GAS AND DUST IN THE INNER FEW DEGREES OF THE GALAXY

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Abstract. This review discusses the complex morphology and perturbed kinematics, as well as the outstanding physical characteristics of the interstellar medium within a few 100 pc of the galactic center. A total of ~$10^{7.9}$ $M_\odot$ of dense molecular gas, representing ~10 % of the Galaxy's neutral mass content, has settled in a thin layer [size: 450 x 40 pc], composed of giant molecular cloud complexes. The spatial distribution is highly asymmetric with respect to the center, and motions differ considerably from equilibrium conditions. The dynamical situation is still obscure (explosive event vs. response to distorted gravitational potential), but any disturbance must have occurred quite recently (τ_{dy} ~10^6 yr). Evidence for large-scale star-forming activity is reviewed, and for a standard IMF, a total star formation rate Φ ~0.5 $M_\odot$ yr^{-1} is inferred.

The galactic center clouds differ considerably in their physical and chemical characteristics from GMC's in the outer Galaxy. Pervasive high bulk gas temperatures (T_{kin} ~70 K), mean H_2 densities of n ~10^4 cm^{-3}, and linewidths ≥10–20 kms^{-1} are probably a consequence of the clouds' location in the steep gravitational potential of the central bulge.

1. Introduction

Much of the neutral gas between a few 100 pc and ~2 kpc from the nucleus (including the prominent HI features that reveal large radial motions, Oort 1977) lies in a tilted disk whose plane of symmetry is inclined ~20° relative to the galactic plane (Burton & Liszt; Liszt & Burton, 1978). Although best traced in the H 21 cm line (M_{HI}~4 10^7 $M_\odot$), the basic characteristics are shared by both the atomic and molecular phase. The dynamics behind the highly perturbed kinematics, with non-circular (outward directed) motions of the same order as the rotation velocities, are not yet understood. According to Liszt & Burton (1980), the major characteristics can be fitted by motions along closed, non-

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self-intersecting elliptical streamlines (thus avoiding the difficulties in accounting for a net mass loss of ~4 $M_\odot\ yr^{-1}$, predicted with true expansion). These dynamics suggest a triaxial configuration of the central bulge, which rotates counter to the gas (see Vietri, 1986, and R. Sanders, this volume, for observational constraints on the stellar mass distribution and kinematics).

2. Global Characteristics of the Central 500 pc

2.1. Morphology of the (Molecular) Gas Layer

Embedded within this tilted (HI) ellipsoid, resides a prominent ~450 pc sized layer of dense molecular clouds. As discussed below, ~10% of the Galaxy's neutral gas is confined within a thin sheet of thickness ~30–50 pc, increasing with galactocentric radius (Sanders et al., 1984; Heiligman, 1987). This turbulent cloud layer (cloud-cloud velocity dispersion: ~30–50 kms^{-1}) seems in approximate hydrostatic equilibrium with the central bulge potential (Bally et al.,1988). The distribution is extremely clumpy, and a major fraction of the mass is found in huge molecular cloud complexes with ~100 pc size (Sgr A, Sgr B2, 'Clump 2'), each revealing fine-structure on scales of 10–20 pc (Sect.3).

As opposed to the larger-scale (HI)-disk, there is little, if any evidence for inclination of the molecular layer (Fig.1; Bally et al., 1987). The distribution is azimuthally asymmetric with ~2/3 of the mass displaced to positive longitudes ($-1° \leq l \leq 2°$; 1°=150 pc). The bulk velocity of the main ridge, v_r ~50–100 kms^{-1}, is significantly below the pattern expected for a smooth gas distribution, and there are only traces of

Table I. Major Line Surveys in the Inner Galaxy

species	frequency [GHz]	survey area l	survey area b	grid l	grid b	beam	telescope	references
HI	1.4	-21...11°	-2....2°	30'	15'	21'	43-m	Sinha ('79)
		-1.5..1.5°	-1.5..1.5°	9'	9'	9'	100-m	Braunsfurth & Rohlfs ('81)
		-11...13°	-10...10°	30'	30'	21'	43-m	Burton & Liszt ('83 b)
OH	1.7	-6....8°	-1....1°	12'	12'	10'	Mk IA	Cohen & Few (1976)
								Cohen & Dent ('83)
H_2CO	4.8	-1.4..2.8°	-0.2..0.1°	3'	3'	4.4'	64-m	Whiteoak & Gardner ('79)
		-0.5..4.0°	-0.5..0.9°	3(6)	3(6)	2.9'	100-m	Zylka et al. ('88),
								Bieging et al.('80)
CS	98	-1...3.7°	-0.4..0.4°	1'	1'	1.9'	7-m	Bally et al. ('87)
^{13}CO	110	-2....2°	-0.5..0.5°	4'	8'	1.7'	7-m	Heiligman ('82,'87)
		-5....5°	-0.6..0.6°	6'	6'	1.7'	7-m	Bally et al. ('87)
		-0.5..0.9°	-0.4..0.4°	1'	1'	1.7'	7-m	Bally et al. ('87)
^{12}CO	115	-10...25°	-0.3..0.3°	30'	10'	1.1'	11-m	Bania ('77,'80,'86)
		-1....1°	-0.3..0.4°	2'	2'	1.1'	11-m	Liszt et al.('77,'78),
								Burton & Liszt ('83a)
		-4...70°	-2....2°	60'	12'	~1'	11/14-m	Sanders et al. ('84)
		---	-8....8°	30'	30'	9'	1.2-m	Dame et al. ('87)

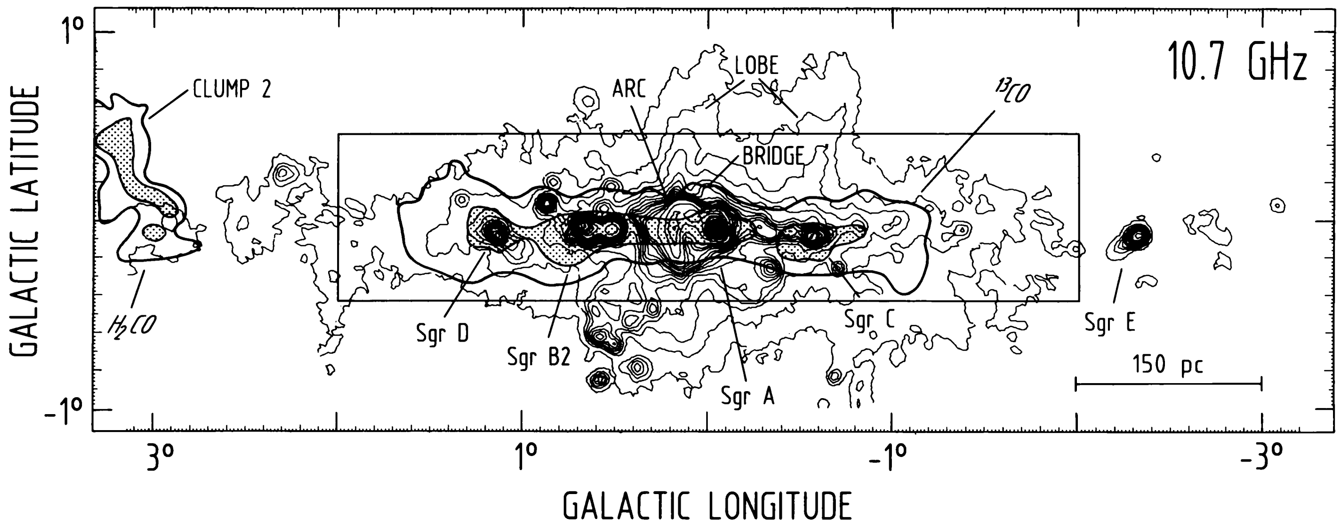

Fig.1. Guide to the inner few 100 pc of the galactic center, showing the molecular gas layer superimposed on the 10 GHz radio continuum emission (Handa et al., 1987). Within ±2° galactic longitude, the 25 and 50% (stippled) contours of the velocity-integrated $^{13}CO(1-0)$ emission (Heiligman, 1987), for 'Clump 2' equivalent H_2CO optical depth (Zylka et al., 1988) contours are displayed. Prominent radio features (Sgr A–E), the galactic center Lobe (Altenhoff et al., 1978; Sofue, this meeting), the non-thermal Arc (Yusef-Zadeh, this meeting), and the connecting Bridge to Sgr A are labelled.

gas observed close to their tangential point ($v_r \sim v_{rot}$; Gardner & Boes, 1987). If the velocity field is controlled by a regular gravitational potential, then according to their (l,v) coordinates most clouds are concentrated in a narrow bar-like structure (Cohen & Dent, 1983). These asymmetries in velocity-space must be transient, as differential galactic rotation around the nucleus tends to wipe out such phenomena in a few 10^6 yr.

A physically and kinematically distinct feature is the so-called 'expanding molecular ring' (EMR), which was first noticed more than two decades ago in OH absorption measurements toward Sgr A (Bolton et al., 1964), and since then has been investigated in a wide variety of molecular species. Spectra towards Sgr A continuum (Fig.2b) show prominent absorption from the near side of the ring at $v_r \sim -135$ kms^{-1} (EMR$^-$); its rear counterpart (EMR$^+$, +165 kms^{-1}) is traced best in the (CO) emission lines. The feature's overall extent is comparable to the size of the molecular gas layer (sharing its longitudinal asymmetry), with a z-width of ~30 pc. The ring is clearly tilted relative to the galactic plane by ~10° (Fig.3), with an orientation similar to that of the tilted HI-disk, which led Liszt & Burton (1978) to consider the expanding ring as the inner extension of this larger-scale structure. The total mass has been estimated to be ~2 10^6 $M_\odot$ (Bania, 1977).

For both features, the molecular cloud layer and the expanding ring, the dynamical situation is rather mysterious, and definitely requires more attention. The perturbed kinematics could result either from an explosive event some 10^6 yr ago, or from the effect of a distorted gravitational potential. In view of the prohibitive energetic requirements (~10^{55} erg), and because of a lack of any evidence for violent activity on these dynamical timescales, an expulsive origin seems rather unlikely. A rapidly rotating (bar-like) gravitational perturbation may result in a strong dynamical response, but although dynamically distinct from the (hot) bulge population, direct observational evidence is absent so far (Sanders, 1979; and this volume). These inner bar(s) would differ from the perturbations required to explain the perturbed structures observed on larger scales (the tilted disk, the (expanding) '3 kpc arm'). What is needed is a unifying field model to understand these phenomena in a self-consistent fashion.

2.2. Mass Distribution

The central bulge represents a highly astrated evolved stellar population with most of the matter locked up permanently in long-lived low-mass stars. Inside 500 pc galactocentric radius, a total mass of ~7 10^9 $M_\odot$ is derived from the HI rotation curve and the 2μm IR radiation of the stellar cluster (Oort, 1977; Sanders & Lowinger, 1972). Only a small fraction of the total mass still resides in the interstellar phase. In Fig.4, recent estimates of the gas mass within R_{gc}=500 pc are compiled in a mass-density histogram, crudely associating a characteristic density regime with each probe. The mass of atomic hydrogen is derived from the (optically thin) H 21cm transition (e.g. Burton & Liszt, 1978). However, as there is no transition of molecular hydrogen easily

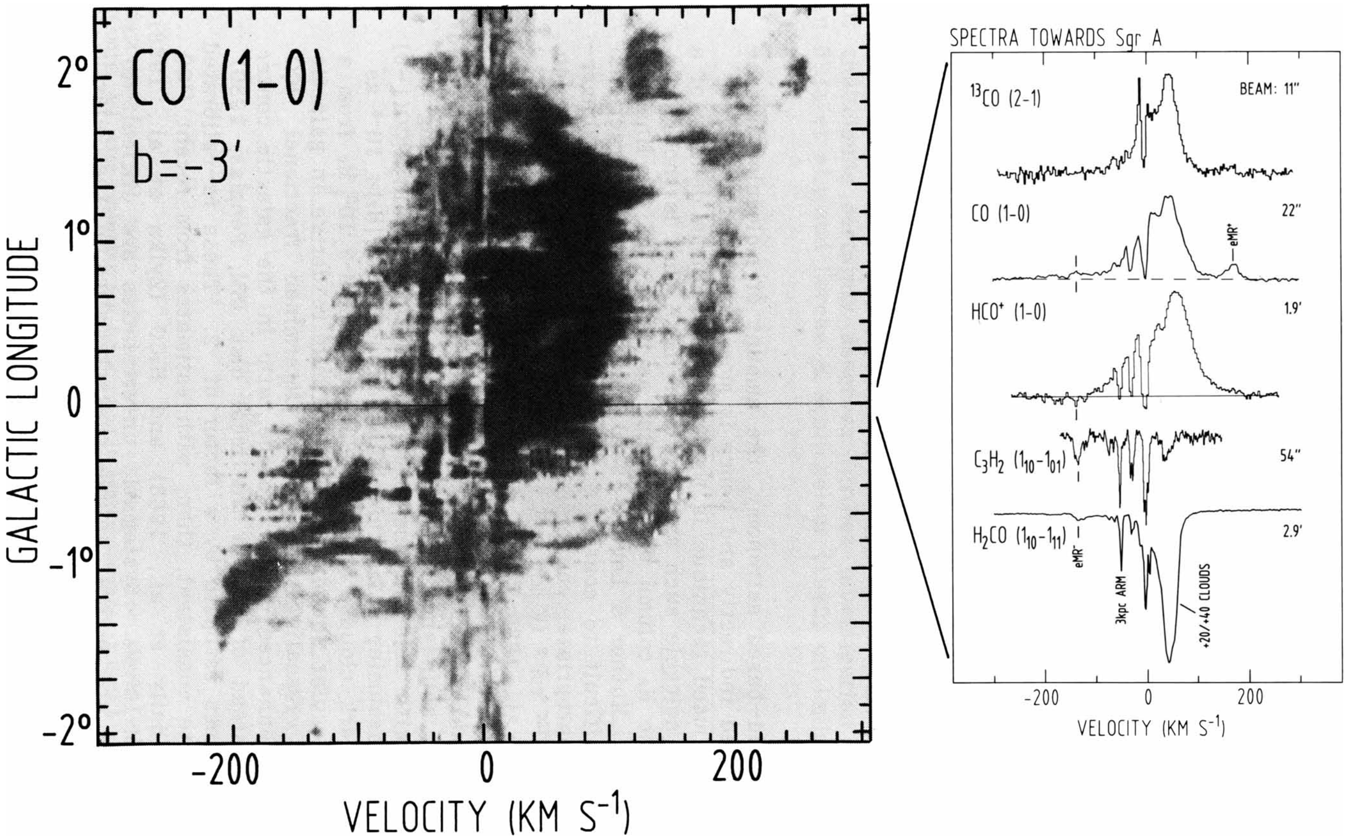

Fig.2. (a) Grey-scale representation of the CO(1-0) longitude-velocity diagram along the galactic plane (b=-3'; Liszt & Burton, 1978; for the corresponding contour arrangement, see their Fig.2a). (b) Selected emission and absorption line spectra towards the galactic nucleus [^{13}CO(2-1), R.Zylka, priv.comm.; CO(1-0), Serabyn et al., 1986; HCO$^+$(1-0), Linke et al., 1981; $C_3H_2(1_{10}-1_{01})$, Cox et al., 1988; $H_2CO(1_{10}-1_{11})$, Güsten & Downes, 1980). Major velocity features arise from the '+20/+40 kms^{-1} clouds' close to the galactic center, the 'expanding molecular ring' (EMR$^{\pm}$) at v~-135 and +165 kms^{-1} (front and rear part, respectively), and from several larger scale line-of-sight structures (gas at v=-54 kms^{-1} resides in the so-called '3 kpc-arm').

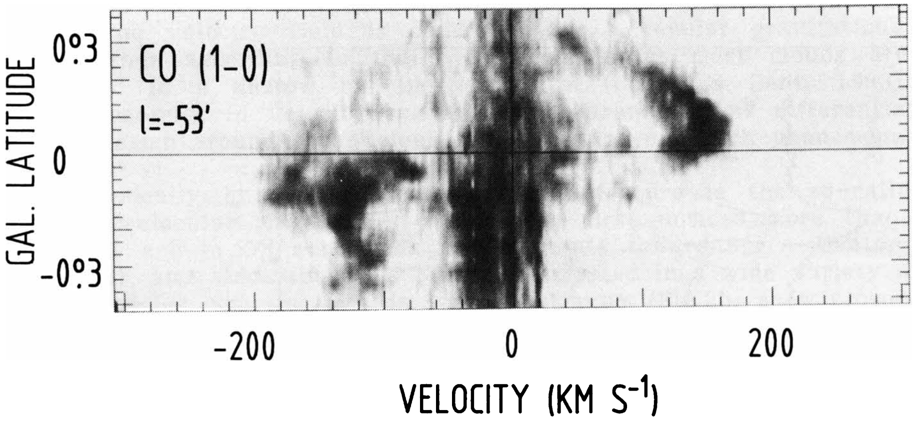

Fig.3. Latitude-velocity diagram of the CO(1-0) emission at longitude offset -50' from Sgr A, depicting the tilt of the expanding molecular ring against the galactic plane (Liszt & Burton, 1978).

accessible to ground-based astronomy, the amount of molecular hydrogen must be inferred indirectly and hence is more controversial.

The generally used technique is to derive the column density of a (widespread) trace molecule such as CO and/or H_2CO, that is thought to be a measure of the H_2 column density. But as details of the line formation process (e.g. Kutner & Leung, 1985), and in particular fractional abundances, are difficult to constrain observationally, there is uncertainty in the appropriate conversion factors. Using a conversion $N(H_2)/W_{CO}$~2.8(±1) 10^{20} cm^{-2} (K km $s^{-1})^{-1}$ as suggested for galactic disk clouds [Bloemen et al., 1986; with an uncertainty of ~30% according to the more recent literature], from the CO(1-0) survey of Sanders et al. (1984), we determine a total gas mass M(R≤500 pc)~1.5 10^8 $M_\odot$ (corrected for a fractional He abundance of 10 percent by number). Probing the CO optical depth with selected complementary optically thin $^{13}CO(1-0)$ measurements and assuming a fractional abundance $[^{13}CO]/[H_2]= 10^{-6}$ as inferred in local dark clouds, Bania (1986) derived M~3 10^8 $M_\odot$ from a survey in ^{12}CO. Molecular abundances are difficult to derive in galactic center clouds, but rescaling the locally determined fractional ^{13}CO abundance by the enhanced carbon isotope ratio in the galactic center ($[^{12}C/^{13}C]$~20-25, instead of ~50 in the local disk ISM; Penzias, 1980) would lower this mass estimate by a factor of ~2. These re-calibrated CO masses are quite consistent, then, with estimates from recent ^{13}CO (Heiligman, 1987; Bally et al., 1988) and H_2CO (Zylka et al., 1988) surveys, yielding M~10^8 $M_\odot$. Systematic uncertainties are difficult to quantify, but there are several unique characteristics of the galactic center cloud population that tend to lead to an overestimate of gas masses when applying 'standard' calibration techniques. Among these are the enhanced bulk gas temperature and metallicity, and the very broad linewidths, which may reduce the effective opacity in the line (Stacey et al., 1988). The optical depth of the H_2CO absorption lines has been calibrated directly to virial mass estimates of selected galactic center clouds, and hence 'H_2CO' masses should be independent of these effects [on the other hand, there is a priori no reason to assume virialization in these clouds].

An independent approach to the gas content of the galactic center region is to observe the high-energy gamma-ray emission, produced by interactions between cosmic rays and the nuclei of the interstellar gas (by the π^0 decay process). The lack of excess hard gamma-ray emission towards the galactic center implies a significantly reduced gamma-ray emissivity per hydrogen nucleus, which may be due to a reduced density of either the intervening high-energy (~GeV) cosmic ray protons or of the target (hydrogen) nuclei. With a cosmic ray density derived for the local disk, an upper limit on the gas mass of ~5 10^7 $M_\odot$ (Blitz et al.,1985; Bath et al.,1985 - R<500 pc) is calculated. This is in conflict with the above results from molecular line surveys (Fig.4). Given the high column density across the central gas layer, the question of whether GeV cosmic ray nuclei may be prevented from penetrating part of the clouds certainly deserves further investigation [see discussion in Blitz et al.; and Lerche & Schlickeiser (1982) on ionization losses].

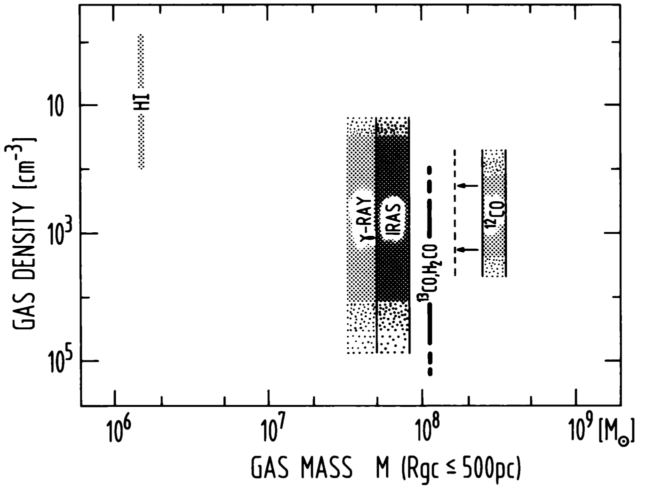

Fig.4 Mass of gas within galactocentric radius $R_{gc} \leq 500$ pc versus characteristic excitation density. All mass estimates are for a galactic center distance of R_o=8.5 kpc, and are corrected for a fractional helium abundance of ~10% by number. For details of the procedure and references, see Sect.2.2.

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Modelling the infrared emission characteristics of interstellar dust grains and assuming a standard dust-to-gas ratio, the far-infrared dust emission can be taken as a measure of the total gas mass. Details of the procedure and inherent uncertainties are reviewed by P.Cox in this volume, and in the following we only address points of interest to the present discussion. From a careful analysis of the FIR/submm spectrum of the galactic center, Cox & Laureys (1988) derive $M(l \leq \pm 1.5°; b \leq \pm 1°)$ ~3.5(±1) 10^7 $M_\odot$. There are no sub-mm measurements available on larger scales, and hence mass extrapolations to our 500 pc sized reference sphere suffer from (more) uncertain bolometric corrections to the IRAS data. Extrapolation of their calibration from the innermost nucleus to the larger scale IRAS luminosity, L(500pc) ~$10^9 L_\odot$, suggests M(500pc) ~$10^{7.85 \pm .15}$ $M_\odot$. However, modelling the data in terms of a one-component emission layer might be misleading. There is evidence that emission in the IRAS(60μm, 100μm) and sub-mm (300μm, 900μm) windows may arise from distinct, although partially coexisting phases of the interstellar gas. This is suggested, for example, by differences in scale height (the latitudinal extent of the IRAS 100μm emission, $dz_{½}$~1.4°, significantly exceeds that of the sub-mm (~1°, Pajot et al.,1988) and ^{13}CO (0.4°) emission layers) and dust temperature ($\langle T_D \rangle_{IRAS}$~27 K, vs. T_D~20 K towards massive cloud cores; Mezger et al.,1986). The IRAS windows may be probing a more diffuse, warmer but lower column density medium, while the longer wavelength sub-mm emission is biased towards the cooler dust associated with the molecular cloud layer (with considerable overlap between these components).

In summary, my (weighted) guess for the mass of the central gas layer is $M(R_{gc} \leq 500$ pc)~$10^{7.9 \pm .25}$ $M_\odot$. Comparison with the total mass of

Table II. Global Characteristics of the Central Gas Layer

	Central 500 pc	Galactic Disk
Masses and Densities		
Stars M_*	$10^{9.8}$ $M_\odot$	--
Gas, atomic	$10^{6.4}$ $M_\odot$	~10^9 $M_\odot$
.., molecular	$10^{7.9}$ $M_\odot$	~10^9 $M_\odot$
Gas fraction $\mu = M_g/M_*$	~0.01	~0.05-0.10
Abundance [HI]/[H_2]	~0.05	~2
Gas density $\langle n \rangle_v$	100 cm^{-3}	1-2 cm^{-3}
.. surface density σ	≥100 $M_\odot pc^{-2}$	~5 $M_\odot pc^{-2}$
Star Formation		
Rate Φ	0.3-0.6 $M_\odot yr^{-1}$	~5.5 $M_\odot yr^{-1}$
Efficiency Φ/M_g	5 10^{-9} yr^{-1}	10^{-9}-10^{-8} yr^{-1}

μ~0.01, is left in the interstellar phase. The central bulge represents a far more evolved system than the galactic disk population (μ_D~0.05–0.10, increasing with R). The advanced state of astration is also reflected in the enhanced chemical composition of the material (Wannier, this conference). From first-order models, the increase in metallicity is proportional to ln(1/μ). Despite this strong depletion, volume-averaged gas densities, $\langle n \rangle$~100 cm^{-3}, and gas surface densities, $\sigma \geq 100$ $M_\odot$ pc^{-2}, exceed corresponding densities anywhere else in the Galaxy by more than 1–2 orders of magnitude (Table II). In contrast to the galactic disk for which comparable masses of atomic and molecular hydrogen are derived, and distinct from the composition of the lower density material outside the innermost few hundred pc (Liszt & Burton, 1978), the gas in the central cloud layer is dominantly molecular ([HI]/[H_2]~0.02).

2.3. Star Formation

From the classical tracers of star formation (e.g., Lequeux, 1979) there are only two methods that have been applied successfully to the highly obscured (optically) galactic center region.

(1) Provided that the spectral analysis of the galactic center FIR emission permits one to extract the fraction of luminosity produced by Pop I stars whose radiation has been absorbed by interstellar dust, the star formation rate (SFR) $\Phi(0.1 \leq M \leq 60\ M_\odot)$ can be estimated from

$$\Phi[M_\odot\ yr^{-1}] \sim 10^{-9\pm .3} \cdot L_{IR,I}[L_\odot].$$

This relation has been established from both an IMF-weighted integration of the stellar luminosity function (Thronson & Telesco, 1987) and empirically from the present-day star formation in the galactic disk [$L_{IR,I}$~$10^{9.6\pm .25}$ $L_\odot$ (Cox & Mezger, 1987; Pérault et al., 1988); $\Phi(R \leq 13$ kpc) ~5.5 $M_\odot$ yr^{-1} (Güsten & Mezger, 1983), with the Garmany et al. (1982) IMF].

(2) From the thermal radio emission, the production rate of Lyc photons $N_{Lyc}[s^{-1}]$, absorbed in the ionized gas, is calculated. With the help of model stellar atmospheres, yielding the Lyc production vs. stellar mass, a SFR can be inferred (Güsten & Mezger, 1983) from

$$\Phi[M_\odot\ yr^{-1}] \sim 0.3 \cdot N_{Lyc}[10^{52}\ s^{-1}].$$

The 'typical' (IMF-weighted) Lyc-producing star is of spectral type O6 (mass: 20–40 $M_\odot$), and only stars more massive than ~10–15 $M_\odot$ make a significant contribution at all. Hence, as according to standard IMFs, the bulk of the mass is transferred into low mass objects, the inferred total SFR depends heavily on the slope of the stellar mass spectrum. The latter is barely understood in the local disk, and is even more uncertain in the galactic center. In particular, as there is increasing evidence, that in (galactic) regions of active star formation, the low-mass cut-off of the IMF may shift towards higher masses (e.g., Scalo, 1986), estimates of total SFR should be considered with caution. A similar conclusion holds for the SFR inferred from the FIR emission, dominated by intermediate mass stars. However, a more serious limitation of this method is that for the galactic center, the fraction of IR luminosity resulting from the young stellar population is difficult to determine [realize, that also in the galactic disk $L_{IR,I}$~0.5·L_{IR}]. From analyzing the IRAS data, Cox & Laureys suggest that a major fraction of the energy absorbed by the warm dust (outside discrete sources) arises from the old population. This may naturally explain the unusually large infrared excess derived for the extended emission: IRE >30, as compared with <10 in the diffuse galactic disk emission. Otherwise, the enhanced IR emission per ionizing photon would imply a steeply declining IMF beyond ~10 $M_\odot$ (Odenwald & Fazio, 1984).

A lower limit on the SFR may be obtained from the luminosity of the discrete FIR sources, $L_{IR,d}$~5 $10^7 L_\odot$ (Odenwald & Fazio, $R_\odot$~8.5 kpc), yielding Φ~0.05 $M_\odot yr^{-1}$. Obviously, star forming activity during the last 10^7 yr (traced by these FIR spots) has occurred in a narrow ridge extending ~30 pc in latitude and ~450 pc in longitude (fitting the size of the CO layer). All the prominent HII/FIR- complexes (Sgr A–E) perfectly line-up along the galactic plane (see Liszt (1988) for a recent compilation of high-resolution radio data).

After separation of the thermal and non-thermal radio emission (S_{th}~S_{nth}~950 Jy at 4.9 GHz, according to Schmidt (1978), and confirmed by the recent Nobeyama 10 GHz survey (Handa et al., 1987)), Mezger & Pauls, 1979, derived

- $N_{Lyc,e}$ ~4 10^{51} s^{-1} for the extended emission component (size of the spheroid: 225 x 90 pc), and
- $N_{Lyc,d}$ ~2 10^{51} s^{-1} in discrete giant HII-regions.

Correcting for the fraction of ionizing photons absorbed by dust and escaping from the (density-bounded) HII-layer, this amounts to a total of N_{Lyc}~1–2 10^{52} s^{-1}. The inferred total SFR, Φ~.3–.6 $M_\odot yr^{-1}$, corresponds to ≤10% of the total galactic rate. The timescale of galactic center star formation, τ~M_g/Φ a few 10^8 yr, seems uncomfortably short, but according to detailed evolution models, the present state may be stationary, with the observed net gas consumption being largely balanced by gas liberated from evolving population II stars (Güsten & Ungerechts, 1985).

The overall star formation efficiency, Φ/M_g~5 10^{-9} yr^{-1}, lies in between numbers inferred for the local disk (~1.5 10^{-9} yr^{-1}) and the inner Galaxy (~10^{-8} yr^{-1}; 4 ≤R ≤6 kpc). In view of the high average gas density inferred for most of the galactic center clouds (Sect.3), one might have expected an enhanced efficiency, but perhaps other (atypical) characteristics (high temperature and turbulence, tidal stresses) counterbalance this effect. While there are sites of spectacular activity (e.g., SGR B2), the general lack of associated FIR- and radio continuum emission suggests that the majority of clouds are currently not the birthsites of stars earlier than ~O7.5 (detection limit, Odenwald & Fazio, 1984).

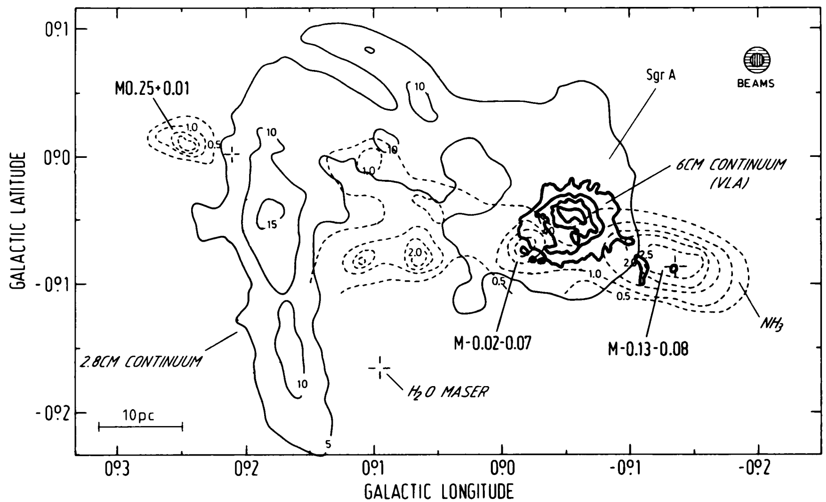
3. Physical Conditions of Galactic Center Clouds

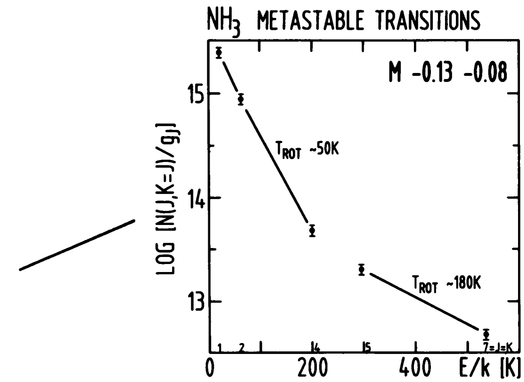
A major fraction of the gas in the innermost few 100 pc resides in a number of giant cloud complexes with diameters of ~100 pc (e.g., Sgr A complex, Sgr B2, Clump 2). Each complex shows substructure with scale sizes of 10-20 pc. In comparison with the galactic disk, these clouds are identified by unique physical and chemical characteristics.

Densities and Masses. Closest (in projection) to the nucleus, the prominent Sgr A molecular clouds (Fig.5) have attracted particular attention. From several, independent methods, mean H_2 densities $\langle n \rangle \sim 10^{4 \pm .5}$ cm^{-3} and masses $M_{cl} \sim 10^{5-6}$ $M_\odot$ have been inferred (e.g., Armstrong & Barrett, 1985, using optically thin $C^{18}O$; Güsten et al., 1981, from the lower NH_3 inversion transitions; Cox et al., 1988, from C_3H_2 absorption line measurements; Mezger et al., 1986, from sub-mm dust emission; and references in these papers). Detailed multi-line excitation analyses of density-tracing molecules like CS and HC_3N (Fig.5c; Walmsley et al.,1986) suggest a clumpy cloud morphology, with some 10% of the mass in higher density clumps (~10^5 cm^{-3}), embedded in a lower density interclump medium, n ~$10^{3.7}$ cm^{-3}. In particular, there is no evidence for a substantial amount of mass at densities $>10^6$ cm^{-3} (see the discussion of tidal stability below). Recent surveys in density-tracing molecules (CS, Bally et al.,1987; and the H_2CO cm-transitions, Zylka et al.,1988) showed that densities $\geq 10^4$ cm^{-3} are representative of the bulk of molecular gas inside a few 100 pc of the galactic center. Comparable densities, ~10^4 cm^{-3}, are derived for the expanding molecular ring, but n ~10^3 cm^{-3} for the 3-kpc arm (Cox et al., 1988).

Table III. Physical Properties of Galactic Center Clouds

	Center Clouds	Disk Clouds
Mass [$M_\odot$]	10^{5-6}	
Size [pc]	20-30	
Density [cm^{-3}] ⟨n⟩	~10^4	~$10^{2.5}$
Temperature [K] ⟨T⟩	~70	~15
hot phase	~200	--
Vel.dispersion [kms^{-1}]	10-20	≤5
Magnetic field [mG]	(~0.5)	≤0.1
Isotopic Abundances		
$[^{12}C]/[^{13}C]$	~25	~75
$[^{16}O]/[^{18}O]$	~200	~400
$[^{14}N]/[^{15}N]$	~1000	~400





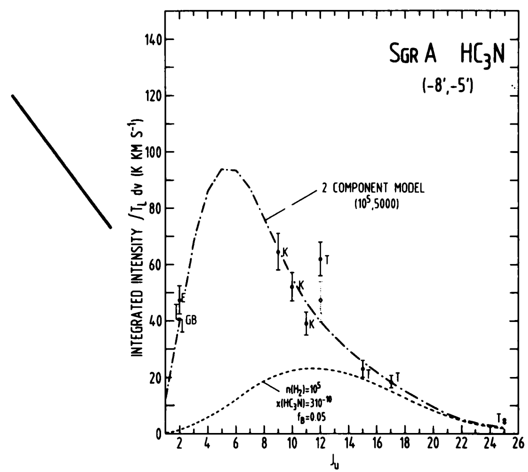


Fig.5. Composite diagram of the Sgr A cloud complex, showing the 2.8 cm radio continuum emission (Pauls et al., 1976) superposed on the ammonia brightness temperature distribution (Güsten et al.,1981). A 6 cm VLA continuum map is overlaid towards Sgr A halo (Ho et al., 1985). To the right, the temperature and density structure of M−0.13−0.08, the +20 kms^{-1} cloud, is displayed. Top right: population diagram of the NH_3 metastable levels vs. excitation energy above ground, revealing the rotation temperature(s) of the gas (Mauersberger et al., 1986). Bottom right: Two-component model fit to the density profile of the cloud, as obtained from a multi-line HC_3N study (Walmsley et al., 1986). Bulk densities are $\leq 10^4$ cm^{-3}, with ~20% of the mass residing in a higher density phase, n ~10^5 cm^{-3}.

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Turbulence. Observed linewidths (deconvolved from velocity gradients across the beam), of ~15–30 kms^{-1} are characteristic of individual clouds [however, if several clumps are in the beam, total widths in excess of 100 kms^{-1} may be obtained (Clump 2, Stark & Bania, 1986)]. This local velocity dispersion is highly supersonic ($c(H_2)$ ~1.5 kms^{-1} for 50 K), and dissipates on a dynamical timescale of ~10^6 yr. If the observed width were due to low-frequency MHD waves, we calculate an equipartition magnetic field strength B ~0.5 mG·[Δv/20]·$[n/10^4]^{.5}$. Note that the broad lines make impossible any direct access to the field strength (via Zeeman splitting) in the neutral ISM.

Temperatures. Excitation studies of symmetric top molecules (Armstrong & Barrett, 1985; Morris et al., 1983; Güsten et al., 1981) reveal uniformly high gas temperatures throughout the central 500 pc – irrespective of the local environment of the cloud and its projected distance to the nucleus (Fig.6). Results rely mainly on the metastable NH_3(J,J=K) inversion transitions, but have been confirmed with the heavy symmetric top species CH_3CN (methylcyanide) and CH_3CCH (propyine) (Güsten et al., 1985). Inspection of Fig.5b (Mauersberger et al., 1986) suggests strong temperature fluctuations inside a cloud, with the higher excitation lines revealing progressively higher rotation temperatures. Likely there exists a whole hierarchy of temperatures, but in first approximation, bulk temperatures are T_{rot} ~50 K, with some few percent of the

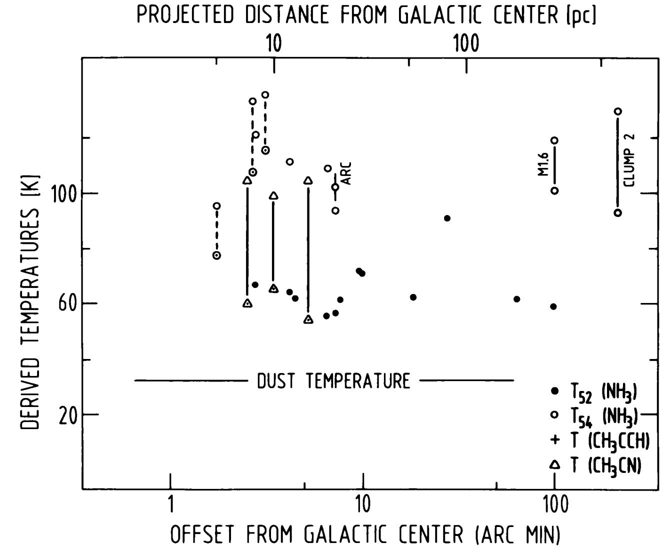

Fig.6. Gas temperatures in galactic center molecular clouds, versus projected galacto-centric distance (updated from Güsten et al., 1985). $T_{52}(NH_3)$, derived from the NH_3(5,5) and (2,2) metastable levels, and temperatures obtained from the heavy symmetric top molecules, CH_3CCH and CH_3CN, closely measure the bulk temperature of the gas, while $T_{54}(NH_3)$ is biased towards the higher temperature phase (cf. Fig.5; T_{54} ~100 K = T_{kin} ~150 K). Note that the temperature of the dust in the region is 20–30 K only.

mass at temperatures up to ~200 K. Note that due to collisional depopulation via the (J,K+1) non-metastable levels, rotation temperatures underestimate true kinetic temperatures; and T_{rot} ~50 K from the lower inversion transitions (J≤4) corresponds to T_{kin} ~70 K (Danby et al., 1988). Important findings for the later discussion of possible heating mechanisms are that (1) the temperature of embedded dust particles, T_D ~20–30 K, is much below the kinetic gas temperature (Stier et al., 1982; Odenwald & Fazio, 1984; Cox, this volume), and that (2) these gas temperatures are pervasive throughout the central gas layer (with the exception of a moderately lower temperature in the expanding molecular ring, T_{kin} ~30–40 K, Serabyn & Güsten, 1986).

Chemical composition. A determination of absolute (interstellar) abundances of the major elements (He, CNO group) is made difficult by the large obscuration of the galactic center. However, recent molecular line studies have allowed quite accurate relative (isotopic) abundances to be derived. The advanced state of chemical evolution of the galactic center system (reviewed by P.Wannier at this conference), is most directly reflected in the enhanced abundance of secondary CNO-nuclei (Table III). Compared to isotope ratios in the local disk, $[^{12}C]/[^{13}C]$ is reduced by a factor ~3, $[^{16}O]/[^{18}O]$ by ~2, while $[^{14}N]/[^{15}N]$ is enhanced by factor of ~2.5 (see Penzias, 1980; and Gardner & Whiteoak, 1982; Wannier et al., 1981; Whiteoak & Gardner, 1981; Güsten & Ungerechts, 1985; Schüller et al., 1988, for more recent contributions). According to surveys in the easier-to-study carbon isotopes, the gas out to ~5° longitude (750 pc) seems chemically homogeneous, and no systematic variations between different kinematic features (including the expanding molecular ring) have been confirmed (Güsten et al., 1985).

Inspection of Table III shows that pervasive high temperatures, densities and linewidths are the outstanding characteristics of the galactic center cloud population. Outside the galactic center, only toward local spots surrounding young stellar objects (like Orion-KL or W3(OH)) are similar conditions observed. On average, these clouds are denser and warmer (by 1–2 orders of magnitude), and more turbulent than clouds in the outer Galaxy. In part, these differences can be understood as a consequence of the clouds' unique location in the steep gravitational potential of the central stellar cluster ($\varrho_\star \propto R^{-1.8}$), as we discuss now.

3.1. Stability Criteria

As necessary condition, for a cloud of radius R_{cl} at galactocentric distance R_{gc} to be stable against tidal disruption, its mean H_2 density must be

$$\langle n\rangle_T \geq 10^4\ \mathrm{cm^{-3}} \cdot [75\ \mathrm{pc}/R_{gc}]^{1.8}$$

(Güsten & Downes, 1980, with $R_{gc} > R_{cl}$; A.Stark, this volume). Hence, just to survive tidal stresses, galactic center clouds must be much denser than clouds in the disk (for reference, $\langle n\rangle_T$ ~10 cm^{-3} in the solar neighborhood). Hence high density cores (n ~10^5 cm^{-3}) might counterbalance tidal forces even at radii close to their (projected) longitude ($R_{gc} \geq 20$ pc), while their lower density 'envelope' (containing the bulk of the mass) would be tidally stripped off on time scales comparable to the cloud's galactic rotation period if $R_{gc} < 75$ pc (τ_{rot} a few 10^6 yr). This of course, does not exclude the possibility that individual clouds (on elongated orbits) may approach much closer to the nucleus than permitted by the above criterion. In particular, for the Sgr A clouds (Fig.5; Ho et al., 1985; Okumura-Kawabe et al. and Ho et al., this volume), but also for the bridge of gas connecting to the Arc (Serabyn & Güsten, 1987), there is increasing evidence for physical interaction with the inner nucleus.

The observed large velocity dispersion therefore strongly suggests virialization in these clouds, with the turbulent pressure approximately adjusted to match the 'virial' density

$$\langle n \rangle_v \sim 10^3 \text{ cm}^{-3} \cdot [\Delta v / R_{cl}]^2,$$

assuming constant density; $v[\text{kms}^{-1}]$ and $R_{cl}[\text{pc}]$ are the observed half-power linewidth and cloud size. Equating these relations, predicts linewidths

$$\Delta v \sim 17 \text{ kms}^{-1} \cdot [R_{cl}/10 \text{ pc}] \, [150 \text{ pc}/R_{gc}]^{.9}$$

close to those inferred observationally. According to Table II, individual clouds seem gravitationally bound against tidal stresses, and close to virialization, but cloud complexes as a whole are often not (Sgr A complex; Clump 2 (Stark & Bania, 1986)).

3.2. Heating Mechanisms

Pervasive high gas temperatures, well in excess of the dust temperature, directly exclude collisions with radiatively heated warm dust particles as a dominant heating process. Instead a heating agent is required that (1) acts directly upon the gas phase, and (2) operates uniformly throughout the innermost few 100 pc. Possible scenarios have been discussed by Morris et al. (1983) and Güsten et al. (1981, 1985).

Because of a lack of associated UV sources, photo-electric heating (i.e. photo-ejection of hot electrons from grain surfaces, that subsequently thermalize with the gas) is unlikely to operate on large scales. An enhanced flux of low-energy (1-10 MeV) cosmic ray nuclei ($\sim 10^{2-3}$ times the local flux) might provide the required heat deposit (ionization rate $\sim 10^{-14}$ s^{-1}), but is difficult to reconcile with available gamma-ray data (Sect.2.2), showing no evidence for an increased density of higher energy particles (>100 MeV). Magnetic viscous heating is difficult to evaluate, mainly because of uncertainties about the field strength and details of the dissipation process. If we take the dissipation timescale τ_B as approximated by Elmegreen et al. (1978) and Arons & Max (1975), then by equating heating ($\Gamma \sim B^2/8\pi\tau_B$) and cooling rates ($\lambda \sim 10^{-21}$ erg cm^{-3} s^{-1}, Hollenbach & McKee, 1981) we estimate an equilibrium gas temperature

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$$T_g \sim 100\ K\ [X_e/10^{-6}]^{-2/5}.[n/10^{4.5}cm^{-3}]^{-4/5}.[B/4\ mG]^{8/5},$$

using Δv=15kms^{-1} and R_{cl}=15 pc; X_e~10^{-6} is the fractional ionization. Thus field strengths significantly in excess of the equipartition field, B_{eq} ~0.5 mG, would be required to account for the high temperatures.

The large velocity dispersion measured in all of the galactic center clouds suggests that dissipation of supersonic 'turbulence' on small scales is the the most attractive heating mechanism (Wilson et al., 1982). Equating molecular line cooling and turbulent heating, Güsten et al. (1985) derived

$$T_g \sim 90\ K\ [n/10^{4.5}cm^{-3}]^{2/5}.[\Delta v/15\ kms^{-1}]^{4/5}.$$

Within the limits of this approach, turbulent energy dissipation may indeed account for the high gas temperatures, but as the dissipation timescale is short (R/v some few 10^6 yr), turbulence has to be replenished continuously, likely by the strong differential rotation within the central bulge (Fleck, 1980).

In conclusion, all of the outstanding characteristics of galactic center clouds, their excessively high temperatures, llinewidths and densities, seem related to their exposed location in the steep galactic center gravitational potential. To survive tidal stresses, densities must be of the order of 10^4 cm^{-3}. In an approach towards virialization, the turbulent pressure (velocity dispersion) is adjusted to match these high densities. The strongly dissipative supersonic turbulence then may provide an attractive gas-phase heating mechanism to account for the uniformly high gas temperatures.

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