaxies.

- ALMA band 3 can overlap with the Z-Spec bandpass for high-z sources (see the red and blue regions for z=1.58 and z=1.79, respectively)
- Such measurements can be used in a joint likelihood analysis with CO to break the degeneracy between the gas density and the kinetic temperature.
- These lines also provide diagnostics for star formation and AGN activity.
- The dense gas tracer lines are 10-20 times fainter than the CO lines, and therefore such observations are only possible for very bright or highly lensed sources.