MOLECULAR GAS NEAR THE GALACTIC CENTER

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1. Molecular Surveys

Surveys of molecular gas in the central kiloparsec of the Galaxy have been underway throughout the 25 years since the discovery of CO. Table 1 lists the large-scale surveys published during this interval, including absorption-line studies of H_2CO and OH and emission-line studies of CO, NH_3, CS, and, to a lesser extent, HCN and H_2. With its several accessible isotopes, and because of its ubiquity, CO has provided perhaps the most complete picture of the large-scale distribution and kinematics of molecular gas, although the denser material ($n(H_2) > 10^4$ cm^{-3}) is better probed by NH_3, CS, and HCN.

2. Contents of the Molecular Arena

The region within 2° (300 pc) of the Galactic center contains the most prominent concentration of molecular gas in the Galaxy, with a mean surface density of ~ 200 M$_\odot$ pc^{-2}. This stands in contrast to the much smaller surface density in the HI nuclear disk beyond a few hundred parsecs from the center: ~ 5 M$_\odot$ pc^{-2}. Figure 1 shows this "central molecular zone" or CMZ, as viewed in ^{12}CO. This large reservoir of gas is probably attributable to the inexorable inflow of gas from the rest of the Galaxy, occuring as a result of the combination of several angular momentum loss processes (Morris & Serabyn 1996), not the least of which are those attributed to the pronounced stellar bar which dominates the central few kiloparsecs of the Galaxy. The residence time for gas in the CMZ is on the order of 0.4–1×10^9 years, far shorter than the age of the Galaxy, so the CMZ is in a quasi-steady state in which the inflow of gas from the Galaxy is balanced primarily by star formation and by evaporation of clouds into the surrounding hot (10^7 - 10^8K) medium implied by X-ray observations (Koyama *et*

TABLE 1. Large-Scale Molecular Line Surveys of the Galactic Center

Year	Molecule & Line	Reference
1970	OH 1667 MHz	Robinson, B.J., McGee, R.X.: Aust. J. Phys. 23, 405. see also p. 541 & p. 777
1972	$H_2CO\ 1_{11} \leftarrow 1_{10}$	Scoville, N.Z., *et al.*: ApJ 172, 335
1972	CO 1→0	Solomon, P.M., *et al.*: ApJ 178, 125
1973	$H_2CO\ 1_{11} \leftarrow 1_{10}$	Scoville, N.Z., Solomon, P.M.: ApJ 180, 55
1974	CO 1→0	Scoville, N.Z., *et al.*: ApJL 187, L63
1974	CO 1→0	Sanders, R.H., Wrixon, G.T.: A&A 33, 9
1975	NH_3 (1,1)	Kaifu, N., *et al.*: ApJ 201, 98
1976	OH 1665/7 MHz	Cohen, R.J., Few, R.W.: MNRAS 176, 495
1977	CO 1→0	Liszt, H.S., *et al.*: ApJ 213, 38
1977	CO 1→0	Bania, T.M.: ApJ 216, 381
1978	CO 1→0	Liszt, H.S., Burton, W.B.: ApJ 226, 790
1979	$H_2CO\ 1_{11} \leftarrow 1_{10}$	Whiteoak, J.B., Gardner, F.F.: MNRAS 188, 445
1980	$H_2CO\ 1_{11} \leftarrow 1_{10}$	Bieging, J.H., *et al.*: A&AS, 42, 163
1980	CO 1→0	Bania, T.M.: ApJ 242, 95
1981	$H_2CO\ 1_{11} \leftarrow 1_{10}$	Cohen, R.J., Few, R.W.: MNRAS 194, 711
1982	CO 1→0	Inatani, J.: PASJ 34, 515
1983	NH_3 (1,1), (2,2), (3,3)	Morris, M., *et al.*: AJ 88, 1228
1984	CO 1→0	Sanders, D.B., *et al.*: ApJ 276, 182
1986	CO 1→0	Bania, T.: ApJ 308, 868
1987	^{13}CO 1→0	Heiligman, G.M.: ApJ 314, 747
1987	CO 1→0	Dame, T.M., Ungerechts, H., Cohen, R.S.: ApJ 322, 706
1987	^{13}CO 1→0 & CS 2→1	Bally, J., *et al.*: ApJS 65, 13
1988	CO 1→0	Bally, J., *et al.*: ApJ 324, 223
1989	CS 1→0, 2→1	Tsuboi, M., *et al.*: in *The Center of the Galaxy,* ed: M. Morris, Dordrecht: Kluwer, p. 121
1992	CO 1→0	Burton, W.B., Liszt, H.S.: A&AS 95, 9
1992	$H_2CO\ 1_{11} \leftarrow 1_{10},\ 2_{11} \leftarrow 2_{12}$	Zylka, R., *et al.*: A&AS 96, 525
1994	OH 1665/7 MHz	Boyce, P.J., Cohen, R.J.: A&AS 107, 563
1996	HCN, CO 1→0	Jackson, J.M., *et al.*: ApJL 456, L91
1996	H_2	Pak, S., Jaffe, D.T., Keller, L.D.: ApJL 457, L43
1996	CO 2→1	Oka, T., *et al.*: ApJ 460, 334
1996	$C^{18}O$ 1→0	Dahmen, G. *et al.*: in *4th ESO/CTIO Workshop: The Galactic Center,* ed: R. Gredel, ASP Conf. Ser., in press
1996	CO 1→0	Uchida, K., Bally, J., Morris, M.: in preparation

al. 1989, Yamauchi *et al.* 1990, Sunyaev *et al.* 1993, Koyama *et al.* 1996). This hot medium, which may lie at the base of a thermally-driven Galactic wind, has approximately the same extent as the CMZ.

Figure 1. The Galaxy's Central Molecular Zone. Top: integrated intensity of ^{12}CO $J = 1 \rightarrow 0$ emission, from the AT&T Bell Labs survey (Uchida *et al.* 1996a). Bottom: IRAS 60 μm emission map, showing the distribution of relatively warm dust.

3. Molecular Streams and other Continous Features

Much of the molecular gas in the CMZ is arranged in well-defined, continuous "streams" which can be followed through longitude-latitude-velocity (l-b-v) data cubes for distances on the order of 10^2 pc (Uchida *et al.* 1996a). These streams probably result from the tidal shear to which the gas clouds are subjected (Güsten & Downes 1980). The most imposing of these features appears as a parallelogram, or ellipse, in longitude-velocity plots (figure 2), and appears to be a quasi-continuous ring of gas completely surrounding the Galactic center at a projected radius of 180 pc. This feature, which approximately coincides with the outer boundary of the CMZ, was originally hypothesized to be an expanding molecular ring (Scoville 1972; Kaifu

Figure 2. ^{12}CO $J = 1 \rightarrow 0$ emission contours in a position-velocity plane in which position extends along the line from l, b = 2.5°, −0.333° to −2.0°, 0.1333°, from the AT&T Bell Labs survey (Uchida *et al.* 1996a). This line, tilted by ∼ 6° with respect to the Galactic plane, was chosen to reflect the tilt of the plane containing the 180 pc molecular ring (Uchida *et al.* 1994a). Contour units are 1.4, 2.8, 4.4, 6.2, 8.2, 10.4, ... K.

et al. 1972) provoked by an explosion at or near the Galactic center. Various implications of this hypothesis have been pursued recently, including the shocks which radially expanding gas should produce (Uchida *et al.* 1994a,b) and the recognition that the expanding molecular ring should really be an expanding molecular shell (Sofue 1995b). However, the 180-pc ring has more recently been modelled as the response of gas to a central bar potential (Binney *et al.* 1991). In this latter model, which has been widely adopted, the 180 pc molecular ring coincides with the innermost of the non-self-intersecting "X_1" family of orbits (Contopoulos & Mertzanides 1977): elongated oval orbits having their major axes aligned with the bar. This kinematics of this ring, and its tilt by about 20° with respect to the Galactic plane, are continuous with the properties of HI located further out in the "HI nuclear disk", indicating that the molecular ring likely marks the location of an HI/H_2 transition, presumably induced by shocks.

The bulk of the gas in the Galactic center, however, about 5×10^7 $M_\odot$ (Güsten 1989, Cox & Laureijs 1989, Sodroski *et al.* 1995, Sofue 1995a), resides inside the 180 pc molecular ring and is said to be on X_2 orbits: oval orbits lying deeper within the central gravitational potential well than the X_1 orbits and having their major axes oriented perpendicular to the bar. Sofue (1995a) has examined the continous gas streams evident in ^{13}CO plotted in the l-v plane and has concluded that most of the gas interior to the 180 pc ring is organized into two "arms" which form large arcs upon a ring of galactocentric radius 120 pc. (A similar picture had earlier been suggested by Scoville *et al.* 1974.) Such structures could arise as gas builds up in the outermost occupied X_2 orbits as a result of the inevitable shock dissipation occuring in the innermost occupied X_1 orbit (Binney *et al.* 1991, Morris & Serabyn 1996).

4. Transience of the Molecular Gas Reservoir

The most massive clouds in the CMZ can reside there for time scales of only a few times 10^8 years, because they are doomed to spiral inwards under the influence of dynamical friction with the stars in the central bulge (Stark *et al.* 1991). Less massive clouds may lose angular momentum on similar time scales, because they are subject to magnetic viscosity and relatively frequent dissipative cloud collisions. Assuming a steady-state inflow, Morris & Serabyn (1996) estimate a mean residence time for gas in X_2 orbits of 0.4×10^8–10^9 years. For a star formation rate of a few tenths of a solar mass per year in the CMZ (Güsten 1989), this is sufficient time for almost all of the gas in the CMZ to be converted to stars. Some gas eventually finds its way into the central circumnuclear disk, which has an inner radius of about 1 pc. However, this feature is likely to be transient, and may represent a recent chance encounter of a cloud with the central gravitational potential well. The reader is referred to Morris & Serabyn (1996) for a more thorough discussion of the structure and evolution of the circumnuclear disk.

5. Tilts and Asymmetries

The CMZ shows a strong asymmetry about the Galactic center, with about 3/4 of the gas lying at positive longitudes. The 180 pc molecular ring is also asymmetric (fig. 2), its centroid being displaced by several tens of parsecs from the Galaxy's dynamical center and the core of the central stellar cluster (Uchida *et al.* 1994a, Blitz 1994). Furthermore, the ring appears to be displaced by about 30 or 40 km s^{-1} toward positive velocity, relative to the expected LSR velocity of 0 km s^{-1}. These displacements and asymmetries are suggestive of a "sloshing" mode (or $m = 1$ wave) in the gas layer, possibly coupled to the strong stellar bar (an $m = 2$ mode), and possibly related to the pronounced tilt of the gas layer (another manifestation of an $m = 1$ mode). Indeed, organized vertical gas motions appear to be an important element of the kinematical picture, and progress in analyzing the dynamics of the CMZ will require accounting for the fact that some of the continuous molecular streams extend well out of the Galactic plane in projection. In at least one location, a strong, large-scale (100 pc) vertical shock is implied by the CO data (Uchida *et al.* 1994b).

6. Temperatures and Internal Motions in Galactic Center Clouds

Several groups, mostly using the ammonia molecule, have shown that the temperatures of clouds in the CMZ are relatively high (25–200 K, typically $\sim$ 70 K, Morris *et al.* 1983, Güsten *et al.* 1985, Armstrong & Barrett 1985, Mauersberger *et al.* 1986, Hüttemeister *et al.* 1993) compared to clouds in the outer Galactic disk. A widespread gas heating mechanism is thus called for, although there is currently no consensus on the nature of that mechanism. Highly supersonic internal velocity dispersions ($\sim$ 15–30 km s^{-1}), comparable to the local intercloud velocity dispersion, are also prevalent throughout the Galactic center. The elevated temperatures and linewidths may be related, as dissipation of turbulent energy is a prime candidate for direct heating of the gas. This remains true if the cloud velocity dispersions represent magnetosonic disturbances, as seems likely in this highly magnetized environment, although the dissipative heating in that case is likely to be dominated by magnetically induced drift of ions and electrons through the viscous, neutral medium (ambipolar diffusion; Roberge *et al.* 1995), rather than by shocks or viscous shear. The tidal field has been suggested as a source of energy to account for the large linewidths (Fleck 1980); Das & Jog (1995) conclude that this mechanism is efficient only for a central bar potential, in which tidal fields vary markedly along elongated orbits. This requirement appears to be satisfied in the Galactic center.

7. Magnetic Fields

As the previous section indicated, there are several lines of evidence that the magnetic field near the Galactic center is quite strong, both inside and outside of clouds. Outside clouds, the field is evidenced by the large-scale synchrotron filaments observed in the radio. The strength of the field is estimated to be in the milligauss range on the basis of the apparent rigidity of the filaments in the face of their clear interactions with the high-velocity-dispersion clouds (Morris 1994, 1996, and references therein). The magnetic field is perpendicular to the Galactic plane wherever it is probed by the presence of a filament; considerations of pressure confinement of the filamentary structures have been used to argue that this poloidal field is uniform and pervasive throughout the inner 100–150 pc.

Inside molecular clouds, the field has been probed using measurements of the polarization of the thermal far-IR emission from dust grains which have presumably been aligned by the field (*e.g.,* Hildebrand *et al.* 1993, Morris *et al.* 1995). Although this technique does not yield the strength of the field directly, the large polarizations measured (up to about 10%) and the uniformity of the polarization vectors are both consistent with a strong and highly organized magnetic field within clouds. Interestingly, among the four Galactic center clouds which have so far been studied with far-IR polarization, the predominant magnetic field direction within three of them is roughly parallel to the galactic plane, while the other (Sgr B2) does not quite conform to this trend, although its interpretation is complicated by the fact that the polarization in that case arises primarily from far-IR absorption rather than from emission (Hildebrand *et al.* 1995). It appears, therefore, that the magnetic field orientation within Galactic center clouds is quite different from that outside of clouds, giving rise to the possibility that interesting MHD phenomena can take place at cloud surfaces. Indeed, Serabyn & Morris (1994) suggested that the nonthermal radio filaments are generated at the surfaces of molecular clumps as a result of particle acceleration accompanying magnetic field line reconnection. The other requisite element of that hypothesis is a source of ionization to provide the needed electrons at the cloud surface. Existing observations are consistent with this hypothesis for all of the radio filaments which have been sufficiently well studied (*e.g.,* Uchida *et al.* 1996b). Zeeman measurements of magnetic fields in Galactic center clouds have been far less revealing than the polarization measurements, in part because of the large intrinsic linewidths there. Beyond the circumnuclear disk, only upper limits have so far been reported (Uchida & Güsten 1995), and the results seem oddly discrepant with the polarization data.

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