A CLASS I AND CLASS II CH3OH MASER SURVEY OF EGOs FROM THE GLIMPSE SURVEY

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Received 2009 May 6; accepted 2009 July 2; published 2009 August 24

ABSTRACT

We present the results of a high angular resolution Very Large Array (VLA) Class I 44 GHz and Class II 6.7 GHz CH3OH maser survey of a sample of ~20 massive young stellar object (MYSO) outflow candidates selected on the basis of extended 4.5 μm emission in Spitzer Galactic Legacy Infrared Mid-Plane Survey Extraordinaire images. These 4.5 μm selected candidates are referred to as extended green objects (EGOs), for the common coding of this band as green in three-color infrared Array Camera images. The detection rate of 6.7 GHz Class II CH3OH masers, which trace molecular outflows, is ~89% toward EGOs associated with 6.7 GHz CH3OH masers. The two types of CH3OH masers exhibit different spatial distributions: 6.7 GHz masers are centrally concentrated and usually coincide with 24 μm emission, while 44 GHz masers are widely distributed and generally trace diffuse 4.5 μm features. We also present results of a complementary James Clerk Maxwell Telescope (JCMT) single-pointing molecular line survey of EGOs in the outflow tracers HCO+(3–2) and SiO(5–4). The HCO+ line profiles and high SiO detection rate (90%) are indicative of the presence of active outflows. No 44 GHz continuum emission is detected at the 5 mJy beam−1 (5σ) level toward 95% of EGOs surveyed, excluding bright ultracompact H II regions as sources for the 4.5 μm outflows. The results of our surveys constitute strong evidence that EGOs are young, massive YSOs, with active outflows, presumably powered by ongoing accretion.

Key words: infrared: stars – ISM: jets and outflows – masers – stars: formation – techniques: interferometric

Online-only material: color figures, figure sets, machine-readable tables

1. INTRODUCTION

The role and physics of accretion in dense (proto)cluster environments are central to understanding massive star formation, yet remain poorly understood (e.g., Zinnecker & Yorke 2007). This is in part attributable to the rapid evolution of massive young stellar objects (MYSOs); sources in a phase of active accretion are expected to be rare (Zinnecker & Yorke 2007), and are observationally difficult to identify in distant, crowded, and heavily extincted massive star-forming regions (MSFRs).

The 4.5 μm band of the Spitzer Space Telescope’s Infrared Array Camera (IRAC; Fazio et al. 2004) offers a promising new approach for identifying MYSOs with outflows that are, presumably, still actively accreting. The 4.5 μm IRAC band (“band 2”) is notably lacking in PAH features (see Figure 1 of Reach et al. 2006) and contains molecular lines that may be shock-excited in protostellar outflows, including both the CO (v = 1–0) bandhead and H2 lines, most notably the v = 0–0, S(9,10,11) transitions. Weaker H2 lines can also, in aggregate, contribute significantly to the 4.5 μm broadband flux under some shock conditions, or if photodissociation region (PDR) emission is present (e.g., Smith & Rosen 2005; Smith et al. 2006; Ybarra & Lada 2009). There are also H2 lines in the other IRAC bands, and indeed, in the more extreme shock environment of supernova remnants (SNRs), Neufeld & Yuan (2008) have found that all IRAC bands may be dominated by H2 emission. In MSFRs, however, PAH emission generally dominates the 5.8 and 8.0 μm bands. Thus, extended 4.5 μm emission with morphology distinct from that in the other IRAC bands is a common and conspicuous feature of MSFRs. Such features are known as “extended green objects” (EGOs; Cyganowski et al. 2008) or “green fuzzies” (Chambers et al. 2009), for the common coding of the [4.5] band as green in three-color IRAC images. In the massive DR21 outflow, comparison to Infrared Space Observatory (ISO) spectra and narrowband near-infrared (NIR) H2 images support the interpretation of extended 4.5 μm emission as tracing shocked H2 in the outflow (Smith et al. 2006; Davis et al. 2007, and references therein).

Reported size scales for outflows in MSFRs span more than an order of magnitude, from <0.1 pc to >1 pc (e.g., Hunter et al. 1995; Beuther et al. 2002), and the apparent extent of an outflow may depend on the angular resolution and tracer (e.g., Hunter et al. 2008; Klaassen & Wilson 2008). The resolution of IRAC (<2″ in all bands; Fazio et al. 2004) is sufficient to resolve MYSO outflows of length ∼0.1 pc as extended emission, distinguishable from point sources, in MSFRs nearer than the Galactic center (2″ ∼ 16,000 AU ∼ 0.08 pc at 8 kpc). Cyganowski et al. (2008) cataloged over 300 EGOs in the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire survey area (GLIMPSE, Benjamin et al. 2003). Cataloged EGOs were divided into “likely” and “possible” MYSO outflow candidates based primarily on the angular extent and morphology of the 4.5 μm emission (Cyganowski et al. 2008). EGOs for which the MIR morphology may be attributable to multiple nearby point sources or to image artifacts around bright sources, instead of to truly extended 4.5 μm emission, were categorized as “possible” outflow candidates (see also Cyganowski et al. 2008). The GLIMPSE survey is also sensitive to another class of objects identified with the early stages of massive star formation: infrared dark clouds (IRDCs), seen in silhouette against mid-infrared (MIR) Galactic background emission, particularly at 8 μm (Churchwell et al. 2009). First identified and cataloged in ISO and Midcourse Space Experiment (MSX) surveys of the Galactic plane, IRDCs are cold (T < 20 K), dense (n(H2) > 103 cm−3)
clouds of molecular gas and dust (e.g., Carey et al. 1998; Egan et al. 1998; Hennebelle et al. 2001; Simon et al. 2006a, 2006b). Recent studies have shown that IRDCs host both protostellar cores and intermediate and massive YSOs, pinpointing IRDCs as sites of the earliest stages of massive star and cluster formation (e.g., Rathborne et al. 2005, 2006, 2007; Pillai et al. 2006; Wang et al. 2008; Ragan et al. 2009). Based on the MIR colors of EGOs and their correlation with IRDCs and published 6.7 GHz CH$_3$OH maser data, Cyganowski et al. (2008) argued that EGOs constitute a population of actively accreting MYSO outflow candidates.

There are two elements to this hypothesis: (1) EGOs are massive YSOs and (2) extended 4.5 $\mu$m emission traces active molecular outflows from these MYSOs (which may then be presumed to be actively accreting). Recent advances in the theoretical and observational understanding of CH$_3$OH masers, particularly the differing conditions under which Class I and Class II transitions are excited, suggest that CH$_3$OH masers are well suited for testing this hypothesis and establishing the nature of EGOs.

Collisionally excited Class I CH$_3$OH masers are observationally well correlated with molecular outflows in MSFRs (Plambeck & Menten 1990; Johnston et al. 1992; Cragg et al. 1992; Kurtz et al. 2004). In the largest interferometric survey to date, Kurtz et al. (2004) found that 44 GHz Class I CH$_3$OH masers were common in MSFRs and well correlated with shocked gas in outflows as traced by SiO and H$_2$. Based on the relation of 95 GHz Class I CH$_3$OH maser emission to molecular cores traced by CS and outflow shocks traced by H$_2$ in DR21 and on the close-to-systemic velocities of the masers ($v_{\text{maser}} \sim v_{\text{LSR, gas}}$), Plambeck & Menten (1990) suggested that Class I CH$_3$OH masers may be excited specifically in interface regions where outflows encounter surrounding molecular material. Class I CH$_3$OH masers in several transitions are associated with shocked H$_2$ knots in the outflow from IRAS 16547$-$4247 (Brooks et al. 2003; Voronok et al. 2006), a well-studied MYSO that is also an EGO cataloged by Cyganowski et al. (2008). Chen et al. (2009) find that 67% of the EGOs cataloged by Cyganowski et al. (2008) are within 1' of a 44 or 95 GHz Class I CH$_3$OH maser, but that the Class I CH$_3$OH maser data avail-

Figure 1. Three-color GLIMPSE IRAC images showing 8.0 $\mu$m (red), 4.5 $\mu$m (green), and 3.6 $\mu$m (blue). Yellow 24 $\mu$m MIPS GAL contours (Carey et al. 2009) are superposed; contour levels for each source are given in Table 5. Each panel is centered on the targeted EGO; north is up and east to the left in all images. The physical scale label on each scalebar (in pc) assumes the distance to the source listed in Table 3. Positions of 6.7 GHz CH$_3$OH masers from Table 7 are marked with diamonds. Positions of 44 GHz CH$_3$OH masers from Table 8 are marked with magenta crosses. The primary beam (FWHP) of the VLA is 6.7 at 6.7 GHz and 1.0 at 44 GHz. (A color version of this figure is available in the online journal.)
able in the literature—mostly from single-dish surveys with poor angular resolution (≥52″)—are insufficient to establish physical association between the maser and MIR emission. The single-dish surveys used by Chen et al. (2009) are also shallow (detection limits ≥5 Jy), and comparison with the Kurtz et al. (2004) results suggests that shallow surveys miss a substantial fraction of the maser population, at least for 44 GHz Class I CH$_3$OH masers. Only ~29% of the masers reported by Kurtz et al. (2004) have peak flux densities ≥5 Jy, although ~33% of Molinari sources and ~59% of all sources with 44 GHz detections are associated with at least one ≥5 Jy maser. There is evidence that relatively weak (≤11 Jy) 44 GHz CH$_3$OH masers can occur in bipolar outflows from low-mass protostars (Kalenskii et al. 2006), but the authors caution that the maser nature of the observed emission requires confirmation with interferometric observations.

Class II 6.7 GHz CH$_3$OH masers, radiatively pumped by IR emission from warm dust (Cragg et al. 1992, 2005, and references therein), are associated exclusively with massive YSOs (e.g., Minier et al. 2003). Sensitive searches toward low-mass YSOs ($L \lesssim 10^3$ $L_\odot$, $M \lesssim 3$ $M_\odot$; Minier et al. 2003; Bourke et al. 2005; Xu et al. 2008, 3σ ≤0.2 Jy), including hot corinos (Pandian et al. 2008, 3σ ~ 0.003 Jy), have uniformly yielded null results. In addition to being an observationally robust result, the lack of 6.7 GHz CH$_3$OH masers toward low-mass YSOs may be understood theoretically in the context of the excitation models: the energetics of low-mass YSOs do not produce regions with the necessary combinations of dust temperature, density, and CH$_3$OH abundance for 6.7 GHz maser emission (Minier et al. 2003; Pandian et al. 2008).

Unaffected by extinction and accessible at high angular resolution with the Expanded Very Large Array (EVLA), 6.7 GHz Class II and 44 GHz Class I CH$_3$OH masers provide an observationally efficient avenue for testing whether EGOs are massive YSOs with outflows. This paper presents the results of a survey for 6.7 GHz Class II and 44 GHz Class I CH$_3$OH masers toward a sample of ~20 EGOs selected from the catalog of Cyganowski et al. (2008), chosen to cover a range of MIR properties and be visible from the northern hemisphere. We also report results from simultaneous EVLA 44 GHz pseudo-continuum observations and from a James Clerk Maxwell Telescope (JCMT) molecular line survey undertaken to complement the maser observations by providing information about the gas kinematics and local standard of rest (LSR) velocities. In Section 2 we describe the observations, in Section 3 we present the results of the surveys, in Section 4 we discuss the implications of our results for understanding the nature of EGOs, and in Section 5 we summarize our main conclusions.
2. OBSERVATIONS

2.1. Very Large Array (VLA)

The 6.7 GHz observations reported here were made possible by the expanded tuning capability of the NRAO\(^3\) Expanded Very Large Array (EVLA) at C band. A sample of 28 EGOs was initially observed in the 6.668519 GHz CH\(_3\)OH (51–60) \(A^+\) (\(E_i = 48.7\) K) maser transition on 2007 October 31 in the B configuration using Doppler tracking: 11 EVLA antennas were available for these observations. Unfortunately, we discovered that Doppler tracking with the EVLA antennas produced large phase jumps between the targets and calibrators for all but one source (G11.92\(-0.61\)) for which the sky frequency of the target and calibrator were sufficiently close to permit calibration (this problem has since been fixed). For the other sources the phase stability was sufficiently good during the short observations that maser emission could be detected in uncalibrated vector-averaged \(u-v\) plots (it is notable that weak masers or masers far from the phase center would not have been apparent in these plots). The 18 uncalibratable sources with maser features apparent in the original \(u-v\) data were re-observed at 6.7 GHz in fixed-frequency mode: 13 EVLA antennas were available for these observations. The sources were split into two groups based on their declinations, and each group of sources was observed twice. The bandwidth was 1.56 MHz (70 km s\(^{-1}\)); aliasing on EVLA–EVLA baselines using the interim system (EVLA antennas and VLA correlator) meant that the usable bandwidth was \(\sim 30\) km s\(^{-1}\). The aliasing is worse for narrow bandwidths and in the presence of broadband continuum emission. The spectral resolution was 3.05 kHz (0.14 km s\(^{-1}\), prior to offline Hanning smoothing). The data were taken in single polarization mode. For each source, the phase calibrator, bandpass calibrator, flux calibrator, observation date, velocity range searched for maser emission, and synthesized beam size are listed in Table 1.

Our 44 GHz VLA observations, of the 18 EGOs observed with fixed frequency at 6.7 GHz plus G11.92\(-0.61\), were obtained on 2008 February 16 and 18 in the CnB configuration, in fixed frequency mode: 26 antennas were available for these observations. One IF was tuned to the 44.069410 GHz CH\(_3\)OH (79–68) \(A^+\) (\(E_i = 62.9\) K) maser transition; the bandwidth was 3.125 MHz (21 km s\(^{-1}\), \(\sim 19\) km s\(^{-1}\) usable due to the aliasing described above) and the spectral resolution 24.4 kHz (0.17 km s\(^{-1}\)), prior to offline Hanning smoothing. Pseudo-continuum observations were obtained simultaneously (\(v = 44.1\) GHz, 25 MHz bandwidth divided into 16 channels). The data were taken in single polarization mode. The bandpass

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\(^3\) The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under agreement by the Associated Universities, Inc.
calibrator was J2253+161 and the flux calibrator was 3C286. Fast switching was used with a cycle time of 2 minutes, and the pointing model was updated once per hour during the observations. For each source, the phase calibrator, observation date, velocity range searched for maser emission, synthesized beam size, and continuum rms from the wideband data are listed in Table 2.

In the calibration of both the 6.7 GHz and 44 GHz data sets, a model was used for 3C286. All maser data were self-calibrated using the channel with the strongest maser emission (except for the G37.48−0.10 44 GHz data, which did not have sufficiently strong masers). We estimate that the absolute flux calibration is accurate to ~10%, and that the absolute positional uncertainty is ~0′.1. Our VLA observations were obtained prior to the single-dish molecular line observations of our EGO sample described in Section 2.2. Source velocities for tuning the VLA correlator were obtained from a broad range of data from archives and the literature. As subsequent follow up shows, this was not always ideal (see Section 3). The primary beam (FWHP) of the VLA is 6.7 at 6.7 GHz and 1.0 at 44 GHz.

The search for maser emission in the 6.7 and 44 GHz image cubes was automated using the AIPS task SAD. These data are dynamic range limited such that the rms noise in channels with bright maser emission is significantly increased compared to non-maser channels (this is due primarily to relatively poor u−v coverage). To account for this limitation, the rms noise cutoff for SAD was adjusted from a conservative value of ~6σ_{channel} for the majority of the channels in each cube to as high as ~10σ_{channel} for those channels containing strong emission. This was a greater issue for the 6.7 GHz data than the 44 GHz data because the former had significantly fewer operational antennas. Tables 1 and 2 list the minimum, maximum, and median threshold values used for each source. Only spectral features above these thresholds in at least two channels are reported. The median 6σ detection limit for the whole sample of 19 EGOs is ~0.16 Jy (brightness temperature \( T_B \) ~ 1247 K) for the 6.7 GHz data and ~0.15 Jy (\( T_B \) ~ 330 K) for the 44 GHz data. Reported maser flux densities and intensities have been corrected for primary beam attenuation.

2.2. James Clerk Maxwell Telescope

Observations of HCO+\((J = 3−2)\) and H13CO\(^+\)(\(J = 3−2)\) were obtained at the JCMT\(^4\) on 2008 May 28–30 toward 18 of the EGOs surveyed for CH\(_3\)OH masers with the VLA (G10.34−0.14 excepted). Two 1 GHz IFs were observed simultaneously: one IF was centered on HCO+\((J = 3−2)\) at 267.558 GHz (\( E_I = 12.8 \) K) in the USB, while the other IF covered H13CO\(^+\)(\(J = 3−2)\) at 260.255 GHz (\( E_I = 12.5 \) K) in the LSB. Also included in the H13CO\(^+\) tuning was the CH\(_3\)OH(52,3−41,3)

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\(^4\) The JCMT is operated by The Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.
Table 1

| Source Name | $V_{\text{range}}$ (km s$^{-1}$) | Phase Cal. | Bandpass Cal. | Flux Cal. | Obs. Date | Syn. Beam ($'' \times ''$) | SAD Cutoff$^b$ Min,Max,Median (Jy beam$^{-1}$) |
|-------------|---------------------------------|------------|---------------|-----------|-----------|-----------------------------|-----------------------------------------------|
| G10.29−0.13 | −4.6 to 22.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.35 × 2.61                | 0.16,0.75,0.20                              |
| G10.34−0.14 | −1.6 to 25.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.49 × 2.68                | 0.16,0.44,0.20                              |
| G11.92−0.61 | 25.3 to 56.8                    | J1733−130  | 3C84,3C286,J2136+006 | J2136+006 | 2007 Oct 31  | 1.94 × 0.96                | 0.20,0.30,0.22                              |
| G18.67+0.03 | 66.4 to 93.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.31 × 2.42                | 0.16,0.35,0.16                              |
| G18.89−0.47 | 44.4 to 71.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.37 × 2.46                | 0.15,0.16,0.16                              |
| G19.01−0.03 | 15.4 to 42.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.47 × 2.27                | 0.16,0.25,0.16                              |
| G19.36−0.03 | 15.4 to 42.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.44 × 2.22                | 0.16,0.36,0.16                              |
| G22.04+0.22 | 38.4 to 65.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.50 × 2.21                | 0.16,0.22,0.17                              |
| G23.01−0.41 | 64.4 to 91.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.48 × 2.13                | 0.16,0.12,0.19                              |
| G23.96−0.11 | 59.4 to 86.8                    | J1733−130  | 3C286,J2136+006 | J2136+006 | 2008 Feb 9,17 | 3.67 × 2.12                | 0.15,0.21,0.15                              |
| G24.94+0.07 | 30.4 to 57.8                    | J1743−038  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 1.82 × 1.40                | 0.16,0.22,0.17                              |
| G25.27−0.43 | 48.4 to 75.8                    | J1743−038  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 1.78 × 1.24                | 0.14,0.20,0.15                              |
| G28.28−0.36 | 28.4 to 55.8                    | J1743−038  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 2.31 × 1.37                | 0.16,0.26,0.16                              |
| G28.83−0.25 | 75.4 to 105.6                   | J1743−038  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 1.96 × 1.49                | 0.16,0.40,0.18                              |
| G35.03+0.35 | 33.4 to 60.8                    | J1743−038  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 2.32 × 1.34                | 0.16,0.25,0.16                              |
| G37.48−0.10 | 47.4 to 74.8                    | J1743−038  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 1.82 × 1.45                | 0.16,0.20,0.16                              |
| G39.10+0.49 | 3.4 to 30.8                     | J1925+211  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 2.37 × 1.30                | 0.15,0.33,0.17                              |
| G49.27−0.34 | 47.4 to 74.8                    | J1925+211  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 1.99 × 1.37                | 0.17,0.42,0.19                              |
| G49.42+0.33 | −5.2 to −32.6                   | J1925+211  | J2136+006     | J2136+006 | 2008 Feb 1,19 | 1.96 × 1.33                | 0.12,0.20,0.20                              |

Notes.

$^a$ Velocity range searched for maser emission.

$^b$ Minimum, maximum, and median cutoff levels used in the automated identification of masers with the AIPS task SAD. Cutoff levels used were $\sim 6$ or $10 \times \sigma_{\text{channel}}$.

$^c$ Assuming $S(6.7 \text{ GHz}) = 9.03 \text{ Jy}$. 
transition at 266.838 GHz ($E_1 = 44.3$ K) in the USB. Position-switching mode was used, with each EGO observed for 3.5 minutes on-source. In addition, a subset of 10 EGOs was observed using the switch mode, with each EGO observed for 3.5 minutes on-source. The "off" positions were chosen to avoid IRDCs and weather and source elevation and ranged from 10 to 15 minutes.

The observation dates, rms, and fitted line properties for each EGO are listed in Table 3. During the 2008 May run, $T_{sys}$ was typically ~250 K for the HCO$^+$ observations, and $\tau_{225} \sim 0.06$, 0.07, and 0.09 on 2008 May 28, 29, and 30, respectively. On 2008 June 12 and 13, $T_{sys}$ was ~370 K and $\tau_{225} \sim 0.15$. The half-power beamwidth of the JCMT is ~19'' at the frequency of HCO$^+(3–2)$ and ~23'' at the frequency of SiO(5–4).

Archival data were downloaded from the JCMT archive for G10.34−0.14. Maps (~40'' × 40'' in extent) of HCO$^+(3–2)$ and H$^{13}$CO$^+(3–2)$, centered at 18$^h$08$^m$59$^{s}$3, −20°03'42'' (J2000.0) and including the EGO position, were obtained on 2002 April 24 and 2002 May 1, respectively, as part of project MO2AU26. $T_{sys}$ was ~470 K on 2002 April 24 and 345 K on 2002 May 1 at the time of the observations; $\tau_{225}$ was ~0.14 (2002 April 24) and ~0.09 (2002 May 1). The data were taken with the A3 receiver and reduced as described above. The spectrum of the pixel containing the EGO position (Table 4) was extracted for each line, and the data smoothed from its native resolution of ~156 kHz (~0.175 km s$^{-1}$) to a resolution of ~0.55 km s$^{-1}$. Fitted line properties for H$^{13}$CO$^+$ from the archival G10.34−0.14 data are included in Table 3.

3. RESULTS

The sample of 19 EGOs successfully observed with the VLA consists entirely of "likely" MYSO outflow candidates (see Section 1). Our sample otherwise spans a range of MIR properties and known associations with other tracers of MYSOs, most available data is from maps targeting other sources that happen to cover the EGO position or from studies of previously identified CH$_3$OH masers (see Section 3.2). The early results of the ATLASGAL 870 µm survey illustrate the promise of upcoming blind surveys of the Galactic plane at (sub)millimeter wavelengths: a partial catalog of compact sources in a 1 × 1.5 deg$^2$ field near l = 19° includes the first reported submillimeter counterparts for two EGOs in our sample (G18.89−0.47 and G19.01−0.03).

Table 2

| Source Name | $V_{range}^a$ (km s$^{-1}$) | Phase Cal. | Line Observations | Wideband Observations |
|-------------|---------------------------|------------|-------------------|-----------------------|
|             |                           | Obs. Date  | Syn. Beam (mJy beam$^{-1}$) | SAD Cutoff (Jy beam$^{-1}$) | Obs. Date  | Syn. Beam (mJy beam$^{-1}$) | rms (mJy beam$^{-1}$) |
| G10.29−0.13 | −3.2 to 15.4              | 2008 Feb 18 | 1.03 × 0.54 | 0.15, 0.18, 0.17 | 2008 Feb 18 | 0.95 × 0.51 | 1.4 |
| G10.34−0.14 | 7.0 to 25.6               | 2008 Feb 18 | 0.87 × 0.49 | 0.16, 0.19, 0.17 | 2008 Feb 18 | 0.89 × 0.48 | 1.5 |
| G11.92−0.61 | 30.5 to 49.1              | 2008 Feb 18 | 0.75 × 0.51 | 0.22, 0.22, 0.22 | 2008 Feb 18 | 0.99 × 0.44 | 1.4 |
| G18.67+0.03 | 71.0 to 89.6              | 2008 Feb 18 | 0.76 × 0.45 | 0.10, 0.10, 0.10 | 2008 Feb 18 | 0.80 × 0.48 | 1.1 |
| G18.89−0.47 | 48.0 to 66.5              | 2008 Feb 18 | 0.57 × 0.43 | 0.32, 0.32, 0.32 | 2008 Feb 18 | 0.76 × 0.47 | 1.1 |
| G19.01−0.03 | 48.5 to 67.1              | 2008 Feb 18 | 0.62 × 0.50 | 0.12, 0.12, 0.12 | 2008 Feb 18 | 0.69 × 0.51 | 1.0 |
| G19.36−0.03 | 18.5 to 37.1              | 2008 Feb 18 | 0.63 × 0.50 | 0.12, 0.27, 0.12 | 2008 Feb 18 | 0.66 × 0.49 | 1.0 |
| G22.04+0.22 | 41.5 to 60.1              | 2008 Feb 18 | 0.58 × 0.51 | 0.10, 0.23, 0.11 | 2008 Feb 18 | 0.59 × 0.51 | 0.9 |
| G23.01−0.41 | 69.5 to 88.1              | 2008 Feb 18 | 0.58 × 0.51 | 0.09, 0.10, 0.10 | 2008 Feb 18 | 0.58 × 0.49 | 0.9 |
| G23.96−0.11 | 59.5 to 78.1              | 2008 Feb 18 | 0.60 × 0.51 | 0.08, 0.11, 0.11 | 2008 Feb 18 | 0.61 × 0.48 | 1.0 |
| G24.94+0.07 | 38.5 to 57.1              | 2008 Feb 18 | 0.64 × 0.46 | 0.10, 0.10, 0.10 | 2008 Feb 18 | 0.59 × 0.44 | 1.0 |
| G25.27−0.43 | 53.5 to 72.1              | 2008 Feb 18 | 0.63 × 0.48 | 0.11, 0.11, 0.11 | 2008 Feb 18 | 0.59 × 0.48 | 1.0 |
| G28.28−0.36 | 32.5 to 51.1              | 2008 Feb 18 | 0.59 × 0.50 | 0.08, 0.08, 0.08 | 2008 Feb 18 | 0.60 × 0.46 | 1.2 |
| G28.83−0.25 | 80.5 to 99.1              | 2008 Feb 18 | 0.61 × 0.41 | 0.08, 0.08, 0.08 | 2008 Feb 18 | 0.62 × 0.44 | 0.9 |
| G35.03+0.35 | 35.5 to 54.5              | 2008 Feb 18 | 0.58 × 0.46 | 0.08, 0.08, 0.08 | 2008 Feb 18 | 0.57 × 0.45 | 0.8 |
| G37.48−0.10 | 50.5 to 69.5              | 2008 Feb 18 | 0.55 × 0.46 | 0.08, 0.08, 0.08 | 2008 Feb 18 | 0.61 × 0.41 | 0.9 |
| G39.10+0.49 | 11.0 to 29.3              | 2008 Feb 18 | 0.66 × 0.43 | 0.26, 0.26, 0.26 | 2008 Feb 18 | 0.61 × 0.38 | 1.0 |
| G49.27−0.34 | 50.5 to 69.5              | 2008 Feb 18 | 0.47 × 0.43 | 0.10, 0.10, 0.10 | 2008 Feb 18 | 0.49 × 0.40 | 0.9 |
| G49.42+0.33 | −32.5 to −1.9$^a$         | 2008 Feb 18 | 0.50 × 0.40 | 0.08, 0.08, 0.08 | 2008 Feb 18 | 0.53 × 0.40 | 0.9 |

Notes.

$^a$ Velocity range searched for maser emission.

$^b$ Minimum, maximum, and median cutoff levels used in the automated identification of masers with the AIPS task SAD. Cutoff levels used were ~6 or 10 $\sigma$ per channel.

$^c$ This source was observed with two different tunings.
Three-color IRAC images for the 19 EGOs in our sample showing 8.0 \( \mu\)m (red), 4.5 \( \mu\)m (green), and 3.6 \( \mu\)m (blue), with MIPS GAL 24 \( \mu\)m contours overlaid, are presented in Figure 1. The levels for the 24 \( \mu\)m contours in Figure 1 are given in Table 5, as are estimated J2000 positions and fluxes for 24 \( \mu\)m EGO counterparts. Most targeted EGOs have MIPS 24 \( \mu\)m counterparts (see Figure 1 and Table 5), as expected for MYSOs (e.g., Robitaille et al. 2006; Carey et al. 2009). Three (G10.29–0.13, G28.28–0.36, G49.42+0.33), however, are located near the edges of 8 and 24 \( \mu\)m bright nebulae, and have no detected discrete 24 \( \mu\)m counterparts (see Figures 1(a), (m), and (s)). In addition, three EGOs included in the Cyganowski
et al. (2008) catalog that were not targeted in our maser survey serendipitously fell within the VLA primary beam at 6.7 GHz (6.7 FWHP), though outside the much smaller 44 GHz primary beam (1.0 FWHP). These sources are listed at the bottom of Tables 4, 5, and 6 and include one “likely” and two “possible” candidates as categorized by Cyganowski et al. (2008). Table 6 summarizes the observational properties of EGOs from our surveys.

Tables 7 and 8, available online in their entirety, present fitted parameters for every maser detected in our survey. Table 7 presents fits for the 6.7 GHz CH$_3$OH masers, and Table 8 presents fits for the 44 GHz CH$_3$OH masers. The maser positions from Tables 7 and 8 are overplotted on the three-color GLIMPSE images of targeted EGOs in Figure 1 (diamonds represent 6.7 GHz CH$_3$OH masers, crosses 44 GHz CH$_3$OH masers). In these images, the symbol sizes are larger than the positional uncertainties. No thermal emission from either the 6.7 or the 44 GHz CH$_3$OH line was detected in our VLA survey.

Continuum emission at 44 GHz was detected toward only one EGO in the sample (G35.03+0.35); this continuum detection is discussed in Section 3.8.15.

3.1. Maser Detection Rates

The detection rate of 6.7 GHz Class II CH$_3$OH masers toward EGOs in our survey is at least 64%: of the 28 sources in our original sample, 18 have maser emission coincident with the EGO. This detection rate is a lower limit because vector-averaged n–v plots select for strong masers near the phase center (see Section 2.1); the 9 sources that were not re-observed could have weak 6.7 GHz masers. Including the three EGOs not targeted but observed serendipitously (see Section 3), the detection rate is essentially the same (20/31, ≥64.5%). The masers range in strength from ~0.5 to 469.4 Jy beam$^{-1}$ ($T_B$ ~ 7390 to 1,743,038 K, see Table 7). This detection rate for 6.7 GHz masers toward EGOs is considerably higher than those of single-dish surveys with comparable sensitivity ($\lesssim 0.3$ Jy)}
The detection rate of 44 GHz CH$_3$OH masers toward EGOs in our survey is $\sim 90\%$ (17/19). The masers span a broad range in intensity, from $\sim 0.2$ Jy beam$^{-1}$ for the weakest masers to 89.5 Jy beam$^{-1}$ for the strongest ($T_B \sim 403$ to 131,994 K; see Table 8). Very few sensitive searches for 44 GHz CH$_3$OH masers in star-forming regions have been done to date. Large single-dish surveys (e.g., Bachiller et al. 1990; Haschick et al. 1990; Slysh et al. 1994) have been comparatively shallow (detection limits of $0.24\text{ Jy}$, the median $6\sigma$ detection limit of the current survey is $0.15\text{ Jy}$). The sample of Kurtz et al. (2004), who searched 44 MSFRs for 44 GHz CH$_3$OH maser emission with the VLA to a median $6\sigma$ detection limit of 0.24 Jy (the median $6\sigma$ detection limit of the current survey is 0.15 Jy). The sample of Kurtz et al. (2004) included compact and ultracompact (UC) H II regions with single-dish 44 GHz CH$_3$OH maser detections (VLA detection rate 28/32, 88%) and young massive protostellar objects from the Molinari sample (VLA detection rate 9/12, 75%). Like the sources from the Molinari sample (Molinari et al. 1996) targeted by Kurtz et al. (2004), EGOs are thought to be MYSOs in an early stage of formation, prior to the development of UC H II regions. Our detection rate for 44 GHz CH$_3$OH masers toward EGOs is greater than that of Kurtz et al. (2004) toward Molinari sources. This higher detection rate toward EGOs is not attributable to the greater sensitivity of our survey; for each EGO with associated 44 GHz CH$_3$OH masers in our survey, at least one maser is above the Kurtz et al. (2004) detection limit.

3.2. Previous Observations of Masers Toward the EGO Sample

H$_2$O and 6.7 GHz CH$_3$OH masers, both established tracers of massive star formation, have been detected previously in the vicinity of some of the EGOs in our sample, either through blind surveys or targeted searches of nearby MSFRs (see Table 4). However, most of the previous data are from single-dish telescopes, and consequently have relatively poor angular resolution (0.7–7' for CH$_3$OH and 0.7–19' for H$_2$O). This resolution makes it difficult to establish a physical association between an EGO and a maser reported in the literature. Table 4 presents a list of all the possible associations that we have found, though there are a number of caveats. For example, the spectrum of the 6.7 GHz maser G24.93+0.08 (Szymczak et al. 2002, a blind survey with 5.5 resolution and 30′ positional accuracy) is a blend of two masers resolved by our VLA observations (G24.94+0.07, coincident with the EGO G24.94+0.08, and G24.92+0.08), and the published position is $\sim 1'$ from the

| EGO Name | J2000 24 $\mu$m Source Position | Flux Density | Contour Levels (Figure 1) |
|----------|---------------------------------|-------------|---------------------------|
| G10.29–0.13 | ... c ... c | ... c ... c | ... c ... c |
| G10.34–0.14 | 18 09 00.0 | -20 03 35 | 900,1200,1500,1800,2100,2400 |
| G11.92–0.61 | 18 13 58.0 | -18 54 18 | 10.5(2.1)$^a$ |
| G18.67+0.03 | 18 24 53.8 | -12 39 21 | 3.9(<0.1) |
| G18.89–0.47 | 18 27 07.8 | -12 41 35 | 0.5(<0.1) |
| G19.01–0.03 | 18 25 44.7 | -12 22 46 | 3.5(0.3) |
| G19.36–0.03 | 18 26 25.6 | -12 03 51 | ... d |
| G22.04+0.22 | 18 30 34.6 | -09 34 46 | 3.3(0.2) |
| G23.01–0.41 | 18 34 40.2 | -09 00 38 | 10(2.0)$^c$ |
| G23.96–0.11 | 18 35 22.2$^f$ | -08 01 22$^f$ | ... |
| G24.94+0.07 | 18 36 31.5 | -07 04 16 | 1.4(0.1) |
| G25.27–0.43 | 18 38 56.9 | -07 00 48 | 0.2(<0.1) |
| G28.28–0.36 | ... c ... c ... c | ... c ... c | 900,1200,1500,1800 |
| G28.83–0.25 | 18 44 51.1 | -03 45 47 | 3.6(<0.1) |
| G35.03+0.35 | 18 54 00.6 | +02 01 19 | 18(0.36)$^d$ |
| G37.48–0.10 | 19 00 07.1 | +03 59 53 | 1.1(0.4) |
| G39.10+0.49 | 19 00 58.0 | +05 42 45 | 14(<0.1) |
| G49.27–0.34 | 19 23 06.8 | +14 20 15 | 11(2.2)$^e$ |
| G49.42+0.33 | 19 20 59.8$^f$ | +14 46 50$^f$ | ... |
| G24.00–0.10 | 18 35 23.5 | -07 59 29 | 0.3(<0.1) |
| G28.85–0.23 | 18 44 47.5 | -03 44 17 | ... d |
| G49.27–0.32 | 19 23 01.9 | +14 20 53 | 0.9(0.2) |

Notes:

$^a$ Estimated, using ds9 regions, as the center of a circle around the most prominent Airy ring for each 24 $\mu$m source. We employ this method because it can be applied consistently for all sources. Estimated uncertainties are $\sim 1'$ for isolated, unsaturated sources, up to $\sim 2'$ for blended and saturated sources (based on comparison with centroids generated by the modified "iracworks" program, see note (c)).

$^b$ Estimated uncertainties are 20%.

$^c$ No discrete 24 $\mu$m counterpart.

$^d$ Probable EGO counterpart is blended with other 24 $\mu$m source(s) and/or diffuse emission that may or may not be associated with the EGO, precluding a reliable flux measurement.

$^e$ Source is saturated. Flux was estimated using a modified version of the "iracworks" saturated source software contributed by Tom Jarrett and available at http://spider.ipac.caltech.edu/staff/jarrett/irac/tools/. The software fits the PSF wings of a source whose core is saturated, and was modified by Katherine Johnston and Remy Indebetouw to operate on MIPS 24 $\mu$m data. Uncertainty in the reported flux is estimated to be 20%.

$^f$ Position of the northern of two blended 24 $\mu$m sources (see Figure 1(j)), the probable EGO counterpart.

$^g$ Nearest 24 $\mu$m source, see Figure 1(s). It is unclear whether or not this MIPS source is associated with the EGO to its west.
Table 6
Observational Properties of EGOsa

| Source Name   | Maser? | Cont.? | Thermal Line Emission? | $V_{6.7\ GHz\ maser}$b |
|---------------|--------|--------|------------------------|------------------------|
|               | 6.7 GHz | 44 GHz | 44 GHz | HCO$^+$(3–2) | H$^{13}$CO$^+$(3–2) | CH$_3$OH (5–4) | SiO (5–4) | v$_{LSR}$d | Line Wingsb |
| G10.29−0.13   | Y       | Y      | N        | SA-R | Y        | Y      | ... | Y         | Y-B,R     |
| G10.34−0.14   | Y       | Y      | N        | SA-B | Y        | Y      | ... | Y         | Y-B,R     |
| G11.92−0.61   | Y       | Y      | N        | SA-R | Y        | Y      | Y   | N         |           |
| G18.67+0.03   | Y       | Y      | N        | SA-R | Y        | Y      | Y   | N         |           |
| G18.89−0.47   | Y       | Y      | N        | SA-B | Y        | Y      | Y   | N         |           |
| G19.01−0.03   | Y       | Y      | N        | SA-R | Y        | Y      | Y   | Y-B       |           |
| G19.36−0.03   | Y       | Y      | N        | SA-B | Y        | Y      | Y   | N         |           |
| G22.04+0.22   | Y       | Y      | N        | SA-R | Y        | Y      | Y   | Y-B       |           |
| G23.01−0.41   | Y       | Y      | N        | SA-R | Y        | Y      | Y   | Y-B       |           |
| G23.96−0.11   | Y       | Y      | N        | SA    | Y        | Y      | ... | Y         |           |
| G24.94+0.07   | Y       | Y      | N        | SA-B | Y        | Y      | Y   | N         |           |
| G25.27−0.43   | Y       | Y      | N        | SA-B | Y        | Y      | N   | N         |           |
| G28.28−0.36   | Y       | N      | N        | SA-R | Y        | Y      | N   | N         |           |
| G28.83−0.25   | Y       | Y      | N        | SA-R | Y        | Y      | Y   | Y-B       |           |
| G35.03+0.35   | Y       | Y      | Y        | SA-B | Y        | Y      | N   | Y-B       |           |
| G37.48−0.10   | Y       | Y      | N        | SP    | Y        | N      | ... | Y         | Y-B,R     |
| G39.10+0.49   | Y       | Y      | N        | SA-R | Y        | Y      | N   | N         | Y-B,R     |
| G49.27−0.34   | N       | Y      | N        | SA-B | Y        | Y      | Y   | Y         |           |
| G49.42+0.33   | Y       | N      | N        | SP    | Y        | Y      | Y   | N         |           |
| G24.00−0.10   | Y       | ...    | ...      | ...   | ...      | ...   | ... | ...       |           |
| G28.85−0.23   | Y       | ...    | ...      | ...   | ...      | ...   | ... | ...       |           |
| G49.27−0.32   | N       | ...    | ...      | ...   | ...      | ...   | ... | ...       |           |

Notes.

a For each source and each transition, Y indicates a detection, a non-detection. A detection is defined as $\geq 6\sigma$ for the VLA maser data (Section 2.1, Tables 1 and 2), $\geq 5\sigma$ for the 6.7 GHz continuum (VLA, Section 3.5), and $\geq 3\sigma$ for the thermal molecular line data (JCMT, Section 3.6). A source is not observed in that transition.

b All observed sources were detected in the HCO$^+$(3–2) line. The coding indicates the profile type: SA=self-absorbed, -R indicates red peak is stronger, -B indicates blue peak is stronger. As-R=asymmetric-red, without a clear self-absorption dip. SP=single-peaked.

c If the source was not included in the JCMT survey or if no 6.7 GHz maser was detected, this is indicated by .

d Indicated as Y=yes if any 6.7 GHz maser velocity component falls within the H$^{13}$CO$^+$ profile.

e Indicated as Y=yes if any 6.7 GHz maser velocity component falls on or beyond the wings of the HCO$^+$ profile. R=red, B=blue.

f Questionable because of low S/N in H$^{13}$CO$^+$ spectrum.

g Red side of HCO$^+$ profile falls outside velocity range searched for maser emission.

h Two spatially and kinematically distinct 6.7 GHz masers within JCMT beam.

Table 7
Fitted Properties: 6.7 GHz Masers

| Field Name    | J2000.0 Coordinates | Intensityb | dlb | Velocity (km s$^{-1}$) |
|---------------|---------------------|------------|-----|-----------------------|
| (Target EGO)  | α (bmas) dx (") dy (") | (Jy beam$^{-1}$) | (Jy beam$^{-1}$) | (Jy beam$^{-1}$) |
| G10.29−0.13   | 18 08 49.359 0.073 | −20 05 58.989 0.068 | 0.52 | 0.03 | 1.70 |
| G10.29−0.13   | 18 08 49.361 0.032 | −20 05 58.914 0.030 | 1.26 | 0.03 | 1.83 |
| G10.29−0.13   | 18 08 49.361 0.023 | −20 05 58.947 0.021 | 1.94 | 0.03 | 1.97 |
| G10.29−0.13   | 18 08 49.361 0.021 | −20 05 58.968 0.019 | 2.16 | 0.03 | 2.11 |
| G10.29−0.13   | 18 08 49.362 0.019 | −20 05 58.970 0.017 | 2.36 | 0.03 | 2.25 |
| G10.29−0.13   | 18 08 49.363 0.018 | −20 05 58.983 0.018 | 2.47 | 0.04 | 2.38 |
| G10.29−0.13   | 18 08 49.364 0.023 | −20 05 59.002 0.021 | 1.87 | 0.03 | 2.52 |
| G10.29−0.13   | 18 08 49.360 0.040 | −20 05 58.976 0.037 | 0.91 | 0.03 | 2.66 |
| G10.29−0.13   | 18 08 49.352 0.108 | −20 05 58.879 0.101 | 0.33 | 0.03 | 2.79 |
| G10.29−0.13   | 18 08 49.360 0.107 | −20 05 58.980 0.099 | 0.32 | 0.03 | 2.93 |

Notes.

a $\alpha_{2000} = 7794 \times \alpha_{\text{Jy beam}}^{-1} \times \frac{1.321}{\theta_{\text{maj}} \theta_{\text{min}}} $, where $\theta_{\text{maj}}$ and $\theta_{\text{min}}$ are the dimensions of the synthesized beam in arcseconds from Table 1 (3.5313 arcsec$^2$ is the median value of $\theta_{\text{maj}} \theta_{\text{min}}$ for the 6.7 GHz observations).
b Error in fitted intensity.

(For this table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

EGO. The position for G35.03+0.35 from Pandian et al. (2007), the single-dish survey with the highest angular resolution (0.7; a blind survey with 7″ pointing rms), is offset from 4.5 and 24 μm emission and is 13″ from our interferometric position. The H$_2$O maser surveys generally have smaller beams, but target maser and IRAS positions that are themselves uncertain. Only three
targeted EGOs (G11.92−0.61, G23.01−0.41, G35.03+0.35) are definitely associated with known H2O masers (maser positions known to < 1″ from interferometric observations, see Table 4).

In addition to the targeted EGOs with possible 6.7 GHz CH3OH maser associations from single-dish observations (Table 4), we re-observed eight EGOs with previous interferometric detections of 6.7 GHz CH3OH masers to obtain improved sensitivity and positional accuracy. Our sample includes five EGOs with 6.7 GHz CH3OH maser detections in the Walsh et al. (1998) Australia Telescope Compact Array (ATCA) survey, and one EGO (G11.92−0.62) that fell within the field of view of that survey but was not detected. The absolute uncertainty in the ATCA maser positions is ≥ 1″ (compared to 0′′1 for our VLA observations). The nominal detection limit of the Walsh et al. (1998) survey (0.5 Jy) is about three times poorer than that of our VLA observations (0.16 Jy), but these authors targeted IRAS sources (0′4−2′2 from our EGO targets), reducing the sensitivity at the EGO positions (ATCA primary beam ∼ 8′5 FWHP at 6.7 GHz). In all cases, we detect maser emission over a wider velocity range than reported by Walsh et al. (1998), and our positions differ by up to 1′.8 (for the weak maser associated with G28.28−0.36 at 03° declination). We also detect two weak (<1 Jy beam−1) 6.7 GHz maser spots toward G11.92−0.61 (Section 3.8.3), which were undetected by Walsh et al. (1998). Since the kinematics of 6.7 GHz CH3OH maser emission are of interest for understanding the nature of EGOs, we also re-observed three sources for which only positions and peak velocities were reported by Szymczak et al. (2007) (and references therein).

3.3. Spatial Relationship of Masers and MIR Emission

While detection rates for both 6.7 GHz Class II and 44 GHz Class I CH3OH masers are very high toward the EGOs in our survey, the spatial distributions of the two maser types are quite different. Figure 1 illustrates several general, salient points: (1) 6.7 GHz Class II CH3OH masers are spatially concentrated, typically within one synthesized beam (∼2′); (2) 6.7 GHz CH3OH masers are usually, but not invariably, coincident with discrete 24 μm sources; (3) each EGO is usually associated with only one (at most two) locus of 6.7 GHz CH3OH maser emission; (4) 44 GHz Class I CH3OH masers are spatially distributed, often across many tens of arcseconds (10″ ∼ 0.2 pc at a typical distance of 4 kpc); (5) most EGOs are associated with two to many tens of loci of 44 GHz CH3OH maser emission; and (6) many 44 GHz CH3OH masers are coincident with extended 4.5 μm emission (seen as green in Figure 1) or appear to trace edges where extended 4.5 μm emission meets the surrounding environment (e.g., an IRDC). A corollary is that the positions of 6.7 and 44 GHz masers are, in general, anticorrelated: 6.7 GHz masers are centrally concentrated, toward 24 μm sources, while 44 GHz masers are distributed across (and in some cases, beyond) the area of extended 4.5 μm emission. These general statements are discussed in more detail below and in Section 3.8.

3.3.1. 6.7 GHz Masers

Each diamond plotted in Figure 1 represents the fitted position of a 6.7 GHz maser in a single velocity channel. Although in general there are many diamonds plotted for each source in Figure 1, they tend to overlap at the sizescale of these images into one or a few maser groups. To account for this we have two approaches: (1) each cluster of masers (typically at different velocities) that lie within a synthesized beam (∼2′, see Table 1) is defined as a “maser group,” with its position defined by the intensity weighted mean (Table 9); and (2) the fitted position of each maser spot is reported in Table 7. The sub-synthesized-beam kinematic analysis facilitated by these fits will be discussed in Sections 3.7 and 3.8. For each EGO in our survey within the FWHP of the VLA primary beam at 6.7 GHz (6.7 GHz targeted EGOs plus 3 serendipitously observed), Table 9 lists the properties of associated 6.7 GHz CH3OH maser group(s) and the angular separation of the 6.7 GHz maser group(s) and 24 μm EGO counterpart. Only two EGOs are potentially associated with multiple 6.7 GHz maser groups: G11.92−0.61 and G49.42+0.33. The case of G49.42+0.33 is ambiguous: two spatially and kinematically distinct maser spots are detected, separated by ∼9″ (∼0.5 pc at 12.3 kpc, see also Section 3.8.19). The western maser spot (G49.416+0.326) is associated with the EGO, but lacks a discrete 24 μm counterpart; however, G49.42+0.33 is much more distant than the other EGOs in our sample, so the sensitivity of the MIPS GAL survey corresponds to an intrinsically brighter 24 μm upper limit. The eastern maser spot (G49.417+0.324) is associated with a 24 μm source, but may not be associated with the EGO.

| Field Name | J2000.0 Coordinates | Intensitya | db | Velocity |
|------------|----------------------|------------|----|----------|
| G10.29−0.13 | 1120 1755 1205 0.040 | −20 05 58.185 | 0.041 | 0.24 | 0.03 | 10.43 |
| G10.29−0.13 | 1120 1755 1205 0.017 | −20 05 58.178 | 0.017 | 0.60 | 0.03 | 10.60 |
| G10.29−0.13 | 1120 1755 1205 0.012 | −20 05 58.198 | 0.013 | 0.79 | 0.03 | 10.76 |
| G10.29−0.13 | 1120 1755 1205 0.014 | −20 05 58.218 | 0.014 | 0.69 | 0.03 | 10.93 |
| G10.29−0.13 | 1120 1755 1205 0.023 | −20 05 58.233 | 0.024 | 0.42 | 0.03 | 11.10 |
| G10.29−0.13 | 1120 1755 1205 0.056 | −20 05 58.254 | 0.057 | 0.18 | 0.03 | 11.26 |
| G10.29−0.13 | 1120 1755 1205 0.052 | −20 05 49.354 | 0.053 | 0.57 | 0.09 | 13.26 |
| G10.29−0.13 | 1120 1755 1205 0.049 | −20 05 49.323 | 0.050 | 0.60 | 0.09 | 13.42 |
| G10.29−0.13 | 1120 1755 1205 0.028 | −20 05 57.074 | 0.028 | 1.05 | 0.08 | 13.59 |
| G10.29−0.13 | 1120 1755 1205 0.032 | −20 05 50.607 | 0.033 | 0.36 | 0.03 | 13.75 |

Notes.

a $\theta_{maj} = 3.3′′ \times \frac{0.2867 \times \theta_{min}}{\theta_{maj} \times \theta_{min}}$, where $\theta_{maj}$ and $\theta_{min}$ are the dimensions of the synthesized beam in arcseconds from Table 2 (0.2867 arcsec2 is the median value of $\theta_{maj} \times \theta_{min}$ for the 44 GHz observations).

b Error in fitted intensity.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Table 9 quantifies the correlation of 6.7 GHz CH$_3$OH masers and 24 $\mu$m emission that is visually apparent in Figure 1. Excluding the ambiguous case of G49.42+0.33, of the 21 remaining EGOs in Table 9 (18 targeted plus 3 serendipitously observed), 2 do not have 6.7 GHz maser detections (G49.27−0.34 and G49.27−0.32), and 2 do not have discrete 24 $\mu$m counterparts (G10.29−0.13 and G28.28−0.36). Of the remainder, the angular separation between a 6.7 GHz CH$_3$OH maser and the nearest 24 $\mu$m counterpart is $\lesssim 1''$ for 13/17 EGOs (76%), and $\lesssim 3''$ for all sources with 24 $\mu$m detections. Carey et al. (2009) characterize the absolute positional accuracy of the MIPS GAL survey by cross-correlating sources in 8 $\mu$m GLIMPSE and 24 $\mu$m MIPS images and examining the distribution of positional offsets. The tail of the distribution extends up to 3', with the median offset being 0'.85. The larger maser–24 $\mu$m angular separations ($\sim 2' - 3''$) that we find in regions where the 24 $\mu$m emission is saturated and/or likely consists of blended contributions from several sources (G11.92−0.61, G19.36−0.03, G35.03+0.35) are consistent with the greater uncertainties in attempting to measure positions in such regions. With the exception of the two sources without discrete 24 $\mu$m EGO counterparts (G10.29−0.13, G28.28−0.36) and the ambiguous case of G49.42+0.33, the positions of 24 GHz masers and 6.7 GHz CH$_3$OH masers from our survey are coincident within the combined uncertainties of the MIPS GAL absolute astrometry (Carey et al. 2009) and our measurements of the 24 $\mu$m source positions (see note (a) to Table 5).

### 3.3.2. 44 GHz Masers

As shown in Figure 1, there is diversity in the relationship of 44 GHz CH$_3$OH masers to extended 4.5 $\mu$m emission. As for the 6.7 GHz CH$_3$OH masers, each individual magenta cross plotted represents a fitted position of a 44 GHz maser in a single velocity channel. Details of the 44 GHz maser kinematics are discussed in Sections 3.7 and 3.8. In stark contrast to the Class II 6.7 GHz masers, the Class I 44 GHz masers are, in general, widely distributed over tens of arcseconds. Of the 17 EGOs with 44 GHz maser emission, only one is associated with a single locus of maser emission. For the majority of sources, the distribution of maser emission is spatially and kinematically complex, and not well characterized as an ensemble of mean “spots” (in contrast to the 6.7 GHz masers discussed above).

A striking feature of the images in Figure 1 is that many sources ($\gtrsim 1/3$) exhibit filamentary arcs of 44 GHz CH$_3$OH maser emission (e.g., G11.92−0.61, G19.01−0.03, G19.36−0.03, G22.04+0.22, G24.94+0.07, G35.03+0.35). In these sources, the maser arcs appear to trace out the edges of 4.5 $\mu$m arcs or lobes. Similarly, in G28.83−0.25, 44 GHz masers are concentrated near the edges of the extended 4.5 $\mu$m emission, though the masers themselves do not trace out an arc. Some 44 GHz CH$_3$OH masers are apparently dissociated from any obvious MIR emission (e.g., the masers in IRDCs, offset from EGOs, in the G18.89−0.47 and G28.83−0.25 fields). Individual sources will be discussed in more detail in Section 3.8.

### 3.4. Serendipitous Maser Detections

The three EGOs that were not targets of our survey but that serendipitously fell within the VLA primary beam at 6.7 GHz are discussed in Sections 3.1 and 3.3.1 and included in Tables 4, 5, 6, 7, and 9. In addition, we serendipitously detect seven 6.7 GHz masers unrelated to EGOs. For each of these serendipitous detections, Table 10 includes the maser
properties, the name of the nearest IRAS point source, and previous reports of 6.7 GHz maser emission in the literature. Most of the serendipitously detected masers in Table 10 are associated with MIR-bright regions of massive star formation and/or are identifiable with IRAS point sources; about half were reported in the study of Walsh et al. (1998; see Table 10). The present survey is about three times more sensitive than that of Walsh et al. (1998), and so detects some masers over a wider velocity range. In addition to the intensity-weighted mean positions in Table 10, we include fitted parameters for a wider velocity range. In addition to the intensity-weighted mean positions in Table 10, we include fitted parameters for a wider velocity range.

Table 10

| Target EGO | Gname | Maser Spot Coord., J2000 | $\nu_{\text{peak}}$ | $v_{\text{peak}}$ | $v_{\text{min}}$ | $v_{\text{max}}$ | Nearest IRAS$^c$ | Ang. Sep.$^b$ | Maser?$^d$ |
|------------|-------|---------------------------|---------------------|-----------------|----------------|----------------|----------------|-------------|------------|
| G10.29−0.13 | G10.299−0.146 | 18 08 55.54 −20 05 57.55 | 2.74 | 10.48 | 7.60 | 20.22 | 18060−2005 | 54 | 6.7 |
| G10.34−0.14 | G10.322−0.160 | 18 09 01.45 −20 05 07.77 | 72.53 | 11.56 | 4.15 | 14.30 | 18060−2005 | 45 | 6.7 |
| G11.92−0.61 | G11.936−0.616 | 18 14 00.90 −18 53 26.11 | 42.77 | 32.26 | 30.07 | 44.22 | 18110−1854 | 9 | 6.7 |
| G18.67+0.03 | G18.662+0.035 | 18 24 51.10 −12 39 22.00 | 3.90 | 79.01 | 77.64 | 82.71 | 18220−1241 | 5 | 6.7 |
| G23.96−0.11 | G23.986−0.089 | 18 35 20.09 −07 59 45.00 | 2.62 | 65.15 | 64.05 | 67.07 | 18326−0802 | 5 | 6.7 |
| G24.94+0.07 | G24.920+0.088 | 18 36 25.94 −07 05 07.89 | 4.19 | 53.16 | 45.34 | 53.71 | 18337−0707 | 30 | 6.7 |
| G37.48−0.10 | G37.546−0.112$^d$ | 19 00 16.00 +04 03 16.23 | 3.98 | 49.99 | 49.31 | 52.87 | 18577+0358 | 10 | 6.7 |

Notes.

$^a$ B1950 coordinates.

$^b$ From IRAS point source.

$^c$ As in Table 4, 6.7 indicates a 6.7 GHz CH$_3$OH maser with an interferometric position. All “6.7” designations are from Walsh et al. (1998). 6.7? indicates a 6.7 GHz CH$_3$OH maser detection from a single-dish survey with a reported or targeted position within one single-dish beam of our interferometric position. All 6.7? are from Szymczak et al. (2000, 2002), and Pandian et al. (2007).

$^d$ This source is located at ~30% level of the VLA primary beam. We include it in this table and Table 7 because, to the best of our knowledge, an interferometric position has not been previously published.

3.6. Thermal Molecular Line Emission

Our JCMT molecular line observations provide context for our maser surveys by establishing the thermal gas $v_{LSR}$ for each EGO and providing independent outflow indicators. Figure 2 presents the JCMT HCO$^+$(3−2) and H$^{13}$CO$^+$(3−2) spectra toward each EGO in our sample. The integrated 6.7 GHz maser spectrum for each EGO-associated maser group (see Section 3.3.1 and Table 9) and the velocity range of 44 GHz maser emission are overplotted on the JCMT spectra to illustrate the relationship of the thermal gas, Class I, and Class II CH$_3$OH maser velocities, discussed in Sections 3.7 and 3.8. For each source, the velocity range shown is that searched for 6.7 GHz CH$_3$OH maser emission (Table 1); the velocity range searched for 44 GHz CH$_3$OH maser emission (Table 2) is delimited by dotted vertical lines. The exception is G49.42+0.33, which was observed at 44 GHz using two different tunings centered on the two kinematically distinct 6.7 GHz maser components; for this source, the velocity range searched for 6.7 GHz maser emission is delimited by vertical dashed lines.

Every EGO in our targeted sample was detected in HCO$^+$(3−2) ($E_T = 12.8$ K); as shown in Figure 2, the HCO$^+$ profiles are, in general, non-Gaussian, and are characterized by self-absorption dips and broad line wings. Due to the self-absorption, we have not fit the HCO$^+$ profiles. The majority of sources in our sample have full widths at zero intensity ($\Delta v_{FWZI}$) in excess of 20 km s$^{-1}$ in HCO$^+$. Of the 17 EGOs in our survey with self-absorbed or asymmetric HCO$^+$(3−2) profiles, the blue peak is stronger in about half (7), while in the other half the red peak is stronger (9), with 1 indeterminate (Table 6). Contracting cloud models predict “blue-skewed” (asymmetric, with the blue peak brighter) profiles for optically thick lines such as low-energy HCO$^+$ transitions (Myers et al. 1996; De Vries & Myers 2005). The approximately equal distribution of red and blue-skewed profiles in our sample is consistent with the results of HCO$^+$(1−0) surveys of 6.7 GHz CH$_3$OH maser sources by Purcell et al. (2006) and Szymczak et al. (2007), although Klaassen & Wilson (2007) suggest that higher J transitions may be better suited to tracing infall. A more detailed analysis of the JCMT spectra will be presented in a future work.

H$^{13}$CO$^+$(3−2) ($E_T = 12.5$ K) emission is also detected at $\geq 3\sigma$ in all observed EGOs. For each EGO, Table 3 lists the amplitude, line centroid velocity, $\Delta v_{FWHM}$, and integrated line intensity.
obtained by a single Gaussian fit to the H$^{13}$CO$^+$(3–2) profile, and the kinematic distance based on the prescription of Reid et al. (2009) and the H$^{13}$CO$^+$ line center velocity. The distance listed is the near kinematic distance, unless otherwise noted; the angular extent of EGOs (see Section 1) and the association of EGOs with IRDCs (see also Cyganowski et al. 2008) support the adoption of the near kinematic distance. Parameters from single Gaussian fits to the CH$_3$OH(5$_2$–4$_1$, 3) and SiO(5–4, $E_l = 20.8$ K) lines are also listed in Table 3, and the spectra are presented in Figures 3 (CH$_3$OH(5$_2$–4$_1$, 3)) and 4 (SiO(5–4)). If a transition was observed but not detected at the 3σ level, the 3σ upper limit is listed in Table 3. We detect thermal CH$_3$OH(5$_2$–4$_1$, 3) emission toward 83% (15/18) of surveyed EGOs. The median line FWHM for our sample is 3.3 km s$^{-1}$ for H$^{13}$CO$^+$(3–2) and 4.8 km s$^{-1}$ for CH$_3$OH(5$_2$–4$_1$, 3).

We detect SiO(5–4) emission toward 9/10 (90%) of EGOs surveyed for SiO emission, with a median FWHM of 10.5 km s$^{-1}$. The weather was relatively poor during the SiO observations of the source (G39.10+0.49) that was not detected, and the 3σ upper limit is comparable to or greater than the fitted amplitudes of SiO lines toward several EGOs observed in better weather. This detection rate is much higher than that of a JCMT SiO(6–5) survey of MYSOs with linear distributions of 6.7 GHz CH$_3$OH masers and H$_2$ emission in narrowband images (9/10; 90%).

Eleven EGOs targeted in our survey have previously been searched for molecular line wings indicative of outflow as part of single-dish surveys (resolution 10′–60′) targeting H$_2$O or CH$_3$OH masers (in HCO$^+$, CO, CS, or SiO; see Table 4). Of these, ∼73% (8/11) were reported to have at least tentative evidence of outflow activity.

### 3.7. Maser and Thermal Gas Kinematics

Figure 2 presents a direct visual comparison of the velocity ranges of thermal gas emission (HCO$^+$ and H$^{13}$CO$^+$), 6.7 GHz CH$_3$OH maser emission, and 44 GHz CH$_3$OH maser emission for each EGO. The sheer kinematic diversity of our sample is illustrated by Figure 2. The velocity extents of both 44 GHz
Figure 2. (Continued)
The usable bandwidth of the 6.7 GHz maser observations is also marks the H13CO+ velocity from Table 3. The velocity range shown for each EGO is the same as that in Figure 2. The dotted vertical line marks the H13CO+ velocity from Table 3.

(A complete figure set (18 images) is available in the online journal.)

Class I and 6.7 GHz Class II CH3OH maser emission vary widely from source-to-source (<1 to ~12 km s⁻¹ and ~1.5–18 km s⁻¹, respectively), as does whether maser emission is continuous across a velocity range or comprised of multiple, kinematically separated components. In general, 6.7 GHz maser emission spans a wider velocity range than 44 GHz maser emission, but this is not universally the case (exceptions include G11.92–0.61, G19.01–0.03, G19.36–0.03, and G24.94+0.07). The usable bandwidth of the 6.7 GHz maser observations is also ~1.5 × greater (in km s⁻¹) than that of the 44 GHz maser observations (Section 2.1, Tables 1 and 2), and there are sources in which 44 GHz maser emission extends to, and most likely beyond, the edge of the observed velocity range (e.g., G10.29–0.13, Figure 2(a); G18.89–0.47, Figure 2(e)).

One generalization that may be made based on Figure 2 is that 44 GHz Class I CH3OH maser emission is invariably (but not exclusively) present at the gas vLSR (as indicated by the H13CO+ emission). The velocity of Class II 6.7 GHz CH3OH maser emission, in contrast, exhibits every possible permutation with respect to the velocity of the thermal gas: coincident, anticorrelated, redshifted, blueshifted, and every combination of these characteristics. The relative velocities of the thermal gas and 6.7 GHz CH3OH maser emission for each source are listed in Table 6.

To investigate the spatial structure of the kinematic complexity of the maser spectra, Figure 5 presents plots of maser positions color-coded by velocity. For each source, the left-hand panel of Figure 5 shows 44 GHz CH3OH maser positions overplotted on the 4.5 µm image from the GLIMPSE survey. On the scale of these plots, the uncertainty in the 44 GHz maser positions is smaller than the symbol size, and every fitted position from Table 8 is plotted individually. For each source, the black rectangle(s) overplotted on the 4.5 µm image is the field of view of the right-hand panel(s), which show the positions of 6.7 GHz masers color-coded by velocity. In the 6.7 GHz maser plots, the sizes of the crosses correspond to the relative positional uncertainties for each maser in Table 7 (from the SAD fitting). While individual 6.7 GHz maser spots are unresolved by the VLA synthesized beam (~2′′), the positional uncertainty of an unresolved source in a well-calibrated image (such as our self-calibrated 6.7 GHz data), relative to other such sources in the same image, goes as Δθ ~ θsyn/beam/(2 × S/N), where S/N is the signal-to-noise ratio of the source (Fomalont 1999). For our 6.7 GHz data, a 10σ detection corresponds to a relative positional uncertainty of ~0′.15 for the low-declination sources (δ < −8°) and ~0′.10 for the high-declination sources (δ > −8°) in our sample (see Table 1), while the strongest masers have relative positional uncertainties at the milliarcsecond level (Table 7). To simplify the plots and concentrate on the best-determined features, 6.7 GHz maser fits with positional uncertainties corresponding to a S/N ≤ 10 are not shown in Figure 5 and 6.7 GHz maser fits with positional uncertainties corresponding to a S/N ≤ 30 are plotted as narrower lines (0′.05 ≤ Δθ < 0′.15 for the low-declination sources and 0′.033 ≤ Δθ < 0′.10 for the high-declination sources).

For each source in Figure 5, the absolute limits in km s⁻¹ of the velocity bins for that source are given in a legend (far right): the bin color-coded as green is approximately centered on the velocity of the SiO line. The dotted vertical line marks the H3CO+ velocity from Table 3.

(A complete figure set (10 images) is available in the online journal.)

In most cases, the targeted EGO is the only or the dominant MIR source within the JCMT beam. Mm-wavelength interferometric observations have revealed protoclusters, on ~10⁴ scales, in young MSFRs without obvious MIR multiplicity in Spitzer images (e.g., NGC6334I(N) and S255N; Hunter et al. 2006; Cyganowski et al. 2007; Klein et al. 2009; Brogan et al. 2009). Additional sources either undetected or unresolved by MIPS at 24 µm may likewise be present within our JCMT beam. In our EGO spectra (Figure 2), however, the profile of the (optically thin) H3CO+ is generally single-peak and at the velocity of the dip in the profile of the (optically thick) HCO+, suggesting that the HOCO⁺ profile shape is likely due to dynamics and not superposition. While 6.7 GHz CH3OH maser emission is believed to originate near the MYSO, there is little consensus in the literature on the kinematics of the maser environment—e.g., disk, outflow, or other (see Section 4.2). For EGOs in which
both thermal CH$_3$OH and H$^{13}$CO$^+$ emission are detected in our JCMT spectra, the median offset between the fitted centroid velocities of the two lines is $\lesssim0.3$ km s$^{-1}$. We thus take the $v_{\text{LSR}}$ of the H$^{13}$CO$^+$ emission as the best indicator of the EGO systemic velocity that is available for all sources in our sample. The preponderance of 44 GHz masers at or near the gas $v_{\text{LSR}}$, noted above with reference to Figure 2, is reflected in Figure 5.

### 3.8. Notes on Individual Sources

#### 3.8.1. G10.29–0.13

This EGO is located in an IRDC, west of an extremely MIR-bright complex of sources in the W31 giant molecular cloud (Figure 1(a)). The extended 4.5 $\mu$m emission is roughly linear and is extended along an E–W axis. Class I 44 GHz CH$_3$OH masers are detected at the ends of the linearly extended 4.5 $\mu$m emission: the 44 GHz masers at the western tip are blueshifted and those at the eastern tip are redshifted relative to the thermal gas $v_{\text{LSR}}$ (Figure 5(a)). The 6.7 GHz CH$_3$OH maser group is located about midway between the red and blueshifted 44 GHz CH$_3$OH masers and near the southern edge of the extended 4.5 $\mu$m emission. Walsh et al. (1998) report a N–S linear distribution of 6.7 GHz masers, but report masers over a much smaller velocity range ($v = 2.2$–7.8 km s$^{-1}$) than detected in our survey ($v = 1.7$–19.9 km s$^{-1}$, Table 9). In aggregate, the 6.7 GHz CH$_3$OH masers detected in our survey are oriented along a NE–SW axis, while the brightest red and blueshifted masers are oriented along an E–W axis (Figure 5(a)), similar to the orientation of the extended 4.5 $\mu$m emission.

The 6.7 GHz CH$_3$OH masers span a much broader velocity range than the 44 GHz masers (Figures 2(a) and 5(a)): to the blue, where our velocity coverage for the two frequencies is comparable, the 6.7 GHz maser emission extends $\sim9$ km s$^{-1}$ further from the thermal gas $v_{\text{LSR}}$ (13.6 km s$^{-1}$; Table 3) than the 44 GHz maser emission. The strongest 6.7 GHz CH$_3$OH maser emission is blueward of the HCO$^+$ emission, while the stronger line wing in the HCO$^+$ profile is to the red (Figure 2(a)).

This source is unique in our sample in that the EGO lacks a discrete MIPS 24 $\mu$m counterpart, but both 6.7 GHz Class II and 44 GHz Class I CH$_3$OH masers are detected. A submillimeter clump is coincident with the EGO (Walsh et al. 2003; Di Francesco et al. 2008; see Table 4), and a weak 24 $\mu$m EGO counterpart could be masked by the wings of the point-spread function (PSF) from the adjacent saturated complex. The submillimeter data, combined with the lack of a clear MIPS 24 $\mu$m counterpart, suggest that the “central” source powering the 4.5 $\mu$m outflow may be very young, with its envelope contributing significantly to its SED at long wavelengths (e.g. Robitaille et al. 2006). Higher resolution observations are, however, required to determine the number, luminosities and masses of compact dust core(s) in this region and their relationship to the extended 4.5 $\mu$m and CH$_3$OH maser emission.

This field is notable for widely distributed 44 GHz CH$_3$OH masers (Figures 1(a) and 5(a)). The eastern and western ensembles of masers are $\gtrsim30^\circ$ ($\gtrsim0.3$ pc at 2.2 kpc) from the EGO and lie along a ridge of 850 $\mu$m dust emission. Without large-scale maps in a molecular outflow tracer, it is impossible to know whether these 44 GHz masers are excited by a large-scale outflow emanating from the EGO or by distinct sources.

#### 3.8.2. G10.34–0.14

This EGO is located north of the MIR-bright complex in the W31 molecular cloud described above (Section 3.8.1), and is located in an IRDC. The extended 4.5 $\mu$m emission of this EGO is predominantly linear, along a NW–SE axis, with an additional patch of more diffuse 4.5 $\mu$m emission $\sim15^\prime$ to the SE (Figures 1(b) and 5(b)). The spatial relationship of the Class I CH$_3$OH masers and the extended 4.5 $\mu$m emission is complex: this is also true of the velocity distribution of the 44 GHz masers. The most coherent features are (from E to W in the left panel of Figure 5(b)): (1) a concentration of slightly blueshifted masers coincident with the diffuse 4.5 $\mu$m emission to the SE; (2) two lines of blueshifted masers to the south of the EGO, roughly parallel to each other and $\sim5^\prime$ apart; and (3) a concentration of redshifted masers near the NW edge of the linear 4.5 $\mu$m emission.

The velocity distribution of the 6.7 GHz CH$_3$OH maser emission is also complex. To the north is a dense concentration of masers spanning $\sim9$ km s$^{-1}$ ($v \sim7$–16 km s$^{-1}$, Table 7). To the south are two linear features, one comprised predominantly of redshifted masers (oriented N–S), and the other of blueshifted masers (oriented NE–SW). This 6.7 GHz CH$_3$OH maser was previously reported by Walsh et al. (1998), but over a much narrower velocity range ($v = 14.3$–16.7 km s$^{-1}$, compared to $v = 3.6$–18 km s$^{-1}$ in our survey, Table 9). The 6.7 GHz maser group is located near redshifted 44 GHz CH$_3$OH maser emission.

#### 3.8.3. G11.92–0.61

This EGO is unique in our sample in having two spatially distinct 6.7 GHz CH$_3$OH maser groups, separated by $\sim5^\prime$ (Figures 1(c) and 5(c)). The 4.5 $\mu$m emission is bipolar in appearance, consisting of a NE and a SW lobe. Both 6.7 GHz CH$_3$OH maser groups, and MIPS 24 $\mu$m emission, are coincident with the NE lobe. The morphology of the MIPS 24 $\mu$m emission is elongated north–south, suggesting that it may be a blend of emission from multiple sources (Figure 1(c)).

In contrast to many of the other EGOs in our sample, the velocity extent of emission from each 6.7 GHz CH$_3$OH maser group is narrow, and the total velocity extent of 6.7 GHz maser emission falls well within the HCO$^+$ profile (Figure 2(c): maser spot 1, northern; maser spot 2, southern). The emission from both 6.7 GHz CH$_3$OH maser groups is weak, and redshifted by a few km s$^{-1}$ from the thermal gas $v_{\text{LSR}}$. A strong ($I_{\text{peak}} \sim 248$ Jy beam$^{-1}$) H$_2$O maser (Hofner & Churchwell 1996), marked by a triangle in Figure 5(c) (left panel), is offset by $\sim0.5$ from the southern 6.7 GHz CH$_3$OH maser. The H$_2$O maser emission peaks $\sim3.3$ km s$^{-1}$ redward of the CH$_3$OH maser emission, but the H$_2$O maser emission spans a wide velocity range (16.4 km s$^{-1}$), and a weaker secondary peak is present in the spectrum at the velocity of the CH$_3$OH maser (see Figure 1(a) of Hofner & Churchwell 1996).

The 44 GHz Class I CH$_3$OH maser emission in the vicinity of the NE 4.5 $\mu$m lobe is dominated by an arc of masers, near and around the edge of the extended 4.5 $\mu$m emission, from the northwest to the southeast, and at or near the thermal gas $v_{\text{LSR}}$ (Figure 5(c)). This EGO is in an IRDC (Figure 1(c)), and this morphology and velocity structure are consistent with the masers tracing the interface between outflow(s) (traced by diffuse 4.5 $\mu$m emission) and the surrounding environment (IRDC). In contrast, the 44 GHz CH$_3$OH masers associated
with the SW 4.5 μm lobe are coincident with the 4.5 μm emission (not along its edges), are arranged linearly (not in an arc), and are predominantly blueshifted (although a redshifted maser is also present). The 44 GHz masers toward the SW lobe are also the strongest in this region. The JCMT beam was centered on the NE lobe, so the reported thermal gas vLSR is that toward the 6.7 GHz masers and MIPS source. Broad SiO(5–4) emission (ΔvFWHM = 9.6 km s⁻¹) was detected in our JCMT survey (Table 3). Taken together, the evidence suggests that the “central” source(s) responsible for driving the outflow(s) (traced by extended 4.5 μm emission and 44 GHz CH3OH masers) are located in the NE lobe (and hence contribute to its MIR emission), while the SW 4.5 μm lobe may be dominated by emission from shocked outflow gas.

3.8.4. G18.67+0.03

The relation of the 44 GHz CH3OH masers to the 4.5 μm emission toward this EGO is varied; some masers are coincident with bright 4.5 μm emission, while others lie near its edge (Figures 1(d) and 5(d)). The velocity range of the 44 GHz maser emission is extremely narrow (≤ 2 km s⁻¹, centered on the thermal gas vLSR; Figure 2(d)). The 6.7 GHz CH3OH maser emission is triple-peaked and spans a wider velocity range (∼ 5 km s⁻¹) but still falls within the HCO⁺ profile. On 0.1 scales, the 6.7 GHz CH3OH masers appear segregated by velocity, with a concentration of blueshifted masers to the NW and a concentration of predominantly systemic to slightly redshifted masers to the SE. Very little is known about this source beyond the results of the present survey. The EGO is not in a clear IRDC, and is ∼ 40" east of a submillimeter source (G18.66+0.04) reported by Schuller et al. (2009).

This field is notable for detections of 44 GHz CH3OH masers that are clearly associated with other MIR sources in the field and not with the targeted EGO. Figure 1(d) shows three compact MIPS 24 μm sources, each with associated masers: from E to W (left to right), these are: (1) the targeted EGO, G18.67+0.03, with associated 6.7 and 44 GHz masers; (2) a MIR source with associated 44 GHz masers (l ∼ 18.665, b ∼ 0.030); and (3) a MIR source with an associated 6.7 GHz CH3OH maser (G18.662+0.035, see Table 10) and 44 GHz CH3OH masers. This westernmost source is encompassed by the dimensions of the submillimeter source G18.66+0.04 (Schuller et al. 2009). As these sources are not the focus of our study and information on the gas kinematics comparable to that provided by our JCMT survey is not available, we do not discuss the kinematics of these serendipitously detected masers.

3.8.5. G18.89−0.47

This EGO is in an IRDC, SW of a multiband IRAC and 24 μm source (Figure 1(e)). Both MIR sources, and much of the IRDC, are encompassed by the dimensions of a submillimeter source reported by Schuller et al. (2009) (G18.89−0.47, M = 2040 M☉). The extended 4.5 μm emission of this EGO is predominantly linear, and is extended along a N–S axis. The 6.7 GHz CH3OH maser emission toward this EGO is kinematically complex (Δv ∼ 4.3 km s⁻¹) and lies on the far blue wing of the HCO⁺ profile (Figure 2(e)). The 6.7 GHz maser emission is offset to the blue by ∼ 9–13 km s⁻¹ from the thermal gas vLSR (66.6 km s⁻¹, Table 3), with the maser emission peak offset by ∼ 10 km s⁻¹. The velocity coverage of our 6.7 GHz maser observations does not extend a comparable amount to the red of the gas velocity, so whether the maser emission is symmetric with respect to the thermal gas emission is not known. Our 44 GHz maser observations (centered on the 6.7 GHz maser velocity) do not extend redward of the gas vLSR. The velocities of the 44 GHz CH3OH masers ∼ 20″ and 25″ to the SW, in the IRDC, are comparable to those of the 44 GHz masers near the EGO (Figure 5(e)). The masers in the IRDC may be associated with an extended outflow from the EGO or may be excited by other sources.

3.8.6. G19.01−0.03

This source is in many ways the MIR prototype of the EGO class: it has a clear bipolar morphology at 4.5 μm, an identifiable central point source at IRAC wavelengths and at 24 μm (Figure 1(f)), and had not been studied prior to the EGO catalog of Cyganowski et al. (2008). This EGO is located in an IRDC, and Schuller et al. (2009) have subsequently reported a submillimeter clump of ∼ 1000 M☉ (dimensions 40″ × 34″) coincident with the EGO. Our detection of 6.7 GHz CH3OH maser emission toward the central source (Figures 1(f) and 5(f)) and the presence of a massive dust core both support the identification of the EGO as a massive YSO.

The 6.7 GHz CH3OH maser emission is kinematically complex (Figures 2(f) and 5(f)). The most blueshifted maser emission is concentrated to the NW and has an arc-like morphology, while redshifted maser emission is concentrated to the east (Figure 5(f)).

Many 44 GHz Class I CH3OH masers are detected toward this EGO; the masers are mostly coincident with the extended 4.5 μm emission and, to the north of the central source, trace out a striking arc or loop. This morphology is similar to that sketched by Kalenski et al. (2006) for Class I CH3OH masers excited in an outflow with its axis perpendicular to the observer (e.g., in the plane of the sky). The arc-like morphology of the 44 GHz CH3OH masers observed in G19.01−0.03 is also similar to that of 44 GHz CH3OH masers attributed to bow shocks in a bipolar outflow in DR21(OH) (Araya et al. 2009).

The velocities of the 44 GHz CH3OH masers in G19.01−0.03 span ∼ 9 km s⁻¹, and the range is asymmetric with respect to the thermal gas vLSR (59.9 km s⁻¹, Table 3); the maser emission extends farther to the blue than to the red (Figure 2(f)). Figure 5(f) shows that there is a pattern to the 44 GHz maser velocities. North of the central source, the masers generally have velocities systemic and blueward (by up to ∼ 6.5 km s⁻¹). In contrast, south of the central source there is a dearth of blueshifted masers; the masers have velocities systemic and redward, though by a maximum of ∼ 2.2 km s⁻¹. This morphology and velocity structure suggest that the 44 GHz Class I CH3OH masers and the extended 4.5 μm emission trace a bipolar outflow, with the blue lobe to the north and the red lobe to the south of the central source. Broad SiO(5–4) emission (ΔvFWHM = 9.8 km s⁻¹) was detected toward this EGO in our JCMT survey (Table 3). Further observations at high angular resolution are required to establish the extent and kinematics of the outflow traced by 4.5 μm emission and Class I 44 GHz CH3OH masers and to determine whether it is excited by a single source or a (proto)cluster.

3.8.7. G19.36−0.03

The extended 4.5 μm emission for G19.36−0.03 extends to the south and to the northwest of several multiband IRAC sources, while the MIPS 24 μm emission is elongated along the same axis, suggesting blended 24 μm emission from multiple sources (Figure 1(g)). The 6.7 GHz CH3OH maser
group is coincident with 24 \( \mu \)m emission, \( \sim 3'' \) south of the nominal MIPS position (Table 9). The most striking feature of the 44 GHz Class I CH\(_3\)OH maser emission is an arc of masers to the southeast that is coincident with 4.5 \( \mu \)m emission. The masers in this arc span the entire observed velocity range, \( \Delta v \sim 7 \text{ km s}^{-1} \) (Figure 5(g)). This EGO is in an IRDC and the arc of 44 GHz CH\(_3\)OH masers may be tracing the interaction of a 4.5 \( \mu \)m outflow with the surrounding environment, similar to G11.92−0.61. North of the arc, other 44 GHz CH\(_3\)OH masers are distributed along the edges of 4.5 \( \mu \)m emission, coincident with the northwestern 4.5 \( \mu \)m extension, and coincident with the 24 \( \mu \)m source. Several 44 GHz masers are also coincident with filamentary 8 \( \mu \)m emission just west of the EGO. A 44 GHz maser \( \sim 20'' \) east of the EGO is associated with an additional weak source of diffuse 4.5 \( \mu \)m emission. Very broad SiO(5–4) emission (\( \Delta v_{\text{FWHM}} = 20.6 \text{ km s}^{-1} \)) was detected toward this EGO in our JCMT survey (Table 3).
Only one locus of 6.7 GHz CH$_3$OH maser emission is detected, implying that despite the complicated MIR morphology, only one YSO of sufficient mass and early enough evolutionary state to excite 6.7 GHz CH$_3$OH maser emission is present. There is structure in the velocity distribution of the 6.7 GHz CH$_3$OH masers: redshifted masers are concentrated to the north and east of blueshifted masers (Figure 5(g)). There is also an E–W velocity gradient in the redshifted masers, with the most redshifted masers to the east. Walsh et al. (1998) report 6.7 GHz CH$_3$OH maser emission toward this source; compared to the present survey, their positions are offset by $\sim 0\farcs5$ to the north. The structure seen in our survey in the 6.7 GHz CH$_3$OH maser velocities on small spatial scales is not reflected in the velocity distribution of the 44 GHz CH$_3$OH masers on much larger spatial scales.

3.8.8. G22.04+0.22

G22.04+0.22 is located in an IRDC, south and east of two bright sources of MIR emission (Figure 1(h)). The 6.7 GHz CH$_3$OH masers detected toward this EGO are coincident with bright 4.5 $\mu$m emission, and with 24 $\mu$m emission (angular separation from 24 $\mu$m peak is $\sim 2\arcsec$; Figure 1(h) and Table 9). In contrast, the 44 GHz CH$_3$OH maser emission tends toward the periphery of the 4.5 $\mu$m emission, and is characterized by three main regions of maser emission—to the north, northeast, and south—and a clump of masers to the southwest. The northeastern masers coincide with and trace the extended 4.5 $\mu$m emission, while the other regions of maser emission lie at the edges of or beyond the extended 4.5 $\mu$m emission. The two northern maser regions are kinematically well-mixed (e.g., include masers across a range of velocities). The southern region, in contrast, consists predominantly of a N–S line of masers redshifted relative to the thermal gas $v_{\text{LSR}}$; south of this line lies an E–W distribution of masers at the systemic velocity and blueward (Figure 5(h)). The 6.7 GHz CH$_3$OH masers have a broadly N–S distribution, with the most blueshifted masers to the south, redshifted masers in the middle, and masers with slightly blueshifted and systemic velocities to the north. The strongest, blueshifted, 6.7 GHz masers appear to be distributed in an arc-like pattern. Very broad SiO(5–4) emission ($\Delta v_{\text{FWHM}} = 18.3$ km s$^{-1}$) was detected toward this EGO in our JCMT survey (Table 3).

The copious 44 GHz CH$_3$OH maser emission, broad line wings of the HCO$^+$ profile (Figure 2(h)), and detection
of SiO all support the presence of molecular outflow(s) from this previously unstudied MYSO, but their number, orientation and kinematics remain unclear from the available data. High-resolution observations of a direct molecular outflow tracer are required to understand the kinematics of the outflow(s) in this region and their relation to the unusual 44 GHz CH$_3$OH maser morphology and kinematics.

3.8.9. G23.01−0.41

This EGO is host to one of only seven known H$_2$CO 6 cm masers, a maser species which is thought to be associated with very young MYSOs (Araya et al. 2008), and is unusual among our sample in having been the subject of detailed multiwavelength studies (see, for example, Araya et al. 2008, for a review). Zeeman splitting analysis of the 6.7 GHz CH$_3$OH maser emission from this source by Vlemmings (2008) indicates that the brightest maser peak ($v_{\text{peak}} = 74.81$ km s$^{-1}$, $I_{\text{peak}} = 469.36$ Jy beam$^{-1}$ in our data) has a strong negative magnetic field ($B_\parallel = -30.3$ mG), while the redshifted maser components ($v > 79$ km s$^{-1}$) have a weaker, positive magnetic field ($B_\parallel \sim 14$ mG). Blueshifted (negative magnetic field) and redshifted (positive magnetic field) 6.7 GHz CH$_3$OH maser emission are spatially distinct (Figure 5(i)). Blueshifted 6.7 GHz maser emission is concentrated to the northeast and consists of two linear features with broadly NE–SW orientations that meet to form a V-like morphology, with the opening of the V oriented ∼45° east of north. Redshifted 6.7 GHz maser emission is concentrated to the south/southwest, in a more diffuse structure. The projected offset between the main concentrations of blueshifted and redshifted 6.7 GHz masers is ∼0.2′′ (≥920 AU at 4.6 kpc).
The 6.7 GHz CH$_3$OH maser emission is coincident with 3 mm continuum emission observed at $\sim 2''$–$5''$ angular resolution by Furuya et al. (2008). The intensity-weighted 6.7 GHz CH$_3$OH maser position from our observations is within 0.4 of the average 3 mm continuum peak position. Scaled to the Brunthaler et al. (2009) parallax distance of 4.6 kpc, the dust mass of the 3 mm core reported by Furuya et al. (2008) is $\sim 70 M_{\odot}$.

The morphology of the high-velocity molecular gas in the region (mapped at $\sim 5''$ angular resolution by Furuya et al. 2008) is complicated, and depends on the tracer, but is generally oriented NE to SW. Both red and blueshifted $^{12}$CO and $^{13}$CO emission are present to the NE and SW of the 3 mm continuum source, while HNCO shows only blueshifted emission to the SW (Figure 6 in Furuya et al. 2008). The 44 GHz Class I CH$_3$OH masers lie on or along the edges of the outflow, but the mix of maser velocities—both red and blueshifted masers to the SW—is more consistent with the complex velocity structure seen in the CO observations. However, red and blueshifted CO emission extends to much higher relative velocities than the 44 GHz masers. Broad SiO(5–4) emission ($\Delta V_{\text{FWHM}} = 14.9$ km s$^{-1}$) was detected toward this EGO in our JCMT survey (Table 3), consistent with the results of Harju et al. (1998; full width 34.4 km s$^{-1}$ for SiO(2–1) and 24.7 km s$^{-1}$ for SiO(3–2)).

The positions of the H$_2$CO maser from Araya et al. (2008) (black diamond) and of H$_2$O masers from Forster & Caswell (1999) (triangles) are overplotted on the 4.5 $\mu$m image in Figure 5(i). The H$_2$CO maser is located $\sim 0''$ to the east of the blueshifted cluster of 6.7 GHz masers (Figure 5(i)) at a comparable blueshifted velocity (73.6 km s$^{-1}$). The velocity range of the H$_2$O masers (68.41–81.59 km s$^{-1}$) is comparable to that of the 6.7 GHz CH$_3$OH maser emission, but the H$_2$O maser positions are offset to the west by $\sim 1''$.5.
3.8.10. G23.96−0.11

The relationship of the CH$_3$OH masers to the MIR emission toward this EGO suggest that the EGO may in fact be comprised of at least two distinct sources: (1) a northern source, associated with a 6.7 GHz CH$_3$OH maser group, a cluster of 44 GHz CH$_3$OH masers, and a weaker 24 $\mu$m source, and (2) a southern multiband IRAC source with a brighter 24 $\mu$m counterpart and extended 4.5 $\mu$m emission to its south. Most of the 44 GHz CH$_3$OH masers are coincident with or at the edges of extended 4.5 $\mu$m emission (Figure 1(j), 5(j)). The brightest 6.7 GHz masers are blueshifted with respect to the thermal gas $v_{\text{LSR}}$. A position and peak velocity for this 6.7 GHz maser were previously reported by Szymczak et al. (2007) (and references therein). The JCMT beam encompassed both the northern and southern 24 $\mu$m emission, and the H$^{13}$CO$^+$ profile is asymmetric, with a weaker, redder secondary bump. High-resolution molecular line observations are required to clarify the number, nature, and kinematics of sources in this region. See note added in proof.

3.8.11. G24.94+0.07

This EGO is extended roughly north–south and lies east of two multiband MIR point sources (Figure 1(k)). The 6.7 GHz masers are coincident with 24 $\mu$m emission, and have an unusually narrow velocity extent ($\Delta v \sim 2$ km s$^{-1}$), with the peak being $\sim$5 km s$^{-1}$ redward of the thermal gas $v_{\text{LSR}}$ and $\sim$2 km s$^{-1}$ redward of the reddest 44 GHz CH$_3$OH maser (Figure 2(k)). The 6.7 GHz maser group is spatially closest to the reddest 44 GHz CH$_3$OH masers (Figure 5(k)). Most of the other 44 GHz CH$_3$OH masers are at or near the thermal gas $v_{\text{LSR}}$ and are distributed on or along the edges of extended 4.5 $\mu$m emission. The arc of masers to the northeast, in particular, traces a 4.5 $\mu$m lobe. SiO(5–4) emission ($\Delta v_{\text{FWHM}} =$
7.2 km s\(^{-1}\)) was detected toward this EGO in our JCMT survey (Table 3).

3.8.12. G25.27−0.43

This EGO, located in an IRDC (Figure 1(l)), is unique in our sample in having only one locus of 44 GHz CH\textsubscript{3}OH maser emission. The extended 4.5 \(\mu\)m emission is roughly linear and is extended along a roughly NW–SE axis; the 44 GHz maser is near the edge of the extended 4.5 \(\mu\)m emission. The velocity of the 44 GHz maser emission corresponds well with that of the HCO\(^+\) and \textsuperscript{13}CO\(^+\) emission (Figure 2(l)) and spans a range of \(\sim 3\) km s\(^{-1}\). The 6.7 GHz CH\textsubscript{3}OH maser emission, in contrast, avoids the velocity range of the HCO\(^+\) emission and is offset to the red by up to \(\sim 8.5\) km s\(^{-1}\) from the thermal gas \(v_{\text{LSR}}\) (Figures 2(m) and 5(m)). No 44 GHz CH\textsubscript{3}OH masers were detected in the vicinity of the EGO.

Longmore et al. (2007) detect two NH\textsubscript{3} cores in the vicinity of the 6.7 GHz CH\textsubscript{3}OH maser group (previously reported by Walsh et al. 1998; see Table 4). As noted by Longmore et al. (2007), neither NH\textsubscript{3} core is coincident with the 6.7 GHz maser emission: Core 1 is offset \(\sim 8.6\) east–southeast and Core 2 is offset \(\sim 10.3\) west–northwest of our intensity-weighted 6.7 GHz maser position. The two NH\textsubscript{3} cores have quite different spectral characteristics, with Core 2 exhibiting extreme NH\textsubscript{3}(1,1) hyperfine asymmetries. Longmore et al. (2007) as-
associate the CH$_3$OH maser with Core 1, but note that the association is uncertain. The 6.7 GHz CH$_3$OH maser appears to lie on a “bridge” of NH$_3$(1,1) emission between the two cores (see Figure 11 of Longmore et al. 2007). The NH$_3$ velocities are redshifted by $\sim$1.1 km s$^{-1}$ (Core 1) to $\sim$1.5 km s$^{-1}$ (Core 2) from that of the H$^{13}$CO$^+$ observed with the JCMT. The JCMT beam also encompasses the 8 $\mu$m source just northeast of the EGO, but the spectrum does not show multiple velocity components.

No 44 GHz continuum emission is detected toward the targeted EGO, but we do serendipitously detect the G28.29$-$0.36 UC H II region (at the center of the MIR-bright MSFR noted above), reported previously at lower frequencies (Walsh et al. 1998; Giveon et al. 2005; Longmore et al. 2007). Fitting a single Gaussian component, we find an integrated 44 GHz flux density for G28.29$-$0.36 of 174 $\pm$ 23 mJy (corrected for the primary beam) at 18$^h$44$^m$15$.$09, $-$04$^\circ$17$'$54$.''9 (J2000) and a deconvolved source size of 2$.''3 \times 1''0$ (P.A. $= 103^\circ$). Our measured 44 GHz integrated flux density is significantly lower than that predicted by extrapolating the 24 GHz continuum flux density of Longmore et al. (2007) assuming optically thin free–free emission. The most likely explanation is that the 24 GHz observations ($\sim$10$''$ beam) are sensitive to extended emission that is resolved out by our higher resolution (0$.'5$ beam) 44 GHz observations. The 44 GHz CH$_3$OH masers shown in Figure 1(m) appear to be associated with the MIR-bright MSFR centered on the G28.29$-$0.36 UC H II region: fitted parameters for these masers are reported in Table 8.

3.8.14. G28.83$-$0.25

This EGO is located in an IRDC on the rim of a MIR “wind-blown bubble” (Churchwell et al. 2006), near two other young sources, and may represent an example of triggered star formation (Watson et al. 2008). From north to south (Figure 1(n)), the three compact 24 $\mu$m sources in this field are: a compact H II region, the EGO counterpart, and a multiband IRAC source that has been modeled as a massive YSO based on its MIR SED (Watson et al. 2008).

The 4.5 $\mu$m morphology of the EGO has a bipolar structure with a 24 $\mu$m counterpart and a 6.7 GHz maser group near the center of the east–west lobes. A more diffuse “tail” of extended 4.5 $\mu$m emission also extends south and east of the two main 4.5 $\mu$m lobes (Figures 1(n) and 5(n)). Class I 44 GHz CH$_3$OH masers are spatially concentrated at the ends of the 4.5 $\mu$m lobes and at the end of the diffuse eastern 4.5 $\mu$m “tail.” These 44 GHz masers show some evidence of a velocity gradient associated with the bipolar lobes: the masers at the end of the western lobe have velocities systemic and blueward, while the masers at the end of the eastern lobe have velocities systemic and redward (Figure 5(n)). The eastern 4.5 $\mu$m tail, however, is associated with blueshifted masers, muddying the picture. The velocity spread of the 44 GHz masers is fairly narrow and symmetric about the gas systemic velocity ($\pm 1.8$ km s$^{-1}$, Figure 2(n)). SiO(5–4) emission was detected toward this EGO in our JCMT survey over a velocity range comparable to that of the 44 GHz CH$_3$OH maser emission (SiO $\Delta$V$_{FWHM} = 5.9$ km s$^{-1}$, Table 3).

Class 144 GHz CH$_3$OH masers are also detected in the IRDC: these masers could be associated with an extended outflow from the EGO, with outflow(s) from the MIR source south of the EGO, or with sources not visible in the MIR.

The 6.7 GHz CH$_3$OH maser emission largely avoids the thermal gas v$_{LSR}$, consisting of spectrally complex components that coincide with the red and blue wings of the HCO$^+$ emission (Figure 2(m)). Walsh et al. (1998) report 6.7 GHz CH$_3$OH maser emission over a similar velocity range, but report an order of magnitude fewer components, and in their data the positional uncertainty is greater than the separation of the maser spots (see their Figure 2, 1842–0348 panel). Spatially, the 6.7 GHz maser emission we detect is generally linearly distributed along a northwest–southeast axis (P.A. $\sim$45$^\circ$), with blueshifted maser emission to the northwest, redshifted maser emission to the southeast, and a $\sim$0$.'3$ gap in between (Figure 5(n)). Notably, the most highly Doppler-shifted maser emission is nearest this central gap, with less Doppler-shifted emission at the extremes of the linear distribution. This configuration is suggestive of Keplerian rotation, though the linear extent of the maser distribution ($\gtrsim$3000 AU at 5.0 kpc) is rather large for the masers to be tracing an accretion disk. A detailed analysis is beyond the scope of this work, and will be presented along with high-resolution observations of dust continuum and molecular line emission in a later paper.

3.8.15. G35.03+0.35

The 4.5 $\mu$m emission of this EGO has a bipolar morphology, with one lobe to the NE and the other to the SW. The 6.7 GHz CH$_3$OH maser group lies on the “waist” between these two lobes, coincident with 24 $\mu$m emission (Figures 1(o) and 5(o)). In contrast to many of the other EGOs in our sample, the 44 GHz CH$_3$OH masers do not lie primarily on or at the edges of these lobes, but rather trace out an arc to the east/southeast of the 6.7 GHz maser position. The 44 GHz maser arc lies between the main EGO and an eastern patch of 4.5 $\mu$m emission; it is unclear from the MIR emission whether this eastern 4.5 $\mu$m emission is part of the EGO or an unrelated source. The velocity spread of the 44 GHz CH$_3$OH masers is narrow ($\sim$2.5 km s$^{-1}$) and all of the masers are either near the thermal gas v$_{LSR}$, or slightly blueshifted (Figures 2(o) and 5(o)). The 6.7 GHz Class II CH$_3$OH maser emission is also blueshifted relative to the thermal gas v$_{LSR}$, but by a much greater amount ($\sim$6–12 km s$^{-1}$). In contrast, the H$_2$O masers reported by Forster & Caswell (1999; see Figure 5(o))—which are positionally coincident, within their reported position uncertainty of 0$.'5$, with the 6.7 GHz CH$_3$OH maser group—are redshifted relative to the gas v$_{LSR}$ by $\sim$13–17 km s$^{-1}$. The velocity coverage of our observations does not extend to the H$_2$O maser velocities ($\sim$66–70 km s$^{-1}$), but neither Szymczak et al. (2000) nor Pandian et al. (2007) report 6.7 GHz CH$_3$OH maser emission outside the range of $\sim$40–47 km s$^{-1}$ in their much wider bandwidth single-dish spectra.

Kurtz et al. (1994) found two unresolved cm–wavelength continuum sources in this region: a western source with a 15 GHz (2 cm) integrated flux density of 12.5 mJy at 18$^h$54$^m$00$.$49, +02$^\circ$01$'$18$.$0 (J2000, positional uncertainty 0$.'1$), and a second, marginally detected source $\sim 2^\circ$ east for which no position or fluxes were reported. We detect both sources at 44 GHz in our pseudo-continuum data, which have a similar resolution. The western source has a 44 GHz integrated flux density of 12.7 $\pm$ 2.4 mJy, based on fitting the source with a single two-dimensional Gaussian component: the deconvolved source size is 0$.'88 \times 0.'26$ (P.A. $= 5^\circ$) and the fitted position is 18$^h$54$^m$00$.$49, +02$^\circ$01$'$18$.$3 (J2000). Based on comparison with the 15 GHz integrated flux density from Kurtz et al. (1994), our measured 44 GHz flux density is consistent within errors with an optically thin spectral index of $-0.1$. The 44 GHz flux density of the western source is consistent with a single ionizing star of spectral type B1.5 (Smith et al. 2002). The eastern source,
which is not sufficiently resolved in our data to fit a reliable source size, has a fitted peak intensity of $3.6 \pm 0.8$ mJy beam$^{-1}$ ($\sim$4.5$\sigma$) at 18$^h$54$^m$00$^s$.65, +02$^\circ$01$'$19.5 (2000). The positions of both 44 GHz continuum sources are overplotted as black asterisks on the 4.5 $\mu$m image in Figure 5(o). The angular separation between the two continuum sources is $\sim$6$^\prime$ 6 ($\sim$9000 AU at 3.4 kpc). The eastern 44 GHz continuum source is between the two 4.5 $\mu$m lobes, and offset from the intensity-weighted 6.7 GHz maser position by $\sim$0$''$.25 ($\sim$860 AU at 3.4 kpc). This geometry suggests that the eastern 44 GHz continuum source may be the powering source of the putative outflow traced by the extended, bipolar 4.5 $\mu$m emission. In this scenario, the western 44 GHz continuum source would be another member of a protocluster, akin to the proto-Trapezia (multiple massive protostars within $\lesssim$10,000 AU) observed in NGC6334I and I(N) (Hunter et al. 2006). The H$^{13}$CO$^+$ line profile provides no additional support for the suggestion that multiple sources are present, as it appears asymmetric, with a red shoulder, and the JCMT beam did not encompass MIR sources other than the EGO. Broad SiO(5–4) emission ($\Delta v_{\text{FWHM}} = 11.1$ km s$^{-1}$) was also detected toward this EGO in our JCMT survey (Table 3). Additional data are, however, required to constrain the nature of the eastern 44 GHz continuum source (e.g., hypercompact H ii region or dust core) and to establish whether the bipolar 4.5 $\mu$m lobes in fact trace a bipolar molecular outflow.

3.8.16. G37.48$+$0.10

Only two loci of (weak) 44 GHz CH$_3$OH maser emission are detected toward this EGO, one at each end of linearly extended 4.5 $\mu$m emission (Figures 1(p) and 5(p)). The extended 4.5 $\mu$m emission is oriented along a roughly east–west axis; a weaker, more diffuse 4.5 $\mu$m tail extends westward from the main 4.5 $\mu$m emission feature. The velocity extent of the 44 GHz maser emission is narrow, $<2$ km s$^{-1}$ near the thermal gas $v_{\text{LSR}}$ (Figure 2(p)). The 6.7 GHz CH$_3$OH maser emission is stronger and spans a much broader velocity range, extending into and beyond the wings of the HCO$^+$ profile. (The peak velocity and position of this 6.7 GHz maser were previously reported by Szymczak et al. 2007.) The spatial distribution of the 6.7 GHz maser emission is characterized by arcs, including a northern arc of predominantly redshifted maser emission and a southern arc of blueshifted maser emission. Both arcs resemble parabolas with their opening axes oriented toward the southeast: maser emission near the systemic velocity is concentrated between the redshifted and blueshifted arcs.

3.8.17. G39.10$+$0.49

The morphology of the extended 4.5 $\mu$m emission in this EGO is predominantly linear, and the 44 GHz Class I CH$_3$OH masers are (with one exception) distributed linearly along the 4.5 $\mu$m emission (Figures 1(q) and 5(q)). While the velocity distribution of the 44 GHz masers is not monotonic, there is a predominance of redshifted masers to the southeast of the 6.7 GHz maser group position while the most blueshifted maser is located northwest of the 6.7 GHz maser (Figure 5(q)). The 6.7 GHz CH$_3$OH maser emission spans a broader velocity range ($\sim$16 km s$^{-1}$) than the 44 GHz maser emission ($\sim$6 km s$^{-1}$). The 6.7 GHz CH$_3$OH maser emission largely avoids the velocity range of the H$^{13}$CO$^+$ emission: the strongest 6.7 GHz maser emission is blueshifted by $\sim$7 km s$^{-1}$ relative to the thermal gas $v_{\text{LSR}}$ (23 km s$^{-1}$, Table 3) and falls on the blue wing of the HCO$^+$ profile, while weaker redshifted maser components are present at $v \sim$25–26 and 28.5–29 km s$^{-1}$ (Figure 2(q)). The velocity coverage of our observations does not include the full extent of the red HCO$^+$ line wing, but Szymczak et al. (2000) do not report 6.7 GHz maser emission outside the velocity range of 12–28 km s$^{-1}$ in their single-dish spectrum. (An interferometric position and peak velocity for this maser were reported in Szymczak et al. 2007 and references therein.) Blueshifted 6.7 GHz masers are concentrated to the northwest, while a line of redshifted 6.7 GHz masers extends to the south and east (Figure 5(q)). The sense of the red–blue velocity gradient of the 6.7 GHz masers matches that suggested by the 44 GHz CH$_3$OH masers on a much larger spatial scale. See note added in proof.

3.8.18. G49.27$+$0.34

This EGO is in an IRDC, and has an unusual cometary 4.5 $\mu$m morphology (Figure 1(r)). The very strong ($>$700 Jy) 6.7 GHz maser in W51 (G49.49$-$0.39 in Pandian et al. 2007, and references therein) falls within the sidelobes of our VLA pointing. This was responsible for the maser feature in the vector-averaged $u$–$v$ plot (Section 2.1). No 6.7 GHz maser is detected toward the EGO. Class I 44 GHz CH$_3$OH maser emission is detected at two loci south of the EGO, coincident with and at the edge of extended 4.5 $\mu$m emission (Figure 1(r)). The velocity range of the 44 GHz maser emission is extremely narrow ($<1$ km s$^{-1}$, Figure 2(r)). SiO(5–4) emission ($\Delta v_{\text{FWHM}} = 6.3$ km s$^{-1}$) was detected toward this EGO in our JCMT survey (Table 3).

Mehringer (1994) reports a 1.4 GHz (20 cm) continuum source, G49.27$-$0.34, with a flux density of 73 mJy and an ionizing flux equivalent to a zero-age main-sequence (ZAMS) star of spectral type B0 at 19$^h$23$^m$06$^s$.84, +14$^\circ$20$'$17.9 (precessed to J2000, positional uncertainty of 3$''$). The size, emission measure, and electron density of the H ii region are not well constrained by the Mehringer (1994) observations, as the source is unresolved at the $\sim$14$''$ angular resolution. Extrapolating the 1.4 GHz flux density assuming optically thin free–free emission ($\alpha = -0.1$) predicts a 44 GHz integrated flux density of $\sim$50 mJy. This is a lower limit to the expected flux density, as a compact H ii region is unlikely to be optically thin over a frequency range of 1.4 to 44 GHz. This source is, however, undetected in our 44 GHz pseudo-continuum observations. The most likely explanation is that the 1.4 GHz emission arises from a relatively smooth extended structure that is resolved out by our much higher resolution observations (0.5$''$ resolution at 44 GHz compared to $\sim$14$''$ at 1.4 GHz), but observations at intermediate frequencies are required to better characterize the nature of the cm continuum emission.

3.8.19. G49.42$+$0.33

This field is notable for having two spatially and kinematically distinct 6.7 GHz CH$_3$OH maser groups, though it is not clear whether both are associated with the target EGO. The western 6.7 GHz maser group (G49.41$+$0.32, Table 9, maser group 1 in Figure 2(s)) is coincident with the 4.5 $\mu$m emission of the targeted EGO, on a slight waist between two bulges of 4.5 $\mu$m emission (Figures 1(s) and 5(r)). The EGO and the associated western maser group do not have a clear 24 $\mu$m counterpart; the 24 $\mu$m source to the east is $\sim$8$''$ distant ($\sim$0.48 pc at 12.29 kpc) and is coincident with another 6.7 GHz CH$_3$OH maser group (G49.41$+$0.324, Table 9, maser group 2 in Figure 2(s)). An east–west extension of 4.5 $\mu$m emission appears to connect the eastern 24 $\mu$m source and CH$_3$OH maser with the extended 4.5 $\mu$m emission of the EGO, but it is unclear from the MIR data which source excites this emission. No 44 GHz Class I CH$_3$OH masers are detected in this field. In light of the nondetection of
4. DISCUSSION

4.1. The Nature of EGOs

The high detection rate of 6.7 GHz CH$_3$OH masers spatially coincident with extended 4.5 $\mu$m emission in our survey is strong evidence for the identification of EGOs as MYSOs. The coincidence of detected 6.7 GHz masers with MIPS 24 $\mu$m EGO counterparts for the vast majority of surveyed EGOs is consistent with the expectation that Class II CH$_3$OH maser emission is excited in the presence of warm dust near an MYSO. Interestingly, De Buizer (2006) found, based on subarcsecond images, that the MIR emission from the MYSO G35.2$-$0.74 (which is an EGO cataloged by Cyganowski et al. 2008) is dominated by thermal continuum emission from heated dust on the walls of an outflow cavity, and suggested that this environment is suitable for pumping Class II CH$_3$OH masers. The resolution of MIPS is too poor to address whether the 24 $\mu$m emission detected toward EGOs traces the central protostar or simply warm dust in the inner outflow cavity. In either case, the three EGOs with detected 6.7 GHz CH$_3$OH maser emission but no detected discrete 24 $\mu$m counterparts (G10.29$-$0.13, G28.28$-$0.36, G49.42$+$0.33) are intriguing. Two sources (G10.29$-$0.13, G28.28$-$0.36) are in regions of high background adjacent to saturated 24 $\mu$m complexes, and are coincident with (sub)millimeter clumps (see Table 4). If these EGOs are the youngest sources in our sample, they may lack discrete 24 $\mu$m counterparts because they are cooler and/or more heavily embedded (see also Section 4.3). Further observations are necessary to clarify the nature of these sources and of G49.42$+$0.33, about which little is known beyond the results of the present study.

The high detection rates of HCO$^+$ line wings, SiO emission, and 44 GHz Class I CH$_3$OH masers in our EGO surveys are all strong evidence for the presence of molecular outflows. While HCO$^+$ may trace relic outflows in MSFRs (e.g. Klaassen & Wilson 2007; Hunter et al. 2008), the mechanisms and timescales governing SiO emission make it well suited to tracing active outflows. Suffciently fast shocks enhance gas phase Si abundance via spattering of grain mantles and cores, and Si is oxidized to SiO via gas-phase reactions (Schilke et al. 1997; Caselli et al. 1997); after ~10$^4$ years, the gas phase abundance of SiO drops due to reaccretion onto grains and conversion to SiO$_2$ (Pineau des Forets et al. 1997). In well-known MSFRs, Class I CH$_3$OH masers trace shocked gas, as seen in H$_2$ and SiO, and interfaces between outflows and surrounding molecular gas (Section 1). The 44 GHz Class I CH$_3$OH masers detected in our survey are predominantly on or along the edges of extended 4.5 $\mu$m emission, which is thought to trace shocked H$_2$ (Section 1). Massive stars form in clusters, however, surrounded by both other massive objects and by intermediate- and low-mass stars, raising the question of whether different sources might be responsible for the 6.7 and 44 GHz maser emission. As discussed in Sections 3.3.2 and 3.8, there are examples of far-flung 44 GHz masers that may be excited by sources other than the EGO. In general, however, the 4.5 $\mu$m morphology shown in Figure 1 argues that the same source—a MYSO—is responsible for exciting both the 6.7 GHz Class II CH$_3$OH maser emission (by heating its surrounding environment) and at least some of the 44 GHz Class I CH$_3$OH maser emission (by driving an outflow). G19.01$-$0.03 is a particularly suggestive example: two bipolar lobes of 4.5 $\mu$m emission, coincident with arcs of 44 GHz CH$_3$OH masers, emanate from a 24 $\mu$m point source coincident with a 6.7 GHz CH$_3$OH maser.

The results discussed above are strong evidence that the EGOs in our survey sample are young MYSOs that are actively driving outflows, and hence actively accreting. While our sample was selected to cover a range of MIR properties, it included only EGOs categorized as “likely” MYSO outflow candidates by Cyganowski et al. (2008), and the sample of EGOs searched for 44 GHz CH$_3$OH maser emission was, in essence, a 6.7 GHz CH$_3$OH maser-selected EGO subsample. Further studies are required to establish whether all EGOs are MYSOs with active outflows, and particularly whether the distinction between “possible” and “likely” outflow candidates drawn by Cyganowski et al. (2008) based on MIR morphology is borne out by observations of other outflow tracers.

The kinematics of the CH$_3$OH masers, while revealing for individual sources, exhibit such diversity across our sample that they allow few generalizations about EGOs as a population, beyond the observation that 44 GHz CH$_3$OH masers are generally at or near the thermal gas $v_{LSR}$. This is consistent with the excitation of maser emission at the interface with surrounding dense ambient gas: for a kinetic temperature of 80 K, Leurini (2004) found that maser emission in the 44 GHz transition is strongest at densities of ~10$^3$–10$^5$ cm$^{-3}$ (n(H$_2$)). This is also consistent with the sketch of Kalenski˘ı et al. (2006) for Class I CH$_3$OH masers excited in a shell behind the shock front for outflows in the plane of the sky—an orientation preferentially selected for by the Cyganowski et al. (2008) criterion of extended 4.5 $\mu$m emission.

4.2. CH$_3$OH Masers in EGOs

As noted above, the sample of EGOs searched for 44 GHz CH$_3$OH maser emission was essentially a 6.7 GHz CH$_3$OH maser-selected subsample. Class I 44 GHz CH$_3$OH maser emission was detected toward ~89% (16/18) of EGOs with 6.7 GHz CH$_3$OH masers, as well as toward the one targeted EGO without an associated 6.7 GHz CH$_3$OH maser. Slysh et al. (1994) noted that 82% of new 44 GHz masers detected in their survey—which targeted HH regions, H$_2$O masers, 6.7 GHz CH$_3$OH masers, and IRDCs—were associated with known 6.7 GHz CH$_3$OH masers. Twelve of the fields with UCH ii regions observed at 44 GHz by Kurtz et al. (2004) were also searched for 6.7 GHz CH$_3$OH masers by Walsh et al. (1998). All 12 have detected 6.7 GHz CH$_3$OH masers, though the relative positions of the two types of masers vary widely, from coincident within the errors to widely separated. The high detection rate of 44 GHz CH$_3$OH masers in our survey adds evidence that 44 GHz Class I and 6.7 GHz Class II CH$_3$OH masers may be excited (via different mechanisms) by the same MYSO.

The range of 6.7 GHz maser spectral properties in our EGO survey is particularly striking because Class II CH$_3$OH maser emission requires the presence of warm dust ($T_d \gtrsim 125$ K), which both releases CH$_3$OH from icy grain mantles into the gas phase and emits the IR photons that pump the population inversions (Cragg et al. 1992; Minier et al. 2003; Cragg et al. 2005, and references therein). As a consequence, Class II masers...
may only be excited relatively near the central protostar, where dust temperatures are high. This is reflected observationally in our data: the 6.7 GHz CH$_3$OH maser emission associated with EGOs is in all cases spatially compact, and in most cases coincident with 24 μm emission likely attributable to an embedded YSO or YSOs. The detection of thermal emission in a warm transition of CH$_2$OH($5_{2,3}-4_{1,3}$, $E_1 = 44.3$ K) toward most EGOs in our JCMT survey also supports the presence of warm, dense gas. Precisely where in the circum(proto)stellar environment 6.7 GHz Class II CH$_3$OH masers originate has been the subject of considerable discussion in the literature (see for example van der Walt et al. 2007, which includes a review of much of the literature to date). Circumstellar accretion disks (e.g., Norris et al. 1998), outflows (e.g., De Buizer 2003), and shocks propagating through rotating clouds (e.g., Dodson et al. 2004) have all been suggested to explain observed maser spatial and velocity distributions. While the evidence from our survey is insufficient to distinguish among these possibilities for individual sources, the kinematic diversity of the ensemble argues against any one physical origin (e.g., in a particular dynamical structure) for 6.7 GHz CH$_3$OH masers.

MSFRs may also exhibit considerable kinematic complexity: for example, velocity dispersions of ~5 km s$^{-1}$ are observed among sources in Cepheus A East (Brogan et al. 2007) and S255N (Cyanogowski et al. 2007). The two 6.7 GHz CH$_3$OH maser groups in G11.92−0.61 are separated by ~1.6 km s$^{-1}$ in velocity and ~44.4 (≥17,000 AU at 3.8 kpc) and may be tracing two distinct protostars, a possibility that exists for other sources in our survey.

4.3. EGOs and Evolutionary Sequences of MSF

The evolutionary sequence of a forming massive star may be broadly described, following the terminology of Zinnecker & Yorke (2007), as a progression from a cold dense massive core (CDMC) to a hot dense massive core (HDMC) to a disk-accreting main-sequence star (DAMS) to the final main-sequence star (FIMS), where the transition from a HDMC to a DAMS occurs when the central, accreting source becomes powered more by hydrogen burning than by disk accretion. Refining this sequence and adding physical detail requires being able to establish the relative ages of large samples of MYSOs on the basis of observational evidence. While Spitzer surveys have provided large samples, the use of broadband MIR data for this purpose is complicated by the fact that multiple molecular, ionic, and PAH lines fall within each of the IRAC bands (see for example Figure 1 of Reach et al. 2006), and evolutionary models that include all these emission mechanisms in realistic geometries are not yet available. At longer wavelengths (e.g., MIPS 24 μm), the broadband flux is more likely to be dominated by thermal dust emission. De Buizer (2006) has argued that such thermal emission may emanate from heated dust in the walls of an outflow cavity (as opposed to pinpointing the protostar itself), and the point in the evolutionary sequence, relative to other indicators, at which 24 μm emission becomes observable is not well characterized as a function of viewing angle or protostellar mass. For our EGO sample, the detection of thermal emission in the CH$_2$OH($5_{2,3}-4_{1,3}$) transition ($E_1 = 44.3$ K) toward the majority of sources in our JCMT survey is suggestive of possible hot core line emission (e.g., van Dishoeck & Blake 1998), but follow up with a more diverse range of organic tracers is required.

Two more established observational indicators of evolutionary state are masers and H II regions, although both remain imperfectly understood. Ellingsen et al. (2007) propose a “straw man” evolutionary sequence in which a forming MYSO first excites Class I CH$_3$OH masers (via a protostellar outflow), then Class II CH$_3$OH masers (radiatively pumped by photons emitted by warm dust), then H$_2$O masers (associated with outflows), and finally OH masers (radiatively pumped by FIR photons) and an UC H II region in quick succession. Each of these stages overlaps with those before and after, and Ellingsen et al. (2007) note that there are sources known to be inconsistent with this sequence.

Most EGOs in our sample are associated with both Class I and Class II CH$_3$OH masers, placing them early in the Ellingsen et al. (2007) evolutionary sequence. Some Class I CH$_3$OH masers detected in our survey—which are apparently isolated from MIR emission or Class II CH$_3$OH masers—may be excited by outflows from even younger protostars, or from YSOs not massive enough to excite 6.7 GHz Class II CH$_3$OH maser emission. The EGOs in our sample have not been systematically searched for H$_2$O or OH masers at high angular resolution. Three sources (G11.92−0.62, G23.01−0.41, G35.03+0.35) are known to also have associated H$_2$O masers; of these, two (G23.01−0.41, G35.03+0.35) also have OH masers coincident with the EGO (Forster & Caswell 1999). These EGOs may thus either be examples of sources inconsistent with the Ellingsen et al. (2007) sequence, or in fact be protoclusters, with YSOs at different evolutionary stages responsible for different types of maser emission.

While it is generally accepted that UC H II regions represent a late stage of massive star formation (the end state (FIMS) in the sequence of Zinnecker & Yorke 2007), the nature of the earliest detectable free–free emission from forming massive stars is still the subject of considerable discussion in the literature (see, for example, Menten & van der Tak 2004; van der Tak & Menten 2005; van der Tak et al. 2005; Hoare et al. 2007; Hoare & Franco 2007; Gibb & Hoare 2007; Lizano 2008). Theoretical calculations suggest that at the earliest stages of massive star formation, high accretion rates can prevent luminous ($L > 10^6 L_{\odot}$) MYSOs from ionizing their surroundings, either by “quenching” the H II region (confining it very close to the stellar surface; Walmsley 1995), or by swelling the radius of the MYSO, thus lowering its effective temperature (below ~30,000 K; Yorke & Sonnhalter 2002; Hoare & Franco 2007, and references therein). Subsequently, ionized gas may exist in a range of dynamical structures, including accretion flows, outflows, jets, ionized/photoevaporating disks and stellar winds, all of which may exist at the scale of hypercompact (HC) H II regions (size ≤0.05 pc, density ≥10$^6$ cm$^{-3}$; e.g., Kurtz 2005; Hoare et al. 2007; Hoare & Franco 2007; Kato 2007; Lizano 2008).

As discussed in Section 3.8, cm wavelength continuum emission has been detected coincident with MIR emission toward two EGOs in our sample (G35.03+0.35 and G49.27−0.34, see also Table 4), but the existing data are insufficient to establish the nature of this emission. At 44 GHz, both thermal emission from dust and free–free emission from ionized gas may contribute to the continuum; without multiwavelength observations, these cannot be disentangled. The nondetections (18/19, ~95%) of 44 GHz continuum emission coincident with EGOs in our survey are consistent with other evidence (masers, MIR properties, Section 4.1) that EGOs are young MYSOs. Given the depth of our survey, however, the nondetections do not provide strong constraints on the properties (luminosity, mass, ionizing photon flux, spectral type) of the “central” sources responsi-
ble for powering the outflows traced by 4.5 μm and Class I CH$_3$OH maser emission. At a typical distance of 4 kpc, an unresolved 5σ detection would correspond to an ionizing photon flux of ∼9.4 × 10$^{45}$ photons s$^{-1}$ (following Kurtz et al. 1994, and assuming a typical electron temperature of 10$^4$ K), equivalent to a single star cooler than spectral type B1.5 (Smith et al. 2002). This estimate gives a lower limit for the ionizing flux that corresponds to our detection threshold, as it assumes that every ionizing photon emitted produces observable free–free radiation (e.g., that quenching and absorption by dust are both unimportant). This estimate also assumes optically thin free–free emission (Mezger & Henderson 1967; Kurtz et al. 1994); in the case of optically thick free–free emission, derived parameters dependent on the electron density (including the ionizing photon flux) will be underestimated (see for example discussion in Keto et al. 2008). Under similar assumptions, the photon flux of 10$^{45}$ photons s$^{-1}$ assumed by Keto (2007) in modeling very young ionized accretion flows around forming MYSOs would be below our detection limit. Extrapolating the peak 15 GHz (2 cm) intensities for UC H II regions in the survey of Kurtz et al. (1994, KCW94) to 44 GHz assuming optically thin free–free emission ($S_v \propto \nu^4$, $\alpha = -0.1$), only ∼50% of the KCW94 UC H II regions would be detected at the 5σ level (∼5 mJy beam$^{-1}$) in our survey. The 15 GHz observations have approximately the same resolution as our 44 GHz observations and KCW94 sources with $S_\nu,\text{peak}(15\text{GHz}) > S_\nu,\text{peak}(8.4\text{GHz})$ (inconsistent with optically thin free–free emission) were excluded.

The overwhelming lack of 44 GHz continuum detections of EGOs in our survey thus serves to rule out bright UC H II regions as powering sources in most cases, but deeper observations are required to constrain the presence of fainter UC or of HC H II regions. Smaller and denser than UC H II regions, most HC H II regions have rising spectral indices ($\alpha \sim 1$) at cm–mm wavelengths and are generally faint (<10 mJy) even at 44 GHz (Kurtz 2005; Garay et al. 2007; Lizano 2008). Emission from MYSOs attributed to ionized stellar winds is likewise faint at 44 GHz (5/8 sources in the sample of Gibb & Hoare 2007, have peak intensity <5 mJy beam$^{-1}$). Sensitive, high angular resolution observations over a range of cm wavelengths are required to further constrain the presence, extent, and physical properties of any ionized gas associated with EGOs.

5. CONCLUSIONS

The results of our VLA and JCMT surveys constitute a preponderance of evidence that EGOs are young MYSOs with active outflows.

1. Class II 6.7 GHz CH$_3$OH masers, which are associated exclusively with MYSOs, are detected toward ≥64% of EGOs surveyed (18/28)—nearly double the rate of surveys using other MYSO selection criteria.

2. Class I 44 GHz CH$_3$OH masers, which trace molecular outflows, are detected toward ∼90% of EGOs surveyed (17/19) and ∼89% (16/18) of EGOs with associated 6.7 GHz CH$_3$OH masers.

3. $\Delta$V$_{FWHM}$ in the HCO$^+$(3–2) line is ≥20 km s$^{-1}$ for the majority of EGOs surveyed, consistent with the presence of outflows.

4. SiO(5–4) emission, which is predicted to persist for only ∼10$^4$ years after the passage of a shock, is detected toward 90% (9/10) of EGOs surveyed—a rate comparable to that of sources with narrowband H$_2$ emission believed to be excited by outflow shocks.

5. Thermal CH$_3$OH(5$_2$,3–4$_1$,3) emission, indicative of the presence of warm dense gas, is detected toward 83% (15/18) of EGOs surveyed.

6. No 44 GHz continuum emission is detected at the 5 mJy beam$^{-1}$ level (5σ) toward ∼95% of EGOs surveyed (18/19), ruling out bright UC H II regions as powering sources.

Class II 6.7 GHz CH$_3$OH maser emission is spatially concentrated in compact maser groups (extent ≤1″), which are generally coincident with 24 μm emission. Each EGO is associated with only one or two 6.7 GHz CH$_3$OH maser groups. Class I 44 GHz CH$_3$OH maser emission, in contrast, is generally widely distributed over many tens of arcseconds, coincident with extended 4.5 μm emission. HCO$^+$(3–2) emission is detected toward all EGOs surveyed (19/19); the profiles are characterized by broad line wings, consistent with the presence of outflows. In addition, all surveyed EGOs (19/19) are detected in H$^13$CO$^+$(3–2) emission, allowing the determination of revised kinematic distances based on the new Galactic rotation model of Reid et al. (2009). Thermal CH$_3$OH(5$_2$,3–4$_1$,3) emission is also detected toward the majority of EGOs in our sample (∼83%, 15/18), at the same velocity as the H$^13$CO$^+$(3–2) emission (median velocity offset ≤0.3 km s$^{-1}$).

These results verify that EGOs are a promising sample for studying accretion and outflow at the early stages of massive star formation. There is also evidence that two of the EGOs surveyed may in fact be protoclusters of at least two MYSOs, providing opportunities to study how MYSO outflows interact in the dense environments characteristic of most MSF. The next steps are to establish the nature of the driving sources. Deep cm continuum observations will more strictly constrain the presence or absence of ionized gas (and hence ionizing photons). High angular resolution (sub)millimeter line and continuum observations will constrain the physical properties (temperature, density, mass) and numbers of compact cores. High angular resolution observations in direct molecular outflow tracers are also required to better characterize outflow kinematics and energetics: 44 GHz Class I CH$_3$OH masers are a strong indicator of the presence of a molecular outflow, but are preferentially excited near the systemic velocity and provide no information about outflow mass or momentum. These projects are well matched with the capabilities of the EVLA and ALMA, and EGOs will be promising targets for these facilities.

This research has made use of NASA’s Astrophysics Data System Bibliographic Services and the SIMBAD database operated at CDS, Strasbourg, France. C.J.C. would like to thank J. Wouterloot for helpful discussions about JCMT data reduction and R. Indebetouw for helpful discussions about MIPS saturated source photometry. We thank M. Reid for providing his new kinematic Galactic distance estimate source code ahead of its publication. Support for this work was provided by NSF grant AST-0808119. C.J.C. was partially supported during this work by a National Science Foundation Graduate Research Fellowship and a NRAO Graduate Summer Student Research Assistantship.

Facilities: VLA (), JCMT (), Spitzer ()

Note added in proof. After this paper was submitted, EVN data for these two sources were published; see also Bartkiewicz et al. 2009 for the kinematics of the strongest 6.7 GHz CH$_3$OH masers in these sources.
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