A SEARCH FOR H2CO 6 cm EMISSION TOWARD YOUNG STELLAR OBJECTS. III. VLA OBSERVATIONS

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ABSTRACT

We report the results of our third survey for formaldehyde (H2CO) 6 cm maser emission in the Galaxy. Using the Very Large Array, we detected two new H2CO maser sources (G23.01—0.41 and G25.83—0.18), thus increasing the sample of known H2CO maser regions in the Galaxy to seven. We review the characteristics of the G23.01—0.41 and G25.83—0.18 star-forming regions. The H2CO masers in G23.01—0.41 and G25.83—0.18 share several properties with the other known H2CO masers, in particular, emission from rich maser environments and close proximity to very young massive stellar objects.

Subject headings: ISM: molecules — masers — radio lines: ISM

1. INTRODUCTION

The first formaldehyde (H2CO) 6 cm maser was discovered in 1974 toward NGC 7538 (Downes & Wilson 1974; Forster et al. 1980); in the following ~28 yr, H2CO masers were detected only toward two other regions in the Galaxy: Sgr B2 (Whiteoak & Gardner 1983) and G29.96—0.02 (Pratap et al. 1994). This low number of H2CO maser regions was unexpected (e.g., Forster et al. 1985; Gardner et al. 1986) given the detection of many H2CO maser spots in a single source (Sgr B2; Whiteoak & Gardner 1983; Mehringer et al. 1994), the widespread distribution of formaldehyde molecules as exemplified by Galactic H2CO 6 cm absorption (e.g., Watson et al. 2003; Araya et al. 2002; Downes et al. 1980; Dieter 1973), and the apparently common astrophysical conditions needed for the maser excitation if the masers were pumped by radio continuum radiation (see Pratap et al. 1992).

The idea that H2CO masers may be pumped by background radio continuum was initially proposed by Boland & de Jong (1981) to explain the maser in NGC 7538 IRS 1. However, the low detection rate of new H2CO masers in dedicated surveys (Mehringer et al. 1995; Forster et al. 1985), the nondetection of maser emission from the H2CO 2 cm transition (e.g., Hoffman et al. 2003) and low emission measure (or nondetection) of radio continuum sources near several of the known H2CO masers, indicate that the pumping mechanism in most cases cannot be due to radio continuum excitation (e.g., see Araya et al. [2007c] for the case of IRAS 18566+0408). The low detection rate of H2CO masers led several authors to speculate that formaldehyde masers are rare because specific and/or short-lived physical conditions may be needed for the excitation (e.g., Forster et al. 1985; Mehringer et al. 1995; Araya et al. 2007a).

In an effort to understand the H2CO maser phenomenon and its place during the formation of massive stars, we conducted two surveys for H2CO masers using Arecibo, the Green Bank Telescope, and the VLA that resulted in the detection of two new Galactic H2CO maser regions (IRAS 18566+0408, with emission first detected by Araya et al. [2004] and confirmed to be a maser by Araya et al. [2005] and G23.71—0.20 with details in Araya et al. [2006], from a survey later reported by Araya et al. [2007b]). In this article we present the results of our third survey for H2CO masers.

2. OBSERVATIONS

2.1. VLA Survey

The initial observations were conducted in 2006 June with the VLA during the BnA → B reconfiguration ($\theta_{syn} \sim 1.5''$). The details of the observations are reported in Table 1. A total of 14 pointing positions were observed toward massive star-forming regions. In some cases, there were multiple radio continuum objects within the primary beam of a given position. Nine of the targets were selected based on their GBT and Arecibo spectra (Araya et al. 2002; Watson et al. 2003; Sewilo et al. 2004; Araya et al. 2007b) that showed profiles suggesting H2CO emission blended with absorption. In addition, given that H2CO 6 cm masers appear to originate mostly from regions that also harbor H2O and Class II CH3OH masers (e.g., Araya et al. 2005), we complemented our sample with five targets from the methanol and water maser catalog of Szymczak et al. (2005). The targets from the Szymczak et al. (2005) sample were observed ~40 minutes on-source. In the case of the targets that were selected based on single-dish H2CO spectra, the time on-source ranged between 10 and 100 minutes depending on the expected intensity of the H2CO emission line candidates. In Table 2 we list the observed targets, phase tracking center, center bandpass velocity, secondary (phase) calibrator used, and single-channel rms of the final data cubes. The data reduction and imaging were conducted using the NRAO package AIPS following the standard procedure for spectral-line observations.

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TABLE 1
VLA H$_2$CO SURVEY

| Parameter | Value |
|-----------|-------|
| Date      | 2006 Jun. 13–15 |
| Configuration$^a$ | BnA → B |
| $\nu_0$ (GHz)$^b$ | 4829.6594 |
| IF Mode $^c$ | 2IF (AD) |
| BW (km s$^{-1}$)$^d$ | 1.56 |
| $\Delta v$ (kHz)$^d$ | 97.0 |
| $\Delta v$ (km s$^{-1}$)$^d$ | 7.3 |
| Flux Density Calib | 3C 286 |
| Assumed $S_0$ (Jy) | 7.52 |
| Phase Calib | J1832−105 |
| Measured $S_0$ (Jy) | 1.26 |
| Phase Calib | J1824+107 |
| Measured $S_0$ (Jy) | 0.80 |
| Phase Calib | J1950+081 |
| Measured $S_0$ (Jy) | 1.07 |

$^a$ Reconfiguration from BnA to B array.
$^b$ Weighted average frequency of the H$_2$CO J$_{K_a}K_c = 1_{16}−1_{11}$.
$^c$ Bandwidth per IF.
$^d$ Spectral resolution.

2.2. High Spectral Resolution Observations

Follow-up H$_2$CO 6 cm observations of G23.01−0.41 and G25.83−0.18 were conducted on 2007 February 16 with the VLA in the D configuration. The goals of the observations were to confirm the H$_2$CO 6 cm emission detected in our survey (§3) and to study the H$_2$CO maser line profiles with higher spectral resolution (1.83 kHz, 0.11 km s$^{-1}$). The VLA correlator was used in the 1 intermediate frequency (IF) mode with a bandwidth of 0.78 MHz (48 km s$^{-1}$) and 512 channels. The central bandpass velocity was set to 70 and 87 km s$^{-1}$ for the G23.01−0.41 and G25.83−0.18 observations, respectively. The phase tracking center of the G23.01−0.41 observations was R.A. = 18$^h$39$^m$03.60$^s$, decl. = −09$^\circ$00′00.0″ (J2000.0); the phase tracking center of the G25.83−0.18 observations was R.A. = 23$^h$37$^m$04.30$^s$, decl. = −62′24″50.0″ (J2000.0). The quasars 3C 286 and J1822−096 were used as primary and secondary calibrators, respectively. We assumed a flux density of 7.52 Jy for 3C 286 and measured a flux density of 2.29 Jy for J1822−096. In addition, 3C 48 was observed to check the flux density calibration. Using 3C 286 as primary calibrator to bootstrap the flux density of 3C 48, we measured a flux density of 5.60 Jy for 3C 48, which agrees within 3% with the expected value of 5.47 Jy. The calibration and imaging were conducted using the NRAO package AIPS.

3. RESULTS

Of the 14 pointing positions observed with the VLA (and a total of 18 targets; see Table 2), we detected H$_2$CO 6 cm emission toward two sources: G23.01−0.41 and G25.83−0.18 (Fig. 1). In both cases the emission was spatially unresolved (deconvolved
size $<0.5''$), implying brightness temperatures greater than $10^4$ K, which indicates maser emission. Thus, G23.01−0.41 and G25.83−0.18 are the sixth and seventh regions in the Galaxy where H$_2$CO 6 cm masers have been detected.

Figure 1 shows the low-velocity resolution spectra and peak channel images of the two new maser regions. The G23.01/C0.41 line is spectrally unresolved, whereas the H$_2$CO emission in G25.83/C0.18 has a double-peaked profile. Figure 2 shows the line profiles of the high spectral resolution (VLA-D, $\lambda=2.2$) observations. H$_2$CO emission was confirmed in both cases. In Table 3 we list the line parameters of the H$_2$CO 6 cm masers from both observing periods.

We detected radio continuum emission as well as H$_2$CO 6 cm absorption toward several of the targets in the sample; a discussion of these data will be the topic of a future paper. Here we focus on the H$_2$CO 6 cm maser emission and discuss the H$_2$CO 6 cm absorption only in the case of G25.83−0.18, since the H$_2$CO maser originates at the (projected) spatial center of a molecular clump traced by H$_2$CO absorption ($\S$ 4.2).

4. DISCUSSION

4.1. G23.01−0.41

4.1.1. H$_2$CO 6 cm Maser Emission

H$_2$CO 6 cm maser emission was detected toward G23.01−0.41 with the VLA in the BnA → B reconfiguration (Fig. 1) and confirmed with VLA-D observations conducted approximately 8 months later ($\S$ 2.2; Figure 2). The peak position, local standard of rest (LSR) velocity, and line width measurements are consistent in both runs (Table 3). If the VLA-D spectrum is smoothed to the channel width of the lower spectral resolution observations (VLA, $\lambda=7$; Table 3), the peak intensities are consistent within 2 mJy beam$^{-1}$, revealing no apparent variability of the line in a ~8 month period.

As mentioned in $\S$ 3, the H$_2$CO 6 cm maser in G23.01−0.41 was not spectrally resolved in the VLA BnA → B observations (line width $<1.0$ km s$^{-1}$, Fig. 1). In the high spectral resolution observations (Fig. 2) the line was barely resolved and appears to be the superposition of two components. The separation of the two possible overlapping lines is $\approx0.4$ km s$^{-1}$. 

![Figure 1](image1.png)

![Figure 2](image2.png)
TABLE 3
LINE PARAMETERS OF H2CO 6 cm MASERS

| Source         | \( V_{\text{peak}}(J2000.0) \) | \( \delta_{\text{peak}}(J2000.0) \) | \( T_{\text{peak}} \) (mJy beam\(^{-1}\)) | \( V_{\text{LSR}} \) (km s\(^{-1}\)) | FWHM (km s\(^{-1}\)) |
|----------------|-------------------------------|---------------------------------|--------------------------------|---------------------------------|-----------------|
| VLA BnA → B (Low Spectral Resolution) Observations | | | | | |
| G23.01−0.41a,b) | 18 34 40.29 ± 0.004 | −09 00 38.26 ± 0.08 | 48 ± 6 | 73.5 ± 0.4 | <1.0 |
| G25.83−0.18c) | 18 39 03.627 ± 0.003 | −06 24 11.18 ± 0.06 | 85 ± 7 | 90.2 ± 0.4 | <0.8 |
| VLA-D (High Spectral Resolution) Observations | | | | | |
| G23.01−0.41c) | 18 34 40.29 ± 0.06 | −09 00 37.7 ± 1.3 | 53 ± 9 | 73.60 ± 0.09 | 0.4 ± 0.2 |
| G25.83−0.18d) | 18 39 03.69 ± 0.07 | −06 24 10.4 ± 0.8 | 102 ± 9 | 90.21 ± 0.02 | 0.29 ± 0.04 |

Notes.—Unless indicated otherwise, we list the intensity of the peak channel (the rms is listed as uncertainty), the LSR velocity of the peak channel (two channels the separation reported as uncertainty), and the FWHM (the two channels the separation reported as uncertainty). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

4.1.2. Infrared Environment

Far-infrared (IR) emission is found at the location of the H2CO maser as shown by IRAS data. However, the far-IR emission at the H2CO maser location is overlapped with several nearby sources. Midcourse Space Experiment (MSX) 21.4 \( \mu m \) data toward G23.01−0.41 is also affected by confusion due to blended emission with a source \( \sim 20'' \) east of the H2CO maser position. At 70 \( \mu m \), MIPS/GALACTIC EMISSION. III

| Source | \( \theta_{\text{syn}} \) | \( \theta_{\text{syn}} \) | \( \theta_{\text{syn}} \) | \( \theta_{\text{syn}} \) |
|--------|-----------------|-----------------|-----------------|-----------------|
| G23.01−0.41a | 1.6'' × 1.1'' | 1.6'' × 1.1'' | 1.6'' × 1.1'' | 1.6'' × 1.1'' |
| G25.83−0.18b | 2.1'' × 1.2'' | 2.1'' × 1.2'' | 2.1'' × 1.2'' | 2.1'' × 1.2'' |

4.1.3. Radio Continuum and Thermal Molecular Lines

We detected no 6 cm radio continuum toward the maser position to a 5 \( \sigma \) level of 2.4 mJy beam\(^{-1}\) (\( \theta_{\text{syn}} = 1.6'' \times 1.1'' \)). Using the VLA in the C configuration (\( \theta_{\text{syn}} \sim 1'' \)), Codella et al. (1997) report an upper limit of the 1.3 cm radio continuum of 0.4 mJy beam\(^{-1}\) (3 \( \sigma \)).

Based on our VLA-D observations, the nearest 6 cm radio continuum source is approximately 50'' north of the maser position. The radio continuum source (a compact H II region that will be discussed in a future paper) has associated H2CO absorption at approximately the same velocity as the H2CO maser, indicating that the H2CO maser belongs to an extended molecular cloud that shows clear evidence for the presence of more evolved massive stars. The LSR velocity of the H2CO absorption (75.0 km s\(^{-1}\)) implies two possible kinematic distances: 4.8 or 10.8 kpc. Codella et al. (1997) as well as Caswell & Haynes (1983) preferred the far kinematic distance; however, the distance ambiguity has not been resolved (Forster & Caswell 1999).

For example, Harju et al. (1998) list the near kinematic distance for the source (see also Scoville et al. 1987; Pestalozzi et al. 2005).

A number of thermal molecular lines have been detected toward G23.01−0.41. Caswell et al. (2000) detected (quasi-)thermal emission of the CH3OH lines at 107.0 GHz and 156.6 GHz (see also Slysh et al. 1999). Harju et al. (1998) detected broad (line width > 20 km s\(^{-1}\)) SiO J = 2–1 and J = 3–2 emission with the Swedish-ESO Submillimetre Telescope (SEST) telescope. CO and 13CO emission was also detected in single-dish surveys (Scoville et al. 1987; Jackson et al. 2006).

Interferometric (Nobeyama Millimeter Array and Plateau de Bure Interferometer) observations of 12CO, 13CO, and C18O have been recently reported by Furuya et al. (2008) with an angular resolution \( \sim 6'' \). Their 12CO spectrum shows high-velocity gas, in particular prominent red-wing emission that traces a massive (>50 M\( _{\odot} \)) molecular outflow, possibly located close to the plane of the sky.

\(^9\) IRSA-IRAS Sky Survey Atlas, available online at http://irsa.ipac.caltech.edu/Missions/iras.html.

\(^{10}\) Caswell & Haynes (1983; see also Caswell et al. 1995b; Anglada et al. 1996; Testi et al. 1998; Forster & Caswell 1999) report a far kinematic distance of 12.8 kpc instead of our value of 10.8 kpc, because they assumed a Sun-Galactic center distance of 10.0 kpc, whereas we assume 8.5 kpc (Brand & Blitz 1993).

\(^{11}\) A maser component was also found superimposed on the thermal profile of the CH3OH 107.0 GHz line.
High-density molecular gas in the region is evident from detection of CS ($J = 1-0$) and NH$_3$ (1,1) lines with the MIT Haystack 37 m telescope (Anglada et al. 1996). Single-dish NH$_3$ (1,1), (2,2), and (3,3) observations were also conducted by Codella et al. (1997) with the Medicina 32 m telescope. Codella et al. (1997) derived a rotational temperature of 13 K.

High angular resolution NH$_3$ observations were conducted by Codella et al. (1997) with the VLA ($\theta_{\text{syn}} \sim 1''$). The NH$_3$ (3,3) data show a compact ($<10''$) molecular core that has a southeast–northwest elongation (Fig. 3, bottom). Codella et al. (1997) derived the following parameters for the ammonia core: deconvolved angular diameter = 3.3'' $T_K$ = 58 K, $M_{\text{syn}} = 886 M_\odot$, and $n_{H_3} = 6.9 \times 10^5$ cm$^{-3}$. The H$_2$CO maser is coincident with the NH$_3$ (3,3) peak emission (Fig. 3, bottom).

Furuya et al. (2008) also conducted high angular resolution ($<10''$) observations of HNCO and CH$_3$CN. Their observations confirm the presence of a hot molecular core characterized by a CH$_3$CN rotation temperature of $\sim120$ K and a core mass of $\sim380 M_\odot$. The velocity distribution of the CH$_3$CN gas is consistent with rotation of a molecular core oriented almost perpendicular to the outflow direction. The elongation and velocity gradient of the CH$_3$CN core is parallel to the elongation of the NH$_3$ emission shown in Figure 3.

4.1.4. Other Astrophysical Masers

A variety of masers have been detected toward G23.01–0.41 in single-dish surveys. Methanol masers have been found at 6.7 GHz (Menten 1991; Caswell et al. 1995b; Szymczak et al. 2002; see also catalogs by Pestalozzi et al. 2005 and Xu et al. 2003), 12 GHz (MacLeod et al. 1993; Caswell et al. 1995a; Błaszkiewicz & Kus 2004), 107.0 GHz (Caswell et al. 2000), 44 GHz (Slysh et al. 1994), and 95 GHz (Val’tts et al. 2000). H$_2$O 22 GHz and OH ($^2\Pi_{1/2} J = 3/2$ ground state) masers have also been reported (Szymczak et al. 2005; Szymczak & Gérard 2004; Caswell & Haynes 1983).

High angular resolution observations of the CH$_3$OH 6.7 GHz masers have been conducted (J. L. Caswell, unpublished; see Caswell et al. 2000); the position of the CH$_3$OH maser is coincident with that of the H$_2$CO maser within 1'' rms. Forster & Caswell (1989; see also Forster & Caswell 1999) conducted VLA observations of H$_2$O 22 GHz ($\theta_{\text{syn}} = 3.9'' \times 1.8''$) and OH 1665 MHz ($\theta_{\text{syn}} = 6.5'' \times 1.0''$) masers in G23.01–0.41. The H$_2$CO maser is located within 2'' of the OH and H$_2$O maser positions (see Fig. 3; bottom).

4.1.5. The Nature of the G23.01–0.41 Star-forming Region

The abundant available multiwavelength data show that G23.01–0.41 is an active site of massive star formation. The H$_2$CO maser is located at the peak of a molecular core traced by NH$_3$ (3,3) and CH$_3$CN. The hot molecular core also harbors a variety of molecular masers. Given the highly confused far-IR environment, it is not possible to reliably measure the bolometric luminosity of the massive stellar object pinpointed by the H$_2$CO maser (Fig. 3); however, based on the available mid- and far-IR data, the upper limit of the luminosity is $\sim10^5 L_\odot$.

As in the case of the IR source associated with the H$_2$CO maser in IRAS 18566+0408 (Araya et al. 2007c), the H$_2$CO maser in G23.01–0.41 is found toward a source with 4.5 $\mu$m IR excess, which likely indicates shocked gas in an outflow. Considering the presence of a hot molecular core at the location of the H$_2$CO maser, the detection of several other maser species, evidence for outflow and shocked gas based on CO, SiO and 4.5 $\mu$m IR excess emission, absence of radio continuum, and evidence for rotation of the molecular core, the H$_2$CO maser appears to pinpoint the location of a very young massive stellar object in an evolutionary stage prior to the formation of a radio-bright ultracompact H II region. The central object may still be undergoing accretion; further observations should be made to clarify this point.
4.2. G25.83−0.18

4.2.1. H2CO 6 cm Maser Emission

As the case of G23.01−0.41 (§ 4.1), maser emission in G25.83−0.18 was first detected in the VLA survey (§ 2.1) and then confirmed with higher spectral resolution observations (VLA-D; § 2.2) ~8 months later. The H2CO maser shows a double-peak line profile (Figs. 1 and 2). The separation between the two peak components is 1.5 km s\(^{-1}\). No significant difference in the maser flux density was found between the two epochs.

As reported in Table 3, the line profile of the high spectral resolution observations is well fit by the superposition of three Gaussian profiles; two broad components (0.7 and 0.9 km s\(^{-1}\) FWHM) and a narrow component (FWHM = 0.29 km s\(^{-1}\)). Whether the line profile is composed of only two non-Gaussian maser lines or three (or more) components is unclear. For example, the profile could be due to an asymmetric line (the blueshifted component) overlapped with a Gaussian line (the redshifted component; see Fig. 2).

4.2.2. Infrared Environment

The H2CO maser is at the center of an IR dark cloud as revealed by 8.0 \(\mu\)m Spitzer GLIMPSE observations (see Fig. 4). The H2CO maser is located between a source with strong 4.5 \(\mu\)m excess emission (green in Fig. 4, top inset) and a source brighter at 8 \(\mu\)m (red in Fig. 4). The peak of the 4.5 \(\mu\)m source is offset (~3\(^\circ\)) from the location of the H2CO maser. No IR emission was detected with MSX toward the position of the H2CO maser; no 2MASS source was found coincident with the H2CO maser either.

Data from Spitzer MIPS at 70 \(\mu\)m reveal a strong (>100 Jy) far-IR source whose peak is within ~1\(^\circ\) from the position of the H2CO maser. At low level, the 70 \(\mu\)m emission is extended and comprises a neighboring IR source; however, the core emission is compact (FWHM < 25\(^\prime\)), i.e., close to the theoretical telescope diffraction limit. The IR source coincident with the H2CO maser is also detected in the 24 \(\mu\)m MIPS band.

4.2.3. Radio Continuum and Thermal Molecular Lines

We detected no radio continuum toward the position of the H2CO maser to a level of 2.8 mJy beam\(^{-1}\) (5 \(\sigma\)) in the VLA BnA → B observations (\(\theta_{\text{syn}} = 1.6^\prime\times1.1^\prime\)); the 5 \(\sigma\) upper limit set by the VLA-D data is 5 mJy beam\(^{-1}\) (see Fig. 4, top). The nearest radio continuum source to the H2CO maser is ~2\(^\circ\) to the west (G25.80−0.16; Fig. 4, top), which was also detected in the continuum at 8.64 and 6.67 GHz by Walsh et al. (1998).

The H2CO maser is coincident with a millimeter and submillimeter core. Walsh et al. (2003) detected compact 450 and 850 \(\mu\)m emission; the H2CO maser is located within 4\(\prime\) of the peak position of the submillimeter source (the JCMT beam is approximately 8\(\prime\) and 15\(\prime\) at 450 and 850 \(\mu\)m, respectively). Hill et al. (2005) conducted SEST SIMBA observations of G25.83−0.18 and detected 1.2 mm emission (\(S_{\text{syn}} = 5.4\;\text{Jy}\)); the FWHM of the millimeter source is 60\(^\prime\). Based on the millimeter detection, Hill et al. (2005) report a mass of \(2.8 \times 10^3\;M_{\odot}\) or \(8.8 \times 10^3\;M_{\odot}\) depending on the kinematic distance (see below). The H2CO maser is coincident with the 1.2 mm peak within ~1\(^\circ\).

We detected H2CO 6 cm absorption in the region (Fig. 4, middle and bottom, VLA-D observations). The main H2CO absorption clump is coincident with the IR dark cloud, and shows a shell-like brightness distribution (Fig. 4, middle).\(^{12}\) The H2CO absorption (Fig. 4, middle) is not due to overlapping H2CO maser emission and absorption at the central position; the measured velocity of the H2CO maser is not in the velocity range used to obtain the H2CO absorption image.

\(^{12}\) The shell-like distribution of H2CO absorption (Fig. 4, middle) is not due to overlapping H2CO maser emission and absorption at the central position; the measured velocity of the H2CO maser is not in the velocity range used to obtain the H2CO absorption image.
maser is located at the projected spatial center of the shell and near the radial velocity edge of the H$_2$CO absorption line (Fig. 4, bottom). The shell brightness distribution could be due to (1) H$_2$CO in gas phase is less abundant in the inner regions of the shell, for example, due to chemical gradients, smaller total molecular density, or depletion (see Young et al. [2004] for the case of preprotostellar cores); and/or (2) the excitation conditions for H$_2$CO absorption are less favorable in the inner regions of the shell (e.g., Zhou et al. [1990] explained the detection of an H$_2$CO shell-like structure in B335 as a consequence of higher molecular density at the core that quenches the anomalous absorption). Observations of other H$_2$CO transitions as well as other mid- and high-density tracers are needed to fully investigate the nature of the shell-like H$_2$CO absorption source. Nevertheless, the recent high angular resolution detection of NH$_3$ at the position of the H$_2$CO depression (Longmore et al. 2007, see below) suggests that the H$_2$CO shell-like structure is due to high-density ($>10^5$ cm$^{-3}$), molecular gas in the center of the molecular core that quenches H$_2$CO anomalous absorption.

We also detected H$_2$CO absorption close to the radio continuum source (compare Fig. 4, top and middle). The similar velocity of the H$_2$CO absorption gas associated with the continuum source and with the IR dark cloud indicates that both are part of the same star-forming complex. Assuming that the LSR velocity of the H$_2$CO absorption line traces the systemic velocity of the cloud, the two possible kinematic distances to this massive star-forming region are 5.6 and 9.7 kpc. Since the H$_2$CO maser is associated with an IR cloud seen in absorption against the mid-IR galactic background (Fig. 4), it is likely that the region is located at the near kinematic position.

G25.83–0.18 has been detected in CH$_3$CN, HCO$^+$, and H$_2$CO$^+$ with the Mopra telescope by Purcell et al. (2006). Based on the CH$_3$CN data, they derived a rotation temperature of $\sim50$ K, and found evidence for infalling motion based on HCO$^+$ data. In addition, Longmore et al. (2007) detected an optically thick NH$_3$ core at the position of the H$_2$CO maser from ATCA observations. The line width of the NH$_3$ (1,1), (2,2), (3,3), and (4,4) transitions range between 6 and 30 km s$^{-1}$, indicating the possible presence of a molecular outflow partially traced by NH$_3$.

4.2.4. Other Astrophysical Masers

Walsh et al. (1998) conducted ATCA observations of 6.7 GHz CH$_3$OH masers in G25.83–0.18; five maser components were found with LSR velocities of between 90.7 and 99.0 km s$^{-1}$. The H$_2$CO maser is located $\sim$2″ south of the CH$_3$OH maser clump$^{13}$ (Fig. 4, top inset).

Single-dish observations of the Class II CH$_3$OH 6.7 and 12 GHz masers were conducted by Blaszczewicz & Kus (2004) with the Torun telescope. The peak LSR velocity of the 6.7 and 12 GHz masers were 91.3 and 90.7 km s$^{-1}$, respectively, i.e., coincident in velocity with the H$_2$CO maser.

Ellingsen (2005) conducted observations with the Mopra Telescope of the 95.1 GHz Class I CH$_3$OH maser transition and detected several maser lines (peak maser emission at 90.2 km s$^{-1}$ overlapped with a broad component. The broad line (4.3 km s$^{-1}$ line width) could be due to thermal emission, given that its peak velocity (94.2 km s$^{-1}$) coincides with the H$_2$CO absorption peak velocity (see §4.2.3).

Other maser species have also been detected in single-dish surveys. Szymczak & Gérard (2004) detected a OH 1667 MHz maser line with a peak LSR velocity of 92.9 km s$^{-1}$; their Figure A.1 also shows detection of a possible high-velocity ($\sim$120 km s$^{-1}$) OH 1612 MHz line. Szymczak et al. (2005) conducted H$_2$O 22 GHz observations with the 100 m Effelsberg telescope and detected several H$_2$O maser features within a velocity range of $\sim$50 km s$^{-1}$, centered at 94.7 km s$^{-1}$.

4.2.5. The Nature of the G25.83–0.18 Star-forming Region

The coincidence of the H$_2$CO maser with other maser species (in particular with Class II CH$_3$OH masers), with an IR dark cloud and molecular core, the absence of radio continuum emission, the detection of a millimeter, submillimeter and far-IR source, and the presence of 4.5 $\mu$m excess emission toward the center of the IR dark cloud, imply that G25.83–0.18 is a very young region of massive star formation in an evolutionary stage prior to the ultracompact H II region phase. The precise location and luminosity of the protostar responsible for the excitation of the different maser species is unclear; higher sensitivity continuum observations are needed to reveal the position of the exciting source.

G25.83–0.18, as well as G23.01–0.41, may be classified as Group 2 cores following the Longmore et al. (2007) nomenclature, i.e., warm NH$_3$ cores associated with CH$_3$OH masers but no detectable radio continuum.

4.3. G23.01–0.41 and G25.83–0.18 with Respect to the Other Known H$_2$CO Maser Regions

Including the two new masers reported in this work, H$_2$CO 6 cm masers have been detected toward seven regions in the Galaxy, and in a total of 15 maser “spots” (at 1″ resolution). The H$_2$CO masers in G23.01–0.41 and G25.83–0.18 share similar characteristics with most of the other known H$_2$CO maser regions, in particular: (1) H$_2$CO masers are found in sources that harbor a variety of other molecular masers (e.g., Hoffman et al. 2003; Mehringer et al. 1994), (2) the velocity difference of the H$_2$CO masers with respect to the systemic velocity of the clouds is typically less than 6 km s$^{-1}$ (e.g., Pratap et al. 1994; Araya et al. 2004), which suggests that H$_2$CO masers do not originate in high-velocity outflows, (3) the flux density of the known masers is less than $\sim$2 Jy (e.g., Hoffman et al. 2007), (4) all known H$_2$CO masers have been detected in regions of massive star formation (E. D. Araya et al., in preparation), (5) excluding Sgr B2, most of the H$_2$CO masers show double-peaked profiles with separations smaller than 3 km s$^{-1}$ (e.g., NGC 7538 IRS 1: Forster et al. 1985; IRAS 18566+0408: Araya et al. 2007d; see also review by Araya et al. 2007a), (6) even though bright radio continuum sources may be found in the same star-forming complexes, most H$_2$CO masers are located toward sources characterized by weak (or no) compact radio continuum emission, typically undetected at a few millijansky sensitivity levels (e.g., Araya et al. 2005; this work), (7) excluding some of the masers in Sgr B2, the known H$_2$CO masers appear to be associated with very young massive stellar objects (in an evolutionary phase prior to the formation of radio-bright ultracompact H II regions) that have strong far-IR emission and molecular core counterparts (e.g., §§4.1 and 4.2).

Many H$_2$CO maser regions show evidence of outflows/jets and shocked gas based on 4.5 $\mu$m excess emission from Spitzer IRAC data (see, for example, Araya et al. [2007c] in the case of IRAS 18566+0408). Further evidence comes from molecular data such as SiO, H$_2$, and H$_2$S (e.g., Zhang et al. 2007; Beuther et al. 2007b; Kraus et al. 2006; Gibb et al. 2004; Maxia et al. 2001; Harju et al. 1998), and radio continuum observations (e.g., Araya et al. 2007c). However, the H$_2$CO masers may not be directly associated with the shocked material (e.g., note the offset
between the 4.5 μm excess source and the H$_2$CO maser in G25.83−0.18; Fig. 4, top).

5. SUMMARY

We report the results of our third survey for H$_2$CO 6 cm masers toward massive star-forming regions in the Galaxy. The observations were conducted with the VLA toward 14 pointing positions and resulted in the detection of two new H$_2$CO maser regions: G23.01−0.41 and G25.83−0.18. Including the new detections, H$_2$CO masers have been found toward a total of seven star-forming regions in the Galaxy, four of them detected in our series of surveys (Araya et al. 2004, 2007b, and this work).

The H$_2$CO maser in G23.01−0.41 is coincident with the center of a hot molecular core that shows evidence of a rotating torus perpendicular to a molecular outflow (Furuya et al. 2008). Excess in the 4.5 μm band from GLIMPSE Spitzer IRAC observations reveals shocked gas in the region, possibly tracing the outflow. Active massive star formation is also evident from the detection of a number of molecular maser lines, including Class II CH$_3$OH masers.

In the case of G25.83−0.18, the maser is located at the center of an infrared dark cloud that harbors a clump of CH$_3$OH 6.7 GHz masers, a high-density molecular core traced by NH$_3$ and CH$_3$CN (Purcell et al. 2006), a millimeter, submillimeter and far-IR counterpart. In addition there is evidence for molecular infall and outflow motions, as well as shocked gas traced by 4.5 μm excess from Spitzer GLIMPSE data.

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In both cases the H$_2$CO masers are found toward objects that have no compact 6 cm radio continuum emission at the few mJy beam$^{-1}$ level. Given the evidence of active massive star formation in G23.01−0.41 and G25.83−0.18, the absence of radio continuum suggests that the regions are in a very early phase of massive star formation, prior to the development of radio-bright ultracompact H ii regions. H$_2$CO 6 cm masers appear to preferentially pinpoint very young massive stellar objects that may be categorized as high-mass protostellar objects (HMPOs; Beuther et al. 2007a) or, in the Zinnecker & Yorke (2007) nomenclature, somewhere in the hot dense massive core (HDMC) or disk-accreting main-sequence star (DAMS) phase.

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