AST/RO Sub-mm Survey of the Galactic Center

C.L. Martin (Oberlin), W.M. Walsh (UNSW), K. Xiao (Case U.), N.F.H. Tothill, J. Harnett, A.P. Lane, A.A. Stark (Harvard-Smithsonian CfA), C.K. Walker (U. Arizona)

For more information please contact: `Chris.Martin@oberlin.edu`

Abstract

To understand the strongly excited gas near the center of our own galaxy, detailed surveys in a variety of higher excitation states are required. To aid in this effort, the Antarctic Sub-millimeter Telescope and Remote Observatory (AST/RO, a 1.7m diameter sub-millimeter-wave telescope at the geographic South Pole) has completed a fully sampled survey of CO(7-6), CO(4-3), [CI]($^3P_2$-$^3P_1$), and [CI]($^3P_1$-$^3P_0$) in a three square degree region around the Galactic Center (Martin et al., ApJS, 150, 239 (2004)). In addition to this dataset, AST/RO has recently completed a survey area around Clump 1 and 2, thus covering the bulk of strongly excited gas near the center of the galaxy.

This dataset comprises nearly a million distinct telescope pointings over many square degrees of the sky. To handle a sub-mm dataset of this size required the development of new automated observational methodologies, reduction techniques, and visualizations. These interactive 3D visualizations and movies of the full dataset are presented (when I am here at the poster) to illustrate the wealth of information available.

The Telescope

Figure 1: Above is a picture of AST/RO in August 2001 with the aurora overhead. AST/RO [Stark *et al.* 2001] is a 1.7 m diameter, offset Gregorian telescope capable of observing at wavelengths between 200 μm and 1.3 mm. Located only 1 km from the geophysical South Pole, and the NSF's Amundsen-Scott South Pole Station, the author (CLM) spent two full years in 2001 & 2003 collecting data for this and other projects.

Movies!

The 2-D slices of the data shown here are a pale comparison to the wealth of information visible in the full 3-D datasets. Please visit this poster again when I'm here with my laptop for the full 3-D tour.

Galactic Center

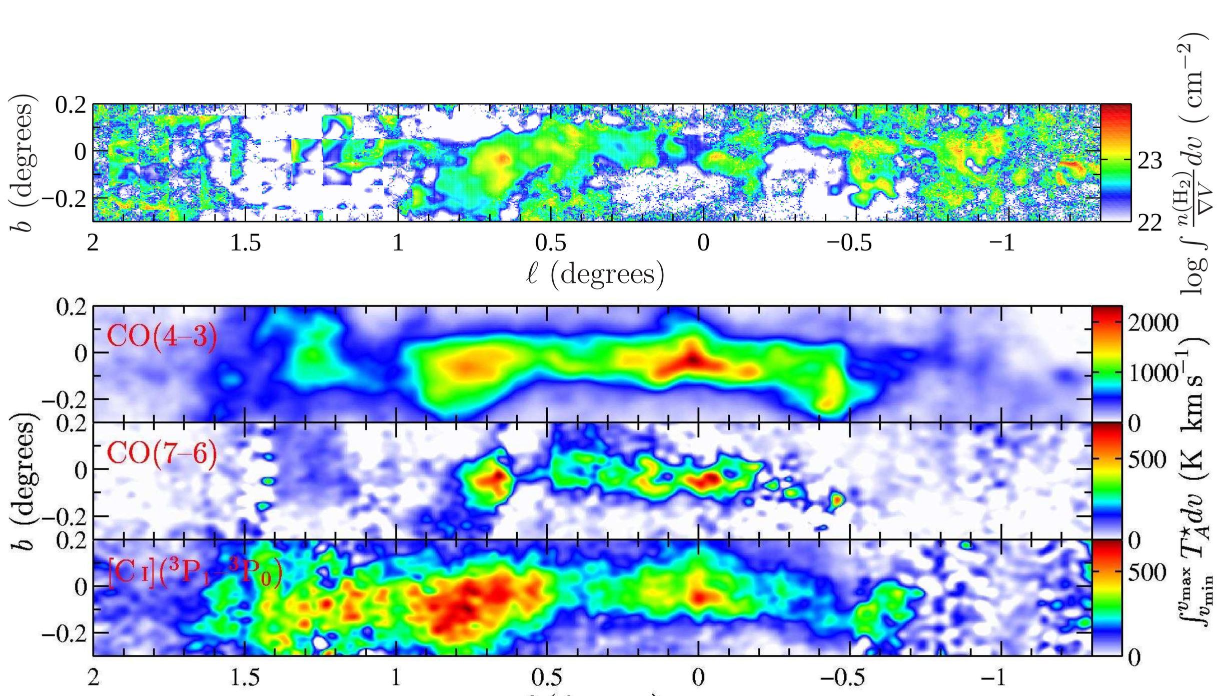

Figure 2: The top panel shows one of the most exciting results of this work. We can use LVG analysis to calculate quantities like the column density (shown above) for every point in our (ℓ, b) map. The lower 3 panels show spatial–spatial (ℓ, b) integrated intensity maps for the 3 transitions observed with AST/RO. Transitions are identified at left on each panel. The emission is integrated over all velocities where data are available. All have been smoothed to the same $2'$ resolution. For electronic versions of results from this region as published in [Martin *et al.* 2004], please speak with me or send email to `Chris.Martin@oberlin.edu`

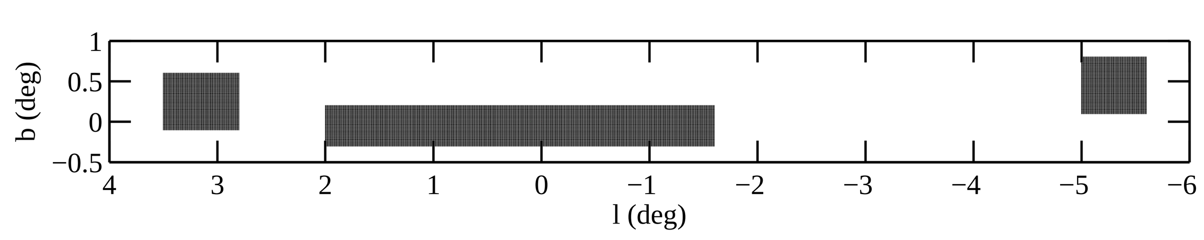

Figure 3: Each point above represents one of the 42,000 positions where a spectrum was taken. The points are spaced $0.5'$ from each other leading to a fully or over-sampled map depending on the frequency. Emission from the 807 GHz $J = 7 \rightarrow 6$ and 461 GHz $J = 4 \rightarrow 3$ transitions of ^{12}CO along with the $^3P_1 \rightarrow {}^3P_0$ transition of [CI] were mapped at $0.^\circ8 > b > 0.^\circ1$, $-5.^\circ0 > \ell > -5.^\circ6$ in Clump 1, $0.^\circ2 > b > -0.^\circ3$, $2.^\circ0 > \ell > -0.^\circ5$ in the center, and $0.^\circ6 > b > -0.^\circ1$, $3.^\circ5 > \ell > 2.^\circ8$ in Clump 2, with $0.5'$ spacing and a beam size of $58'' - 118''$ (depending on frequency). The atmosphere-corrected system temperature during the observations ranged from 9,000 to 26,000 K at 806 GHz and from 2000 to 4000 K at 461 GHz. Observing time at each of the 42,000 observed positions was typically 1–3 minutes in order to achieve a consistent noise level across the map.

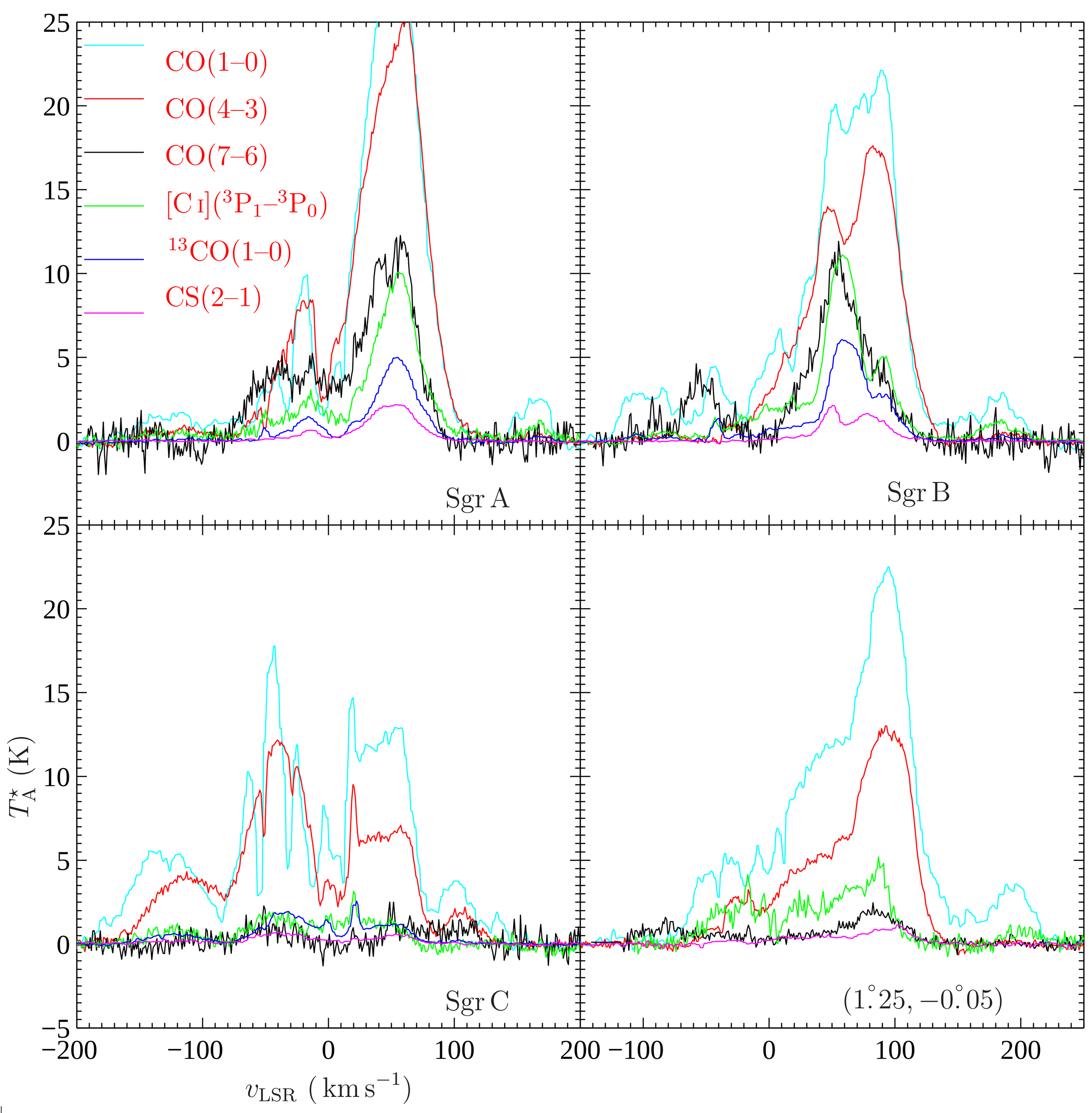

Figure 4: Spectra toward the respective positions of peak CO $J = 7 \rightarrow 6$ emission in the Sgr A (ℓ= $0.^\circ00$, b= $-0.^\circ07$), Sgr B (ℓ= $0.^\circ66$, b= $-0.^\circ05$), Sgr C (ℓ= $-0.^\circ45$, b= $-0.^\circ20$) (CO $J = 4 \rightarrow 3$ emission peak)', and $\ell \simeq 1.^\circ3$ (ℓ= $1.^\circ25$, b= $-0.^\circ05$) clouds (as indicated at lower right in each frame) in 6 different transitions, as indicated by the color identifications at upper left. The 461 GHz CO $J = 4 \rightarrow 3$, 807 GHz CO $J = 7 \rightarrow 6$, and 492 GHz [CI] $^3P_1 \rightarrow {}^3P_0$ data are from the AST/RO survey, and the 115 GHz CO $J = 1 \rightarrow 0$, 110 GHz ^{13}CO $J = 1 \rightarrow 0$, and 98 GHz CS $J = 2 \rightarrow 1$ data are from the Bell Laboratories 7-m telescope [Stark *et al.* 1988; Bally *et al.* 1987; Bally *et al.* 1988].

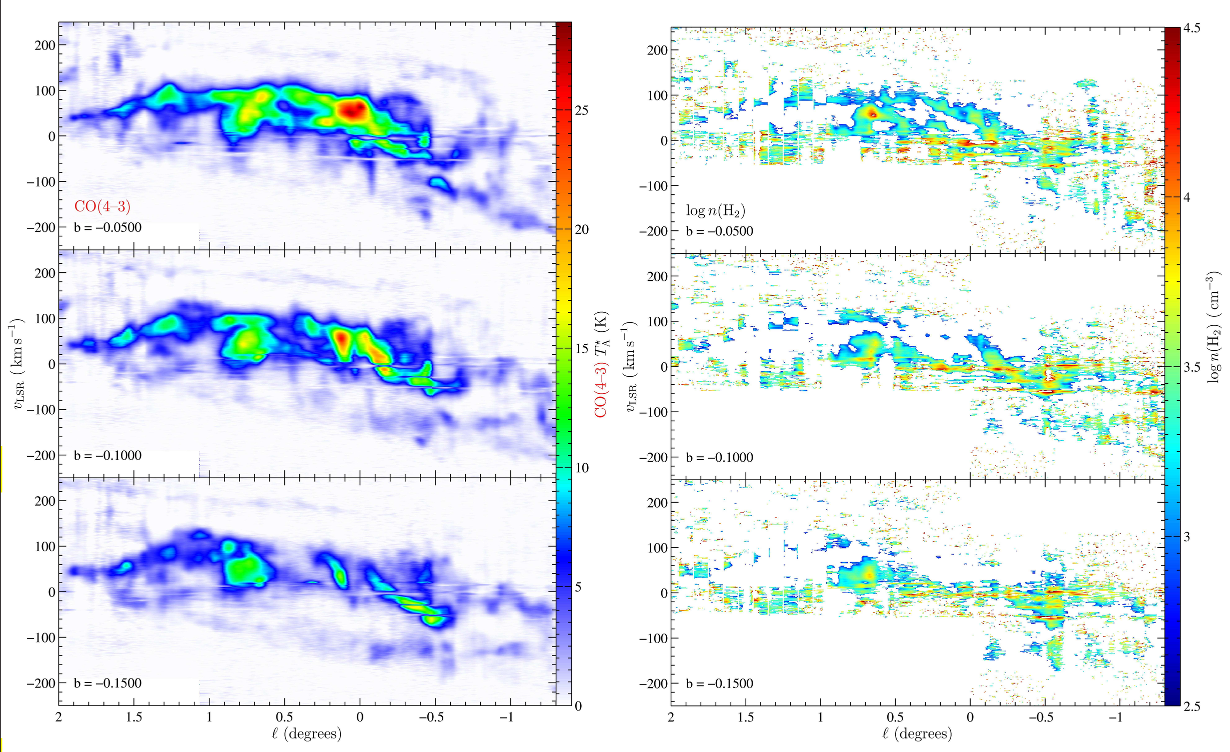

Figure 5: Position-velocity (LV) plots of the Galactic Center region over a range of galactic latitudes (noted in the lower corner of each frame). On the left the CO(4-3) transition and on the right the density as determined by the LVG model described below.

In the right panel of Fig. 5, the full set of observed data are translated to density using a reverse LVG model. These density slices can then be combined to determine the column density in the galactic center.

Clump 1 & 2

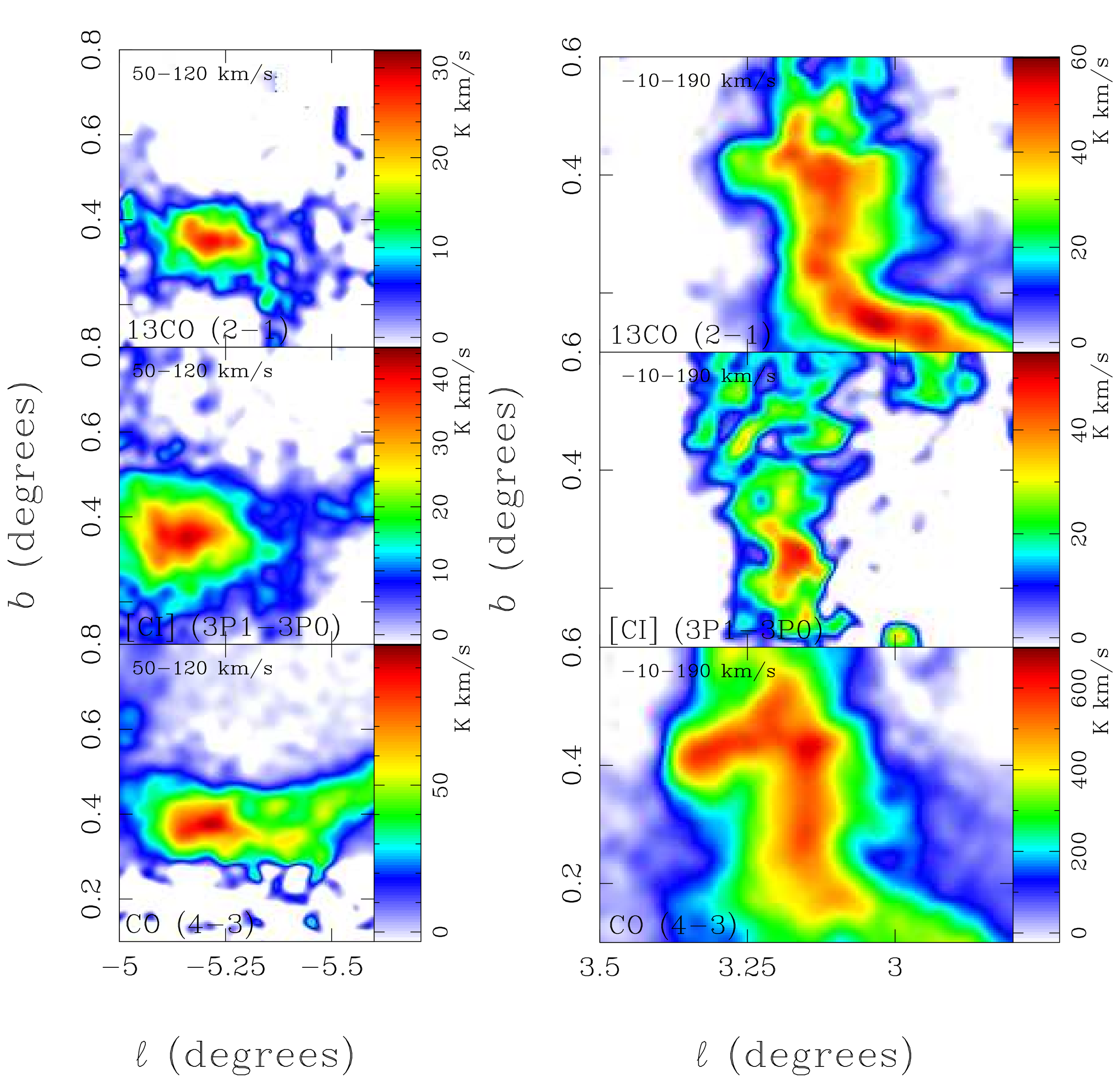

Figure 6: Integrated position-position (LB) plot of Clump 1 on the left and Clump 2 on the right

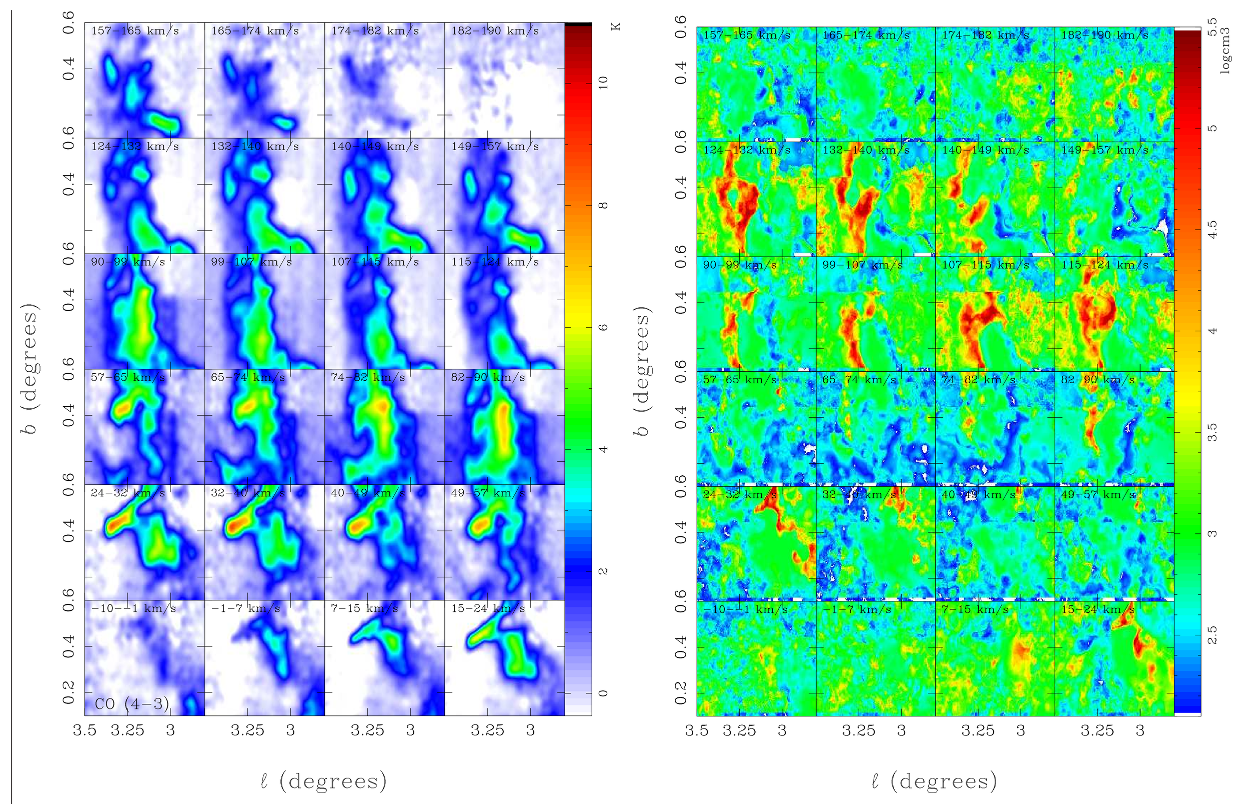

Figure 7: Position-position (LB) plots of Clump 2 over a range of velocities (noted in the upper corner of each frame). On the left the CO(4-3) transition and on the right the density as determined by the LVG model described below.

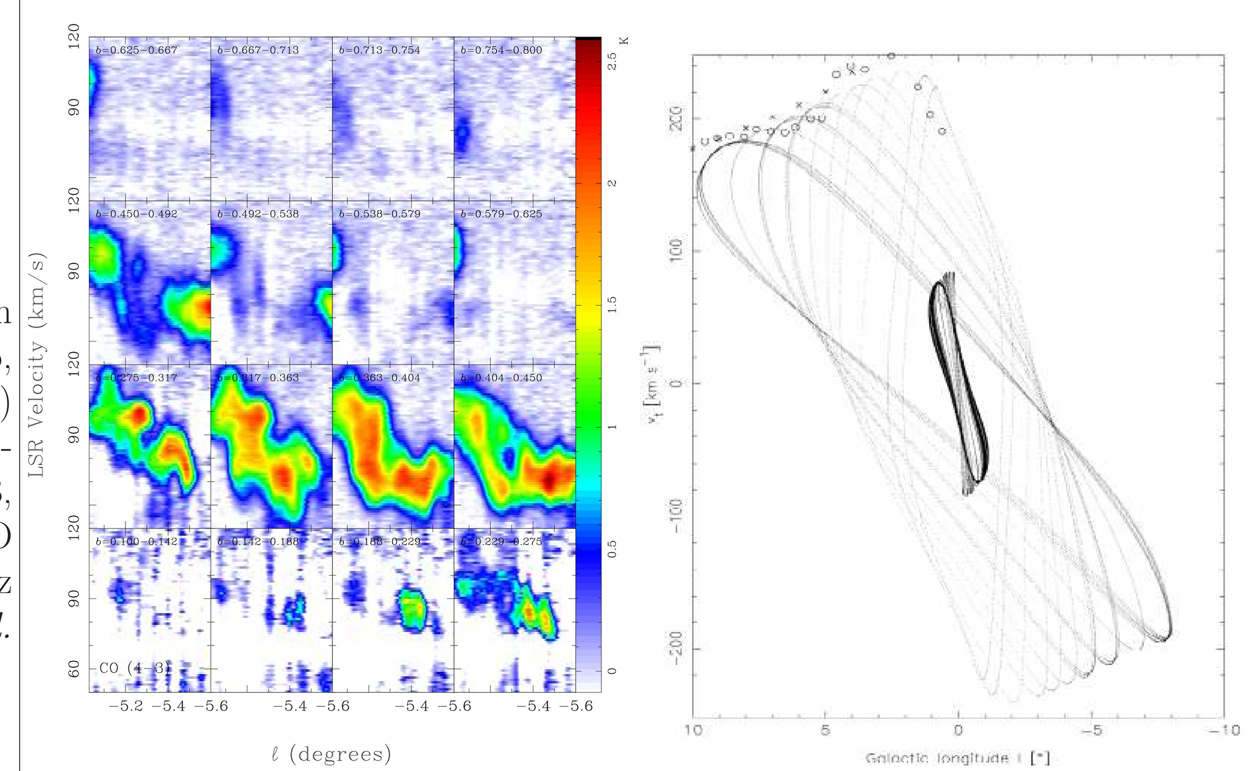

Figure 8: Position-velocity (LV) diagram of Clump 1 on the left and LV diagram of [Bissantz, Englmaier, and Gerhard 2003] on the right

LVG Model

Using the line ratios, we can estimate the kinetic temperature, T_{kin}, and the number density of molecular hydrogen, $n(H_2)$, through a large velocity gradient (LVG) radiative transfer analysis [Goldreich and Kwan 1974]. The LVG approximation simplifies radiative transfer by the assumption that an emitted spectral line photon can only be absorbed "locally", within a small region whose velocity is similar to the point of emission. This approximation is robust, in the sense that the results of LVG models are often reasonably accurate, even when reality violates the assumptions underlying the models [Ossenkopf 1997]. Our LVG radiative transfer code simulates a plane-parallel cloud geometry. It uses the CO collisional rates from [Turner 1995] and newly-derived values for the H_2 ortho-to-para ratio ($\approx$ 2) and the collisional quenching rate of CO by H_2 impact (Yan, Balakrishnan, & Dalgarno, in preparation). The model has two input parameters: the ratio of ^{12}CO to ^{13}CO abundance, and the ratio $X(CO)/\nabla V$, where $X(CO)$ is the fractional CO abundance parameter and ∇V denotes the velocity gradient. The abundance ratio ^{12}CO/^{13}CO is taken to be 25 in the Galactic Center region [Langer and Penzias 1990; Langer and Penzias 1993]. We take $X(CO)/\nabla V = 10^{-4.5}\,\mathrm{pc\,km^{-1}\,s}$, assuming that the ^{12}CO/H_2 ratio is 10^{-4} and the velocity gradient of Galactic Center clouds is typically 3 to 6 km s^{-1}pc^{-1}.

For each observed point, we can invert the ratios of the observed data to determine the kinetic temperature and molecular hydrogen volume density.

Acknowledgments

This research was supported by the National Science Foundation under grant number ANT-0126090.

References

Bally, J., Stark, A. A., Wilson, R. W., and Henkel, C. 1987. Galactic center molecular clouds. I - Spatial and spatial-velocity maps. ApJS, **65**, 13–82.

Bally, J., Stark, A. A., Wilson, R. W., and Henkel, C. 1988. Galactic center molecular clouds. II - Distribution and kinematics. ApJ, **324**, 223–247.

Bissantz, N., Englmaier, P., and Gerhard, O. 2003. Gas dynamics in the Milky Way: second pattern speed and large-scale morphology. MNRAS, **340**(3), 949.

Goldreich, P. and Kwan, J. 1974. Molecular Clouds. ApJ, **189**, 441–454.

Langer, W. D. and Penzias, A. A. 1990. C-12/C-13 isotope ratio across the Galaxy from observations of C-13/O-18 in molecular clouds. ApJ, **357**, 477–492.

Langer, W. D. and Penzias, A. A. 1993. (C-12)/(C-13) isotope ratio in the local interstellar medium from observations of (C-13)(O-18) in molecular clouds. ApJ, **408**, 539–547.

Martin, C. L. *et al.* 2004. The AST/RO survey of the Galactic Center region. I. the inner 3 degrees. ApJS, **150**, 239–262.

Ossenkopf, V. 1997. The Sobolev approximation in molecular clouds. New Astronomy, **2**, 365–385.

Stark, A. A. *et al.* 2001. The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO). PASP, **113**, 567–585.

Stark, A. A., Bally, J., Knapp, G. R., and Wilson, R. W. 1988. The Bell Laboratories Co/ Survey. In Dickman, R. L., Snell, R. L., and Young, J. S., editors, *Molecular Clouds in the Milky Way and External Galaxies*, page 303. Springer-Verlag.

Turner, B. E. 1995. The Physics and Chemistry of Small Translucent Molecular Clouds. V. SO and SO 2. ApJ, **455**, 556.