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Radio Continuum and Methanol Observations of DR21(OH)

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ABSTRACT

We report high sensitivity sub-arcsecond angular resolution observations of the massive star forming region DR21(OH) at 3.6, 1.3, and 0.7 cm obtained with the Very Large Array. In addition, we conducted observations of CH₃OH 44 GHz masers. We detected more than 30 new maser components in the DR21(OH) region. Most of the masers appear to trace a sequence of bow-shocks in a bipolar outflow. The cm continuum observations reveal a cluster of radio sources; the strongest emission is found toward the molecular core MM1. The radio sources in MM1 are located about 5'' north of the symmetry center of the CH₃OH outflow, and therefore, they are unlikely to be associated with the outflow. Instead, the driving source of the outflow is likely located in the MM2 core. Although based on circumstantial evidence, the radio continuum from MM1 appears to trace free-free emission from shock-ionized gas in a jet. The orientation of the putative jet in MM1 is approximately parallel to the CH₃OH outflow and almost perpendicular

to the large scale molecular filament that connects DR21 and DR21(OH). This suggests that the (accretion) disks associated with the outflows/jets in the DR21 – DR21(OH) region have symmetry axes mostly perpendicular to the filament.

Subject headings: HII regions — ISM: molecules — masers — stars: formation — ISM: individual (DR21(OH))

1. Introduction

Located about $3'$ north of DR21, the DR21(OH) region, also known as W75S, is a site of dense molecular gas within the Cygnus-X complex. Both DR21 and DR21(OH) have been extensively studied in the infrared, sub-millimeter, and millimeter bands. Both are regions of massive star formation, but DR21 is in a more evolved state (as evident from the presence of ultracompact H II regions) while DR21(OH) is in an earlier phase, in which the massive (proto)stars have not yet substantially ionized the surrounding molecular gas.

The DR21(OH) region has four principal condensations, i.e., DR21(OH)-N, M, W, and S (Mangum et al. 1992). DR21(OH)-M contains two main clumps (MM1 and MM2) that are warm, 60 and 30 K, and massive, 350 and $570 M_{\odot}$, respectively (Mangum et al. 1992; see also Liechti & Walmsley 1997). The total mass and luminosity of the region are about $3 \times 10^4 M_{\odot}$ and $5 \times 10^4 L_{\odot}$ (Chandler et al. 1993a, 1993b). Star formation activity is indicated by the presence of millimeter continuum sources (e.g., Mangum et al. 1991; Chandler et al. 1993a), a high velocity molecular outflow detected in CS J=5–4 (Richardson et al. 1994) and various species of masers (e.g., Plambeck & Menten 1990; Kurtz et al. 2004; Fish et al. 2005). Particularly interesting is the outflow traced by CH₃OH 44 GHz masers: sub-arcsecond angular resolution observations by Kogan & Slysh (1998) show the presence of several CH₃OH 44 GHz masers grouped in a bipolar structure. The morphology of the blueshifted masers resembles a bow shock. Higher sensitivity CH₃OH 44 GHz observations by Kurtz et al. (2004) confirm the Kogan & Slysh (1998) results and reveal a possible second bow shock.

In summary, numerous observations of DR21(OH) clearly identify it as a very young massive star forming region, with multiple OB-star clusters forming. All of the clusters appear to be in a pre-ultracompact H II region stage. The unambiguous evidence of massive

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star formation and the relatively nearby distance (~ 2 kpc; Odenwald & Schwartz 1993) make DR21(OH) an ideal laboratory to study early stages of massive star formation.

Extensive work by several groups (e.g., see Eislöffel et al. 2000) has shown that star formation regions usually contain numerous weak centimeter continuum sources. These sources trace a variety of astrophysical phenomena, including thermal jets, stellar winds, and gyro-synchrotron emission from young stellar objects. The location and characterization of these weak radio sources has proved extremely valuable to our understanding of star formation phenomena (e.g., Zapata et al. 2004; Ignace & Churchwell 2004; Girart et al. 2002; Reipurth et al. 2002).

Despite a wealth of molecular line and millimeter continuum observations of DR21(OH), it has never been reliably imaged with high sensitivity and angular resolution in the centimeter continuum. Relatively low quality VLA² archive continuum observations were reported by Argon et al. (2000) and Fish et al. (2005), and the most sensitive cm continuum data available in the literature has 3σ sensitivities of $10 - 15$ mJy beam⁻¹ (Johnston et al. 1984; Mangum et al. 1992). In this work we present high angular resolution ($\theta_{syn} < 1''$) and high sensitivity ($rms < 1$ mJy) observations of the radio continuum at 3.6, 1.3, and 0.7 cm, as well as observations of the CH₃OH 44 GHz masers in DR21(OH).

2. Observations and Data Reduction

We used the VLA to conduct radio continuum observations of DR21(OH) at X (3.6 cm), K (1.3 cm) and Q (7 mm) bands. In addition, we report observations of CH₃OH 44 GHz masers. Details of the observations are summarized in Table 1³.

The 3.6 cm and 1.3 cm observations were conducted using the standard VLA continuum mode, i.e., 50 MHz bandwidth, 4IF mode. The quasar 3C48 was used as primary (flux) calibrator and J2007+404 was used as secondary (phase) calibrator. The calibration cycle of the 3.6 cm and 1.3 cm observations was $\sim 600/60$ and $220/40$ s (source/calibrator), respectively. All data reduction was done in AIPS following standard procedures.

The 7 mm continuum was observed simultaneously with the CH₃OH masers using two IF pairs. The goal of this setup was to cross-calibrate the radio continuum observations

²The Very Large Array (VLA) is operated by the National Radio Astronomy Observatory (NRAO), a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

³The observations reported in this paper are from the NRAO proposals AH745 and AK586.

using the CH₃OH masers to minimize phase decorrelation due to tropospheric variations. One pair of IFs was set to a narrow bandwidth of 3.125 MHz (63 channels, 48.83 kHz) to observe the CH₃OH $\nu_0 = 44.06943$ GHz ($7_0 - 6_1, A^+$) line; the second pair of IFs was used with a bandwidth of 25.0 MHz to observe the radio continuum (excluding the maser lines). The narrow band IF was centered on $V_{LSR} = 0.0$ km s⁻¹. The CH₃OH spectra were Hanning smoothed to a final channel width of 97.6 kHz (0.66 km s⁻¹). We observed 3C286 as primary (flux) calibrator and 1229+020 as bandpass calibration; in addition, J2007+404 was observed approximately every hour to correct for phase offsets between the CH₃OH and continuum passbands. Assuming the position reported in Kurtz et al. (2004) for the brightest CH₃OH maser in the region, we self-calibrated the peak maser channel and transferred the calibration table to all CH₃OH channels, as well as to the broadband (25 MHz) continuum IFs. All calibration and imaging was done using the NRAO package AIPS.

3. Results & Discussion

We detected radio continuum emission in all three bands (3.6 cm, 1.3 cm, and 7 mm) as well as CH₃OH 44 GHz masers. Figure 1 shows the radio continuum contour maps; Table 2 lists the parameters of the final continuum images and in Table 3 we report the observed properties of all radio continuum sources. Figure 2 shows the combined CH₃OH spectrum (measured from a 35" × 11" box centered between the MM1 continuum sources and 3.6 cm source R1), and Figure 3 shows the integrated intensity (zero velocity moment) image of the CH₃OH emission. In Figure 4 we show the velocity field (first velocity moment) of the CH₃OH maser arcs seen in Figure 3. To facilitate comparison between the figures, we also show in Figure 4 the 3.6 cm radio continuum emission (contours; see Figure 1). CH₃OH line parameters are listed in Table 4.

3.1. CH₃OH 44 GHz Masers: Outflow in DR21(OH)

The CH₃OH masers were observed in this work with a two-fold goal: to cross-calibrate the 7 mm radio continuum and to observe the masers with higher angular resolution ($\theta_{syn} \sim 0.6''$ versus $1.7''$) and sensitivity (rms ~ 5 mJy beam⁻¹ versus 50 mJy beam⁻¹) than the observations reported by Kurtz et al. (2004). Our observations however, have poorer spectral resolution than those of Kurtz et al. (2004), i.e., 0.7 versus 0.17 km s⁻¹. Given the difference in spectral and angular resolution, as well as flux density calibration uncertainties (see Kurtz et al. 2004), we consider that our data are not suitable for a variability study of the masers by comparing these data sets.

Figure 3 shows the integrated intensity distribution of CH₃OH masers in DR21(OH). We detected more than 30 new maser spots. Figure 4 shows the velocity distribution. As noted by Kurtz et al. (2004) and Kogan & Slysh (1998), the CH₃OH 44 GHz masers trace a bipolar structure, with blueshifted masers located predominately in the eastern lobe, and red shifted masers located in the western lobe. As proposed by Kurtz et al. (2004, see also Plambeck & Menten 1990 for the case of 95 GHz CH₃OH masers), this organized maser distribution (in space and velocity) is likely tracing an outflow in DR21(OH). Given the mass and temperature of the MM2 core (Mangum et al. 1991), the presence of an east-west molecular outflow (e.g., Lai et al. 2003; Chandler et al. 1993b) and the widespread association of CH₃OH Class I masers with young massive stars (e.g., Ellingsen 2006; Pratap et al. 2008), the driving source is likely a young massive stellar object somewhere in MM2, located toward the center of the bipolar maser distribution.

The distribution of masers within each lobe is quite intriguing. Kogan & Slysh (1998) found that the CH₃OH 44 GHz masers in the blueshifted group are distributed along an arc, suggestive of a bow-shock origin. The higher sensitivity observations of Kurtz et al. (2004) confirm the morphology in the blue lobe and show the presence of a possible second arc. Our still higher sensitivity observations enable a more detailed characterization of the CH₃OH maser distribution in DR21(OH).

Our data confirm the two-arc maser distribution of the eastern (blue) lobe and reveal that the masers in the *western* lobe are also grouped in two arc-like structures. As explicitly suggested by thin lines in Figure 4, the CH₃OH masers appear to trace two nested bow-shocks in the outflow. This distribution is remarkably similar to the jet bow-shock outflow model shown by Arce et al. (2007). The occurrence of sequential bow-shocks (outflow events) is also reminiscent of the morphology of the outflow in DR21 (Smith et al. 2006). Clearly, the sky distribution of the CH₃OH masers traces a 2D projection of a 3D structure; the masers might originate in a cut through parabolic-like outflow lobes where the velocity coherence and beaming are favorable for maser amplification toward our line of sight.⁴

Given the symmetric bow-shock morphology and the low velocity gradient between the red and blueshifted maser groups ($< 10 \text{ km s}^{-1}$, Figure 4), it appears that the outflow is almost in the plane of the sky. Assuming that the CH₃OH masers are tracing two individual (nested) outflow events, and assuming, for simplicity, a constant expansion velocity of 100 km s^{-1} for each lobe (e.g., as observed in H₂O masers in IRAS 20126+4104, Moscadelli et al. 2005), then the dynamical ages are $\sim 900 \text{ yr}$ and $\sim 1500 \text{ yr}$ for the inner and outer shocks, respectively (a distance of 2 kpc was assumed), i.e., the lower limit of the outflow age is

⁴We thank P. T. P. Ho for stressing this point.

~ 1500 yr. Thus, the outflow could be quite young — younger than the ‘pulsed’ outflow in Cep-A (e.g., Bally 2008). However, we note that high angular resolution (VLBI) proper motion studies are required to determine the velocity of the CH₃OH masers in the region. In particular, CH₃OH molecules may not survive in high velocity J-shock environments (e.g., Garay et al. 2002). Alternatively, the CH₃OH masers may be tracing a slower shock traveling along the high speed flow and/or the working surface between two shocks.⁵

A complication to the single-outflow interpretation of the CH₃OH masers in DR21(OH) is the misalignment between the arcs, particularly with respect to the eastern arc (Figure 4; i.e., a change in position angle of $\sim 15^\circ$ east of north). Such a change in position angle could result from jet precession combined with inhomogeneities in the molecular gas that is interacting with the flow, similar to the large scale outflow in G192.16–3.82 (Devine et al. 1999). Nevertheless, despite the misalignment, the outflow seems to be quite collimated, with an apparently constant opening cross-section at scales greater than 10^4 AU (~ 0.05 pc) from the symmetry center.

3.2. Radio Continuum: A Cluster of Radio Sources

In order to investigate the driving source of the CH₃OH maser outflow in DR21(OH), we conducted sub-arcsecond radio continuum observations at 3.6 cm, 1.3 cm, and 7 mm (Figure 1). We detected eight radio continuum sources (see Table 3). In Figure 4 we show the CH₃OH velocity field superimposed on the 3.6 cm continuum map. One of the 3.6 cm continuum sources (R1) is located close to the projected center of the CH₃OH maser outflow; it may mark the position of the massive (proto)star that drives the outflow.

Alternatively, DR21(OH)-R1 could mark the position of a young low-mass star. The radio emission could be gyro-synchrotron radiation from an active magnetosphere, just as the low mass companion of θ^1 Ori A (Felli et al. 1993) or the variable radio source in IRAS 20126+4104 (Hofner et al. 2007). This hypothesis is supported by the detection of other weak radio sources (R5, R6 and possibly R2; Figure 1), that together with R1 may represent the high end of the (radio) luminosity function of a cluster of low mass objects forming among the young massive stars.

In Table 5 we list the spectral index between 3.6 and 1.3 cm of all sources detected at both wavelengths. The spectral indexes of R1, R2, R5, and R6 (a different interpretation of the radio emission from R3 and R4 is given below) are between -0.6 and 0.4 , which

⁵We acknowledge E. Churchwell and J. Cantó for pointing out these possibilities.

is similar to the range of spectral index variability of the low mass star in θ^1 Ori A (Felli et al. 1993). Further observations of the weak population of radio sources in DR21(OH) are necessary to assess whether the radio emission is variable as expected from the gyro-synchrotron hypothesis, and with this, to study how low-mass pre-main-sequence stars (class I/II) and very young class 0 high-mass objects can coexist considering their clearly different evolutionary timescales.

In contrast to the radio emission from R1, R5, and R6 (and possibly R2), the radio sources MM1-NW, MM1-SE, R3 and R4 appear to be related to the massive young stellar object in MM1. We propose that these radio sources are tracing shock-ionized gas in the jet from a young massive star. We prefer this interpretation because:

1. MM1-NW, SE, R3 and R4 are collinear (southeast-northwest orientation), which suggests a common driving source.
2. In principle the similar flux densities of MM1-NW and SE could be explained by radio emission from two hypercompact H II regions that are in a very similar evolutionary state. However, the morphology of the two radio sources is also similar; after deconvolution, both sources appear to be elongated at approximately the same position angle ($\sim 40^\circ$; see Table 3). This position angle is almost perpendicular to the MM1-NW to R4 orientation (i.e., orthogonal to the putative jet; see Figure 1), and may arise from a bow shock aligned with the MM1-NW to R4 axis. The elongation would result from our edge-on view of the shocks, corresponding to the broad tail of a relatively large-opening-angle bow shock, emitting free-free radiation. Given the symmetry, we consider it more likely that MM1-NW and SE are manifestations of a single radio jet.
3. The spectral indexes between X and K bands are very similar for MM1-NW and SE ($\alpha \sim 0.8$); in addition, the spectral index of R4 is also similar to those of MM1-NW and SE within the errors (Table 5). A spectral index of ~ 0.8 is consistent with thermal emission from finite stratified density gas being ionized by UV photons from the cooling region of a shock (e.g., Ghavamian & Hartigan 1998).

The weak radio emission supports the interpretation that the most massive stellar object in MM1 is a high mass protostellar object (HMPO; e.g., Beuther et al. 2007).

In Figure 1 we show the location of 6.7 GHz CH_3OH masers (Harvey-Smith et al. 2008) and H_2O masers (Palmer & Goss, *in prep.*). The H_2O masers are distributed throughout the region, and thus are unlikely to be driven by a single young stellar object. Two of the weak radio sources (R1 and R6) may be associated with H_2O masers, and another H_2O maser is found almost at the center of MM1-NW/SE. The detection of a H_2O maser at the center of the double radio source is reminiscent of IRAS 20126+4104 (Hofner et al. 2007; Moscadelli

et al. 2005) where a clump of H₂O masers is also located toward the center of a double radio source. The radio continuum emission associated with the H₂O masers in IRAS 20126+4104 is likely due to shock-ionized gas in the jet from a young massive star (see also §3.5).

3.3. The Nature of the 7 mm Emission

As evident from Figure 1, the 7 mm source has the elongation expected from superposition of emission from MM1-NW, SE, R2, R3, and R4 when observed with lower angular resolution. The southeast – northwest elongation is also consistent with the 2 cm continuum map shown by Fish et al. (2005). To further investigate the nature of the 7 mm source we convolved the 3.6 and 1.3 cm observations to the synthesized beam of the 7 mm map. In Figure 5 we show the (radio) flux density distribution of MM1 after convolution, i.e., MM1-NW + SE + R2 + R3 + R4. The 7 mm flux density point lies slightly above the power law fit. This indicates that at 7mm the flux is dominated by free-free emission with a small (~ 1.4 mJy or 10% of the total flux density) excess, most likely due to thermal dust emission.

3.4. Infrared Counterparts

The DR21/W75 region (including DR21(OH)) has been extensively studied in the infrared (e.g., Davis et al. 2007; Kumar et al. 2007; Smith et al. 2006; Marston et al. 2004). In Figure 6 we show the *Spitzer* IRAC image of the region (3.6 μ m blue; 4.5 μ m green; 8.0 μ m red)⁶. These IRAC observations have been discussed in a number of papers (e.g., Kumar et al. 2007) and are presented here to facilitate comparison between the CH₃OH, radio continuum and infrared data.

Figure 6 shows a number of sources with 4.5 μ m excess particularly along the large scale north-south (dark) filament (see Kumar et al. [2007] for a larger scale view of the region). Excess in the 4.5 μ m band is a known tracer of shocks (e.g., Smith et al. 2006; Cyganowski et al. 2008), thus, Figure 6 exemplifies that star formation in DR21(OH) is not limited to the mm cores but is found throughout the region. The eastern CH₃OH arcs may be associated with 4.5 μ m excess emission, however there is no clear evidence for 4.5 μ m excess toward the western arcs.

⁶Data were retrieved from the *Spitzer* archive (<http://irsa.ipac.caltech.edu/applications/Spitzer/Spitzer/>), project PID-1021, “DR21 and its Molecular Outflow”, Marston et al. (2004).

Shocked gas in the region has also been studied by Davis et al. (2007) based on H_2 $2.12\ \mu\text{m}$ observations. These authors did not find H_2 emission corresponding to the CH_3OH masers. This might be due to the high optical depth at $2.12\ \mu\text{m}$ for these deeply embedded regions in the vicinity of MM1 and MM2. However, slightly outside the area shown in Figure 4, Davis et al. (2007) found two H_2 regions that are somewhat aligned with the maser outflow (B7-1 and B5-1; see Table 3 and Fig. A.2 of Davis et al. [2007]).

The MM1 radio continuum sources are almost coincident with the peak of an extended “red” object (see Figure 6); the infrared counterpart of MM1 was also detected at $24\ \mu\text{m}$ (saturated) and $70\ \mu\text{m}$ with MIPS. Figure 6 also shows a “blue” star located very close to the symmetry center of the CH_3OH outflow. The star is clearly detected at 3.6 and $4.5\ \mu\text{m}$ (brighter at $3.6\ \mu\text{m}$) and tentatively detected at $5.8\ \mu\text{m}$ blended with the MM1 emission. The star is also detected in J, H, and K bands (2MASS), and in optical DSS images.

The near-infrared (NIR) colors of the “blue” object are intriguing. The 2MASS colors are $J - H = 0.32$ and $H - K_s = 0.11$, which, if placed into a NIR color-color diagram (e.g., Hillenbrand et al. 1998, Meyer et al. 1997, Marston et al. 2004, Apai et al. 2005), are consistent with an early F-type main sequence star with ~ 1 mag of optical extinction⁷. If it is a F0 star, then to attain $V = 13$ mag (as roughly observed), such a star would be at a distance of ~ 700 pc, and hence would not be associated with the DR21 region. However, the *Spitzer* colors are inconsistent with this interpretation. If the optical extinction were 1 mag, a *Spitzer* IRAC color of $[3.6]-[4.5] = 0.53$ could not be caused by extinction, because this color indicates much higher extinction values ($A_V > 10$ mag). Hence, the blue object could still be associated with the DR21 region, and other circumstances (unresolved multiplicity, existence of a transitional circumstellar disk, etc.) might govern the infrared colors. Based on the current data, it is hard to decide whether the blue object is the driving source for the CH_3OH outflow. An in-depth investigation of the nature of this near-IR source is beyond the scope of this work, and should be the topic of a future study.

3.5. A New Observational Phase during the Formation of Massive Stars

It is interesting to compare the characteristics of the radio emission in DR21(OH) with that of other young massive stellar objects, in particular G31.41+0.31 and IRAS 20126+4104 (Araya et al. 2003, 2008; Hofner et al. 2007). In all three cases, there are multiple radio

⁷More specifically, one magnitude of optical extinction corresponds to extinctions of 0.28 mag in J band, 0.18 mag in H band, and 0.11 mag in K band (Mathis 1990). Correcting the 2MASS colors for these extinction values and based on Ducati et al (2001), the colors are consistent with those of an F0 - F2 star.

continuum sources toward the center of molecular cores. Some of the continuum sources are consistent with radio emission from shock-ionized gas and not due to direct photo-ionization from an embedded massive star (see for example figure 1 of Hofner et al. 2007). The intermediate mass object GGD27 (HH80/81) is a clear example of ionized knots moving along a collimated jet as shown by proper motion studies (Martí et al. 1995, 1998).

We propose that there is a period during the formation of massive stars when (possibly recurrent) jet events interact with the molecular core and ionize the medium via shocks. Such a process could produce the double radio sources we have detected in the core of several young massive star forming regions. The ionization process would eventually become dominated by the development of hypercompact and then ultracompact H II regions.

3.6. Further Implications

The data reported in this paper show regularities in the orientation of outflows among themselves and also with respect to the large scale distribution of dust and gas in the region. The angular distance between the MM1 radio emission and the geometrical center of the CH₃OH outflow (see Figure 4) is too large to assume that the driving source of the outflow is located in MM1. Thus, our data indicate the presence of two distinct young massive stellar objects (or systems) with nearly parallel outflows/jets; i.e., both the putative MM1-NW to R4 jet and the CH₃OH outflow have similar position angles ($\sim 130^\circ$). This suggests that the orientation of jets/outflows is, to first order, determined by the large scale properties of the parent cloud. This conclusion is further supported by the powerful outflow from DR21 which also has a dominant east-west orientation (e.g., Marston et al. 2004). The statistically significant orientation of the outflows in an east-west direction was also discussed by Davis et al. (2007). Other examples of quasi-parallel outflow from different young massive stellar objects within the same star forming region include Cep-A and IRAS 05358+3543 (Beuther et al. 2002; Bally 2008).

The complete DR21 to DR21(OH) region is part of a long molecular cloud filament (or sheet seen edge-on) oriented north-south (e.g., Marston et al. 2004; Motte et al. 2005, 2007). The outflows are mostly perpendicular to the large scale north-south filament, and approximately aligned with the large scale direction of the magnetic field through the filament, which, as discussed by Vallée & Fiege (2006), shows a predominant east-west orientation (see also Lai et al. 2003). If the outflows arise from (proto)stars with accretion disks, then the disks would tend to be oriented edge-on along the filament, with disk symmetry axes

oriented east-west.⁸

4. Summary

We report sub-arcsecond observations of the radio continuum at 3.6, 1.3, and 0.7 cm, and also of the CH₃OH 44 GHz masers in the DR21(OH) region. We detected a cluster of radio sources; the two brightest sources are located toward the molecular core MM1 and appear to trace radio emission from shock-ionized gas.

We detected more than 30 new CH₃OH 44 GHz maser spots in DR21(OH). Our observations confirm and delineate a bow-shock distribution of the masers. The masers show a well-separated (in space and velocity) bipolar outflow almost symmetrically located with respect to the MM2 core, which is likely to harbor the driving source of the flow. The CH₃OH masers appear to trace two different outburst events. The sequential bow-shock morphology observed in DR21(OH) is reminiscent of that of the DR21 outflow (Smith et al. 2006).

The driving source of the CH₃OH outflow in DR21(OH) is unlikely to be the one responsible for the radio emission in MM1. More likely, two different young massive stellar objects are driving outflows/jets at very similar position angles. At even greater scales, the prominent outflow from DR21 also has an \sim east-west orientation. As also noted by Davis et al. (2007), throughout the large scale filament in the DR21-DR21(OH) region we find that the outflows/jets are quite parallel in a \sim east-west direction, which is perpendicular to the (north-south) filament. This suggests that the accretion disks form mostly edge-on along the large scale filament, i.e., disk symmetry axis orthogonal to the filament elongation.

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⁸A potential counterexample is ERO3 in the DR21(OH)N region, where Harvey-Smith et al. (2008) and Harvey-Smith & Soria-Ruiz (2008) report a possible Keplerian disk traced by CH₃OH masers and oriented east-west. However, we consider that future studies may be needed to confirm their result.

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Table 1. VLA Observations

Parameter	X-Band (3.6 cm)	K-Band (1.3 cm)	Q-Band (7 mm) ^a	CH ₃ OH 44 GHz ^a
Date	Nov 16, 2004	May 05, 2005	Sep 07, 2001	Sep 07, 2001
VLA Configuration	VLA-A	VLA-B	VLA-C	VLA-C
RA ^b	20 39 01.000	20 39 01.000	20 39 00.900	20 39 00.900
Dec ^b	42 22 40.00	42 22 40.00	42 22 47.00	42 22 47.00
ν_o (GHz)	8.46	22.4	44.1	44.06943
Correlator Mode	4IF Cont.	4IF Cont.	4IF Line	4IF Line
Bandwidth per IF (MHz)	50 MHz	50 MHz	25.0 (2 Pol)	3.125 (2 Pol)
Flux Density Calib.	3C48	3C48	3C286	3C286
Assumed S_ν (Jy)	3.15	1.12	1.43	1.43
Phase Calib.	J2007+404	J2007+404	J2007+404 ^c	J2007+404 ^c
Measured S_ν (Jy)	2.54±0.01	1.78±0.02	1.34±0.04	1.35±0.04

^aThe Q-Band (7 cm) and CH₃OH 44 GHz observations were conducted simultaneously using a 4IF mode. Self-calibration solutions from the CH₃OH maser observations were used to calibrate the Q-Band continuum.

^bPhase tracking center (J2000).

^cUsed to correct phase offsets between the wideband and CH₃OH spectral line band.

Table 2. Parameters of the Radio Continuum Images

Parameter	X-Band (3.6 cm)	K-Band (1.3 cm)	Q-Band (7 mm)
Syn. Beam	$0''.20 \times 0''.19$	$0''.25 \times 0''.25$	$0''.92 \times 0''.74$
Syn. Beam P.A.	-18.2°	62.1°	-74.9°
rms ($\mu\text{Jy b}^{-1}$)	19	36	400

Table 3. Radio Continuum Sources^a

Source	Band	RA(J2000) 20 ^h 39 ^m	Dec(J2000) 42°22′	Size ^b , P.A. (AU, °)	I _ν (mJy beam ⁻¹)	S _ν (mJy)
DR21(OH)-R1	3.6 cm	00 ^s 612(1)	43′44(1)	440 × 100, 86°	0.17(2)	0.26(4)
	1.3 cm	00 ^s 606(4)	43′45(3)	670 × <160, 59°	0.14(4)	0.20(8)
MM1-NW	3.6 cm	00 ^s 9763(1)	48′980(2)	290 × <50, 34°	1.14(2)	1.40(4)
	1.3 cm	00 ^s 9765(1)	48′981(1)	200 × 80, 37°	2.70(4)	2.95(7)
MM1-SE	3.6 cm	01 ^s 0079(1)	48′707(2)	280 × 155, 46°	1.18(2)	1.55(4)
	1.3 cm	01 ^s 0079(1)	48′695(1)	235 × 225, 51°	2.83(4)	3.43(7)
MM1 ^c	7 mm	01 ^s 02 ^d	48′8 ^d	1830 × <460, 123°	9.4(4)	13.4(8)
DR21(OH)-R2	3.6 cm	01 ^s 042(1)	48′93(1)	330 × <100, 65°	0.16(2)	0.18(4)
	1.3 cm	01 ^s 045(3)	48′91(2)	440 × <300, 70°	0.16(4)	0.20(7)
DR21(OH)-R3	1.3 cm	01 ^s 054(2)	48′43(2)	690 × <300, 111°	0.19(3)	0.32(9)
DR21(OH)-R4	3.6 cm	01 ^s 083(2)	48′35(2)	465 × 420, 94°	0.14(2)	0.31(6)
	1.3 cm	01 ^s 077(3)	48′32(2)	745 × 315, 97°	0.21(3)	0.45(10)
DR21(OH)-R5	3.6 cm	01 ^s 303(1)	49′019(8)	285 × <135, 77°	0.18(2)	0.21(4)
	1.3 cm	01 ^s 308(2)	49′05(2)	< 230 × < 90, 144°	0.16(4)	0.12(5)
DR21(OH)-R6	3.6 cm	01 ^s 337(1)	52′00(2)	190 × <310, 60°	0.11(2)	0.12(4)
	1.3 cm	01 ^s 343(2)	51′98(2)	180 × < 100, 125°	0.20(4)	0.18(6)

^aParameters obtained from a 2D Gaussian fit of the brightness distribution using the task JMFIT in AIPS. The format of the error notation is, e.g., xx.xxx(y) = xx.xxx ± 0.00y.

^bNominal deconvolved size (major and minor axes, and position angle). A distance of 2 kpc was assumed (Odenwald & Schwartz 1993). We list a quarter of the synthesized beam (0′′05 ≈ 100 AU at X-Band) as upper limit of the size in the case of unresolved sources for which JMFIT does not report a limit.

^cThe sources MM1-NW, MM1-SE, DR21(OH)-R2, R3, and R4 are blended at 7 mm.

^dFor the self-calibration, we assumed the position of the brightest CH₃OH maser as given by Kurtz et al. (2004). Thus, the position error of our Q-band observations is dominated by the Kurtz et al. (2004) astrometric accuracy of ∼0′′6.

Table 4. CH₃OH Line Parameters

Maser ID	RA (J2000)	Dec (J2000)	I_{ν}^a (Jy b ⁻¹)	V_{LSR} (km s ⁻¹)	$\Delta V_{3\sigma}^a$ (km s ⁻¹)	$\int I_{\nu} dv$ (Jy b ⁻¹ km s ⁻¹)	Notes ^b
CH ₃ OH-1	20 38 58.68	42 22 22.1	0.40	-1.7	2.0	0.41	N
CH ₃ OH-2	20 38 58.92	42 22 27.2	0.39	-6.3	3.3	0.92	N
CH ₃ OH-3	20 38 59.29	42 22 48.8	76.8	0.3	3.3	79.3	Y-1
CH ₃ OH-4	20 38 59.32	42 22 49.6	2.95	1.0	2.0	3.28	N
CH ₃ OH-5	20 38 59.35	42 22 47.4	2.05	-1.7	2.6	2.68	Y-2
CH ₃ OH-6	20 38 59.56	42 23 05.3	0.49	-1.0	2.0	0.57	Y-3
CH ₃ OH-7	20 38 59.64	42 22 47.2	0.092	-0.3	2.6	0.16	N
CH ₃ OH-8	20 38 59.72	42 22 49.6	0.27	-0.3	2.6	0.29	N
CH ₃ OH-9	20 38 59.73	42 23 16.2	0.27	-0.3	2.6	0.49	N
CH ₃ OH-10	20 38 59.73	42 22 47.6	0.12	-0.3	1.3	0.12	N
CH ₃ OH-11	20 38 59.76	42 22 45.5	0.23	-0.3	2.6	0.37	N
CH ₃ OH-12	20 38 59.83	42 22 50.1	0.14	-1.7	3.3	0.23	N, O
CH ₃ OH-13	20 38 59.89	42 22 46.0	3.01	-0.3	3.3	3.93	Y-4, O
CH ₃ OH-14	20 38 59.92	42 22 47.9	0.12	-0.3	3.3	0.18	N
CH ₃ OH-15	20 38 59.92	42 22 50.3	0.21	-1.0	3.3	0.28	N, O
CH ₃ OH-16	20 38 59.93	42 22 45.0	5.27	0.3	2.6	6.07	Y-6
CH ₃ OH-17	20 38 59.99	42 22 35.2	0.16	-2.3	1.3	0.14	N
CH ₃ OH-18	20 39 00.08	42 22 47.1	0.26	-1.7	2.0	0.38	N
CH ₃ OH-19	20 39 00.09	42 22 44.7	0.14	-8.3	1.3	0.16	N
CH ₃ OH-20	20 39 00.12	42 22 43.7	0.38	-5.6	2.0	0.42	N
CH ₃ OH-21	20 39 00.13	42 22 47.1	0.43	-0.3	2.6	0.83	N
CH ₃ OH-22	20 39 00.14	42 22 48.8	0.081	-3.0	3.3	0.19	N
CH ₃ OH-23	20 39 00.19	42 22 47.7	3.26	-1.7	2.0	3.48	Y-7
CH ₃ OH-24	20 39 00.26	42 22 46.0	21.3	-0.3	3.3	25.7	Y-8
CH ₃ OH-25	20 39 00.29	42 22 47.4	5.74	-0.3	3.9	7.10	N
CH ₃ OH-26	20 39 00.33	42 22 48.5	0.15	-1.0	2.0	0.23	N, O
CH ₃ OH-27	20 39 00.49	42 22 46.3	0.097	-3.0	2.0	0.14	N
CH ₃ OH-28	20 39 00.55	42 22 47.7	1.08	1.7	2.6	1.47	Y-9
CH ₃ OH-29	20 39 00.60	42 22 45.0	0.12	-2.3	2.0	0.20	N
CH ₃ OH-30	20 39 01.05	42 22 41.6	0.29	-1.7	3.3	0.40	N
CH ₃ OH-31	20 39 01.05	42 22 17.6	0.34	-3.7	2.0	0.37	N
CH ₃ OH-32	20 39 01.09	42 22 01.0	2.21	-2.3	3.3	2.51	N
CH ₃ OH-33	20 39 01.17	42 22 06.8	0.59	-1.0	2.6	0.82	N
CH ₃ OH-34	20 39 01.18	42 22 06.8	0.88	-3.7	3.3	1.41	N
CH ₃ OH-35	20 39 01.22	42 22 41.2	0.58	-3.0	2.6	0.75	Y-10
CH ₃ OH-36	20 39 01.47	42 23 06.3	0.064	-2.3	1.3	0.073	N, O
CH ₃ OH-37	20 39 01.48	42 22 07.6	0.78	-4.3	2.0	0.96	N
CH ₃ OH-38	20 39 01.50	42 22 45.2	0.66	-3.0	2.0	0.85	Y-11
CH ₃ OH-39	20 39 01.51	42 22 40.8	4.68	-5.0	3.3	6.07	Y-12
CH ₃ OH-40	20 39 01.54	42 22 02.8	0.76	-3.7	2.0	1.00	N
CH ₃ OH-41	20 39 01.67	42 22 43.4	2.50	-6.3	2.6	3.05	Y-13
CH ₃ OH-42	20 39 01.70	42 22 45.2	0.30	-5.0	1.3	0.38	N
CH ₃ OH-43	20 39 01.76	42 22 45.3	0.21	-3.7	1.3	0.20	N, T
CH ₃ OH-44	20 39 02.02	42 22 41.2	2.23	-4.3	1.3	2.62	Y-14, O
CH ₃ OH-45	20 39 02.02	42 22 40.8	1.94	-5.6	1.3	1.82	N, O

Table 4—Continued

Maser ID	RA (J2000)	Dec (J2000)	I_{ν}^a (Jy b ⁻¹)	V_{LSR} (km s ⁻¹)	$\Delta V_{3\sigma}^a$ (km s ⁻¹)	$\int I_{\nu} dv$ (Jy b ⁻¹ km s ⁻¹)	Notes ^b
CH ₃ OH-46	20 39 02.08	42 22 45.2	6.29	−3.7	2.6	6.45	Y-15
CH ₃ OH-47	20 39 02.21	42 22 43.4	0.32	−4.3	2.0	0.30	N, O
CH ₃ OH-48	20 39 02.22	42 22 42.6	1.82	−3.7	2.0	1.80	N, O
CH ₃ OH-49	20 39 02.24	42 22 44.0	8.77	−5.0	2.6	12.5	Y-17, O

^aThe typical rms in one channel is 5 mJy beam⁻¹ for those channels with no strong (> 1 Jy) masers. The values reported in this table have been corrected for primary beam attenuation. $\Delta V_{3\sigma}$ is the full linewidth at 3σ level.

^bWe mark with ‘Y’ or ‘N’ whether the maser was previously reported by Kurtz et al. (2004). The number after ‘Y’ is the maser number as reported by Kurtz et al. (2004). We denote with ‘O’ maser features that are blended in frequency with other maser emission. Tentative detections are marked with ‘T’.

Table 5. Spectral Index between X and K Bands

Source	α
MM1-NW	0.8 ± 0.2
MM1-SE	0.8 ± 0.2
DR21(OH)-R1	-0.3 ± 0.2
DR21(OH)-R2	0.1 ± 0.2
DR21(OH)-R4	0.4 ± 0.3
DR21(OH)-R5	-0.6 ± 0.2
DR21(OH)-R6	0.4 ± 0.2

Notes: Spectral index ($S_\nu \propto \nu^\alpha$) between 3.6 and 1.3 cm using the values reported in Table 3.

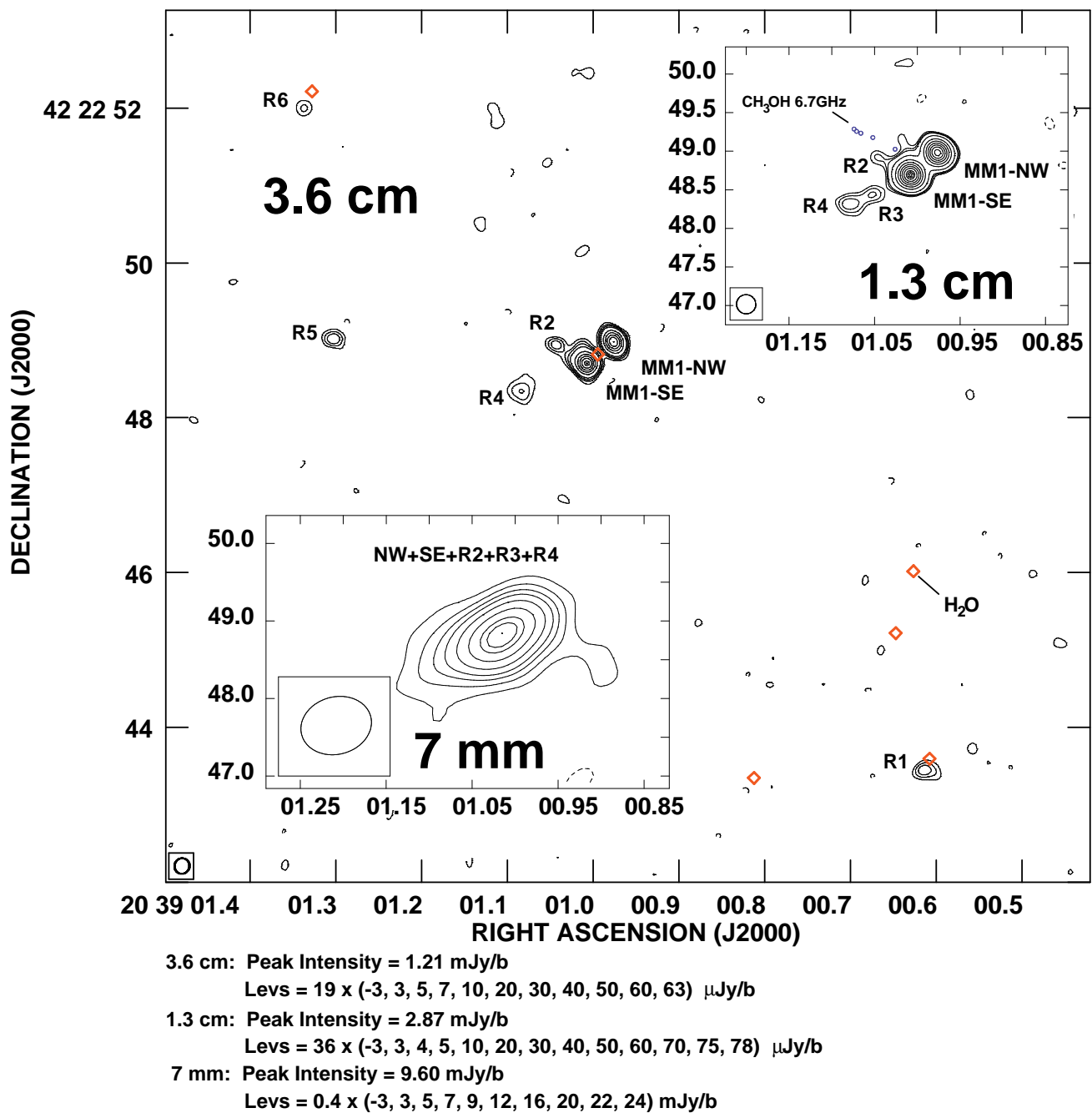


Fig. 1.— Radio continuum emission in DR21(OH) at 3.6 cm (X-band), 1.3 cm (K-band) and 7 mm (Q-band). The synthesized beams are shown in the lower left corner of the maps (see Table 2). The location of the 6.7 GHz CH_3OH masers from Harvey-Smith et al. (2008) are shown with circles in the 1.3 cm continuum map; H_2O masers are shown with diamonds in the 3.6 cm continuum map (Palmer & Goss, *in prep.*).

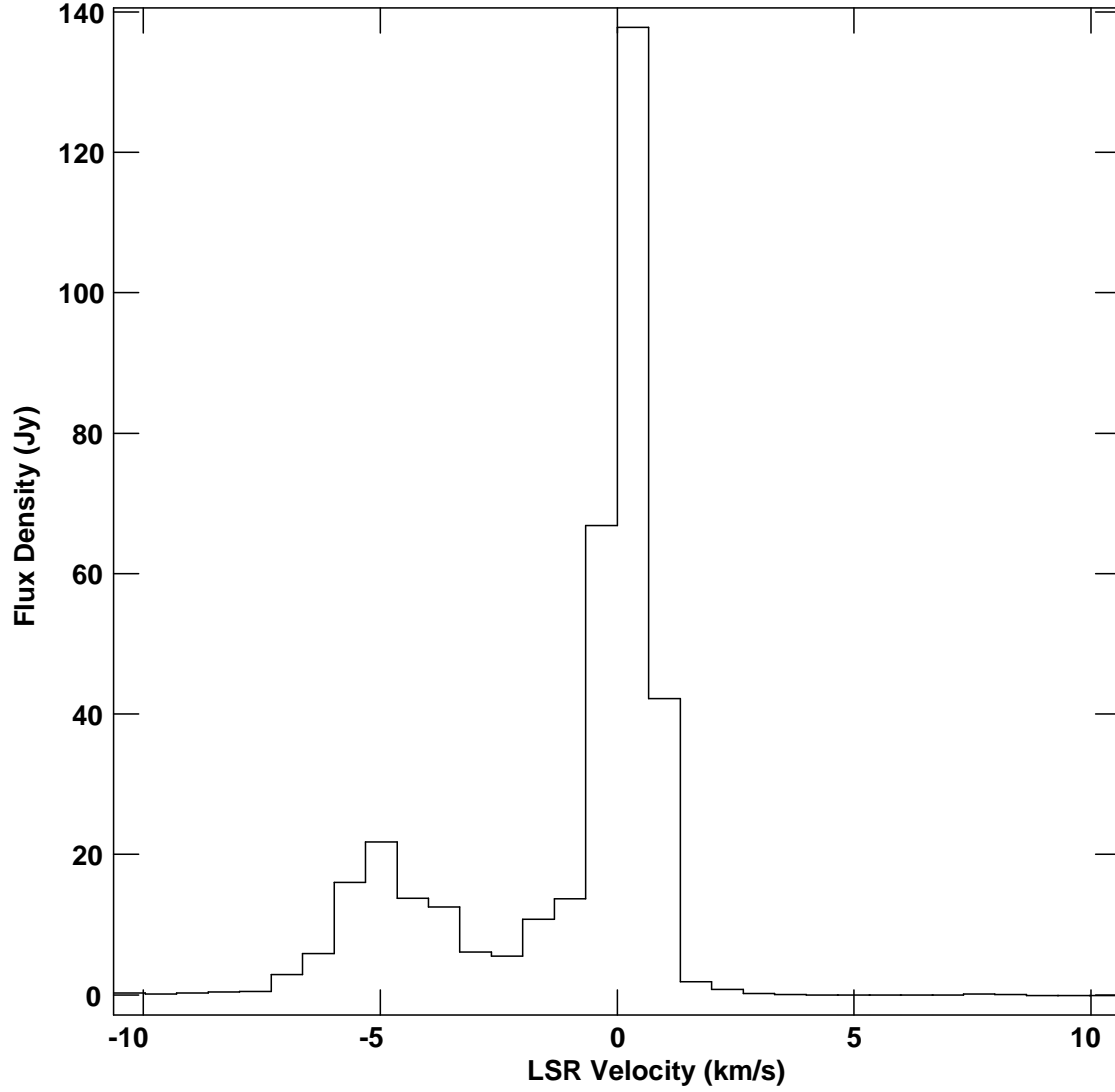


Fig. 2.— CH₃OH 44 GHz spectrum of the DR21(OH) region. The spectrum was obtained from a 35'' × 11'' area encompassing the CH₃OH maser arcs shown in Figure 4.

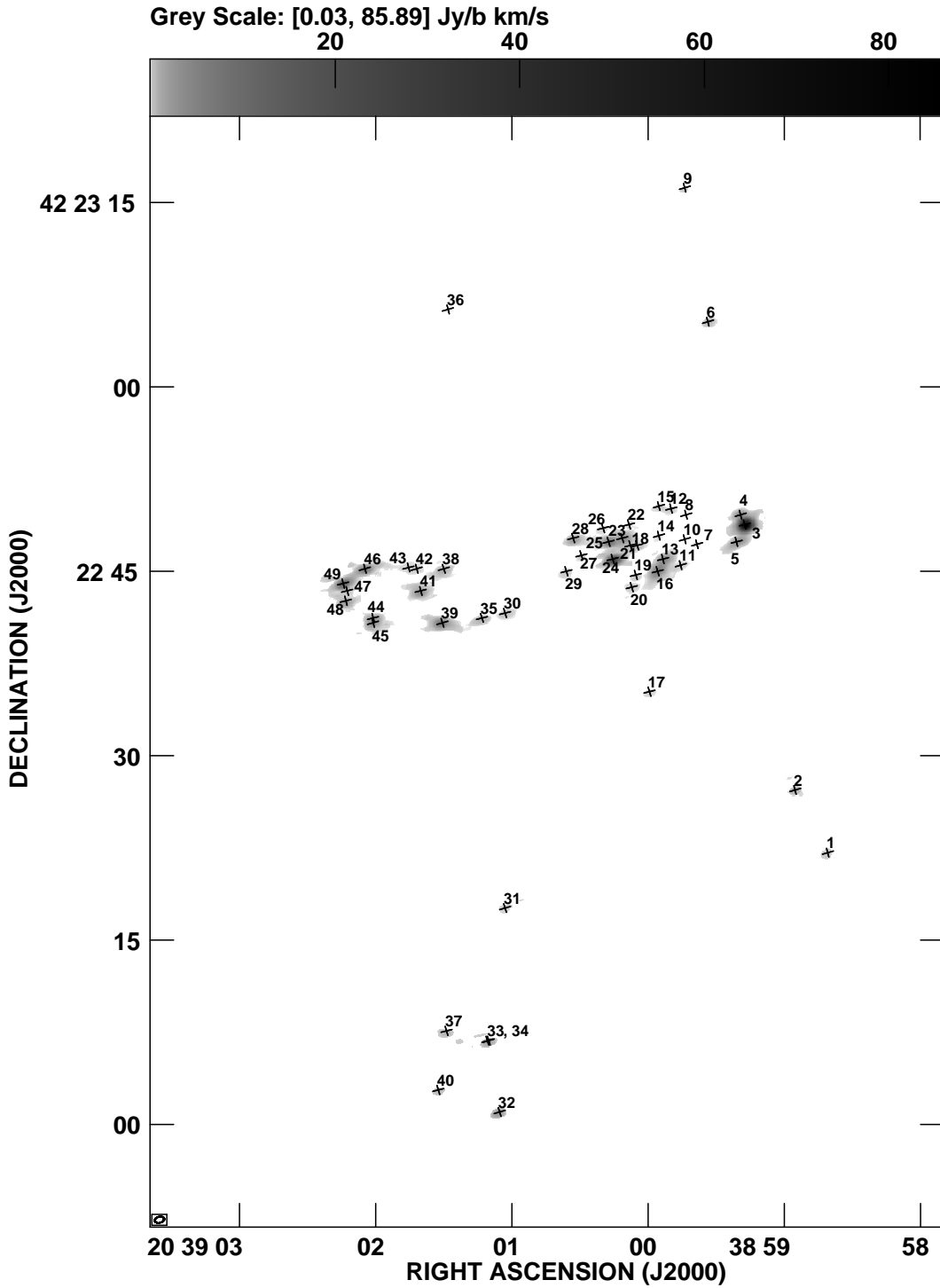


Fig. 3.— Integrated intensity (zero velocity moment) of the CH₃OH 44 GHz masers in the DR21(OH) region. The numbers mark the position of the masers as given in Table 4.

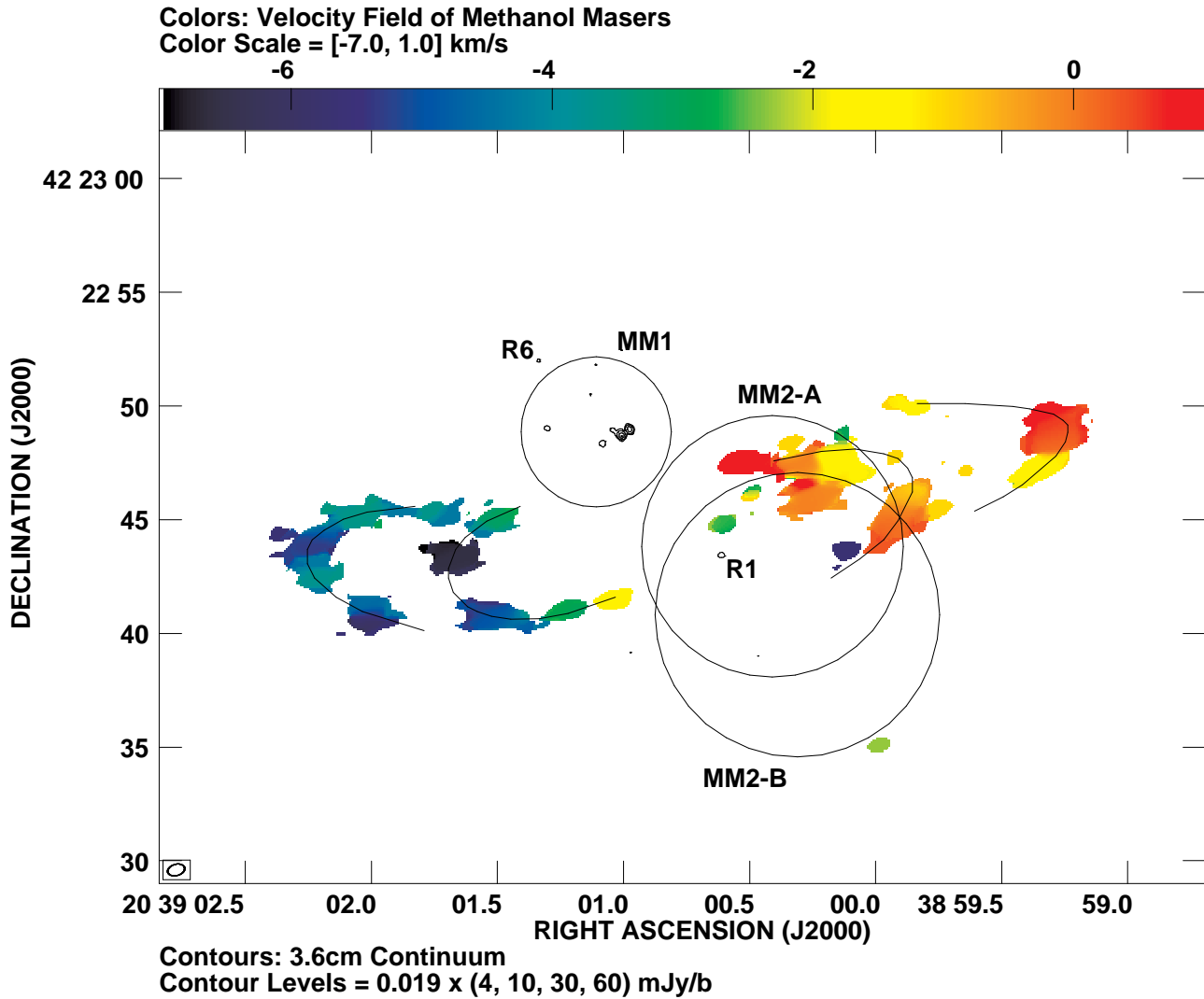


Fig. 4.— Velocity field (first velocity moment) of the CH_3OH 44 GHz masers in the DR21(OH) region. The 3.6 cm continuum from Figure 1 is shown in contours; sources R1 and R6 are explicitly marked to facilitate comparison with Figure 1. The location of the NH_3 molecular cores from Mangum et al. (1992) are shown with circles; the diameter of the circles equals the major axis of the cores as reported by Mangum et al. (1992).

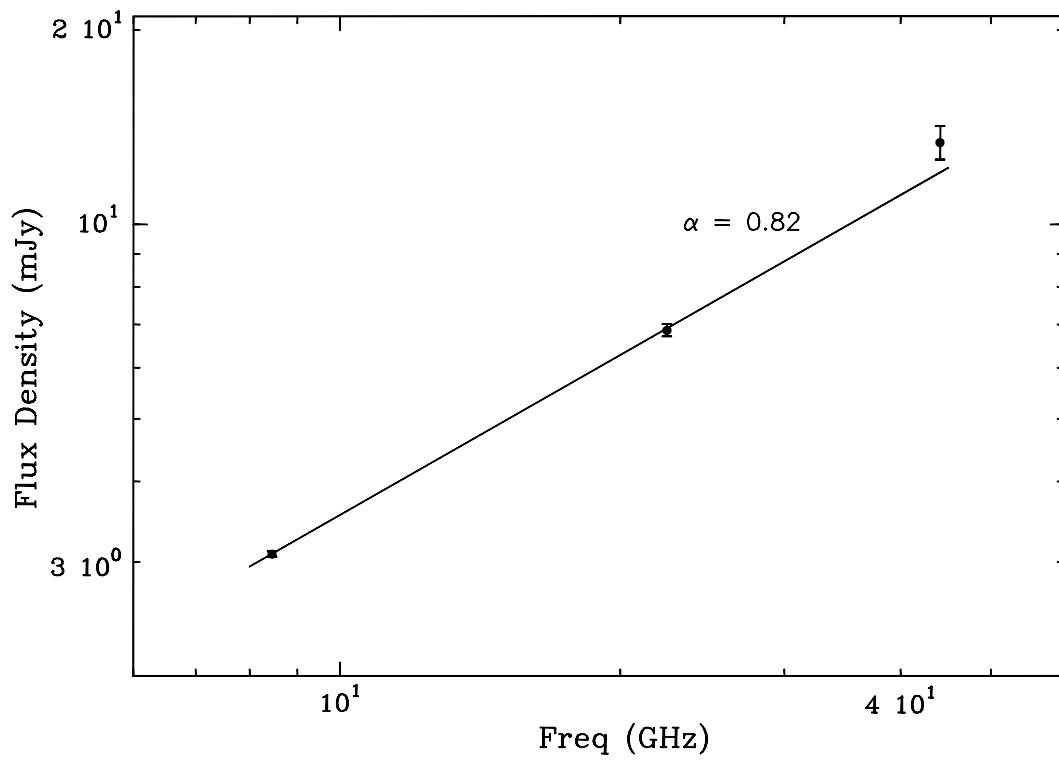


Fig. 5.— Radio spectral energy distribution of the MM1 continuum detected in this work. The flux densities at X and K bands were obtained after convolving the maps to the synthesized beam of the Q band observations. A weighted power law fit ($S_\nu \propto \nu^\alpha$) to the data is shown.

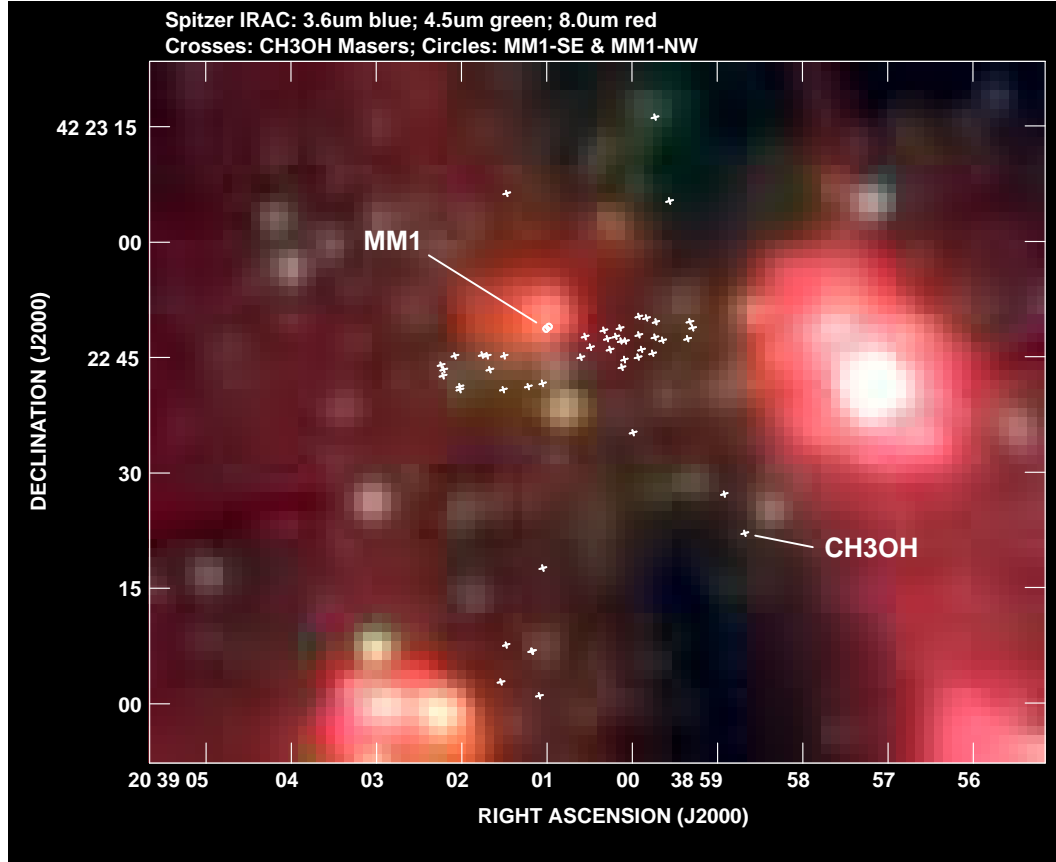


Fig. 6.— *Spitzer* IRAC image of the DR21(OH) region ($3.6\ \mu\text{m}$ blue; $4.5\ \mu\text{m}$ green; $8.0\ \mu\text{m}$ red). The images were retrieved from the *Spitzer* archive (<http://irsa.ipac.caltech.edu/applications/Spitzer/Spitzer/>). The crosses mark the positions of CH₃OH 44 GHz masers from this work (Figure 3) and the two circles show the positions of the radio sources MM1-NW and SE (Figure 1). Note the $8.0\ \mu\text{m}$ dark area oriented north-south that corresponds to the large scale molecular filament in the DR21 region (e.g., Kumar et al. 2007).