MILLIMETER MULTIPLICITY IN DR21(OH): OUTFLOWS, MOLECULAR CORES, AND ENVELOPES

Luis A. Zapata1, Laurent Loinard1, Y.-N. Su2, Luis F. Rodríguez1,3, Karl M. Menten4, Nimesh Patel5, and R. Galván-Madrid1,2,5

1 Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia 58090, Mexico
2 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan
3 Astronomy Department, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia
4 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
5 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

ABSTRACT

We present sensitive high angular resolution (~1") millimeter continuum and line observations from the massive star-forming region DR21(OH) located in the Cygnus X molecular cloud. Within the well-known dusty MM1–2 molecular cores, we report the detection of a new cluster of about 10 compact continuum millimeter sources with masses between 5 and 24 $M_\odot$, and sizes of a few thousands of astronomical units. These objects are likely to be large dusty envelopes surrounding massive protostars, some of them most probably driving several of the outflows that emanate from this region. Additionally, we report the detection of strong millimeter emission of formaldehyde (H$_2$CO) and methanol (CH$_3$OH) near 218 GHz as well as compact emission from the typical outflow tracers carbon monoxide and silicon monoxide (CO and SiO) toward this massive star-forming region. The H$_2$CO and CH$_3$OH emission is luminous ($\sim 10^{-2} L_\odot$), well resolved, and found along the collimated methanol maser outflow first identified at centimeter wavelengths and in the sources SMA6 and SMA7. Our observations suggest that this maser outflow might be energized by a millimeter source called SMA4 located in the MM2 dusty core. The CO and SiO emission traces some other collimated outflows that emanate from MM1–2 cores, and are not related with the low-velocity maser outflow.

Key words: ISM: individual (DR21(OH), W75S) – stars: formation – techniques: imaging spectroscopy

Online-only material: color figures

1. INTRODUCTION

DR21(OH) (also known as W75S) is a well-known high-mass star-forming region due to its richness of centimeter and millimeter maser emission from numerous transitions, e.g., OH, H$_2$O, and CH$_3$OH (Araya et al. 2009; Fish et al. 2005, 2011; Kurtz et al. 2004; Kogan & Slys 1998; Mangum et al. 1992; Plambeck & Menten 1990). DR21(OH) is located at a distance of about 2–3 kpc (Odenwald & Schwartz 1993), and about 3' (assuming a distance of 2 kpc, this is equivalent to a physical projected size of around 2 pc) north of the famous H II region DR 21 in the Cygnus X molecular cloud. In this work, we assume a distance of 2 kpc to DR21(OH). However, the exact value of the distance is uncertain.

Its total luminosity is estimated to be about $5 \times 10^4 L_\odot$ (Harvey et al. 1977). The region contains two main dust condensations (MM1 and MM2) that are warm (~50 K and 30 K) and very massive (350 and 570 $M_\odot$, respectively; Mangum et al. 1991, 1992). DR21(OH) and its surroundings have been studied in numerous molecular transitions of NH$_3$, CS, $^{13}$CO, and C$^{18}$O (Padin et al. 1989; Mangum et al. 1991, 1992; Richardson et al. 1994; Lai et al. 2003).

Multiple molecular outflows have been reported to emanate from the MM1 and MM2 dusty condensations. A well-collimated east–west (E–W) bipolar flow driven from within the MM2 condensation has been reported and discussed by Plambeck & Menten (1990), Kogan & Slys (1998), and Kurtz et al. (2004). The LSR radial velocity of that flow is nearly ambient (10 to $-5$ km s$^{-1}$). The LSR radial velocity of DR21(OH) is about $-3.0$ km s$^{-1}$; this value was found by Araya et al. (2009) using the 44 GHz methanol maser line. The detailed distributions of 36 and 44 GHz methanol maser emission toward that flow have been established by Fish et al. (2011) and Araya et al. (2009), respectively. Additionally, Lai et al. (2003) reported high-velocity $^{12}$CO(2–1) outflows with $\nu \geq 25$ km s$^{-1}$ relative to the systemic velocity powered by MM1–2. A CO bipolar outflow expels material to the northwest (blueshifted) and southeast (redshifted) and originates from MM2. A second bipolar outflow emanates from MM1–2 with its blueshifted lobe toward the southwest while its redshifted one is to the northeast. Lai et al. (2003) also suggested the possibility of having a single E–W bipolar outflow with a cone-like morphology, with the CO lobes tracing the limb-brightened region of the outflow and emanating from MM1–2. Richardson et al. (1994) reported high-velocity wings in CS($J = 5–4$) toward DR 21(OH), extending over 80 km s$^{-1}$, probably produced by a young and compact outflow.

In this paper, we present high angular resolution (~1") or 2000 AU) millimeter and submillimeter continuum and line observations of the region DR21(OH) made with the Submillimeter Array (SMA). In Section 2, we discuss the observations undertaken in this study. In Section 3, we present and discuss the data, and in Section 4 we give the main conclusions of this study.

2. OBSERVATIONS

The millimeter ($\nu \simeq 217–230$ GHz or $\lambda \simeq 1.4–1.3$ mm) observations of DR21(OH) were obtained with the SMA on 2006 May 23 and 2007 August 26. The SMA at those epochs was
The phase reference center was \( \alpha \) baselines ranging in projected length from 18 to 162 \( \lambda \) in its extended configuration, which included 28 independent sources reported by Araya et al. (2009). The purple squares represent the positions of the 2.7 mm sources (with angular sizes of about 10\( \prime\prime \)) at 230 GHz has an FWHM diameter of about 50\( \lambda \). The half-power contours of the synthesized beams for the different wavelengths are shown in the bottom-left corner of the image. For the 1.4 mm observations the beam is 1.16 \( \times \) 0.96 with a P.A. = –82.67 and for the 7 mm observations is 1.88 \( \times \) 1.71 with a P.A. = –61:12. The green triangles mark the positions of the radio sources reported by Araya et al. (2009). The purple squares represent the positions of the 2.7 mm sources (with angular sizes of about 10\( \prime\prime \)) reported by Mangum et al. (1991).

(A color version of this figure is available in the online journal.)

Figure 1. SMA 1.4 mm continuum (color and white contour image) of the DR21(OH) region overlaid with the 7 mm continuum emission from Zapata et al. (2009; red contours). The color-scale bar on the right indicates the 1.4 mm continuum emission in mJy beam\(^{-1}\). The white contours are 2, 4, 6, 8, 10, 15, 20, 25, 30, 35, and 40 times 5 mJy beam\(^{-1}\), the rms noise of the 1.4 mm image. The red contours are –5, 5, 6, 7, 8, 9, and 10 times 0.9 mJy beam\(^{-1}\), the rms noise of the 7 mm image. The half-power contours of the synthesized beams for the different wavelengths are shown in the bottom-left corner of the image. For the 1.4 mm observations the beam is 1.16 \( \times \) 0.96 with a P.A. = –82.67 and for the 7 mm observations is 1.88 \( \times \) 1.71 with a P.A. = –61:12. The green triangles mark the positions of the radio sources reported by Araya et al. (2009). The purple squares represent the positions of the 2.7 mm sources (with angular sizes of about 10\( \prime\prime \)) reported by Mangum et al. (1991).

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in its extended configuration, which included 28 independent baselines ranging in projected length from 18 to 162 \( \lambda \). The phase reference center was \( \alpha \) (J2000.0) = 20\(^h\)39\(^m\)00\(^s\), \( \delta \) (J2000.0) = +42\(^\circ\)22\(^\prime\)48\(^\prime\prime\). The central frequency of the lower sideband (LSB) was 217.1049 GHz, while the upper sideband (USB) central frequency was 227.1049 GHz for the night in 2006 May. The frequency was centered for the night in 2007 August about 3 hr. Further technical descriptions of the SMA and its calibration schemes can be found in Ho et al. (2004).

The data were calibrated using the IDL superset MIR, originally developed for the Owens Valley Radio Observatory (Scovalle et al. 1993) and adapted for the SMA. The calibrated data were imaged and analyzed in the standard manner using the MIRIAD and AIPS packages.

To obtain the continuum map, we only use the data from the night in 2006 May for which the phase stability was slightly better. The resulting image rms noise of line and continuum images were around 20 mJy beam\(^{-1}\) for each velocity channel and 5 mJy beam\(^{-1}\) for a 2 GHz total bandwidth, respectively, at an angular resolution of 1.16 \( \times \) 0.96 with a P.A. = –82.67. The resulting continuum map was self-calibrated in phase. We use the LSB of the 2006 run to reconstruct the line-free continuum image since the USB is more affected by line emission from different molecular species.

3. RESULTS AND DISCUSSION

3.1. Continuum Emission

In Figure 1, we show a color and contour map of the 1.4 mm continuum emission detected by the SMA and the Very Large Array toward DR21(OH). We resolved the strong 2.7 mm sources MM1 and MM2 reported by Mangum et al. (1991, 1992) into a cluster of nine compact sources. Here, the term “compact sources” is with respect to the size of the extended sources reported by Mangum et al. (1991, 1992). Five of these sources are associated with MM1 (SMA5–9) and four with MM2 (SMA1–4). We give their positions and total flux densities

\(^{7}\) The MIR-IDL cookbook by C. Qi can be found at http://cfa-www.harvard.edu/~cqi/mircook.html
Table 1
Parameters of the 1.4 mm Continuum Sources in DR21(OH)

| Source | Positiona | Flux Density (mJy) | Deconvolved Angular Sizeb | Mass (M⊙) |
|--------|------------|-------------------|--------------------------|-----------|
| SMA 1  | 00:400 46.60 | 122 ± 24 | 3′.6 ± 0′.3 × 1′.3 ± 0′.2; +1° ± 10′ | 8 |
| SMA 2  | 00:406 46.78 | 185 ± 20 | 2′.1 ± 0′.2 × 1′.5 ± 0′.2; +137° ± 32′ | 12 |
| SMA 3  | 00:453 44.86 | 80 ± 9 | ≤ 2′0 | 6 |
| SMA 4  | 00:598 44.94 | 49 ± 9 | ≤ 2′0 | 5 |
| SMA 5  | 01:010 48.72 | 44 ± 8 | 4′.5 ± 0′.2 × 1′.4 ± 0′.2; +104° ± 2′ | 5 |
| SMA 6  | 01:002 48.93 | 346 ± 12 | 1′.90 ± 0′.09 × 1′.00 ± 0′.09; +77° ± 3′ | 23 |
| SMA 7  | 01:079 49.06 | 357 ± 13 | 1′.8 ± 0′.1 × 1′.1 ± 0′.1; +88° ± 4′ | 24 |
| SMA 8  | 01:192 51.26 | 201 ± 13 | 1′.9 ± 0′.1 × 0′.8 ± 0′.1; +30° ± 5′ | 14 |
| SMA 9  | 01:251 51.43 | 217 ± 14 | 1′.9 ± 0′.1 × 1′.1 ± 0′.1; +72° ± 7′ | 14 |

Notes.

a Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds.
b Major axis × minor axis; position angle of major axis. The values were obtained using the task JMFTT of AIPS.

in Table 1. Additionally, in Figure 1, we have overlaid a 7 mm contour continuum map obtained from Zapata et al. (2009) and the positions of the centimeter compact sources reported by Araya et al. (2009). The 7 mm continuum emission peaks at the position of the centimeter sources (NW+SE+R2+R3+R4) reported by Araya et al. (2009) and is not coincident with any SMA 1.4 mm continuum sources. Only SMA6 has a clear counterpart at centimeter wavelengths (MM1-NW and MM1-SE). The 1.4 mm sources are well resolved at these wavelengths and show sizes of a few thousands of astronomical units at an assumed distance of 2 kpc.

Assuming a very steep spectral index of α = 3.5 (S ∝ να) for all the millimeter sources, which is consistent with optically thin dust emission from dusty envelopes or disks, we can estimate the masses of the 1.4 mm sources. These steep spectral indices have been observed in many star-forming regions and are associated with very young stellar objects (see, for example, Hunter et al. 2006; Rodriguez et al. 2007; Galván-Madrid et al. 2010).

Following Beckwith et al. (1990), we adopt a value for the dust mass opacity of κv = 10 (ν/1000 GHz)6 cm2 g−1, where ν is the frequency and here β = α − 2 = 1.5. Thus, at this wavelength, we obtain κ1.4mm = 0.01 cm2 g−1. Assuming optically thin, isothermal dust emission and a gas-to-dust ratio of 100, the total mass of the 1.4 mm sources is given by

$$\frac{M_{\text{gas}}}{M_{\odot}} = 1.6 \times 10^{-6} \left(\frac{S_T}{Jy}\right) \left(\frac{T}{K}\right)^{-1} \left(\frac{D}{\text{pc}}\right)^2 \left(\frac{\nu}{1000 \text{ GHz}}\right)^{-(2+\beta)},$$

where $S_T$ is the flux density, $T$ is the dust temperature, and $D$ is the distance to the source. Assuming a temperature of $T = 20$ K for all the millimeter sources, we derive masses on the range of 5–24 solar masses for the sources (see Table 1). The gas-to-dust ratio of 100 might not be the most adequate to use for protostellar sources since dust settling to the midplane of the disk and erosion of the circumstellar envelope by photodissociation may decrease the gas-to-dust ratio (Throop & Bally 2005). The sources SMA6 and SMA7 seem to show hot core activity and their temperatures could be higher, so the estimation of the mass for these sources might be overestimated. For the rest of the sources a temperature of 20 K seems adequate because they do not show hot core activity.

Since SMA6 is associated with free–free emission (Araya et al. 2009), the emission at 1.4 mm may be contaminated with this type of emission. However, this contamination seems to be almost negligible at these wavelengths due to the relatively flat spectral index ($\alpha = 0.6$) obtained at centimeter wavelengths for this source (Araya et al. 2009).

The values of the masses obtained here (Table 1) have uncertainties of at least two or larger due to the error in the determination of the distance to DR21(OH), the estimation of temperatures of the millimeter sources, and the error in the dust mass opacity coefficient at this wavelength.

Similar dust mass values have been recently found for the gas structures associated with the massive protostars in the young clusters W33A and NGC6334N(I) (Galván-Madrid et al. 2010; Hunter et al. 2006).

3.2. Millimeter Line Emission

Five strong spectral lines were detected in the LSB (2006 May) and in the USB (2007 August) of the observations, corresponding to the H2CO[3(0,3)−2(0,2)], H2CO[3(2,2)−2(1,1)], CH3OH[4(2,2)−3(1,2)−E], SiO(5–4), and 12CO(2–1) transitions (see Table 2).

3.2.1. H2CO and CH3OH

Figure 2 shows maps of the H2CO[3(0,3)−2(0,2)], H2CO[3(2,2)−2(1,1)], and CH3OH[4(2,2)−3(1,2)−E] integrated intensity (moment 0) and intensity-weighted velocity (moment 1), overlaid with the 1.4 mm continuum emission obtained in our SMA observations. These maps reveal strong line millimeter molecular emission arising from the E–W outflow and from the two compact continuum sources SMA6 and SMA7, first reported here (see Section 3.2). The three lines show comparable integrated flux densities. The radial velocities covered by the outflow are from −8 to 5 km s−1, whereas those corresponding to the molecular core sources range from −11 to 11 km s−1.

The emission appears to be concentrated in compact bow-shock structures within the outflow where the line profiles are narrow (a few km s−1) and intense (∼3–5 Jy). Overall, the methanol and formaldehyde millimeter emission reported here follow a morphology very similar to that seen in the 44 GHz methanol maser line (Araya et al. 2009). This combination of properties suggests that the formaldehyde and methanol spectral lines reported here might correspond to maser transitions. However, the low brightness temperatures of all lines ($T_B \sim 280, 200, 70$ K for the CH3OH, H2CO[3(2,2)−2(1,1)], and
H$_2$CO[$3(0,3)$–$2(0,2)$], respectively, and assuming the emission extends over all the beam) suggest thermal emission. These low brightness temperatures, however, are also seen in most of the 44 GHz methanol masers at centimeter wavelengths (Araya et al. 2009). One possibility is that the millimeter line spots detected here are probably much more compact and not resolved with our present angular resolution ($\sim 1''$) resulting thus in true maser emission. More observations are needed to confirm if these millimeter lines are masing. The flux of all three lines integrated over the entire outflow is 80 to 150 Jy km s$^{-1}$, corresponding to isotropic luminosities of about $10^{23}$ L$_{\odot}$. This is comparable to the luminosity of other typical maser lines in star-forming regions (Zapata et al. 2009).

This molecular emission, with low radial velocities that suggest motion near the plane of the sky, are reminiscent of some water masers tracing outflows that are known to be found within a few degrees from the plane of the sky (Claussen et al. 1998; Desmurs et al. 2009). At the center of symmetry of the outflow lies a continuum source (labeled SMA4 on Figure 2, middle panel). The source likely traces the envelope of a high- or intermediate-mass young star (Table 1) and is part of the larger dusty core MM2. The “blue” infrared source proposed by Araya et al. (2009) as a possible candidate for the exciting source of the E–W flow is a bit offset (2'') from SMA4 and the center of symmetry of the outflow. The symmetry center of the outflow is approximately where the systemic clouds velocity resides, that is, in the middle of the outflow. The blueshifted velocities are found toward the east with the redshifted velocities toward the west. Clearly, more observations will be required to discriminate firmly the true powering source of the outflow, and to examine the relation between SMA4 and the blue infrared source identified by Araya et al. (2009).

In contrast to the narrow spectra found within the outflow, the methanol and formaldehyde line profiles associated with the sources SMA6 and SMA7 are broad ($\sim 15$ km s$^{-1}$) and with the morphology being much more compact. This emission may trace hot molecular core emission associated with these dusty objects. However, a more complete molecular line analysis is required to firmly confirm this hypothesis. Furthermore, both lines (CH$_3$OH and H$_2$CO) show a clear E–W velocity gradient of a few kilometers per second within the molecular core, probably suggesting that SMA6 and SMA7 are at slightly different systemic velocities or maybe that emission is tracing a molecular compact outflow.

3.2.2. $^{12}$CO and SiO

Together with the H$_2$CO and CH$_3$OH observations, we obtained observations of the classical outflow tracers $^{12}$CO(2–1) and SiO(5–4) to study in depth the methanol maser outflow; however, such emission was not detected at all toward the methanol outflow. We instead found some other compact high-/low-velocity outflows within the region emanating from MM1 or MM2 (see Figure 3). Some of these outflows were already reported with lower angular resolution ($\sim 4''$) by Lai et al. (2003) in $^{12}$CO(2–1).

The observations of $^{12}$CO(2–1) revealed two collimated outflows emanating from MM2, a high-velocity bipolar outflow with its redshifted side (30 to 15 km s$^{-1}$) in the east and with its blueshifted side (−65 to −15 km s$^{-1}$) toward the west, and a second monopolar outflow with its blueshifted emission (−40 to −15 km s$^{-1}$) toward the southwest. None of these outflows is associated with the low-velocity (−10 to 7 km s$^{-1}$) E–W methanol maser bipolar outflow. This might be explained as a result of removing the $^{12}$CO emission from velocities close to ambient in order to make the map presented in Figure 3; however, as we will see below, even SiO, an outflow tracer that is supposedly weak at ambient velocities, is not present at the position of the maser outflow. Furthermore, one would think that the E–W carbon monoxide outflow could be the counterpart of E–W maser methanol outflow; however, the blueshifted and redshifted sides of both outflows are found in contrary positions, see Figures 2 and 3.

There is one more very compact north–south $^{12}$CO(2–1) outflow emanating from the MM1 core with its redshifted side to the north, powered maybe by SMA6 or SMA7. Its blueshifted side is not detected. Our $^{12}$CO(2–1) map does not favor the idea of having a single bipolar E–W outflow with a cone-like morphology, with the CO lobes tracing the limb-brightened region of the outflow as suggested by Lai et al. (2003). Our results instead confirm the presence of multiple compact outflows with different orientations emanating within the MM1–2 cores.

The SiO(5–4), on the other hand, shows a more clumpy structure over the whole region. The radial velocities displayed by this molecule are very similar to those of the methanol maser bipolar outflow (−10 to 7 km s$^{-1}$); however the SiO emission is not arising from this outflow (see Figure 3). There is instead faint blueshifted emission clearly associated with the east–west and southeast–northwest $^{12}$CO(2–1) outflows. Toward the MM1 core, the SiO traces some different compact outflows than the north–south outflow revealed by the $^{12}$CO(2–1) emission. However, their orientations are not clear from the present observations. Some of these molecular outflows could be powered by the thermal jets (MM1-NW and MM1-SE) reported toward this position by Araya et al. (2009).

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**Table 2**

Observational and Physical Parameters of the Millimeter Lines

| Lines | Rest Frequency* (GHz) | $E_{J,\text{lower}}$ (K) | Range of Velocities (km s$^{-1}$) | Line Width* (km s$^{-1}$) | LSR Velocity* (km s$^{-1}$) | Intensity Peak (mJy beam$^{-1}$) |
|-------|----------------------|--------------------------|----------------------------------|--------------------------|--------------------------|-------------------------------|
| H$_2$CO[$3(0,3)$–$2(0,2)$] | 218.22219 | 10.4 | $-10$, +10 | 14 | $-3$ | 80 |
| H$_2$CO[$3(2,2)$–$2(2,1)$] | 218.47563 | 57.6 | $-10$, +11 | 13 | $-3$ | 60 |
| CH$_3$OH[$4(2,2)$–$3(1,2)$–E] | 218.44005 | 35.0 | $-11$, +10 | 13 | $-3$ | 78 |
| SiO(5–4) | 217.10490 | 20.8 | $-11$, +7 | 10 | $-3$ | 26 |
| $^{12}$CO ($J = 2–1$) | 230.53801 | 05.3 | $-40$, +30 | 40 | $-5$ | 170 |

Notes.

* The rest frequencies were obtained from the JPL Molecule Catalog: http://spec.jpl.nasa.gov/ftp/pub/catalog/catform.html

* The line width and LSR velocity were obtained by fitting a Gaussian profile to the spectra.

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Figure 2. Integrated intensity of the weighted velocity color maps of the CH$_3$OH $4(2,2)-3(1,2)$ (upper panel), H$_2$CO $3(0,3)-2(0,2)$ (middle panel), and H$_2$CO $3(2,2)-2(2,1)$ (lower panel) emission from the DR21(OH) region overlaid in contours with the SMA 1.4 mm continuum emission (black thick line) and the integrated intensity emission of the specific molecule (gray thin line) in every panel. The black contours are from 30% to 94% with steps of 8% of the peak of the line emission; the peak 1.4 mm emission is 150 mJy beam$^{-1}$. The gray contours are from 5% to 85% with steps of 10% of the peak of the line emission. The color-scale bars on the right indicate the LSR velocities in km s$^{-1}$. The three spectra shown on top of the panels were obtained from different positions across the outflow and the molecular cores as indicated. The colors of the spectra indicate the transition (green = CH$_3$OH $4(2,2)-3(1,2)-$E], pink = H$_2$CO $3(0,3)-2(0,2)$], and blue = H$_2$CO $3(2,2)-2(2,1)$]. The synthesized beam of the CH$_3$OH image is shown in the bottom left corner of the image. The pink dashed arcs in the top panel indicate the same "arc" morphology found in the outflow in the methanol masers at centimeter wavelengths (Araya et al. 2009). (A color version of this figure is available in the online journal.)
4. SUMMARY

We have reported the detection of a new cluster of about 10 compact millimeter sources with masses in a range of $4-25 M_\odot$ at the center of DR21(OH). These sources are likely to be large dusty envelopes surrounding high- or intermediate-mass protostars, and some of them most probably drive multiple outflows that emanate from this region.

We also reported for the first time the detection of strong millimeter emission of formaldehyde (H$_2$CO) as well as methanol (CH$_3$OH) at around 218 GHz toward DR21(OH). The line emission is detected within the E–W flow driven by DR21(OH) and the sources SMA6 and SMA7, and is well coincident with methanol centimeter (36 and 44 GHz) maser emission previously reported.

The SiO and $^{12}$CO emission revealed a group of compact outflows emerging from the cluster of young stars present in DR21(OH). We find neither $^{12}$CO high-velocity emission nor low-velocity SiO emission coincident with the methanol maser outflow.

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REFERENCES

Araya, E. D., Kurtz, S., Hofner, P., & Linz, H. 2009, ApJ, 698, 1321
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Guesten, R. 1990, AJ, 99, 924
Claussen, M. J., Marvel, K. B., Wootten, A., & Wilking, B. A. 1998, ApJ, 507, L79
Desmurs, J.-F., Codella, C., Santiago-García, J., Tafalla, M., & Bachiller, R. 2009, A&A, 498, 753
Fish, V. L., Muehlbrad, T. C., Pratap, P., et al. 2011, ApJ, 729, 14
Fish, V. L., Reid, M. J., Argon, A. L., & Zheng, X.-W. 2005, ApJS, 160, 220
Galván-Madrid, R., Zhang, Q., Keto, E., et al. 2010, ApJ, 725, 17
Ho, P. T. P., Moran, J. M., & Lo, K. Y. 2004, ApJ, 616, L1
Hunter, T. R., Brogan, C. L., Megeath, S. T., et al. 2006, ApJ, 649, 888
Kogan, L., & Slysh, V. 1998, ApJ, 497, 800

(A color version of this figure is available in the online journal.)
Kurtz, S., Hofner, P., & Álvarez, C. V. 2004, ApJS, 155, 149
Lai, S.-P., Girart, J. M., & Crutcher, R. M. 2003, ApJ, 598, 392
Mangum, J. G., Wootten, A., & Mundy, L. G. 1991, ApJ, 378, 576
Mangum, J. G., Wootten, A., & Mundy, L. G. 1992, ApJ, 388, 467
Odenwald, S. F., & Schwartz, P. R. 1993, ApJ, 405, 706
Padin, S., Sargent, A. I., Mundy, L. G., et al. 1989, ApJ, 337, L45
Plambeck, R. L., & Menten, K. M. 1990, ApJ, 364, 555

Richardson, K. J., Sandell, G., Cunningham, C. T., & Davies, S. R. 1994, A&A, 286, 555
Rodríguez, L. F., Zapata, L. A., & Ho, P. T. P. 2007, ApJ, 654, L143
Scoville, N. Z., Carlstrom, J. E., Chandler, C. J., et al. 1993, PASP, 105, 1482
Throop, H. B., & Bally, J. 2005, ApJ, 623, L149
Zapata, L. A., Menten, K., Reid, M., & Beuther, H. 2009, ApJ, 691, 332