THE ASTROPHYSICAL JOURNAL, 423:L39–L42, 1994 March 1

STAR FORMATION IN THE GALACTIC CENTER DUST RIDGE

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Received 1993 October 20; accepted 1993 December 13

ABSTRACT

We present multiwavelength submillimeter and radio continuum, as well as 22 GHz H_2O line observations of the giant molecular cloud core M0.25+0.01 located in the "dust ridge" near the Galactic center radio arc. At $\lambda = 350$ μm the continuum emission region is spatially resolved by our 12″ beam, and we find no evidence for compact dust sources similar to those found in Sgr B2. Although existing far-infrared data do not allow for accurate determination of the dust temperature, the steep rise of the submillimeter spectrum between 800 and 350 μm suggests that the grain emissivity law in the M0.25+0.01 core may be significantly steeper than in previously studied Galactic center dust sources. The detection of an H_2O maser source located near the 350 μm emission peak implies the presence of at least some ongoing low-mass star formation. However, in spite of the relatively large molecular mass of the core implied by the submillimeter observations ($\approx 1.6 \times 10^5$ $M_\odot$), our 8.4 GHz continuum data show that current star formation in the M0.25+0.01 core is limited to stars with spectral types later than B0; there is no evidence for more massive young stars. This GMC core thus appears distinctly different from the Sgr C and D cores, which, although much less massive, harbor O-type stars.

Subject headings: Galaxy: center — masers — stars: formation

1. INTRODUCTION

The total far-infrared luminosity and the ionizing flux inferred from radio continuum observations of the Galactic center region ($R < 200$ pc; the region often referred to as the nuclear disk) imply a rate of star formation per unit mass of molecular material comparable to that in the Galactic disk (Mezger & Pauls 1979; Güsten 1989). However, H_2O and OH masers commonly found in sites of high-mass star formation are relatively rare in the nuclear disk (Güsten & Downes 1983). Based on their far-infrared data, Boissé et al. (1981) and Odenwald & Fazio (1984) suggest that the formation rate of stars with masses greater than ≈ 20 $M_\odot$ is reduced in the Galactic center. Morris (1989) argues that star formation might currently be suppressed in the Galactic center compared to the disk as a result of the different geometry and strength of the magnetic field in the central region, which arguably might tend to inhibit cloud collapse.

Determining the degree of star-forming activity will yield important information on the nature of the Galactic center clouds and the contribution of young high-mass stars to the heating and ionization in the nuclear disk. We therefore have started a program to, first, identify possible sites of star formation by means of their submillimeter continuum emission, second, produce high-quality maps of the dust emission in candidate regions, and, third, obtain kinematic information from molecular line observations. Finally, we use the Very Large Array (VLA)[4] to search for compact radio continuum sources and H_2O masers toward candidate dust cores. While it is presently unknown what fraction of young stellar objects (YSOs) exhibit water maser action during some part of their pre–main-sequence lifetimes, it is nevertheless clear that the presence of an H_2O maser unambiguously probes mass-outflow activity associated with many YSOs. We note that a number of known water masers associated with intermediate- and low-luminosity objects in the ρ Oph and Orion molecular clouds would be readily detectable if put at the distance of the Galactic center.

One of the most interesting results of the 800 μm continuum emission survey of a region of size $\approx 1^\circ\!.5 \times 0^\circ\!.2$ toward the center of the Milky Way (Lis & Carlstrom 1994) was the detection of a narrow, clumpy ridge of dust emission apparently connecting the H II region Sgr B1 with the Galactic center radio arc. The southernmost dust condensation in this ridge is located about 3′ north of the arc and coincides with the ammonia peak M0.25+0.01 (Güsten, Walmsley, & Pauls 1981). No compact radio continuum or far-infrared sources associated with this dust condensation can be found in the surveys of Downes et al. (1978), Dent et al. (1982), Odenwald & Fazio (1984), or the *IRAS* Point Source Catalogue. This prompted the speculation that the dust may be heated by the external radiation field rather than embedded young stars, in contrast to the well-studied Galactic center giant molecular cloud (GMC) cores, such as Sgr B2 and Sgr C.

To study the small-scale structure of the M0.25+0.01 core and determine its submillimeter spectrum we have mapped its continuum emission at the wavelengths of 350 and 450 μm using the Caltech Submillimeter Observatory (CSO). These are the first CSO continuum observations at an angular resolution close to the diffraction limit of the telescope at these short wavelengths (FWHM beam size $\approx 12''$), which have been made possible by the recent improvements in the dish surface accuracy. In this *Letter* we also report on our VLA observations of 22 GHz H_2O maser emission and 8.4 GHz continuum emission toward M0.25+0.01.

2. OBSERVATIONS

The 350 and 450 μm continuum emission toward the M0.25+0.01 core was observed in 1993 May using the Caltech

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Submillimeter Observatory (CSO) 10.4 m telescope on Mauna Kea, Hawaii. A description of the CSO bolometer can be found in Lis, Carlstrom, & Keene (1991), and the on-the-fly (OTF) observing mode employed during the observations, as well as the data reduction and calibration procedures are described in Lis & Carlstrom (1994). For the present observations we employed a new 10″ aperture Winston cone. The mean frequencies for the 350 and 450 μm filters and this Winston cone are 867 and 666 GHz, respectively. The shape of the telescope beam was determined from OTF observations of Mars, which, correcting for the planet's apparent diameter of 5″.9 at the time of the observations, yielded a beam size of $\approx 12''$ (FWHM). The effective resolution for the final images of M0.25+0.01 is $\approx 14''$. The data were calibrated by comparison with OTF observations of the compact dust core Sgr B2(N) which was observed at an airmass very close to that of M0.25+0.01. We assumed flux densities of 1070 Jy (450 μm, 16″ beam) and 3140 Jy (350 μm, 20″ beam) for Sgr B2(N), based on Goldsmith et al. (1990). The uncertainties of the flux densities reported here are $\approx 30\%$. The flux calibration was cross-checked through OTF observations of Uranus which led to a peak flux density consistent with that obtained from Sgr B2(N) observations, given the uncertainties quoted above. Pointing of the telescope was verified from OTF observations of Sgr B2(N). Absolute position uncertainties are $\lesssim 5''$.

Our VLA observations were made on 1993 June 6 when the array was in its B/C hybrid configuration. Observations were alternated between a position at $(\alpha, \delta)_{1950} = 17^h42^m58^s.3$, $-28°41'30''$, which covered M0.25+0.01, and two other positions, over a period of 5 hours in "standard" continuum mode, affording two 50 MHz-wide IF bands, centered at frequencies of 8.4149 and 8.4649 GHz, respectively. With each IF right circular (RCP) and left circular (LCP) polarization were detected. NRAO 530 was used as a phase calibrator. When M0.25+0.01 was near transit, a snapshot spectral line observation of 12 minutes duration was made toward the position quoted above at the frequency of the $6_{16} \rightarrow 5_{23}$ transition of H_2O (22.23508 GHz). A 2-IF setup was employed with each IF band having a width of 6.25 MHz subdivided into 64 channels, resulting in a velocity resolution of 1.32 km s^{-1}. The first IF detected RCP and was centered at a frequency corresponding to an LSR velocity of -10 km s^{-1}, the other detected LCP and was centered at $v_{LSR} = 50$ km s^{-1}. This setup yielded a total velocity coverage of about 120 km s^{-1} centered at $v_{LSR} = 20$ km s^{-1}. To provide amplitude calibration, 3C 286 was observed which has flux densities of 5.27 and 2.55 Jy at 8.4 and 22 GHz, respectively (Baars et al. 1977). The data were calibrated, Fourier transformed, and CLEANed using the AIPS software package. The final 8.4 and 22 GHz maps were restored with circular beams of size 2″.6 and 1″ (FWHM), respectively.

3. RESULTS AND DISCUSSION

The M0.25+0.01 core is located near the southern end of the dust ridge seen in the 800 μm continuum map of Lis & Carlstrom (1994), which forms a half-ellipse with the radio source 45 of Downes et al. (1978) and the far-infrared source FIR 13 of Odenwald & Fazio (1984) near its center. Our 350 μm map of M0.25+0.01 is shown in Figure 1 (left panel). The 450 μm map shows essentially the same morphology, but with a significantly lower signal-to-noise ratio. The 350 μm emission from M0.25+0.01 is spatially resolved by our beam; the data do not show evidence for the presence of very compact dust sources similar to those present in Sgr B2.

TABLE 1

SUBMILLIMETER FLUX DENSITIES FOR M0.25+0.01

λ (μm)	S (14″) (Jy)	S (30″) (Jy)	S (Total) (Jy)
350...........	170	610	5300
450...........	90	265	2900
800...........	...	24	300

NOTES.—Entries are wavelength, flux densities in the 14″ and 30″ beams, and the integrated flux density. The 800 μm data are from Lis & Carlstrom 1994. The coordinates of the 350 μm emission peak in a 14″ beam are $(\alpha, \delta)_{1950} = 17^h43^m00^s.0$, $-28°41'20''$.

The measured 350 μm and 450 μm flux densities of M0.25+0.01 are given in Table 1, along with 800 μm flux densities from Lis & Carlstrom (1994). The submillimeter spectrum rises as $\approx \nu^{3.9}$ between 800 and 350 μm. For optically thin dust emission, the observed spectrum is consistent with a $\nu^{1.9}$ grain emissivity law, assuming that both wavelengths are in the Rayleigh-Jeans limit. This would require, however, a relatively high dust temperature ($\gtrsim 50$ K). Such a high dust temperature appears unlikely in view of the relatively weak far-infrared emission toward the source (Dent et al. 1982; Odenwald & Fazio 1984). A formal fit to the far-infrared and submillimeter flux densities toward M0.25+0.01 yields a dust temperature $\lesssim 20$ K. However, the far-infrared fluxes are quite uncertain due to the large beam used, and in the following discussion we assume a more conservative value of 30 K, typical for the Galactic center region. Assuming optically thin emission at this temperature, the observed 350–800 μm flux density ratio then implies a grain emissivity varying as $\nu^{2.4 \pm 0.7}$ between 800 and 350 μm (the uncertainty quoted above assumes 30% uncertainties in the two flux measurements, but does not take into account an uncertainty in the dust temperature). The exponent of the submillimeter grain emissivity law thus appears to have a significantly higher value in the M0.25+0.01 core than in the other Galactic center GMC cores, where typically $Q \propto \nu^{\approx 1.5}$ (e.g., Lis et al. 1991). Given the rather low temperature of the source we consider it unlikely that the steep submillimeter spectrum results from a strong molecular line contamination increasing with frequency.

The dust optical depth averaged over the telescope beam can be calculated from the formula $1 - e^{-\tau_\nu} = S_\nu[B_\nu(T)\Omega]^{-1}$, where S_ν is the observed flux density, $B_\nu(T)$ is the Planck function at the mean dust temperature T, and Ω is the solid angle of the telescope beam. Assuming a mean dust temperature of 30 K, we derive a 350 μm optical depth of ≈ 0.1 in a 14″ beam toward the peak of the emission. We can thus use equations (3) and (4) of Lis et al. (1991), which assume optically thin emission, to calculate the H_2 column density and mass of the molecular material. In this *Letter* we use the same grain parameters Lis et al. (1991) adopted for other Galactic center GMC cores, which imply a 350 μm grain emissivity of 1.6×10^{-4}. We also assume that the core is located at the Galactic center (8.5 kpc distance). This assumption is justified by the observed broad line widths of molecular emission lines, which are characteristic of Galactic center molecular clouds (see the CS $J = 5 \rightarrow 4$ spectrum obtained with the CSO; Fig. 1,

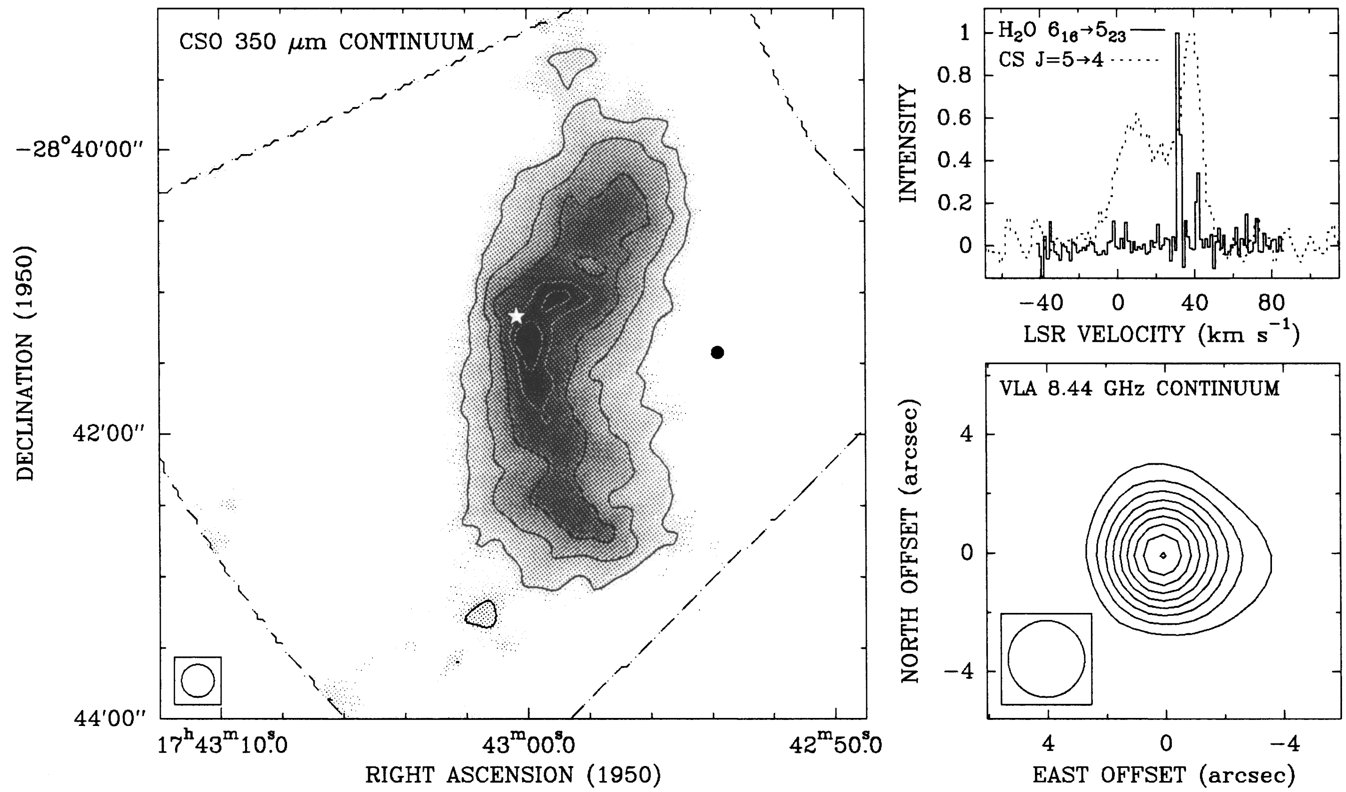

FIG. 1.—*Left panel:* The 350 μm continuum map of M0.25+0.01. The contour levels correspond to 20%, 40%, 60%, 80%, and 90% of the peak flux density, which is 170 Jy in the 14″ (FWHM) beam indicated in the lower left corner. The white star symbol and the black dot mark, respectively, the positions of the 22 GHz H_2O maser and the 8.44 GHz continuum source detected with the VLA. *Upper right panel:* The H_2O maser spectrum (*solid line*) and the CS $J = 5 \rightarrow 4$ spectrum (*dashed line*) observed at $(\alpha, \delta)_{1950} = 17^{\rm h}43^{\rm m}00^{\rm s}.32$, $-28°41'10''.2$. The intensity scale has been normalized so that unity corresponds to a flux density of 0.5 Jy in the case of the H_2O spectrum and to a main-beam brightness temperature of 0.67 K for the CS spectrum. The H_2O intensity has been corrected for primary beam response. *Lower-right panel:* The 8.44 GHz map of the compact radio continuum source. Offsets are relative to the peak of the 8.44 GHz emission, which is at $(\alpha, \delta)_{1950} = 17^{\rm h}42^{\rm m}53^{\rm s}.81$, $-28°41'25''.4$. Contour levels run in steps of 10% from 20% to 99% of the peak flux density, which is 7.4 mJy beam^{-1}. The lowest contour value and the contour spacing correspond, respectively, to ~4 and 2 times the rms noise level. The restoring beam (FWHM = 2″.6) is indicated in the lower left corner.

upper-right panel). For a 30 K mean dust temperature, the H_2 column density toward the 350 μm emission peak is $\approx 8 \times 10^{23}$ cm^{-2} and the total H_2 mass is $\approx 1.6 \times 10^5$ $M_\odot$. The column density and mass reported here are uncertain due to the poorly constrained dust temperature and grain emissivity. Assuming a line-of-sight linear size equal to the FWHM deconvolved source size in the E-W direction ($\approx 37''$, or 1.5 pc), we derive a lower limit of $\approx 2 \times 10^5$ cm^{-3} for the mean H_2 density, based on the column density estimate given above.

The M0.25+0.01 core appears an order of magnitude more massive than the Sgr C and D cores (Lis et al. 1991) which both are sites of current high-mass star formation. However, existing far-infrared and radio continuum data show *no evidence for high-mass star formation associated with M0.25+0.01.* Clear-cut evidence that *low-mass star formation* is taking place in this GMC core is provided by our detection of an H_2O maser source near the peak of the 350 μm dust emission. We observe two narrow spectral components at LSR velocities of 32.1 and 41.6 km s^{-1} with peak flux densities of 0.5 and 0.15 Jy, respectively (Fig. 1, upper-right panel). From two-dimensional Gaussian fits we determine the position of the stronger (32.1 km s^{-1}) component as $(\alpha, \delta)_{1950} = 17^{\rm h}43^{\rm m}00^{\rm s}.32$, $-28°41'10''.2$ with an estimated absolute position error of $\leq 1''$. The 41.6 km s^{-1} component arises from the same position, within the 0″.2 relative position errors. The maser emission is displaced with respect to the 350 μm emission peak by $\approx 15''$.

To assess whether the H_2O emission could arise from one of the OH/IR stars that are found in large numbers throughout the Galactic center region, we note that the OH/IR water maser survey of Lindqvist, Winnberg, & Forster (1990) indicates that generally the 22 GHz H_2O maser flux density in a given star is comparable to or smaller than its 1612 MHz OH flux density. Since no 1612 MHz OH was detected toward M0.25+0.01 during the sensitive survey of Lindqvist et al. (1992), which had a noise level of ≈ 20 mJy, we consider it quite unlikely that the H_2O maser arises from an OH/IR star. Moreover, the velocity separation of the two detected maser spikes is only 9.5 km s^{-1}, while in most OH/IR stars H_2O and OH spectra cover similar velocity ranges with the most prominent emission features usually being separated by twice the terminal outflow velocity, that is, $\approx$30–40 km s^{-1}.

The derived isotropic 22 GHz line luminosity of the H_2O maser associated with M0.25+0.01 is 1.5×10^{-6} $L_\odot$. This is 10–100 times smaller than the luminosity of the powerful masers found in Sgr B2, but of the same order of magnitude as that of the H_2O masers recently detected by Mehringer, Palmer, & Goss (1993) toward the Sgr B1 region. As pointed out by these authors, H_2O masers associated with intermediate and low-mass young stellar objects typically have 22 GHz line luminosities between 10^{-8} and 10^{-7} $L_\odot$. Our data provide a 5 σ upper limit of 10^{-7} $L_\odot$ for the isotropic luminosity of any additional H_2O masers in M0.25+0.01.

Our 8.44 GHz VLA data reveal the presence of a compact radio source located $\approx 70''$ west of the 350 μm peak, at $(\alpha, \delta)_{1950} = 17^h42^m53\overset{s}{.}81$, $-28°41'25\overset{''}{.}4$ (Fig. 1, lower-right panel). A two-dimensional Gaussian fit yields a peak 8.44 GHz flux density of 7.4 mJy beam^{-1} and an integrated flux density of 14.6 mJy. The source appears to be nearly circularly symmetric with a deconvolved size of $2\overset{''}{.}6$ (FWHM). While a single frequency detection is insufficient to determine the nature of the source conclusively, and its relationship to M0.25+0.01 is unclear, its relatively high flux density suggests that it is not likely to be an extragalactic background object. No compact radio sources are detected *within the boundaries* of the dust emission at a 3 σ upper limit of 1.1 mJy in a $2\overset{''}{.}6$ beam.

Assuming that the continuum source is a spherically symmetric optically thin compact H II region with a 10,000 K electron temperature located at a distance of 8.5 kpc, and using the formulae from Panagia & Walmsley (1978) and Spitzer (1968), we derive an electron density of ≈ 2000 cm^{-3}, an emission measure of $\approx 5 \times 10^5$ cm^{-6} pc, and a Lyman continuum photon luminosity of $\approx 1 \times 10^{47}$ s^{-1}, which corresponds to a single ZAMS star with a spectral type B0–B0.5 (Panagia 1973). A far-infrared source powered by a star of that spectral type is below the detection limit of the Odenwald & Fazio (1984) survey.

In summary, our VLA results indicate that in spite of the relatively large H_2 mass and high density implied by the 350 μm continuum data ($\approx 1.6 \times 10^5$ $M_\odot$), only stars with spectral types later than B0 seem to have recently formed in M0.25+0.01; we find no evidence for more massive young stars. M0.25+0.01 thus appears to be distinctly different from the Sgr C and D cores, which, despite their much smaller masses, contain O-type stars. Given the cloud's high density, future molecular line observations will be essential for explaining why no early-type stars are present in M0.25+0.01.

Research at the CSO is founded by NSF grant AST 90-15755. We thank an anonymous referee for a number of constructive comments.

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