Thermal Formaldehyde Emission in NGC 7538 IRS 1

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ABSTRACT

Spectral lines from formaldehyde (H$_2$CO) molecules at cm wavelengths are typically detected in absorption and trace a broad range of environments, from diffuse gas to giant molecular clouds. In contrast, thermal emission of formaldehyde lines at cm wavelengths is rare. In previous observations with the 100 m Robert C. Byrd Green Bank Telescope (GBT), we detected 2cm formaldehyde emission toward NGC7538 IRS1 – a high-mass protostellar object in a prominent star-forming region of our Galaxy. We present further GBT observations of the 2cm and 1cm H$_2$CO lines to investigate the nature of the 2 cm H$_2$CO emission. We conducted observations to constrain the angular size of the 2 cm emission region based on a East-West and North-South cross-scan map. Gaussian fits of the spatial distribution in the East-West direction show a deconvolved size (at half maximum) of the 2 cm emission of $50\pm800$. The 1 cm H$_2$CO observations revealed emission superimposed on a weak absorption feature. A non-LTE radiative transfer analysis shows that the H$_2$CO emission is consistent with quasi-thermal radiation from dense gas ($\sim10^5$ to $10^6$ cm$^{-3}$). We also report detection of 4 transitions of CH$_3$OH (12.2, 26.8, 28.3, 28.9GHz), the (8,8) transition of NH$_3$ (26.5GHz), and a cross-scan map of the 13GHz SO line that shows extended emission ($>50''$).

Key words: stars: formation — ISM: molecules — radio lines: ISM — ISM: individual (NGC7538)

1 INTRODUCTION

Formaldehyde is a tracer of high density gas in high-mass star forming regions and it is a reliable density probe in Galactic molecular clouds (e.g., Mangum et al. 2008, Ginsburg et al. 2011). The rotational levels of ortho-formaldehyde (H$_2$CO) are split in doublets, commonly known as K-doublets. The K-doublet lines from the three lowest H$_2$CO rotational energy levels correspond to wavelengths of 6, 2, and 1 cm (e.g., Mangum & Wootten 1993, Thaddeus 1972).

While thermal emission of high-frequency formaldehyde transitions has been detected in high-mass star forming regions (e.g., Ceccarelli et al. 2003), thermal emission of the lowest K-doublet transitions is rare (e.g., Evans et al. 1975b; Araya et al. 2006a). At present, thermal 6 cm H$_2$CO emission has been detected only toward the Orion BN/KL region (e.g., Araya et al. 2006b). Galactic quasi-thermal emission of the 2 cm transition has been reported toward a few sources (Orion-KL, OMC-2, P$ho$ Oph B, DR 21(OH), and three regions in W51; e.g., Ginsburg et al. 2016, Johnston et al. 1984, and references therein).1 Thermal emission at 1 cm has been found toward 17 sources (McCauley et al. 2011). In contrast, formaldehyde masers have only been unambiguously detected in the 6 cm

1 We use the term quasi-thermal to refer to gas in between a state dominated by non-LTE excitation resulting in anomalous absorption ($T_{ex} < T_{CMB}$ in the low-density regime; e.g., Evans et al. 1975a) and LTE excitation dominated by molecular collisions (high-density regime).
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transition (e.g., Chen et al. 2017b, Ginsburg et al. 2015, Araya et al. 2007b, Hoffman et al. 2003)\(^2\). Currently, 10 Galactic regions are known to harbor 6 cm masers (Andreev et al. 2017; Chen et al. 2017b), one of them is NGC 7538 – the region where 6 cm H\(_2\)CO masers were first confirmed (see review by Araya et al. 2007b). NGC 7538 is an active site of high-mass star formation located at a distance of 2.65 ± 0.12 kpc (Moscadelli et al. 2009). This region is one of the richest maser sources known (e.g., Galván-Madrid et al. 2010). Over a dozen different molecular maser transitions have been found in NGC 7538, including one of the rare 6 cm H\(_2\)CO masers (e.g., Araya et al. 2007a).

Using the 100 m Robert C. Byrd Green Bank Telescope (GBT), we detected 2 cm H\(_2\)CO emission toward NGC 7538 IRS 1 (Andreev et al. 2017). This emission was independently detected by Chen et al. (2017a). Given the non-detection of a 2 cm maser in interferometric observations (Hoffman et al. 2003), Chen et al. (2017a) argued that the 2 cm H\(_2\)CO emission in NGC 7538 IRS 1 is a variable maser, noting that variability has been detected in the 6 cm H\(_2\)CO maser in the same source (e.g., Andreev et al. 2017).

In this work, we present GBT observations of the 2 cm and 1 cm H\(_2\)CO transitions to investigate the nature of the 2 cm emission\(^3\). Depending on whether the emission is thermal or maser, the line would provide information on completely different scales, from tens of a.u.’s in the case of masers, to sub-pc structures in the case of thermal emission. In particular, if the 2 cm H\(_2\)CO emission is thermal, it would trace a connection between the large-scale molecular cloud in NGC 7538 and the molecular core hosting the IRS1 star formation site.

2 OBSERVATIONS

2.1 2 cm H\(_2\)CO

Observations of the 2 cm H\(_2\)CO transition in NGC 7538 were conducted with the GBT in November 2008. We observed the \(J_{K_aK_c}=3_{12}-3_{13}\) transition of formaldehyde \((v_0=14.488480\ GHz,\ H_2CO\ 2\ cm\ line)\)^4 with a bandwidth (BW) of 12.5 MHz observed in frequency switching mode (5 minutes per scan) that resulted in an effective bandwidth of 6.25 MHz (\(\sim130\ km\ s^{-1}\)), 9 level sampling, 8192 channels and final channel separation of 21.3 kHz (0.442 km s\(^{-1}\)) after smoothing. Given the capabilities of the GBT spectrometer, we conducted observations using additional independent bands (spectral windows) tuned to the \(J_K=2_{0}\)–\(3_{-1}\) transition of CH\(_3\)OH (12.178593 GHz) and the \(J_{K}=2_{1}\)–\(1_{0}\) transition of SO (13.043814 GHz). The system temperature was approximately 30 K. A calibration diode was used to set the antenna temperature scale, and data reduction were done using GBTIDL. We observed the quasars 3C48 and 2148+6107 for pointing and system checking. We measured a 3C48 flux density of \(S_V=0.92\ Jy\) at 29 GHz, which agrees within 12% with the expected value of 0.82 Jy\(^5\). The pointing errors are estimated to be \(\sim5''\) in both RA and Dec based on the observations of 2148+6107.

2.2 1 cm H\(_2\)CO

We also observed the \(J_{K_aK_c}=3_{12}-3_{13}\) transition of formaldehyde \((v_0=28.974804\ GHz,\ 1\ cm\ H_2CO\ line)\) with the GBT on 30 October 2008. The spectrometer was used with a 50 MHz BW (\(\sim500\ km\ s^{-1}\)), 9 level sampling, 8192 channels and final channel separation of 18.3 kHz (0.190 km s\(^{-1}\)) after smoothing. In the spectral window of the 1 cm H\(_2\)CO line, the \(J_K = 2_2-2_1\ A^\prime\) transition of CH\(_3\)OH (28.969942 GHz) was also included\(^6\). Three additional spectral windows were used to simultaneously observe the (J,K) = (8.8) NH\(_3\) (26.518981 GHz) line, and two transitions 12\(_{-12}\ E\) (26.847205 GHz) and 4\(_{0}\)–3\(_{-1}\) \((28.316031\ GHz)\ of\ CH_3OH.\ The\ HPBW\ of\ the\ telescope\ at\ 29\ GHz\ is\ \sim26''.

The observation procedure was position-switching (ON-OFF mode) with 2 minutes on both ON and OFF (reference) positions per scan. We obtained 12 scans of NGC 7538 IRS 1. The reference position was set to match the azimuth-elevation path tracked by the telescope during the corresponding 2 minutes ON-source observations. The system temperature was approximately 45 K. Calibration and data reduction were done using GBTIDL. We observed the quasars 3C48 and 2148+6107 for pointing and system checking. We measured a 3C48 flux density of \(S_V=0.92\ Jy\) at 29 GHz, which agrees within 12% with the expected value of 0.82 Jy\(^6\). The pointing errors are estimated to be \(\sim5''\) in both RA and Dec based on the observations of 2148+6107.

3 RESULTS

Figure 1 shows the emission and absorption spectra of the three lowest K-doublet transitions of H\(_2\)CO towards NGC 7538 IRS1. The 1 cm and 2 cm H\(_2\)CO spectra are from the observations reported in this work, while the 6 cm H\(_2\)CO spectrum is from GBT observations reported by Araya et al. (2007a). Spectra of the other molecular transitions observed in this work are shown in Figures 2 and 3.

As mentioned above, we conducted cross-scan observations of 2 cm H\(_2\)CO, 12.2 GHz CH\(_3\)OH and 13.044 GHz SO transitions, simultaneously. The spectra of the 2 cm H\(_2\)CO cross-scan are shown in Figure 4. To explore the distribution of 2 cm H\(_2\)CO in the context of the IR and radio continuum environment in NGC 7538 IRS1, we

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\(^2\) Chen et al. (2017a) reported possible 2 cm H\(_2\)CO emission lines toward G23.01–0.41 and G29.96–0.02, in addition to NGC 7538; see below.

\(^3\) Preliminary results from this work were presented at a conference by Yuan et al. (2011).

\(^4\) Spectroscopy information in this paper is from Splatalogue (http://www.cv.nrao.edu/pl.php/splat/) and the NIST Lows catalog (https://physics.nist.gov/cgi-bin/micro/table5/start.pl), unless indicated otherwise.

\(^5\) IDL (Interactive Data Language) is a trademark of Harris Geospatial Corp.

\(^6\) https://www.vla.nrao.edu/astro/calib/manual/fluxscale.html

\(^7\) Given the HPBW of the telescope, our IRS1 pointing also includes IRS2 and IRS3, e.g., Akabane et al. (1992).

\(^8\) Rest frequency from the JPL catalog (https://spec.jpl.nasa.gov/hp/public/catalog/catform.html) as listed at the time of the observations, which was also used by McCauley et al. (2011). This frequency differs by 12 kHz with respect to the rest frequency reported in the Lovas catalog.

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show the 2 cm H$_2$CO spectra superimposed with a Spitzer/IRAC$^9$ image and 6 cm VLA continuum from the NRAO image archive$^{10}$.

The detections were fit with Gaussian profiles; Figures 5 to 8 show the Gaussian fits of all 13 cross-scan pointings (East-West, North-South) of the 2 cm H$_2$CO, 12.2 GHz CH$_3$OH, and 13.044 GHz SO observations. The line parameters of 2 cm H$_2$CO observations from the free fit are listed in Table 1, whereas the line parameters from the fit after constraining the peak absorption velocities are listed in Table 2 (see Section 4.1 for details). The free fit line parameters of 12.2 GHz CH$_3$OH, and 13.044 GHz SO observations are listed in Tables 3, and 4 respectively. In the case of 12.2 GHz CH$_3$OH, absorption was detected only in the pointing positions (108$''$.0) and (0, $-108''$); we highlight the absorption spectra in Figure 7. Table 5 lists the line parameters of other transitions of H$_2$CO, CH$_3$OH, and NH$_3$.

We note that McCauley et al. (2011) also report GBT observations of the 1 cm H$_2$CO line toward NGC 7538 IRS1. At a first glance, the spectrum in their Figure 1 shows a very similar line profile to the one shown in our Figure 1. However, converting their 26.847 GHz spectrum (VLA) flux calibrator 3C48 to independently check our data directly to $T_A^*$ in GBTIDL. We argue that the line parameter values reported in this work (Table 5) are more reliable than the values reported by McCauley et al. (2011) in their Table 2 because: 1) as explained in Section 2.2, we observed the NRAO K. Jansky Very Large Array (VLA) flux density calibrator 3C48 to independently check our flux density scale and our measurement agrees within 12% with the expected value$^{11}$, 2) the line parameters of the 1 cm H$_2$CO line

$^9$ https://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/

$^{10}$ http://www.aoc.nrao.edu/~vlbacald/ArchIndex.shtml

$^{11}$ Note that our observations were conducted years before the 3C48 flare began in 2018; https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/fdscale.
4 Analysis and Discussion

Figure 4 shows extended 2 cm H$_2$CO absorption toward the East, West, and South of NGC 7538 IRS1. The figure also shows 2 cm emission overlapping absorption toward the center of the cross-scan. While it is clear that the absorption is extended, the extent of the emission is not as clear because of the superposition with absorption. In this section we discuss deconvolution of the emission and absorption features to measure the angular size of the 2 cm absorption. In order to characterize the emission, we need to reliably deconvolve the absorption from the emission in the central pointing positions. To accomplish this, we have to characterize the absorption profiles toward the pointing positions with significant emission overlap. Comparing the velocities of the H$_2$CO absorption not affected by emission in the East-West direction, i.e., $V_{LSR}$ (108", 0) = $-54.69(0.38)$ km s$^{-1}$, $V_{LSR}$ (54", 0) = $-55.19(0.07)$ km s$^{-1}$, $V_{LSR}$ (-108", 0) = $-57.22(0.15)$ km s$^{-1}$ (see Table 1), we find a smooth velocity gradient across the East-West scan, with redshifted absorption toward the East and blueshifted absorption toward the West. We note that similar velocity gradients are seen at ~1" scales, e.g., HCO$^+$ (Figure 7 of Sun & Gao (2009), with the caveat that the HCO$^+$ (1-0) map is centered 1.3" South of IRS1; see also Sandell et al. 2012), CO (Qiu et al. 2011, Sandell et al. 2012), CS (Kameya et al. 1986), although see the complex NH$_3$ velocity structure reported by Zheng et al. (2001).

As a way to better constrain the line parameters of the absorption, we spatially interpolated the peak absorption velocity in the central pointing positions, and fixed the value of the peak absorption in new Gaussian fits of the combined emission-absorption profiles (East-West spectra highlighted in black in Figure 5, left column). As a clear H$_2$CO absorption profile was not detected toward the North pointing positions, we used the interpolated H$_2$CO absorption velocity toward the central pointing position (0,0) and the absorption velocity at (0, -108") and (0, -54") pointing, i.e., $-57.27(0.09)$ km s$^{-1}$ (see Table 1) to interpolate (and extrapolate in the case of the (0,27") pointing) the H$_2$CO peak absorption velocities in the North-South direction, and used them as fixed parameters to fit the emission spectra (Figure 5, right column). The Gaussian fits of the emission components obtained by constraining the peak absorption velocities are shown with orange solid lines in Figure 5; the line parameters are listed in Table 2. Inspection of the fits in Figure 5 shows that constraining peak absorption velocities results in detection of a weak emission line toward the (0, 27") position, and reasonable fits for all but the (0, -54") pointing position, where the line profile is fit by two overlapping lines, an emission and absorption line of similar absolute peak intensities. Both the free and constrained Gaussian fits show that we cannot reliably measure the line parameters of the emission line toward (0, -54"), as demonstrated by the large peak flux density uncertainty for this pointing position (Table 2). The (0, -54") pointing includes NGC 7538S, which shows a complex multi-peak emission profile in H$_2$CO rotational transitions (e.g., Sandell & Wright 2010), which likely contributes to the observed complex line profile.

A graphical view of the absorption line parameters obtained from the unconstrained (Table 1) and constrained (Table 2) fits is shown in Figure 9. While some differences between the two fits are evident (e.g., line velocities), both sets of absorption line parameters show a consistent description of the molecular cloud traced by 2 cm H$_2$CO. For instance, the line parameters obtained from both methods show that the linewidth of the absorption in the East-West scan is greater toward the central pointing position where active star formation is taking place (e.g., Moscadelli & Goddi 2014).
The greater linewidth could be due to greater turbulence at the star formation site and/or to the molecular outflow in NGC 7538 IRS1 (e.g., Wright et al. 2014).

4.2 Line Parameters and Angular Size of the 2 cm H$_2$CO Emission Region

As discussed below, our observations show that the 2 cm H$_2$CO emission has a much wider spatial distribution than the 6 cm H$_2$CO masers imaged by Hoffman et al. (2003) and the multiple disk system around massive YSOs in the central region of IRS1 as shown by VLBI observations (Moscadelli & Goddi 2014). Table 2 shows the line parameters of the emission lines after fixing the peak velocity of the absorption in each pointing position. The LSR velocity of the emission line at the center position from the constrained fit is $-57.3(0.1)$ km s$^{-1}$, which agrees within the errors with the velocity of $-57.34(0.07)$ km s$^{-1}$ obtained from the unconstrained fit (Table 1). This peak velocity also agrees with the systemic veloc-
Figure 5. Spectra of 2 cm H$_2$CO emission and absorption toward NGC7538. Gaussian fits are included as dashed lines (green curves show individual components, red curves show the combined fit when more than one component was fit). The East-West spectra are shown in the left column, the North-South pointings are shown in the right column. Note that the same central pointing spectrum is shown in both the left and right columns. The highlighted spectra (bold coordinates) were used to interpolate the H$_2$CO absorption velocities (see Section 4.1 and Figure 4). Thick solid (orange) lines are Gaussian fits of the emission lines after constraining the peak absorption velocities (see Section 4.1). The data shown in the figure are available as Supporting Information.
Figure 6. Same as Figure 5 but for 12.2 GHz CH$_3$OH. We show the same velocity range in all panels for consistency; however, the velocity range was optimized for emission and not for the (108°, 0) and (0°, −108°) pointings that show significant absorption. The two absorption spectra are shown with a larger velocity range in Figure 7. The data shown in the figure are available as Supporting Information.
Figure 10 shows the line parameters from the free (Table 1) and constrained (Table 2) fits for the emission line. As demonstrated in the figure, the line parameters of the emission line are not greatly modified by constraining the absorption velocities. This indicates that the line parameters of the emission are reliably measured, with the exception of the (0,−27") pointing. We find that the linewidth is approximately uniform across the four East-West pointing positions, which indicates that the emission line is tracing a relatively uniform turbulent environment. We also found an East-West velocity gradient (Figure 10). At smaller scales than our cross-scan (~ 40"), Wright et al. (2014) find a CO outflow centered on NGC 7538 IRS1 that is red-shifted toward the South-East and blue-shifted toward the North-West; a complete half-beam spacing mapping of the 2 cm H₂CO emission in the region is necessary to further investigate the nature of the observed velocity gradient and its possible connection with the outflow in NGC 7538 IRS1, rotation or infall.

Table 1. Line parameters of 2 cm H₂CO observations.

| Position (ΔRA, ΔDec) | S_ν (Jy) | RMS (Jy) | V_LSR (km s⁻¹) | Width (km s⁻¹) | J(ν).dv (Jy km s⁻¹) |
|----------------------|---------|---------|-----------------|---------------|-------------------|
| NGC7538 IRS1         | 0.077(0.005) | 0.006  | −57.34(0.07)   | 2.5(0.2)      | 0.21(0.03)        |
| (108",0)             | −0.025(0.003) | 0.006  | −57.75(0.52)   | 13.6(1.5)     | −0.36(0.09)       |
| (54",0)              | −0.018(0.002) | 0.007  | −54.69(0.38)   | 6.5(0.9)      | −0.12(0.03)       |
| (27",0)              | 0.049(0.006)  | 0.008  | −57.47(0.12)   | 2.4(0.4)      | 0.13(0.04)        |
| (−27",0)             | −0.042(0.006) | 0.008  | −56.01(0.32)   | 7.7(0.6)      | −0.34(0.08)       |
| (−54",0)             | 0.064(0.004)  | 0.006  | −57.76(0.07)   | 2.4(0.2)      | 0.17(0.02)        |
| (−108",0)            | −0.011(0.002) | 0.006  | −57.50(1.10)   | 15.8(3.0)     | −0.18(0.07)       |
| (0,108")             | 0.027(0.003)  | 0.004  | −58.39(0.12)   | 2.4(0.3)      | 0.07(0.02)        |
| (0,54")              | −0.011(0.002) | 0.004  | −55.46(0.86)   | 10.0(1.5)     | −0.11(0.04)       |
| (0,27")              | −0.026(0.004) | 0.006  | −57.22(0.15)   | 1.9(0.4)      | −0.05(0.02)       |
| (0,0)                | ...       | 0.006  | ...            | ...           | ...               |
| (0,54")              | ...       | 0.005  | ...            | ...           | ...               |
| (0,27")              | −0.018(0.004) | 0.007  | −63.51(0.38)   | 3.7(0.9)      | −0.07(0.03)       |
| (0,−27")             | 0.079(0.006)  | 0.006  | −57.29(0.06)   | 2.6(0.2)      | 0.21(0.03)        |
| (0,−54")             | −0.047(0.006) | 0.006  | −56.48(0.21)   | 8.4(0.6)      | −0.42(0.08)       |
| (−54")               | 0.060(0.019)  | 0.005  | −56.37(0.14)   | 3.9(0.7)      | 0.25(0.12)        |
| (−108")              | −0.062(0.019) | 0.005  | −56.85(0.22)   | 8.0(0.9)      | −0.53(0.22)       |
| (0,108")             | −0.067(0.003) | 0.006  | −57.27(0.09)   | 4.2(0.2)      | −0.30(0.03)       |

Line parameters obtained from Gaussian fits, 1σ statistical errors from the fit are reported in parenthesis. The spectra were smoothed to a channel width of 0.442 km s⁻¹.

Table 2. Line parameters of 2 cm H₂CO for pointing positions that were fit after constraining the absorption velocities.

| Position (ΔRA, ΔDec) | S_ν (Jy) | RMS (Jy) | V_LSR (km s⁻¹) | Width (km s⁻¹) | J(ν).dv (Jy km s⁻¹) |
|----------------------|---------|---------|-----------------|---------------|-------------------|
| NGC7538 IRS1         | 0.074(0.005) | 0.006  | −57.30(0.1)    | 2.3(0.2)      | 0.18(0.03)        |
| (27",0)              | −0.020(0.003) | 0.006  | −55.91*        | 15.8(1.8)     | −0.35(0.09)       |
| (−27",0)             | 0.045(0.005)  | 0.008  | −57.43(0.12)   | 2.2(0.3)      | 0.10(0.03)        |
| (−54",0)             | −0.039(0.004) | 0.008  | −55.59*        | 7.7(0.6)      | −0.32(0.05)       |
| (−108")              | 0.063(0.004)  | 0.006  | −57.75(0.07)   | 2.3(0.2)      | 0.16(0.02)        |
| (0,27")              | −0.010(0.002) | 0.006  | −56.24*        | 17.7(3.3)     | −0.18(0.07)       |
| (0,−27")             | 0.029(0.003)  | 0.004  | −58.39(0.12)   | 2.6(0.3)      | 0.08(0.02)        |
| (0,−54")             | −0.012(0.002) | 0.004  | −56.56*        | 10.0(1.5)     | −0.12(0.04)       |
| (0,108")             | 0.016(0.005)  | 0.007  | −57.49(0.30)   | 2.3(0.8)      | 0.04(0.03)        |
| (0,−108")            | 0.076(0.005)  | 0.006  | −57.28(0.06)   | 2.5(0.2)      | 0.20(0.03)        |
| (0,−54")             | −0.044(0.004) | 0.006  | −56.25*        | 8.6(0.6)      | −0.41(0.07)       |
| (0,0)                | 0.075(0.032)  | 0.005  | −56.24(0.15)   | 4.5(0.7)      | 0.36(0.21)        |
| (0,54")              | −0.078(0.033) | 0.005  | −56.60*        | 7.7(0.9)      | −0.64(0.34)       |

* Fixed parameter in the fit, thus, no uncertainty reported. All other uncertainties are 1σ statistical errors from the fit.
cross-scan, is needed to better characterize the absorption and thus, better deconvolve the emission from the absorption. As pointed out by McCauley et al. (2011), mapping is necessary to obtain reliable source sizes for densitometry studies using H$_2$CO K-doublers.

Our simultaneous cross-scan observations of 12.2 GHz
in NGC7538IRS1, e.g., Andreev et al. (2017). Given the compact nature of the source, it is not surprising as multiple maser species are known to be variable. In particular, the same line profile as the VLBI spectrum shown in Figure 2 of Hoffman et al. (2003) is consistent with the angular size and brightness temperature values reported here. Hoffman et al. (2003) employed the VLA CnB configuration for which the shortest baselines were 65 m, corresponding to a largest angular scale of ~60″ at 2 cm. The 2 cm emission that we describe here would have been significantly filtered out by the interferometer. Moreover, the RMS brightness temperature of the 2 cm H2CO VLRA observations reported by Hoffman et al. (2003) is ∼10 K, which is much greater than the peak brightness temperature we obtained from theGBT observations (0.33 K), which is much greater than the peak brightness temperature obtained from the GBT observations. The GBT beam of 62″±1″ at 12.2 GHz implies an unresolved source, i.e., the masers are unresolved, as expected. The case of 13.044 GHz SO is the opposite extreme: as shown in Figure 13 the emission is extended, with a deconvolved size of 75″ (East-West) and 114″ (North-South), and the emission is not centered at NGC 7538 IRS1. These CH3OH and SO tests validate our deconvolution strategy. We conclude that the 2 cm H2CO emission in NGC 7538 IRS1 is resolved; it is tracing a molecular core of ~50″ FWHM size (~0.7 pc) in the East-West direction, and possibly narrower in the North-South direction. This physical size is more extended than the hypercompact HII region near NGC 7538 IRS1 (Gaume et al. 1995) and than the molecular core assumed by McCauley et al. (2011), i.e., 16″; while it is similar to the size of the millimeter and sub-millimeter dust core reported by Sandell & Sievers (2004) (see, their figure 3), and more compact than the NH3 (1,1) molecular cloud imaged by Keown et al. (2019). The physical size we measured is similar to the extent of the 2 cm H2CO emission filament-like structure in OMC-1 (Bastien et al. 1985). In summary, our observations clearly show that the 2 cm H2CO emission does not originate from the sub-arcsecond 6 cm maser region (Hoffman et al. 2003), but from an extended molecular cloud.

### 4.3 Nature of the 2 cm H2CO Emission

Based on the angular size of the 2 cm H2CO emission region discussed above, we obtain a peak brightness temperature of 0.33 K (assuming a symmetric Gaussian distribution of FWHM equal to the East-West major axis), which is consistent with optically thin thermal emission.

The non-detection of 2 cm H2CO emission by Hoffman et al. (2003) is consistent with the angular size and brightness temperature values reported here. Hoffman et al. (2003) employed the VLA CnB configuration for which the shortest baselines were 65 m, corresponding to a largest angular scale of ~60″ at 2 cm. The 2 cm emission that we describe here would have been significantly filtered out by the interferometer. Moreover, the RMS brightness temperature of the 2 cm H2CO VLRA observations reported by Hoffman et al. (2003) is ~10 K, which is much greater than the peak brightness temperature we obtained from the GBT observations (0.33 K), thus, the extended region would have been resolved out.
**Figure 8.** Same as Figure 5 but for 13 GHz SO. The data shown in the figure are available as Supporting Information.
As shown in Figure 1 (see also Table 5), we detected 1 cm \( \text{H}_2\text{CO} \) emission in NGC 7538 IRS1. Given the similar line profiles of the 2 cm and 1 cm lines, it is likely that the 1 cm transition is also due to thermal emission (see profiles of the 6 cm \( \text{H}_2\text{CO} \) masers with respect to the 1 cm and 2 cm lines in Figure 1). Assuming LTE excitation of the 1 and 2 cm lines and optically thin emission, we can estimate the excitation temperature of the gas by using the ratio of population levels (e.g., see equations A5 and A11 in Araya et al. 2005). We estimate an LTE excitation temperature of \( \sim 20 \) K, which is similar to the value obtained for OMC-1 (Bastien et al. 1985).

To further explore the physical conditions that can lead to thermal emission of the 2 cm and 1 cm lines, without detectable emission of a thermal line in the 6 cm transition, we modeled our multi-transition data using RADEX, which is a one dimensional non-LTE radiative transfer code developed by Van der Tak et al. (2007). We explored a range of densities between \( n_{\text{H}_2} = 10^3 \) to \( 10^6 \text{cm}^{-3} \) (with steps of 0.1 in \( \log_{10}(n(\text{H}_2)) \)), \( \text{H}_2\text{CO} \) column densities \( (N_{\text{H}_2\text{CO}}) \) between \( 10^{13} \) to \( 10^{15} \text{cm}^{-2} \) (with 10 steps per decade, and finer steps when converging to the final solution), kinetic temperatures between 10 to 500 K (in steps of 10 K), and assumed a simple characterization of the background radio continuum consisting of Cosmic Microwave Background and free-free emission from Luisi et al. (2016) with a turnover frequency near 8 GHz (e.g., Akabane et al. 1991). Refining the model would require mapping the molecular lines and the background radio continuum at the frequencies of interest to determine the appropriate beam-filling factors.

Figure 14 shows the results of the model for the three K-doublet
transitions included in this work as a function of molecular density at $T_K = 40$ K and $N_{\text{H}_2CO} = 1.5 \times 10^{14}$ cm$^{-2}$. We show with a solid line (red), dot-dashed line (green), and dotted line (blue) the predicted flux densities for the 1 cm, 2 cm, and 6 cm H$_2$CO lines, respectively. With parallel horizontal lines (same line style patterns and colours as above), we show the range of peak flux densities based on our observations. For the 2 cm and 1 cm H$_2$CO transitions, the range is given by the uncertainties listed in Tables 2 and 5. In the case of the 6 cm H$_2$CO line (Figure 1), the absorption must be caused by the extended molecular cloud also traced by 2 cm absorption (Figure 4), while the emission lines are caused by very compact masers, e.g., Hoffman et al. (2003). We inspected the 6 cm H$_2$CO line profile, and concluded that a line asymmetry due to the material traced by 2 cm and 1 cm H$_2$CO emission is undetectable at a level of ±60 mJy, which is the range shown with horizontal dotted lines (blue) in Figure 14. We find that a gas density of $\sim 10^{5.7}$ cm$^{-3}$ (vertical dashed line in Figure 14) is consistent with our detection of 2 cm and 1 cm H$_2$CO emission and non-detection of 6 cm thermal emission. This density is similar to the density obtained from the 1 cm and 48 GHz H$_2$CO lines ($n_{\text{H}_2} = 10^{5.78}$ cm$^{-3}$) by McCauley et al. (2011). We note that McCauley et al. (2011) assumed a source size of $16''$, while our cross scan shows that the region traced by 2 cm H$_2$CO emission is significantly more extended (Section 4.2).

The ortho-H$_2$CO column density of our model ($1.5 \times 10^{14}$ cm$^{-2}$) is similar to the value reported by McCauley et al. (2011) ($N_{\text{H}_2CO}/\Delta v = 10^{13.79}$ cm$^{-2}$(km s$^{-1}$)$^{-1}$, see their Table 4), although the temperature in our model is lower than what they assumed (40 K vs 220 K). We find this temperature difference reasonable because the 2 cm H$_2$CO emission likely traces a more extended region than that seen at the higher energy 48 GHz H$_2$CO

Figure 10. As in Figure 9 but for the emission line. Emission was detected in only the central 4 pointing positions in the East-West scan, and in 4 positions in the North-South scan (see also Figure 4).
transition.\textsuperscript{12} We note that Mitchell et al. (1990) reported evidence for a two-temperature environment in NGC 7538 IRS1 (25 K and 176 K components). McCauley et al. (2011) argued that the 1 cm H$_2$CO absorption detected in their spectrum (see also our absorption detection in Figure 1) and the 2 cm H$_2$CO absorption reported by Hoffman et al. (2003) originate from the low temperature component. Our analysis is consistent with detection of high-density and warm-temperature molecular material, i.e., the transition region between the cold extended component (traced by 6 cm and 2 cm H$_2$CO absorption) and the NGC 7538 IRS1 hot and dense core traced by higher excitation transitions.

Although we use a simple non-LTE model, we can reliably conclude that the 2 cm H$_2$CO line in NGC 7538 IRS1 traces quasithermal emission, not a variable maser. We note that more complex models can be proposed to explain the results reported in this article. For example, several 2 cm masers separated by a few arcseconds would look like an extended source in our GBT cross-scan. However,

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\textsuperscript{12} McCauley et al. (2011) caution that their assumed temperature may not be correct but that the density determination is not greatly affected by temperature.
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such masers would have to show simultaneous variability (to explain the non-detection by Hoffman et al. 2003), the masers would need to have a very similar LSR velocity (otherwise the emission line would be asymmetric or multi-peaked), and a similar maser distribution would be needed for the 1 cm transition (see Figure 1). Therefore, the simplest explanation is that 2 cm H$_2$CO traces extended, quasithermal emission that was resolved out by the VLA observations of Hoffman et al. (2003).

5 SUMMARY

We present observations conducted with the GBT of the 2 cm and 1 cm H$_2$CO lines toward NGC7538 IRS1, which complement previous observations by our group of the 6 cm line. The observations were designed to investigate the nature of the 2 cm H$_2$CO emission in the region, as its velocity corresponds to the velocity of 6 cm H$_2$CO masers and also the systemic velocity of the thermal molecular gas. An East-West/North-South cross scan of the region revealed that the 2 cm H$_2$CO emission is tracing an extended molecular core (~ 50$''$ in the East-West direction), which implies a low brightness temperature (~ 0.33 K). In addition, LTE and non-LTE analyses, including the 6 cm and 1 cm data, show that the 2 cm emission is not caused by a maser mechanism, but rather is a quasi-thermal line. Our analysis indicates that the 2 cm H$_2$CO emission originates from a dense (~ $10^3$ to $10^6$ cm$^{-3}$) and warm (~ 40 K) molecular core, which marks the transition between the lower temperature/density extended molecular cloud (traced by 6 cm H$_2$CO absorption) and the hot and dense core in NGC 7538 IRS1 (traced by higher excitation transitions). Although this intermediate-temperature and high-density region is expected as molecular clouds collapse to form hot molecular cores, 2 cm H$_2$CO emission (like the one detected in this work) is rare. It is likely that in other regions the 2 cm H$_2$CO emission is engulfed (spectrally blended) with 2 cm H$_2$CO absorption from the most extended and lower-density gas, preventing detection of the emission. Given that both components (absorption and emission) are extended, detection of 2 cm H$_2$CO emission is challenging with interferometers, and therefore, single-dish high-angular resolution mapping is required to investigate this high-density warm-temperature transition envelope. Our work further exemplifies the potential of low K-doublet H$_2$CO observations as density probes in high-mass star forming regions as highlighted in the literature (e.g., McCauley et al. 2011).

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Figure 14. Predicted flux density of 1 cm (red, solid line), 2 cm (green, dot-dashed line) and 6 cm (blue, dotted line) H$_2$CO lines in NGC 7538 IRS1 as a function of density computed with RADEX. Shaded colour regions within horizontal lines (same line style mentioned above) show the range of observed flux density values including uncertainties (see Figure 1 and discussion in Section 4.3). We found that a density above 10$^5$ cm$^{-3}$ (vertical dashed line) would result in flux density values for the three transitions that are consistent with our observations.
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DATA AVAILABILITY

The data underlying this article are available in the article and in its online Supporting Information.

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