A CATALOG OF CH$_3$OH $7_0$–$6_1$A$^+$ MASER SOURCES
IN MASSIVE STAR-FORMING REGIONS. II. MASERS IN NGC 6334F, G8.67–0.36, AND M17

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ABSTRACT

We present Very Large Array (VLA) observations of the $7_0$–$6_1$A$^+$ methanol maser transition at 44 GHz toward NGC 6334F, G8.67–0.36, and M17. These arcsecond resolution observations complete a previous, larger VLA survey of this maser transition in high-mass, star-forming regions reported by Kurtz et al. We confirm the presence of 44 GHz methanol maser emission in all 3 sources, detecting 8 distinct maser components in NGC 6334F, 12 components in G8.67–0.36, and 1 in M17.

Key words: H II regions – ISM: individual objects (NGC 6334F, G8.67–0.36, M17) – masers – stars: formation for high-frequency, high-spatial-resolution radio observations. When sufficiently strong masers are present within the field of view, they permit self-calibration on very short timescales. This can substantially alleviate the problems caused by the dearth of high-frequency calibrators. Araya et al. (2009), for example, have used this technique with 44 GHz methanol masers to obtain high-resolution 7 mm continuum images of the DR21(OH) massive star formation region.

Kurtz et al. (2004, hereafter KHV04) presented an arcsecond resolution survey of 44 massive star formation regions in the 44 GHz class I CH$_3$OH maser line. At the time of their observations, less than half of the 27 Very Large Array (VLA) antennas were equipped with Q-band (40–50 GHz) receivers. The relatively poor uv coverage that resulted proved problematic for imaging the fields observed, and for three sources—NGC 6334F, G8.67–0.36, and M17—they were unable to uniquely determine the maser positions, although maser emission was clearly present. More recently, the Max-Planck-Institut für Radioastronomie equipped the remaining VLA antennas with Q-band receivers, thus mitigating the uv coverage problems that plagued the KHV04 survey.

The goal of the present project is to complete the KHV04 survey by providing accurate positions and line parameters for the 44 GHz masers in NGC 6334F, G8.67–0.36, and M17. In Section 2, we describe the observations and the data reduction procedures. In Section 3 we present our results, and in Section 4 we provide a more detailed discussion of each source. A brief summary is given in Section 5.

1. INTRODUCTION

Maser emission from various molecular species is a well-established signpost of massive star formation. Masers of the hydroxyl (OH), water ($^2$H$_2$O), and methanol (CH$_3$OH) molecules are particularly prevalent, and numerous studies of these masers in star formation regions exist in the literature; see Fish (2007) for a recent review.

Methanol masers have sometimes proven difficult to interpret, yet they have also been fruitful tracers of phenomena within star formation regions (Ellingsen 2005, 2006). They appear in two distinct classes (I and II) which differ in their pumping mechanisms (Cragg et al. 1992; Menten 1991a, 1991b) and, correspondingly, their locations within the star-forming regions. Collisionally pumped class I masers are thought to be tracers of shocked gas and hence frequently of molecular outflows (e.g., Araya et al. 2009, 2010; Voronkov et al. 2010; Plambeck & Menten 1990). Class II masers—found in closer proximity to young stellar objects (YSOs) and pumped by their mid-infrared emission—show a variety of structures, including linear (Minier et al. 2000) and ring-like (Bartkiewicz et al. 2009) that provide information on the gas dynamics very close to the YSO (Moscadelli et al. 2002).

Methanol masers also have significant potential as tracers of magnetic field morphology and strength via their linear polarization (Wiesemeyer et al. 2004) and via the Zeeman effect. Zeeman splitting has been reported for both class I masers (Sarma & Momjian 2009) and class II masers (Vlemmings 2008; Surcis et al. 2009). Owing to their locations within the star-forming regions, class I masers should be better tracers of the magnetic field within the molecular core or clump, while class II masers should be better tracers of the circum-protostellar magnetic field.

Quite apart from their intrinsic scientific interest, masers also serve a valuable practical role by permitting the use of a cross-calibration technique first described by Reid & Menten (1990); see also the Appendix of Reid & Menten (1997). The lack of nearby phase calibrators is a significant problem for high-frequency, high-spatial-resolution radio observations. When sufficiently strong masers are present within the field of view, they permit self-calibration on very short timescales. This can substantially alleviate the problems caused by the dearth of high-frequency calibrators. Araya et al. (2009), for example, have used this technique with 44 GHz methanol masers to obtain high-resolution 7 mm continuum images of the DR21(OH) massive star formation region.

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2. OBSERVATIONS AND DATA REDUCTION

2.1. Very Large Array

NGC 6334F, G8.67–0.36, and M17 were observed with the VLA of the NRAO$^8$ on 2005 November 5. We observed the methanol $7_0$–$6_1$A$^+$ maser transition with a rest frequency of 44069.43 MHz. The array was in the D configuration, which provides an angular resolution of about 2′′ at 44 GHz (7 mm).

$^8$ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
The actual resolution depends on $uv$ coverage, which varies from source to source; the precise resolution for each source is listed in Table 1. The absolute amplitude calibrator was J1331+305 (3C286) with an adopted flux density of 1.434 Jy at 44 069.43 MHz. The phase calibrators were J1700$-261$ and J1733$-130$ with bootstrapped flux densities of 0.71 ± 0.03 Jy and 2.47 ± 0.05 Jy, respectively.

We observed the right-hand circular polarization, using one intermediate frequency and a 3.125 MHz (21 km s$^{-1}$) bandwidth, providing 127 spectral line channels that were Hanning-smoothed online. The 24.4 kHz channel widths correspond to 0.17 km s$^{-1}$, providing 127 spectral line channels that were Hanning-smoothed online. (AIPS) of NRAO. After the initial external calibration, each source was imaged and inspected for maser emission. The brightest maser component was identified and the peak channel was self-calibrated, first in phase, and then a second iteration in phase and amplitude. These self-calibration solutions were applied to all channels, which were then imaged using weights intermediate between natural and uniform (with the ROBUST parameter set to 0) and CLEANed in an iterative fashion. For the initial iteration, clean boxes were assigned only to the strongest masers; for subsequent iterations additional clean boxes were added, as weaker masers became visible. A final image cube was made for each source, with clean boxes for all identified maser components, and CLEANed to a level of twice the theoretical rms.

The maser parameters (see Table 2) were extracted from the final image cubes using the AIPS tasks JMFIT, IMSTAT, and ISPEC. The absolute flux calibration uncertainty is $\sim 15\%$, and we estimate the absolute positional uncertainty to be 0$\prime$$\prime$2 for all the masers, although the uncertainty of the Gaussian fit of stronger masers is smaller (Reid et al. 1988).

### Table 1

| Source    | R.A. (J2000) | Decl. (J2000) | Central Velocity (km s$^{-1}$) | Synthesized Beam (Arcsec) | Channel Map rms (mJy beam$^{-1}$) |
|-----------|--------------|---------------|--------------------------------|---------------------------|----------------------------------|
| NGC 6334F | 17 20 54.00  | −35 47 00.0   | −10.4                          | 3$\prime$.83 x 1$.27; −2$^\circ$ | 45                               |
| G8.67$-0.36$ | 18 06 19.20  | −21 37 30.0   | +30.6                          | 2$\prime$.41 x 1$.31; −7$^\circ$ | 40                               |
| M17       | 18 20 24.40  | −16 11 32.0   | +14.0                          | 2$\prime$.07 x 1$.36; −10$^\circ$ | 47                               |

**Notes.**

a Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

b Major axis $\times$ minor axis; position angle of major axis.

### Table 2

| Source    | Maser Peak Position | $S_{\text{peak}}$ (Jy) | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $\int S dV$ (Jy km s$^{-1}$) |
|-----------|---------------------|--------------------------|-------------------------------|--------------------------|-------------------------------|
| (1)       | (2)                 | (3)                      | (4)                          | (5)                      | (6)                          |
| **NGC 6334F** | 17 20 52.54        | −35 46 42.2              | 1.3                          | −8.1                     | 1.5                           |
|           | 17 20 52.74        | −35 47 07.7              | 1.2                          | −10.2                    | 10.9 to −8.7                  | 1.0                           |
|           | 17 20 52.75        | −35 47 02.3              | 5.9                          | −6.2                     | 1.3                           |
|           | 17 20 52.87        | −35 46 41.9              | 1.5                          | −8.1                     | −9.0 to −6.9                  | 1.1                           |
|           | 17 20 52.97        | −35 47 03.8              | 2.9                          | −8.9                     | −10.9 to −6.2                 | 2.7                           |
|           | 17 20 53.54        | −35 47 11.4              | 0.7                          | −10.1                    | 1.7                           |
|           | 17 20 54.63        | −35 46 47.1              | 9.4                          | −6.9                     | −7.4 to −4.6                  | 12.6                          |
|           | 17 20 54.88        | −35 46 49.6              | 2.8                          | −5.7                     | 1.2                           |
| **G8.67$-0.36$** | 18 06 18.47        | −21 37 10.6              | 0.4                          | 37.9                     | 0.5                           |
|           | 18 06 18.61        | −21 37 22.9              | 1.9                          | 38.1                     | 0.7                           |
|           | 18 06 18.79        | −21 37 12.7              | 1.3                          | 37.7                     | 1.3                           |
|           | 18 06 18.82        | −21 37 19.9              | 1.3                          | 38.7                     | 36.9 to 39.9                  | 0.8                           |
|           | 18 06 18.84        | −21 37 42.7              | 1.4                          | 34.8                     | 1.2                           |
|           | 18 06 18.97        | −21 37 19.7              | 6.2                          | 37.6                     | 36.9 to 38.7                  | 4.2                           |
|           | 18 06 19.00        | −21 37 41.5              | 7.9                          | 35.1                     | 1.3                          |
|           | 18 06 19.00        | −21 37 26.5              | 16.5                         | 35.4                     | 34.1 to 38.2                  | 21.1                          |
|           | 18 06 19.04        | −21 37 40.0              | 9.3                          | 33.6                     | 1.8                          |
|           | 18 06 19.17        | −21 37 25.5              | 18.2                         | 35.9                     | 2.5                           |
|           | 18 06 19.18        | −21 37 21.3              | 1.4                          | 33.8                     | 2.2                           |
|           | 18 06 19.54        | −21 37 14.8              | 0.9                          | 36.4                     | 35.0 to 36.9                  | 0.7                           |
| **M17**   | 18 20 23.21        | −16 11 46.5              | 9.0                          | 19.1                     | 0.7                           |

**Notes.**

a Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

b A single number indicates the line width for $S > 3\sigma$. Two numbers indicate the velocity range when a single sky position has multiple components, even if some intermediate channels fall below $3\sigma$.

c These two masers are spatially blended; $\Delta V$ and $\int S dV$ are approximate values.
Figure 1. VLA 3.6 cm continuum contours (Carral et al. 2002) overlaid on the three-color GLIMPSE IRAC image of NGC 6334F showing 8 μm (red), 4.5 μm (green), and 3.6 μm (blue) emission. The contour levels are from 10% to 85% (step 15%) of the peak emission of 127.5 mJy beam$^{-1}$. "Plus" symbols represent 44 GHz CH$_3$OH masers (this work), while squares indicate OH masers (Brooks & Whiteoak 2001), circles represent H$_2$O masers (Forster & Caswell 1989), and the diamond indicates a 23 GHz methanol maser (KHV04).

2.2. Spitzer Space Telescope

Spitzer images, shown in Figures 1–3, were taken from the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003) program, based on observations with the Infrared Array Camera (IRAC; Fazio et al. 2004).

3. RESULTS

We confirm the presence of 44 GHz CH$_3$OH maser emission in all 3 sources, detecting 8 distinct maser components in NGC 6334F, 12 masers in G8.67$-$0.36, and 1 maser in M17.

The observed parameters of all detected masers are listed in Table 2. Column 1 gives the source name, while Columns 2 and 3 give the J2000 peak position, determined from a two-dimensional Gaussian fit to the peak channel. Column 4 gives the peak flux density, also from the Gaussian fit. Column 5 gives the local standard of rest (LSR) velocity of the peak channel, while Column 6 provides the full width at zero intensity at the 3σ level. If multiple velocity components at the same sky position are present then we report the full velocity range, even if some intermediate channels fall below the 3σ level. Column 7 gives the integrated line flux, calculated as $\Sigma S \Delta V$ summed over channels above the 3σ level.

Figures 1–3 show the three-color GLIMPSE image of each region, with radio continuum emission plotted as contours and various maser species shown as symbols. The symbol sizes are larger than the positional uncertainty in all cases.

4. DISCUSSION OF INDIVIDUAL SOURCES

4.1. NGC 6334F

NGC 6334F is a well-known ultracompact (UC) H II region, lying within the NGC 6334 cloud complex, at a distance of 1.7 kpc (Neckel 1978). It is also known as NGC 6334I, where “I” is a roman numeral “one,” originating from far-infrared studies (e.g., Gezari 1982). We adopt the convention of Rodríguez et al. (1982) in which the letter “F” refers to the UC H II region.

The eight 44 GHz class I masers detected within the one arcminute VLA primary beam indicate a higher level of maser activity than the majority of the sources in the KHV04 survey, which has a median of four maser features per field. Figure 1 shows the three-color Spitzer/GLIMPSE image of NGC 6434F and the location of the maser components. The eight masers...
are distributed over an area ~0.25 pc × 0.25 pc. As is typical for class I masers, these eight components do not appear to be associated with the UC H\,\Pi region, other masers, or the infrared emission. Nor do they coincide with thermal ammonia peaks or ammonia masers as reported by Beuther et al. (2005, 2007) or with the millimeter peaks reported by Hunter et al. (2006). The average projected distance from the masers to the geometric center of the UC H\,\Pi region is 0.12 pc.

Neglecting the two northernmost masers, there is a southwest to northeast positional orientation of the remaining six masers. This orientation corresponds to the blueshifted (southwest) and redshifted (northeast) high-velocity outflow mapped with the APEX 12 m telescope by Leurini et al. (2006). There is a weak tendency in the maser velocity structure in accordance with this pattern: the average velocity of the southwestern masers is \(-9.5\ \text{km}\ \text{s}^{-1}\), while the average for the northeastern masers is \(-6.3\ \text{km}\ \text{s}^{-1}\). We suggest that these six masers are related to the bipolar outflow reported by Leurini et al. (2006). We caution, however, that the trends in both position and velocity are not particularly strong.

The velocity range of emission that we detected (\(-10.9\) to \(-4.6\ \text{km}\ \text{s}^{-1}\)) is slightly shifted from that reported by KHV04 (\(-9.0\) to \(-2.5\ \text{km}\ \text{s}^{-1}\)) and also differs from the single-dish observations of Slysh et al. (1994, \(-8.4\) to \(-4.8\ \text{km}\ \text{s}^{-1}\)).

### 4.2. G8.67−0.36

The UC H\,\Pi region G8.67−0.36, at a distance of 4.8 kpc (Fish et al. 2003), was classified by Wood & Churchwell (1989) as having a core–halo morphology, i.e., a single compact peak surrounded by an extended, low-surface-brightness halo.

As in NGC 6334F, the relatively large number of masers detected in this field (12) indicates an unusually high level of maser activity. We identify two regions of maser activity in the field (see Figure 2): one to the north and the other to the south of the UC H\,\Pi region. No velocity trend with respect to position is seen. The strongest two masers in this field lie at the edge of an Extended Green Object (EGO; Cyganowski et al. 2008), consistent with the idea that EGOSs trace molecular outflows from massive YSOs and that class I methanol masers arise from the interaction of outflows with dense clumps of gas (Plambeck & Menten 1990). Cyganowski et al. (2008) did not catalog the G8.67−0.36 region because it lies outside their survey area (10\(^\circ\) < l < 65\(^\circ\) and 295\(^\circ\) < l < 350\(^\circ\), b = ±1\(^\circ\)). Although 8 of the 12 masers lie at the edge of some infrared feature, four of the masers appear relatively isolated from the infrared emission; hence, our data do not suggest a unique correlation of these masers with a particular set of gas conditions.

KHV04 report maser emission from 33 to 37 km s\(^{-1}\), and we detect maser emission in a velocity range of 33.6−39.9 km s\(^{-1}\). Both detections are in close agreement with the velocity of HCO\(^+\) and H\(^{13}\)CO\(^+\) emission at 34.8 km s\(^{-1}\) reported by Purcell et al. (2006).

The average projected distance from the masers to the geometric center of the UC H\,\Pi region is 0.29 pc.

### 4.3. M17

The M17 region hosts, among other features, the cometary UC H\,\Pi region UC-1 (e.g., Felli et al. 1980; Johnson et al. 1998). Distances reported for the M17 nebula have ranged from 2.2 kpc (Chini et al. 1980) to 1.3 kpc (Hansen et al. 1997). More recently, a distance of 1.6 kpc has been reported by Nielbock et al. (2001), which we adopt here.

Unlike the previous two sources, M17 presents very limited 44 GHz maser activity with only a single maser component detected in the field, at a projected distance of 0.2 pc from the UC H\,\Pi region (see Figure 3). The maser properties are listed in Table 2: the 19.1 km s\(^{-1}\) velocity that we find is the same as found by KHV04.

### 5. SUMMARY

Using the VLA, we have observed 44 GHz class I methanol maser emission in the massive star-forming regions NGC 6334F, G8.67−0.36, and M17. Our principal result is to provide accurate maser positions and parameters, thus completing the catalog of KHV04.

In addition, we find that (1) two of the sources (NGC 6334F and G8.67−0.36) show significantly higher levels of maser activity than the typical survey source. (2) For all the three sources, the masers are well separated from the H\,\Pi region, with projected distances ranging from 0.1 to 0.3 pc. This is in good agreement with the KHV04 survey, which found a median separation of 0.2 pc for a subsample of 22 sources that had both H\,\Pi regions and maser emission.

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