STAR FORMATION IN THE GALACTIC CENTER

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Abstract

We discuss recent FIR and submillimeter continuum and spectral line observations of massive GMC cores in the region between the radio Arc and Sgr B2 in the Galactic center and their implications for the star formation properties of typical quiescent Galactic center GMCs.

Key words: Galaxy: center – ISM: clouds — ISM: continuum — ISM: individual (GCM0.25+0.11, Sgr B1) — stars: formation

1. Introduction

The harsh environment in the Galactic center region (central $\sim$ 200 pc of the Milky Way; the region referred to as the central molecular zone; see reviews by Morris & Serabyn 1996 and Mezger et al. 1996), characterized by disruptive tidal forces, high gas pressures (Bally et al. 1988; Spergel & Blitz 1992) and strong magnetic fields (Morris 1989) may suppress gravitational collapse in all but the most massive clouds. Consequently, star formation there may be caused primarily by shock compression due to cloud-cloud collisions, resulting in a flatter initial mass function than in the Galactic disk (Morris 1993). Recent NIR imaging and spectroscopic observations have revealed several new high-mass star-formation sites in the Galactic center. In excess of 100 main sequence stars with masses up to 120 $M_\odot$ have been detected in the Arches and Quintuplet clusters, the most massive young clusters in the Galaxy (Serabyn et al. 1998; Figer et al. 1999). In particular, the HST observations of Figer et al. (1999) allow detection of main sequence stars with initial masses well below 10 $M_\odot$. The resulting IMF in the two clusters has a slope significantly more positive than the average for young clusters elsewhere in the Galaxy ($\Gamma = -0.65$ compared to -1.4).

Compact, massive clusters thus clearly form in the central region. However, as discussed by Serabyn et al. (1998) and Figer et al. (1999), their characteristics suggest a formation mechanism substantially different from that for the disk clusters, presumably a more violent one. We might expect to see many more similar clusters that would have formed $\gtrsim$5 Myr ago, but that are still younger than the cluster disruption time-scale. However, no such clusters have been identified, suggesting that the formation of such clusters is relatively rare, possibly related to a coordinated burst of star formation triggered by the passage of a shock front, or that the cluster disruption time-scale is short. A number of isolated hot emission-line stars have also been detected in the central $\sim$ 40 pc (see Cotera et al. 1999 and references therein).

Although NIR observations provide the most direct census of the stellar population, they are quite ineffective in highly obscured regions. Therefore, large-scale star-formation patterns in the Galactic center still remain largely unestablished. Early searches for OH and H_2O masers, which are also considered direct signposts of high-mass star formation resulted in relatively few detections (Güsten & Downes 1983; Caswell et al. 1983; Morris 1989). The most recent published search for H_2O masers in the inner $4^\circ \times 4^\circ$ region by Taylor et al. (1993) resulted in the detection of only 7 new maser sources (out of 97 IRAS selected sources observed), associated with star-forming regions that can be tentatively located at the Galactic center. Taylor et al. (1993) argue that the amount of molecular gas within 2° of the Galactic center ($10^7 - 10^8$ $M_\odot$) would normally contain a few hundred masers associated with protostars, HH objects, and T Tauri stars for a maser frequency comparable to that in the Galactic disk. A more recent targeted search for H_2O masers in the Galactic center region carried out by Levine et al. (2001) with a typical 6 σ sensitivity limit of 100 mJy, brings the total number of known water masers in the region to 119. Masers associated with star forming regions dominate at the low-end of the maser luminosity function. This suggests, that the low maser detection rates reported in early studies may be largely a result of the sparse spatial coverage and relatively low sensitivity of the maser searches carried out to date (owing to the large distance to the Galactic center). For example, a search by Mehringer et al. 1993, twice as sensitive as that of Taylor et al. 1993 ($\sim$ 10 mJy rms sensitivity compared to 16–22 mJy) resulted in the detection of 10 relatively weak (50–430 mJy) H_2O masers in a $7' \times 7'$ field in the Sgr B1 region. As a comparison, Gaume et al. 1998 detected 36 masers with fluxes of 0.2-190 Jy at 15 mJy sensitivity level in the Orion S region. Given the $\sim$ 20 times larger distance to the Galactic center, many of

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these Orion masers would not be detectable in the existing Galactic center surveys.

In a separate study Caswell 1996 carried out a search for 6.668 GHz methanol masers over a 2 square degree area, which resulted in the detection of 23 maser sites. Caswell argues that the space density of methanol masers in the Galactic center is similar to that in the spiral arms, implying that massive star-formation is neither enhanced nor suppressed in the Galactic center at the present time. However, these results are heavily influenced by the cluster of masers in the Sgr B2 complex, which accounts for nearly half of the maser sites detected.

2. Quiescent GMCs in the Ridge

In an effort to identify possible sites of future star formation (namely high-density GMC cores) in the Galactic center, Lis & Carlstrom (1994) made an unbiased survey of the 800 μm continuum emission over a 1.5° × 0.2° region using the single pixel CSO bolometer.[1] In this survey, in addition to the well studied sources like Sgr B2, Sgr C, and the 50 and 20 $\mathrm{km\,s^{-1}}$ clouds in Sgr A, a number of GMC cores were detected, forming a long (∼ 0.25°, or ∼ 40 pc for a distance to the Galactic center of 8.5 kpc), clumpy ridge of dust emission (hereafter referred to as the "Ridge"), stretching from the radio Arc toward Sgr B2 (Fig. 1). No evidence for the presence of embedded FIR sources or compact HII regions associated with the brightest and most massive GMC core in the Ridge, GCM0.25+0.11 (hereafter GCM0.25), was found by Lis et al. (1994), and their VLA observations revealed the presence of only a weak H_2O maser associated with this source, suggesting the presence of some ongoing low-mass star formation. The broad line widths (∼ 30 $\mathrm{km\,s^{-1}}$ FWHM), characteristic of Galactic center GMCs, indicate that the clouds in the Ridge are indeed located within a few hundred parsecs of the Galactic center. In addition, as discussed by Lis & Menten (1998), the velocity of the molecular emission in GCM0.25 is close to that of the molecular cloud associated with the HII region G0.18-0.04 (Serabyn & Güsten 1991), which is believed to be interacting with the non-thermal filaments in the Galactic center radio Arc.

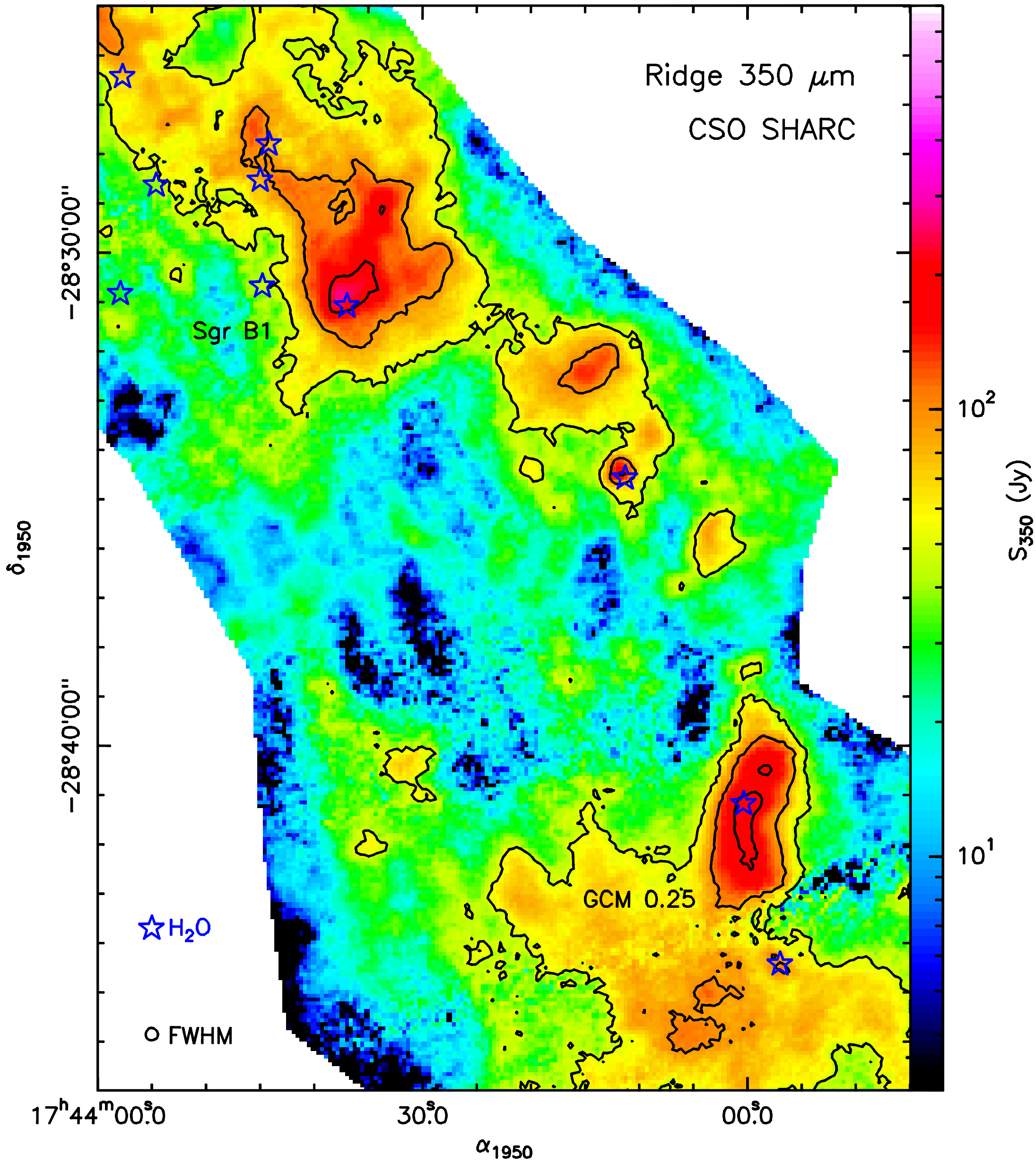
To better constrain the dust temperature and mass of the Ridge sources, we have obtained sensitive multiwavelength images of the region with the Long Wavelength Spectrometer aboard the Infrared Space Observatory (Lis & Menten 1998; Lis et al. 2001). The observed far-infrared and submillimeter spectral energy distributions imply low temperatures (∼ 15–22 K) for the bulk of the dust in all the sources, consistent with external heating by the diffuse ISRF and suggest that these GMCs do not harbor high-mass star-formation sites, in spite of their large molecular mass. Observations of FIR atomic fine structure lines of CII and OI indicate an ISRF enhancement of $\sim 10^3$ in the region. Continuum radiative transfer modeling shows that this radiation field strength is in agreement with the observed FIR and submillimeter spectral energy distributions, assuming primarily external heating of the dust with only limited internal luminosity ($\sim 2\times10^5$ $L_\odot$). Spectroscopic observations of millimeter-wave transitions of H_2CO, CS, and $C^{34}S$ carried out with the Caltech Submillimeter Observatory (CSO) and the Institut de Radio Astronomie Millimétrique (IRAM) 30-meter telescope indicate a gas temperature of ∼ 80 K, significantly higher than the dust temperatures, and a density of $\sim 1\times10^5$ $\mathrm{cm^{-3}}$ in GCM0.25, the brightest submillimeter source in the region. We suggest that shocks caused by cloud collisions in the turbulent interstellar medium in the Galactic center region are responsible for heating the molecular gas. This conclusion is supported by the presence of wide-spread emission from molecules such as SiO, SO, and CH_3OH, which are considered good shock tracers. We also suggest that the GMCs studied here are representative of the "typical", pre-starforming cloud population in the Galactic center.

2.1. Star Formation in the Ridge

After accounting for external heating, the observed SED of GCM0.25 (Fig. 1) is consistent with internal heating equivalent to $\lesssim$3 main sequence B0 stars. It is informative to consider how many such stars can be expected to form in this cloud, given its total molecular mass ($\lesssim 1 \times10^6$ $M_\odot$; Lis & Menten 1998, an upper limit to the virial mass based on CO data). The stellar initial mass function is defined as $n(M)dM = n_o M^{\Gamma-1} dM$, where $\Gamma = -1.35$ is the Salpeter slope (e.g. Elmegreen 1999). Given the upper limit of 1×10^6 $M_\odot$ for the molecular mass of GCM0.25, and assuming a star formation efficiency of 1% and a Salpeter IMF with the lower and upper mass cutoffs of 0.1 and 60 $M_\odot$, respectively, the number of stars of spectral type B0 or earlier (with stellar masses greater than 17.5 $M_\odot$) expected to form over the lifetime of this cloud is ∼ 20. This is an order of magnitude higher than the maximum number allowed by our continuum models. The expected number of early type stars increases significantly for a shallower IMF, such as that derived by Figer et al. 1999 for the Arches and Quintuplet clusters (∼ 120 B0 stars for $\Gamma = -0.65$).

On the other hand, the radio continuum observations of Lis et al. 1994 impose an even more stringent limit on the number of massive stars associated with GCM0.25. The 3σ upper limit of 1.1 mJy in a 2.6″ beam for the 8.4 GHz continuum flux density within the boundaries of the submillimeter continuum emission gives a Lyman continuum luminosity of $\sim 8\times10^{45}$ $\mathrm{s^{-1}}$, which corresponds to

[1] Much more sensitive, high-angular resolution submillimeter continuum surveys of the Galactic center region have been recently carried out by Dowell et al. 1999 using the SHARC bolometer camera at the CSO and by Pierce-Price et al. 2000 using the SCUBA array at the JCMT.



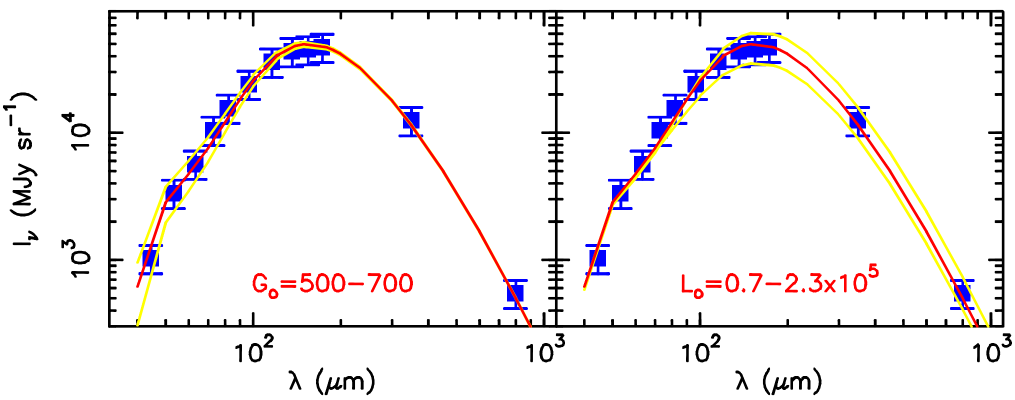


Figure 1. (Top) False-color image of the 350 μm continuum emission toward the Ridge observed with the SHARC camera at the CSO (from Dowell et al 1999). Blue stars mark the location of known H_2O masers in the region. (Bottom) Observed SED toward GCM0.25 together with a range of continuum radiative trasfer models that constrain the external radiation field and internal source luminosity.

a single B0.5–B1 ZAMS star (Panagia 1973). The presence of stars of spectral types earlier than B0.5 in GCM0.25 is thus excluded by the 8.4 GHz observations. We thus conclude that either (a) the current star formation efficiency in the Ridge must be very low, on the order of 0.1% or lower, or alternatively (b) the upper mass cutoff of the IMF for any stars already formed must be $\lesssim$10 $M_\odot$ to explain the FIR and radio continuum data. Both of these conclusions are consistent with a quiescent cloud, still largely in a pre-collapse phase.

3. Summary

The observations presented by Lis & Menten (1998) and Lis et al. (2001) firmly establish that the GMCs in the Ridge, located between the Galactic center radio Arc and the Sgr B2 molecular cloud, are different from the well studied starforming Galactic center clouds, such as Sgr B2, Sgr C, Sgr D, or the 50 km s^{-1} cloud in Sgr A. Our FIR continuum and fine structure line observations imply low dust temperatures (15–22 K) in all the sources we studied, consistent with external heating by the diffuse interstellar radiation field with an enhancement factor $G_o \simeq 500 - 1000$. We find no evidence for the presence of luminous internal heating sources and thus for ongoing high-mass star formation associated with these GMCs, in spite of their large molecular masses.

The kinetic temperatures in the Ridge sources appear significantly higher than the dust temperatures. We suggest that shocks associated with cloud collisions may be the dominant heating source for the gas in this region. In fact, molecular observations of GCM0.25 show complicated gas kinematics, possibly indicating an early stage of a cloud-cloud collisions. However, the remaining sources show simpler velocity fields.

The integrated 350 μm flux density in a $\sim 50 \times 70$ pc region including the Ridge is $\sim$ 100 kJy (this only includes pixels with 350 μm fluxes greater than 50 Jy in a 15$''$ beam, corresponding to an 8 σ detection; this cutoff is introduced to separate the emission from the dense GMC cores from that of the low-density extended component that contributes an additional 50 kJy to the integrated flux density in the region). Assuming a dust temperature of 20 K, the combined molecular mass of all the Ridge sources is $\sim 1 \times 10^7$ $M_\odot$, comparable to that of Sgr B2, the most massive GMC in the Galactic center region (Lis & Goldsmith 1989). These clouds are thus a significant component of the Galactic center ISM. Owing to the time constraints, we have been able to study in detail only a limited sample of Galactic center GMCs with ISO. However, the shorter wavelength MSX continuum observations of Egan et al. (1998) indicate that a large number of presumably similar, cold dust sources are present in the Galactic center region and throughout the Galaxy. We thus suggest that quiescent clouds, such as those that we have studied here actually represent "typical" pre-collapse Galactic center GMCs. In contrast, the bright, well-known clouds, such as Sgr B2, Sgr C, Sgr D, and the 50 km s^{-1} cloud in Sgr A are already in the active star formation phase. The latter sources were all identified by their strong FIR and/or radio continuum emission, which are natural tracers of high-mass star formation. Therefore they may represent that subset of the Galactic center cloud population in which energetic activity (shocks, compression) and prolific high-mass star formation are already present. The presence of shock activity in GCM0.25, as evidenced by the widespread SiO emission, indicates that star formation may be "turning on" at least in this cloud.

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