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Understanding sub-mm radio emission in our own backyard

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Abstract. As we look for red-shifted mm and sub-mm radio emission in distant galaxies, we need to understand our own galaxy's emission to serve as a comparison. To aid in this effort, the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) has completed a survey of CO(7-6), CO(4-3), [CI]($^3P_2$-$^3P_1$), and [CI]($^3P_1$-$^3P_0$) from a three square degree region around the Galactic Center. In addition to this dataset, AST/RO has recently completed a survey area around Clumps 1 and 2, thus covering the bulk of strongly excited gas near the center of the Galaxy.

Using this dataset, we explain the variety of features in our own Galaxy and how they can be used to interpret the data that will be collected using future observations of distant galaxies.

1. Introduction

Much has been learned about dense gas in the Galactic Center region through radio spectroscopy. Early observations of $F(2 \rightarrow 2)$ OH absorption (Robinson *et al.* 1964; Goldstein *et al.* 1964) suggested the existence of copious molecular material within 500pc of the Galactic Center. This was confirmed by detection of extensive $J = 1 \rightarrow 0$ ^{12}CO emission (Bania 1977; Liszt and Burton 1978). Subsequent CO surveys (Bitran 1987; Stark *et al.* 1988; Oka *et al.* 1988; Bitran *et al.* 1997) have measured this emission with improving coverage and resolution—these surveys show a complex distribution of emission, which is chaotic, asymmetric, and non-planar; there are hundreds of clouds, shells, arcs, rings, and filaments. On scales of 100pc to 4kpc, however, the gas is loosely organized around closed orbits in the rotating potential of the underlying stellar bar (Binney *et al.* 1991). Some CO-emitting gas is bound into clouds and cloud complexes, and some is sheared by tidal forces into a molecular intercloud medium of a kind not seen elsewhere in the Galaxy (Stark *et al.* 1989). The large cloud complexes, Sgr A, Sgr B, and Sgr C, are the among the largest molecular cloud complexes in the Galaxy ($M \gtrsim 10^{6.5}\,M_\odot$). Such massive clouds must be sinking toward the center of the galactic gravitational well as a result of dynamical friction and hydrodynamic effects (Stark *et al.* 1991). The deposition of these massive lumps of gas upon the center could fuel a starburst or an eruption of the central black hole (Genzel and Townes 1987; Stark *et al.* 2004).

To better understand the molecular gas of the Galactic Center, we need to determine its physical state—its temperature and density. This involves understanding radiative transfer in CO, the primary tracer of molecular gas. Also useful is an understanding of the atomic carbon lines, [C I], since those lines trace the more diffuse molecular regions, where CO is destroyed by UV radiation but H_2 is still present.

2. Observations

The observations were performed during the austral winter seasons of 2001–2003 at the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) located at 2847m altitude at the Amundsen-Scott South Pole Station. This site has very low water vapor, high atmospheric stability and a thin troposphere making it exceptionally good for submillimeter observations (Chamberlin, Lane, & Stark 1997; Lane 1998). AST/RO is a 1.7m diameter, offset Gregorian telescope capable of observing at wavelengths between 200μm and 1.3mm (Stark *et al.* 2001).

Emission from the CO $J = 4 \rightarrow 3$ and CO $J = 7 \rightarrow 6$ lines at 461.041GHz and 806.652GHz, together with the [C I] $^3P_1 \rightarrow {}^3P_0$ and $^3P_2 \rightarrow {}^3P_1$ lines at 492.262GHz and 809.342GHz, was imaged over the Galactic Center region $-1.^\circ3 < \ell < 2^\circ$, $-0.^\circ3 < b < 0.^\circ2$, Clump 1 at $-5.^\circ6 < \ell < -5^\circ$, $0.^\circ3 < b < 0.^\circ5$ and Clump 2 at $2.^\circ8 < \ell < 3.^\circ5$, $0.^\circ1 < b < 0.^\circ6$ with $0.5'$ spacing in ℓ and b; i.e., a spacing of a half-beamwidth or less. Maximum pointing errors were no larger than $1'$, and the beam sizes (FWHM) were 103–109$''$ at 461–492GHz and 58$''$ at 807GHz (Stark *et al.* 2001). To facilitate comparison of the various transitions, the data were regridded onto a $0.25'$ grid and smoothed to a FWHM spatial resolution of $2'$ and a uniform velocity resolution of $1\,\mathrm{km\,s^{-1}}$. For more details on the observations and reduction of the data from the Galactic Center region please see Martin *et al.* (2004).

3. Data Presentation and Analysis

Fig. 1 presents spatial–spatial (ℓ, b) maps integrated over velocity for the three transitions observed in the Galactic Center. The most striking result is that CO $J = 4 \rightarrow 3$ emission in the Galactic Center region is essentially coextensive with the emission from the lower J transitions of CO as observed with the Bell Labs 7m. This contrasts sharply with the outer Galaxy where CO $J = 4 \rightarrow 3$ emission is rather less extensive than CO $J = 1 \rightarrow 0$. Four major cloud complexes are seen in the maps, from left to right: the complex at $\ell \simeq 1.^\circ 3$, the Sgr B complex near $\ell \simeq 0.^\circ 7$, the Sgr A cloud near $\ell \simeq 0.^\circ 0$, and the Sgr C cloud near ($\ell \simeq -0.^\circ 45$, $b \simeq -0.^\circ 2$). As noted by Kim *et al.* (2002), the CO $J = 7 \rightarrow 6$ emission is much more spatially confined than the lower-J CO transitions. In contrast, the [C I] emission is comparable in spatial extent to the low-J CO emission, but its distribution appears somewhat more diffuse (less peaked). The Sgr C cloud is much less prominent in the [C I] map than in the other five transitions (Ojha *et al.* 2001; Mookerjea *et al.* 2005). For further details on a Large Velocity Gradient analysis, please see the paper by K. Xiao in this volume.

Fig 2 presents spatial–spatial (ℓ, b) maps integrated over velocity for the three transitions observed in Clumps 1 and 2. Further analysis (Martin *et al.* 2006) of the data highlight the tidally shocked nature of the gas as it interacts with the bar-shaped gravitational potential of the Milky Way.

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References

Bania, T. M. 1977. ApJ, **216**, 381–403.
Binney, J. *et al.* 1991. MNRAS, **252**, 210–218.
Bitran, M. *et al.* 1997. A&AS, **125**, 99–138.
Bitran, M. E. 1987. PhD Thesis, University of Florida.
Chamberlin, R. A., Lane, A. P., and Stark, A. A. 1997. ApJ, **476**, 428–+.
Genzel, R. and Townes, C. H. 1987. ARA&A, **25**, 377–423.
Goldstein, S. J. *et al.* 1964. Nature, **203**, 65.
Kim, S. *et al.* 2002. ApJ, **580**, 896–903.
Lane, A. P. 1998. In Novack, G. and Landsberg, R. H., editors, *Astrophysics From Antarctica*, volume 141, page 289. ASP Conference Series.
Liszt, H. S. and Burton, W. B. 1978. ApJ, **226**, 790–816.
Martin, C. L. *et al.* 2004. ApJS, **150**, 239–262.
Martin, C. L. *et al.* 2006. The AST/RO Survey of the Galactic Center Region. II. Clump 1 & 2. in preparation.
Mookerjea, B. *et al.* 2005. [CI] 492 GHz Study of the Galactic Center. submitted.
Ojha, R. *et al.* 2001. ApJ, **548**, 253–257.
Oka, T. *et al.* 1998. ApJS, **118**, 455–515.
Robinson, B. J. *et al.* 1964. Nature, **202**, 989–991.
Stark, A. A. *et al.* 2001. PASP, **113**, 567–585.
Stark, A. A. *et al.* 1991. MNRAS, **248**, 14P–17PP.
Stark, A. A. *et al.* 1988. 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.
Stark, A. A. *et al.* 1989. In Morris, M., editor, *IAU Symp. 136: The Center of the Galaxy*, page 129. Kluwer.
Stark, A. A. *et al.* 2004. ApJ, **614**, L41–L44.

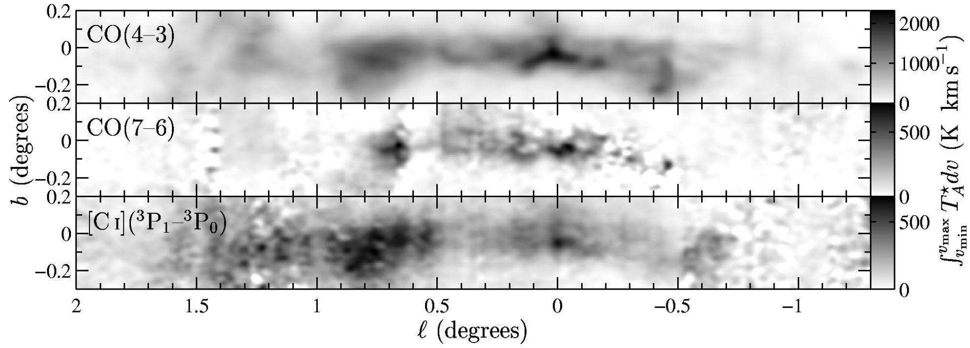

Figure 1. Spatial–spatial (ℓ, b) integrated intensity maps for the 3 transitions observed with AST/RO. Transitions are identified at left on each panel. The emission is integrated over all velocities where data are available. All 3 maps have been smoothed to the same $2'$ resolution. For electronic versions of results from this region as published in Martin *et al.* (2004), please send email to `Chris.Martin@oberlin.edu` or visit `http://cfawww.harvard.edu/ASTRO`

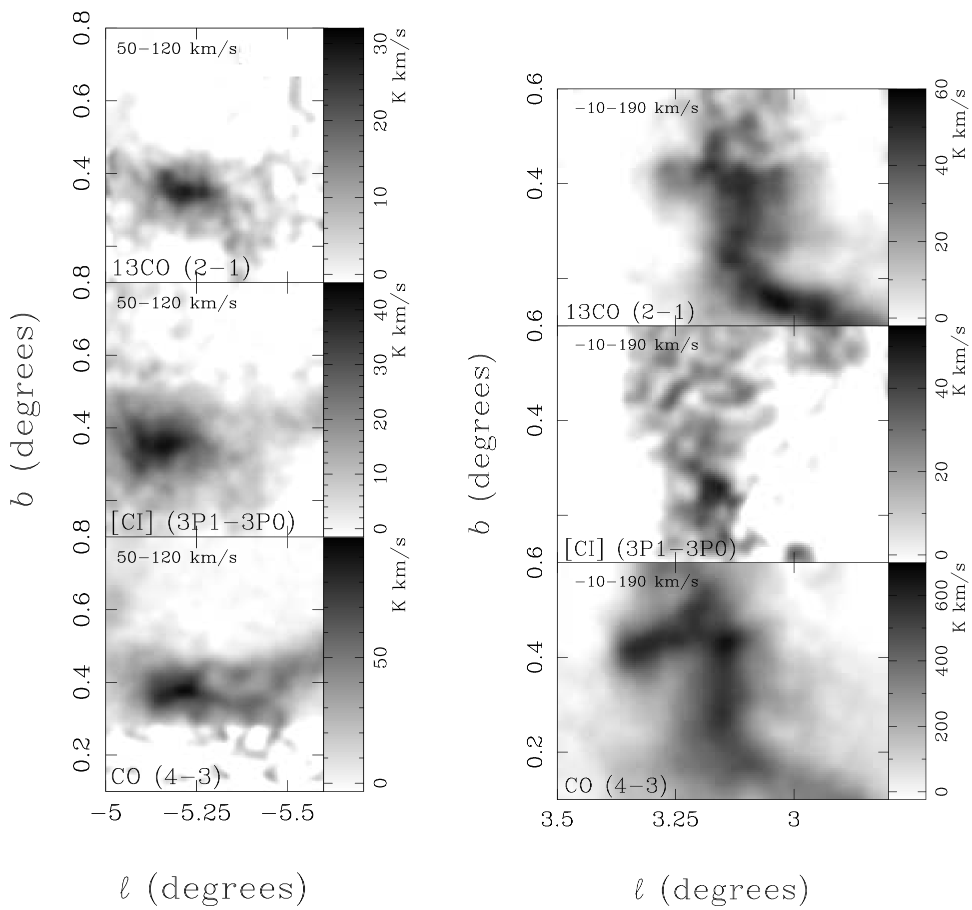

Figure 2. Integrated position-position (LB) plot of Clump 1 on the left and Clump 2 on the right. Maps are integrated over the velocity ranges shown in the upper left corner and smoothed to the same $2'$ resolution.