A WATER MASER AND NH₃ SURVEY OF GLIMPSE EXTENDED GREEN OBJECTS

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ABSTRACT

We present the results of a Nobeyama 45 m H₂O maser and NH₃ survey of all 94 northern GLIMPSE extended green objects (EGOs), a sample of massive young stellar objects (MYSOs) identified based on their extended 4.5 μm emission. We observed the NH₃(1,1), (2,2), and (3,3) inversion lines, and detected emission toward 97% (median rms ~ 0.11 Jy). The derived H₂O maser and clump-scale gas properties are consistent with the identification of EGOs as young MYSOs. To explore the degree of variation among EGOs, we analyze subsamples defined based on mid-infrared (MIR) properties or maser associations. H₂O masers and warm dense gas, as indicated by emission in the higher-excitation NH₃ transitions, are most frequently detected toward EGOs also associated with both Class I and II CH₃OH masers. Ninety-five percent (81%) of such EGOs are detected in H₂O (NH₃(3,3)), compared to only 33% (7%) of EGOS without either CH₃OH maser type. As populations, EGOs associated with Class I and/or II CH₃OH masers have significantly higher NH₃ line widths, column densities, and kinetic temperatures than EGOs undetected in CH₃OH maser surveys. However, we find no evidence for statistically significant differences in H₂O maser properties (such as maser luminosity) among any EGO subsamples. Combining our data with the 1.1 mm continuum Bolocam Galactic Plane Survey, we find no correlation between isotropic H₂O maser luminosity and clump number density. H₂O maser luminosity is weakly correlated with clump (gas) temperature and clump mass.

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

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1. INTRODUCTION

The early stages of massive star formation remain poorly understood, due in part to the difficulty of identifying young massive young stellar objects (MYSOs)¹² that are actively accreting and driving outflows. Large-scale Spitzer Space Telescope surveys of the Galactic Plane have recently yielded a promising new sample of candidates: extended green objects (EGOs; Cyganowski et al. 2008), selected based on extended 4.5 μm emission, and named for the common coding of three-color Infrared Array Camera (IRAC; Fazio et al. 2004) images (RGB: 8.0, 4.5, 3.6 μm). Modeling, mid-infrared (MIR) spectroscopy, and narrowband near-infrared (NIR) imaging have shown that shock-excited molecular line emission, predominantly from H₂, can dominate the 4.5 μm broadband flux in active protostellar outflows (e.g., Smith & Rosen 2005; Smith et al. 2006; Davis et al. 2007; Ybarra & Lada 2009; Ybarra et al. 2010; De Buizer & Vacca 2010). While all the IRAC filters include H₂ lines, only the 4.5 μm band lacks polycyclic aromatic hydrocarbon (PAH) emission features (e.g., Figure 1 of Reach et al. 2006), which are readily excited in massive star-forming regions (MSFRs). Morphologically distinct extended 4.5 μm emission is thus a common feature of well-known MSFRs (e.g., DR21, S255N, NGC 6334I(N), G34.4+0.23, IRAS 18566+0408; Davis et al. 2007; Cyganowski et al. 2007; Hunter et al. 2006; Shepherd et al. 2007; Araya et al. 2007), and a means of identifying candidate MYSOs with active outflows.

Cyganowski et al. (2008, hereafter C08) cataloged over 300 EGOs in the Galactic Legacy Infrared Mid-Plane Survey Extraordinary (GLIMPSE-I; Churchwell et al. 2009) survey area. At the time, the only data available for most EGOs were IR surveys. Using the GLIMPSE images, C08 divided cataloged EGOs into “likely” and “possible” outflow candidates based on the morphology and angular extent of their extended excess 4.5 μm emission. As detailed by C08, two phenomena in the IRAC images have the potential to be confused with moderately extended 4.5 μm emission: multiple nearby point sources and image artifacts near bright IRAC sources. To categorize the C08 EGOs, two observers independently reviewed three-color IRAC images; if either observer thought the MIR morphology could be attributable to one of these phenomena, the EGO was considered a “possible” outflow candidate. Of the 302 EGOs in the C08 catalog, 133 (44%) were classified as “likely” outflow candidates, 165 (55%) as “possible” outflow candidates, and 2 (1%) as “outflow-only” sources (in which the extended outflow emission could be readily separated from the central source). C08 also tabulated whether each EGO was or was

¹¹ NSF Astronomy and Astrophysics Postdoctoral Fellow.
¹² We define MYSOs as young stellar objects (YSOs) that will become O- or early B-type main-sequence stars (M₆AMS > 8 M☉).
not associated with an Infrared Dark Cloud (IRDC) visible against the diffuse 8 μm background. A majority (67%) of GLIMPSE EGOs are associated with IRDCs, which are thought to be sites of the earliest stages of massive star and cluster formation (e.g., Rathborne et al. 2006, 2007; Chambers et al. 2009; Wang et al. 2011). A somewhat higher fraction of EGO “likely” outflow candidates is found in IRDCs: 71% compared to 64% of “possible” outflow candidates (C08). The GLIMPSE survey is too shallow to detect distant low-mass outflows; based primarily on the MIR data, C08 argued that GLIMPSE EGOs were likely outflow-driving massive YSOs.

Testing this hypothesis required correlating extended 4.5 μm emission with other massive star formation tracers at high angular resolution. Interferometric studies at cm–mm wavelengths have provided much of the key evidence to date that EGOs are indeed young, massive YSOs driving active outflows. The first strong evidence was remarkably high detection rates for two diagnostic types of CH3OH masers in sensitive, high angular resolution Very Large Array (VLA) surveys (Cyganowski et al. 2009, hereafter C09): 6.7 GHz Class II and 44 GHz Class I CH3OH masers. Radiatively pumped by IR emission from warm dust, Class II CH3OH masers are excited near the (proto)star (e.g., Cragg et al. 2005; Cyganowski et al. 2009 and references therein), and recent work suggests that the luminosities and relative strengths of different Class II transitions change as the central source evolves (e.g., Ellingsen et al. 2011; Breen et al. 2011 and references therein). The 6.7 GHz transition is the strongest and most common Class II CH3OH maser; importantly, numerous searches have shown that these masers are not found toward low-mass YSOs (e.g., Minier et al. 2003; Bourke et al. 2005; Xu et al. 2008; Pandian et al. 2008). Collisionally excited in the presence of weak shocks, Class I CH3OH masers are generally associated with molecular outflows and outflow/cloud interactions (e.g., Plambeck & Menten 1990; Kurtz et al. 2004; Voronkov et al. 2006), though recent work suggests Class I masers may also be excited by shocks driven by expanding H II regions (Voronkov et al. 2010). As a result of their association with outflows, Class I CH3OH masers are more spatially distributed than Class II masers, and may be found many tens of arcseconds from the driving (proto)star (e.g., C09).

C09 detected 6.7 GHz CH3OH masers toward ≥64% of their 28 EGO targets, and 44 GHz CH3OH masers toward ~90% of the subset searched for Class I emission (19 EGOs, 18 with 6.7 GHz CH3OH masers). Their full sample of 28 EGOs was chosen to be visible from the northern hemisphere and to span a range in MIR properties including presence/absence of 8 and 24 μm counterparts, morphology, IRDC association, and angular extent of 4.5 μm emission. The 19 sources observed with the VLA at 44 GHz were all “likely” outflow candidates and, in essence, a 6.7 GHz CH3OH maser-selected subsample (for further details, see C09). Subsequent high-resolution mm–λ observations of two of the C09 EGOs revealed high-velocity bipolar molecular outflows coincident with the 4.5 μm lobes, driven by compact millimeter continuum cores that exhibit hot core line emission (Cyganowski et al. 2011a, hereafter C11a).

Recently, exceptionally deep VLA 3.6 and 1.3 cm continuum observations of a sample of 14 C09 EGOs have shown that the vast majority of the targets (12/14) are not ultracompact (UC) H II regions (Cyganowski et al. 2011b, hereafter C11b). Most (8/14) are undetected at both 3.6 and 1.3 cm (σ ∼ 30 and 250 μJy beam−1, respectively); four sources are associated with weak (∼1 mJy) cm–λ emission consistent with hypercompact (HC) H II regions or ionized winds or jets. Based on their cm survey results and complementary multiwavelength data, C11b argued that these EGOs represent an early stage of massive star formation, before photoionizing feedback from the central MYSO becomes significant.

Detailed, high-resolution follow-up studies have, of necessity, been limited to relatively small EGO subsamples, and have generally focused on C08 “likely” outflow candidates (see also C09). Assessing the variation within the C08 catalog and the significance of their MIR classifications requires large, uniform surveys in tracers of dense gas and star formation activity. Few such surveys have been conducted to date. Chen et al. (2010) searched 88 (of 94) northern (δ ≥ −20°) EGOs for 3 mm HCO+, 12CO, 13CO, and C18O emission, with the primary goal of detecting infall signatures. They found a larger “blue excess” toward EGOs associated with IRDCs compared to those not associated with IRDCs, and toward “possible” compared to “likely” outflow candidates; however, the interpretation of these results was complicated by the likelihood that multiple sources/dynamical phenomena were present within their large (~60–80′) beam. Recently, He et al. (2012) conducted a 1 mm line survey, covering ~251.5–252.5 GHz and ~260.2–261.2 GHz, toward 89 northern EGOs (resolution ~29′). He et al. (2012) focus on line width and line luminosity correlations, however, and do not analyze EGO subsamples. Chen et al. (2011, hereafter CE11) searched for 95 GHz Class I CH3OH masers toward 192 northern and southern EGOs (of 302 total) with the MOPRA telescope (θFWHP ∼ 36′, 3α ∼ 1.6 Jy). They found a higher 95 GHz CH3OH maser detection rate toward “likely” than toward “possible” C08 EGOs (62% and 49%, respectively), and very similar detection rates toward EGOs associated/not associated with IRDCs (55%/53%). Their Class I CH3OH maser detection rate is also much higher toward EGOs associated with Class II CH3OH masers (80%) than toward those without (38%), consistent with the very high Class I maser detection rate of C09.

Like Class I CH3OH masers, H2O masers are collisionally pumped (e.g., Elitzur et al. 1989) and associated with protostellar outflows; notoriously variable, H2O masers also often exhibit high-velocity emission features, offset by 30 km s−1 or more from the systemic velocity (e.g., Breen et al. 2010a; Caswell & Breen 2010). While Class I CH3OH masers are excited under moderate conditions (T ∼ 80 K, n(H2) ∼ 105–106 cm−3, e.g., Leurini 2004) and associated with outflow/cloud interfaces, H2O masers require more extreme conditions (T ∼ 400 K, n(H2) ∼ 106–1010 cm−3, Elitzur et al. 1989) and are thought to originate behind fast shocks in the inner regions of the outflow base. Numerous correlations have been reported between the properties of H2O masers and those of the driving source or surrounding clump, including recent evidence that L(H2O) ∝ Lbol over many orders of magnitude (e.g., Urquhart et al. 2011; Bae et al. 2011). This suggests that H2O masers may be used to investigate the properties of their driving sources, at least in a statistical sense for different subsamples—a possibility of interest for EGOs, since their bolometric luminosities are in most cases poorly constrained by available data (see also C11b).

Large H2O maser and NH3 surveys with single-dish telescopes have long been recognized as powerful tools for characterizing MSFRs (e.g., Churchwell et al. 1990; Anglada et al. 1996; Sridharan et al. 2002), and continue to be applied to new samples (e.g., Urquhart et al. 2011; Dunham et al. 2011b). NH3 traces high-density gas (~104 cm−3, e.g., Evans 1999; Stahler & Palla 2005), and provides a wealth of information about clump kinematics and physical properties; notably, it is an excellent
Table 1
EGO Sample: Properties from the Literature

| Source Name | J2000 Coordinates<sup>a</sup> | EGO Catalog<sup>c</sup> | IRDC<sup>d</sup> | CH3OH Maser<sup>b</sup> |
|------------|-------------------------------|---------------------|--------------|---------------------|
|            | α (h m s) δ (° ')             |                     |              |                     |
| G10.29−0.13| 18 08 49.3 −20 05 57          | 2                   | Y            | Y                   |
| G10.34−0.14| 18 09 00.0 −20 03 35          | 2                   | Y            | Y                   |
| G11.11−0.11| 18 10 28.3 −19 22 31          | 3                   | Y            | Y                   |
| G11.92−0.61| 18 13 58.1 −18 54 17          | 1                   | Y            | Y                   |
| G12.02−0.21| 18 12 40.4 −18 37 11          | 1                   | Y            | N                   |

Notes.
<sup>a</sup> From C08. The table number from C08 is given in the “EGO Catalog” column. Tables 1 and 2 of C08 listed “likely” outflow candidates. Tables 3 and 4 listed “possible” outflow candidates. Table 5 sources are those for which only “outflow-only” photometry was presented; we do not include them in our analysis of “likely” and “possible” subsamples.
<sup>b</sup> From CE11 (only). EGOs in our sample that are not included in CE11 are indicated by . . . “−” indicates a source with a single-dish 6.7 GHz CH3OH maser detection but no positional information, considered as having “no information” at 6.7 GHz by CE11 (see Section 3.1.1).

“This thermometer.” This paper presents the results of a H2O maser and NH3 survey of the 94 northern (δ ≥ −20°) EGOs from the C08 catalog with the Nobeyama Radio Observatory 45 m telescope. The motivation for this survey was to characterize the properties of the C08 EGO sample as a whole, the main goals being to evaluate the significance of the MIR classifications from C08 and to place EGOs in the context of other large MYSO samples. We also compare the H2O maser and NH3 properties of EGO subsamples associated with Class I and/or II CH3OH masers and explore correlations between H2O maser and clump properties. Evolutionary interpretations have been suggested for both CH3OH masers and H2O maser properties (e.g., Ellingsen 2006; Ellingsen et al. 2007; Breen et al. 2010b; Breen & Ellingsen 2011), and our survey, in conjunction with the 1.1 mm Bolocam Galactic Plane Survey (BGPS; Aguirre et al. 2011; Rosolowsky et al. 2010), provides the necessary data to test these scenarios.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Nobeyama 45 m Observations

We targeted all 94 EGOs in the C08 catalog visible from Nobeyama (those in the northern Galactic plane, δ ≥ −20°). Our sample sources are listed in Table 1, along with information from the literature on their MIR properties and CH3OH maser associations. The NH3 (J, K) = (1,1), (2,2), and (3,3) inversion transitions and the 22.235 GHz H2O maser line were observed simultaneously with the Nobeyama Radio Observatory 45 m telescope (NRO45) in 2008–2010. During our winter (January/February) observing sessions, the system temperature was typically ~100–160 K. The beam size and main-beam efficiency of the NRO45 at 22 GHz are θWHM = 73” and ηMB = 0.825, respectively. We pointed at the EGO positions tabulated in C08, which are the positions of the brightest 4.5 μm emission associated with each candidate outflow. We note that these positions will not necessarily be those of the driving sources (which in many cases are difficult to identify solely from the MIR data; see also C08), though in most cases the NRO beam is large enough to encompass likely driving sources as well as the 4.5 μm extent of the EGO.

We used the H22 receiver, a cooled HEMT receiver, and eight high-resolution acousto-optic spectrometers (AOSs) to observe both polarizations for each line simultaneously. The bandwidth and spectral resolution of the AOSs are 40 MHz and 37 kHz, respectively, corresponding to velocity coverage of ~500 km s<sup>−1</sup> and resolution of ~0.5 km s<sup>−1</sup> for the observed lines. The spectral channels were Nyquist-sampled.

The observations were conducted in position-switching mode, using “off” positions ~5’ away. All spectra were checked for evidence of emission in the chosen “off” position, and, if necessary, reobserved. Initially, each target was observed for 2 minutes (on-source). The spectra were then inspected, and weak sources were reobserved to improve the signal-to-noise ratio as time permitted. The pointing was measured and adjusted at the beginning of each observing run using Galactic maser sources. The absolute pointing of the NRO45 is very accurate for 22 GHz observations, from a few arcsec (no wind) to ~10” in the windiest conditions in which we observed—still a small fraction of the beam size at 22 GHz.

The data reduction followed standard procedures using the NRO NEWSTAR software package (Ikeda et al. 2001). For each spectrum, emission-free channels were used to estimate and subtract a linear spectral baseline. For each line, the two polarizations were then co-added, weighted based on system temperature. The temperature scale was calibrated to the antenna temperature (T<sub>A</sub>) in Kelvin with the standard chopper-wheel method, and the main-beam temperature (T<sub>MB</sub>) calculated as T<sub>MB</sub> = T<sub>A</sub>/η<sub>MB</sub>. For the H2O maser data, we then convert to the Jansky scale to facilitate comparisons with other surveys.

Histograms of the rms are shown in Figure 1. The median 1σ rms is ~50, 51, and 52 mK for NH3(1,1), (2,2), and (3,3), respectively. For our H2O maser observations, the median 1σ rms is ~0.11 Jy, corresponding to a median 4σ detection limit of ~0.44 Jy.

2.2. NH3 Modeling and Physical Parameter Estimation

We estimate physical properties from the observed NH3 spectra following the philosophy developed by Rosolowsky et al. (2008) and adapted for use in Dunham et al. (2010) and Dunham et al. (2011b). The emission is modeled as

<sup>13</sup> The 45 m radio telescope is operated by the Nobeyama Radio Observatory, a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences.
a beam-filling slab of NH$_3$ with a variable column density ($N_{\text{NH}_3}$), kinetic temperature ($T_{\text{kin}}$), Gaussian line width ($\sigma_v$), and LSR velocity ($v_{\text{LSR}}$). The model assumes the molecules are in thermodynamic equilibrium using an ortho-to-para ratio of 1:1, which is the high temperature formation limit (Takano et al. 2002). Hence, the ammonia molecules are partitioned among the energy levels as

$$Z_O = 1 + \sum_{J,K,i} 2(2J + 1) \times \exp \left\{ -\frac{h [BJ(J+1)+(C-B)J^2] + \Delta E(J,K,i)}{kT_k} \right\}$$
for $J = K = 3, 6, 9, \ldots; i = 0, 1$, \hspace{1cm} (1)

$$Z_P = \sum_{J,K,i} 2(2J + 1) \times \exp \left\{ -\frac{h [BJ(J+1)+(C-B)J^2] + \Delta E(J,K,i)}{kT_k} \right\}$$
for $J = K = 1, 2, 4, 5, \ldots; i = 0, 1$. \hspace{1cm} (2)

Here, $J$ and $K$ are the rotational quantum numbers of NH$_3$ and, for the metastable inversion transitions, $J = K$. The energy difference, $\Delta E(J,K,i)$, is the splitting of the symmetric and antisymmetric states, representing both levels of the inversion transition. The antisymmetric state, $\Delta E(J,K,1)$, is $\Delta E/k \sim 1.1\text{ K}$ above the symmetric state ($\Delta E(J,K,0) = 0$). The column density of the molecules in the $N_{\text{NH}_3}(J,K,i)$ ortho state is thus $N_{\text{NH}_3}Z_O(J,i)/(2Z_O)$ and in the para state $N_{\text{NH}_3}Z_P(J,i)/(2Z_P)$, where the factor of two arises because of the assumption of a 1:1 ortho-to-para ratio.

The optical depths in the individual transitions are calculated from the column densities in the individual states. The optical depth, hyperfine structure, velocity information and excitation conditions are then used to model the individual spectra. Free parameters are optimized using the MPFIT least-squares minimization routine including parameter bounds (Markwardt 2009). Uncertainties in the derived parameters are also determined from this optimization, accounting for the covariance between the parameters. We note that parameter uncertainties cannot account for systematic errors stemming from the uniform slab model being an incomplete description of the physical system. In all cases, derived quantities should be considered summary properties of the system and not a complete description. In most cases, this simple model reproduces the emission features observed on the large scales sampled.

For some sources in our sample, however, a single-slab model does not adequately represent the amplitudes of all three NH$_3$ transitions. Figure 2 shows examples of the two cases that prompted a revision of our model: (1) spectra that showed velocity components with different $v_{\text{LSR}}$ or $\sigma_v$; and (2) spectra that could not be well represented by a single-temperature fit. We found that including a second component produced significantly better fits in these cases (see Rosolowsky et al. 2008, for more details). A second component was introduced for any fit where the $\chi^2$ per degree of freedom was larger than two for any individual inversion line (23 sources, $\sim$25% of our sample). For two sources that met this criterion, the best-fit two-component model included a component with an unphysically low excitation temperature ($<2.73\text{ K}$). For these sources (G14.33−0.04 and G19.36−0.03), we retain the single-component fits (leaving 21 sources with two-component fits). In the two-component model, the two slabs are nominally beam-filling, but no radiative transfer is performed from one slab through the other. We see no
Figure 2. Single-component (left) and two-component (right) fits to sample NH$_3$ spectra. The best-fit models are overplotted on the observed spectra. For the two-component fits, model spectra for each component are shown (dashed line: warmer component; dotted line: cooler component), as well as their sum (solid line). The “D” at upper right in each panel indicates that our 4$\sigma$ detection criterion was met for that transition. G12.91$-$0.26 (top) has two velocity components. For G11.92$-$0.61 (bottom), two temperature components significantly improve the fit to the NH$_3$(1,1), (2,2), and (3,3) spectra. The evidence for absorption of one component through the other in the spectra, suggesting such a treatment is not needed. A simple two-component fit yields a substantial improvement in the quality of the fit for many sources, successfully identifying two velocity/temperature components. We again note, however, that slab models are an incomplete description of the physical system; the best-fit physical parameters of the two components are thus likely representative but not definitive. We also note that a contradiction arises because the model takes $T_{\text{MB}} = \eta_{\text{ff}} (T_{\text{ex}} - T_{\text{bg}})(1 - e^{-\tau})$ where $\eta_{\text{ff}} = 1$ is the assumed beam filling factor. However, the parameter $\eta_{\text{ff}}$ is degenerate with $T_{\text{ex}}$, and our assumption that $\eta_{\text{ff}} = 1$ means $T_{\text{ex}}$ is a lower limit. Relaxing this constraint on $\eta_{\text{ff}}$ leaves $T_{\text{ex}}$ undetermined for the two components, and suggests that the success of the simple two-component fitting means the two NH$_3$ components are spatially distinguished on smaller scales.

3. RESULTS

3.1. Detection Rates

3.1.1. Water Masers

We define a water maser detection as $>4\sigma$ emission in at least two adjacent channels. The overall detection rate is 68% (64/94), and Table 2 summarizes the H$_2$O maser detection rates toward various EGO subsamples. The uncertainties quoted in Table 2 were calculated using binomial statistics. Throughout, we treat each EGO separately, though we note that for EGOs separated on the sky by $\lesssim 36\arcmin$ (half the FWHP Nobeyama beam), our data are insufficient to determine whether one or all are associated with H$_2$O masers. An unavoidable limitation of single-dish surveys is the possibility that some H$_2$O maser detections are chance alignments within the single-dish beam, and not physically associated with the target EGOs. While this can only be definitively addressed by future high-resolution observations of all detected EGOs, available data suggest that the effect on the sample as a whole is small. We searched the literature for reported H$_2$O masers with interferometric positions within 2$\arcmin$ of each EGO with a H$_2$O maser detection in our survey. Of 27 sources with such data available, there are only three cases ($\sim 11\%$) of H$_2$O masers within the Nobeyama beam and not associated with the EGO (see also Section 3.3).

One of the goals of this survey is to investigate whether the MIR EGO classifications from C08 correspond to differences in H$_2$O maser associations or dense gas properties. We find a somewhat higher H$_2$O maser detection rate for EGOs classified as “likely” MYSO outflow candidates, compared to those classified as “possible” outflow candidates based on their MIR
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Table 2
Detection Statisticsa

| Categoryc | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate |
|-----------|------------------|---------------------|------|-----------------|---------------------|------|-----------------|---------------------|------|-----------------|---------------------|------|-----------------|---------------------|------|
| Overall   | 94               | 91                  | 0.97(0.02) | 59             | 59                  | 0.63(0.05) | 43             | 43                  | 0.46(0.05) | 64             | 64                  | 0.68(0.05) |
| IRDC Assoc.| 47               | 47                  | 1.00 | 35             | 35                  | 0.74(0.06) | 29             | 29                  | 0.62(0.07) | 29             | 29                  | 0.62(0.07) |
| No IRDC Assoc.| 47               | 44                  | 0.94(0.04) | 24             | 24                  | 0.51(0.07) | 14             | 14                  | 0.30(0.07) | 35             | 35                  | 0.74(0.06) |
| “Likely” | 48               | 47                  | 0.98(0.02) | 34             | 34                  | 0.71(0.07) | 29             | 29                  | 0.60(0.07) | 36             | 36                  | 0.75(0.06) |
| “Possible” | 43               | 41                  | 0.95(0.03) | 22             | 22                  | 0.51(0.08) | 12             | 12                  | 0.28(0.07) | 25             | 25                  | 0.58(0.08) |
| “Outflow-only” | 3               | 3                   | 1.00 | 3              | 3                   | 1.00     | 2              | 2                   | 0.67(0.27) | 3              | 1.00                 |

Detected in:
- NH$_3$(1,1) only: 32
- NH$_3$(1,1) and (2,2): 16
- NH$_3$(1,1), (2,2), and (3,3): 43

Methanol Maser Associationsd

| Categoryc | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate | $N_{\text{obs}}$ | $N_{\text{detect}}$ | Rate |
|-----------|------------------|---------------------|------|-----------------|---------------------|------|-----------------|---------------------|------|-----------------|---------------------|------|-----------------|---------------------|------|
| Class I   | 41               | 41                  | 1.00 | 35             | 35                  | 0.85(0.06) | 31             | 31                  | 0.76(0.07) | 37             | 37                  | 0.90(0.05) |
| Class I ND | 28               | 25                  | 0.89(0.06) | 10             | 10                  | 0.36(0.09) | 3              | 3                   | 0.11(0.06) | 13             | 13                  | 0.46(0.09) |
| Class II  | 28               | 27                  | 0.96(0.04) | 23             | 23                  | 0.82(0.07) | 18             | 18                  | 0.64(0.09) | 24             | 24                  | 0.86(0.07) |
| Class II ND | 23              | 22                  | 0.96(0.04) | 9              | 9                   | 0.39(0.10) | 6              | 6                   | 0.26(0.09) | 10             | 10                  | 0.43(0.10) |
| Class I Only | 8               | 8                   | 1.00 | 6              | 6                   | 0.75(0.15) | 5              | 5                   | 0.63(0.17) | 5              | 5                   | 0.63(0.17) |
| Class II Only | 7             | 6                   | 0.86(0.13) | 4              | 4                   | 0.57(0.19) | 1              | 1                   | 0.14(0.13) | 4              | 4                   | 0.57(0.19) |
| Class I and II | 21             | 21                  | 1.00 | 19             | 19                  | 0.90(0.06) | 17             | 17                  | 0.81(0.09) | 20             | 20                  | 0.95(0.05) |
| Neither   | 15               | 14                  | 0.93(0.06) | 3              | 3                   | 0.20(0.10) | 1              | 1                   | 0.07(0.06) | 5              | 5                   | 0.33(0.12) |

Notes.
- a Uncertainties in detection rates calculated using binomial statistics.
- b Includes only sources detected in NH$_3$(1,1) and (2,2) as well as (3,3); see Section 3.1.2.
- c IRDC associations and “likely/possible” designations from C08; see also Section 1.
- d For consistency, all data on Class I and II CH$_3$OH maser associations are taken from Table 1 of CE11, see Section 3.1.1. “Class I”: all EGOs with a Class I maser detection in CE11, regardless of Class II association (or lack of Class II information). “Class I ND”: all EGOs listed as Class I nondetections in CE11, regardless of Class II association (or lack of Class II information). “Class II”: all EGOs listed as Class II maser detections in CE11, regardless of Class I association. “Class II ND”: all EGOs listed as Class II nondetections in CE11, regardless of Class I association. “Class I Only”: EGOs listed as Class I detections and Class II nondetections in CE11. “Class II only”: EGOs listed as Class I nondetections and Class II detections in CE11. “Class I and II”: EGOs listed as both Class I and Class II detections in CE11. “Neither”: EGOs listed as both Class I nondetections and Class II nondetections in CE11.

properties. Two-tailed binomial tests reject the null hypothesis that these two detection rates are the same at the 5% significance level ($p$-values $\sim$0.02). We also find a slightly higher H$_2$O maser detection rate toward EGOs not associated with IRDCs, compared to EGOs that are associated with IRDCs. In this case, however, two-tailed binomial tests are consistent with the detection rates being the same, at the 5% significance level ($p$-value $= 0.07(0.10)$ adopting the non-IRDC(IRDC) detection rate as the null hypothesis). If, instead, EGOs are grouped based on the NH$_3$ transitions detected in our survey, much larger differences in the H$_2$O maser detection rates emerge. We detect H$_2$O masers toward only 44% of EGOs with NH$_3$(1,1) emission only, compared to 81% of EGOs with emission in the higher-excitation NH$_3$ transitions: a difference of nearly a factor of two.

There are comparably striking differences in the H$_2$O maser detection rates toward EGO subsamples defined based on CH$_3$OH maser associations (see Table 2). To group EGOs by their CH$_3$OH maser associations, we use the data in Table 1 of CE11. This dataset, derived from single-dish surveys, is the most uniform available that includes the majority ($\sim$3/4) of our northern EGO targets. CE11 searched for 95 GHz Class I CH$_3$OH masers toward 192 EGOs (northern and southern) with the MOPRA telescope ($\theta_{\text{FWHP}} \sim 36''$, $3\sigma \sim 1.6$ Jy). They also observed EGOs without known Class II masers at 6.7 GHz with the University of Tasmania Mt. Pleasant telescope ($\theta_{\text{FWHP}} \sim 7''$, $3\sigma \sim 1.5$ Jy). This produced a three-tiered classification for Class II maser associations: (1) EGOs associated with Class II masers, based on published high-resolution data (maser positions known to $\sim1''$ or better); (2) EGOs for which 6.7 GHz emission was detected in the large Mt. Pleasant beam but no positional information was available (“no information”); and (3) EGOs undetected in the Mt. Pleasant observations. For this reason, definitive Class II maser information is available in CE11 for a smaller number of the EGOs in our sample (51) than for Class I masers (69 EGOs). We note one additional caveat. The 95 GHz Class I transition observed by CE11 is generally weaker than that at 44 GHz, and their MOPRA observations are significantly less sensitive than the VLA survey of C09. As a result, one source in the C09 sample that has weak 44 GHz Class I masers (G37.48$-0.10$) is listed as a Class I nondetection in CE11.

The most dramatic difference in H$_2$O maser detection rates in our survey is between EGOs associated with both Class I and II CH$_3$OH masers (20/21 $\sim$ 95%) and EGOs associated with neither type of CH$_3$OH maser (5/15 $\sim$ 33%). The H$_2$O maser detection rate is also very high ($\sim$90%) toward EGOs with Class I CH$_3$OH masers (considering all Class I detections, regardless of Class II detections/information). This correlation is consistent with both Class I CH$_3$OH and H$_2$O masers being associated with outflows, though H$_2$O masers are also observed toward $\sim$46% of EGOs undetected at 95 GHz. Unfortunately, comparison of “Class I only” and “Class II only” EGO subsamples is limited by the small number statistics.
Thus, we conservatively treat this source as an NH$_3$(1,1)-only detection in our Class I masers (regardless of Class II association without either type. The (3,3) detection rate toward EGOs associated with IRDCs is about twice that for non-IRDC EGOs; similarly, the detection rate toward “likely” outflow candidates (as classified by C08) is about twice that for “possible” outflow candidates. The (2,2) detection rates show the same trends.

The strongest correlation we see, however, is again with CH$_3$OH maser associations. The highest (3,3) detection rate of any subsample is 81%, toward EGOs with both Class I and II CH$_3$OH masers, while the lowest (7%) is toward EGOs without either type. The (3,3) detection rate toward EGOs with Class I masers (regardless of Class II association/information) is also high, at 76%. The (2,2) and (3,3) detection rates show similar trends, with (3,3) showing larger differences between subsamples.

3.1.3. NH$_3$ Nondetections

Our extremely high NH$_3$(1,1) detection rate raises the question of whether the three nondetections are in some way unusual, or interlopers in the EGO sample. The (1,1) nondetections do have some common characteristics: they are not associated with IRDCs and do not have Class I CH$_3$OH masers. Two have detected H$_2$O maser emission in our survey. G49.42+0.33, a C08 “possible” outflow candidate, was included in the C09 sample and detected in thermal HCO$^+$ (3–2), H$^{13}$CO$^+$ (3–2), and CH$_3$OH (5$_2$–4$_1$) emission with the James Clerk Maxwell Telescope. Thus, there is dense gas associated with the EGO: in combination with the detection of Class II CH$_3$OH (C09) and H$_2$O masers (Table 6), strong evidence for the presence of MYSO(s). This EGO is among the most distant in our sample, so our Nobeyama NH$_3$ nondetection may be attributable to sensitivity and/or beam dilution.

We also detect H$_2$O maser emission toward G53.92-0.07, a C08 “possible” outflow candidate. Its MIR morphology is unusual amongst the EGO sample; the “green” source appears embedded in an 8 $\mu$m bright pillar, and the 4.5 $\mu$m emission is only slightly extended. Little is known about this source beyond its identification as an EGO and its association with a BGPS 1.1 mm source, but it is possible it may be a comparatively evolved outflow in the EGO sample.

Finally, G57.61+0.02 is a “possible” outflow candidate located on the edge of an 8 and 24 $\mu$m bright nebula, likely a more evolved source (e.g., compact or UC H II region). Formally undetected by our 4$\sigma$ criterion, we do see a weak ($\sim$3.9$\sigma$) NH$_3$(1,1) line in our spectrum (see also Section 3.2.1).

3.2. NH$_3$ Properties

Table 3 presents the physical properties obtained from the single-component NH$_3$ modeling for all EGOs detected in NH$_3$ emission in our survey. The NH$_3$(1,1), (2,2), and (3,3) peak temperatures ($T_{\text{kin}}$) are also listed, with 4$\sigma$ upper limits given for undetected transitions (for all sources, including NH$_3$ nondetections). If NH$_3$(2,2) is not detected, the best-fit $T_{\text{kin}}$ is treated as an upper limit and is indicated as such in Table 3. The observed NH$_3$ spectra for each detected source, overlaid with the best-fit model, are shown in Figure 3 (available online in its entirety), and the property distributions for our EGO sample are shown in Figure 4. Throughout, the NH$_3$(1,1) peak ($T_{\text{MB}}$), $\sigma_v$, $T_{\text{kin}}$, $\eta_{\text{fit}}$, and NH$_3$ column density are presented for all EGOs detected in NH$_3$(1,1) emission. In Figure 4, the $T_{\text{kin}}$ and NH$_3$(2,2) peak distributions include only sources with $>4\sigma$ NH$_3$(2,2) detections, and the NH$_3$(3,3) peak distribution includes only sources with $>4\sigma$ detections in all three NH$_3$ transitions. For EGOs for which a two-component model provides a better fit to the observed NH$_3$ emission (Section 2.2), Figure 5 (available online in its entirety) shows the spectra overlaid with the best-fit two-component model, and Table 4 presents the parameters of the two-component fits.
Table 3
NH3 Properties: Single-component Fits

| Source Name | v<sub>LSR</sub> (km s<sup>-1</sup>) | σ<sub>v</sub> (km s<sup>-1</sup>) | Distance<sup>b</sup> (kpc) | T<sub>MB(1,1)</sub><sup>c</sup> (K) | T<sub><i>η</i></sub> (1<sub>+,1<sub>-</sub></sub>) N(H<sub>3</sub>) × 10<sup>14</sup> | T<sub>ex</sub> (K) | T<sub>kin</sub><sup>d</sup> (K) | T<sub>MB(2,2)</sub><sup>e</sup> (K) | T<sub>MB(3,3)</sub><sup>f</sup> (K) | 2 comp<sup>g</sup> | H<sub>2</sub>O Maser? |
|-------------|---------------------------------|-----------------|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------------|--------------|
| G10.29−0.13 | 13.97 (0.01)                    | 1.18 (0.01)     | 1.58 (+0.86, −1.13)  | 1.94 (0.04)     | 4.76            | 22.1 (0.6)      | 0.096 (0.002)   | 4.52 (0.05)     | 21.19 (0.17)   | 1.19 (0.04)   | 0.61 (0.05)   | Y            | Y            |
| G10.34−0.14 | 12.02 (0.02)                    | 1.07 (0.02)     | 1.29 (+0.42, −1.23)  | 1.56 (0.06)     | 4.28            | 18.2 (1.0)      | 0.047 (0.002)   | 3.95 (0.07)     | 28.23 (0.38)   | 0.94 (0.05)   | 0.76 (0.07)   | Y            | Y            |
| G11.11−0.11 | 29.79 (0.02)                    | 0.68 (0.01)     | 12.67 (+0.48, −0.41)<sup>f</sup> | 1.79 (0.07)     | 5.15            | 11.9 (0.6)      | 0.150 (0.006)   | 4.45 (0.09)     | 14.15 (0.27)   | 0.65 (0.06)   | 0.32 (0.07)   | Y            | N            |
| G11.92−0.61 | 36.11 (0.01)                    | 1.09 (0.01)     | 3.48 (+0.44, −0.52)  | 3.02 (0.07)     | 6.40            | 31.7 (0.8)      | 0.087 (0.001)   | 4.79 (0.04)     | 26.27 (0.19)   | 1.83 (0.06)   | 1.14 (0.07)   | Y            | Y            |
| G12.02−0.21 | −3.15 (0.06)                    | 1.04 (0.05)     | 5.30 (+0.20, −0.20)<sup>g</sup> | 0.46 (0.06)     | 5.18            | 13.2 (2.1)      | 0.042 (0.004)   | 3.16 (0.15)     | <12.85         | <0.19         | <0.22         | N            | N            |
| G12.20−0.03 | 51.16 (0.06)                    | 1.24 (0.05)     | 11.70 (+0.31, −0.27)<sup>f</sup> | 0.55 (0.06)     | 3.76            | 13.5 (2.3)      | 0.032 (0.004)   | 3.27 (0.13)     | 19.56 (0.76)   | 0.28 (0.05)   | <0.25         | N            | Y            |

Notes.

<sup>a</sup> Uncertainties are given in parentheses. For kinematic distances, the uncertainties are based on the prescription of Reid et al. (2009; see also Section 3.2.1); for maser parallax distances, the uncertainties are taken from the cited reference. For the NH<sub>3</sub>(1,1), (2,2), and (3,3) peak temperatures, the quoted uncertainty is the 1σ rms. For all other quantities, the uncertainties are estimated from the model optimization, and uncertainties of 0.00 indicate the case T<sub>kin</sub> = T<sub>ex</sub> (see Section 2.2).

<sup>b</sup> Near kinematic distance estimated using the NH<sub>3</sub> v<sub>LSR</sub>, except as otherwise noted. See also Section 3.2.1.

<sup>c</sup> Peak temperature of the NH<sub>3</sub> emission on the T<sub>MB</sub> scale. All upper limits are 4σ.

<sup>d</sup> T<sub>kin</sub> is indicated as an upper limit if NH<sub>3</sub>(2,2) emission is not detected at >4σ.

<sup>e</sup> Indicates whether a two-component model was fit (Section 2.2). If “Y,” the two-component model results are listed in Table 4.

<sup>f</sup> Associated with a 6.7 GHz CH<sub>3</sub>OH maser assigned the far distance by Green & McClure-Griffiths (2011). Except for G12.20−0.03 and G45.80−0.36, all far distance assignments are “B” classifications in their scheme (see also Section 3.2.1). We adopt the far kinematic distance estimated from the NH<sub>3</sub> v<sub>LSR</sub>.

<sup>g</sup> Indicates whether a two-component model was fit (Section 2.2). If “Y,” the two-component model results are listed in Table 4.

<sup>i</sup> Associated with a 6.7 GHz CH<sub>3</sub>OH maser assigned the far distance by Green & McClure-Griffiths (2011). Except for G12.20−0.03 and G45.80−0.36, all far distance assignments are “B” classifications in their scheme (see also Section 3.2.1). We adopt the far kinematic distance estimated from the NH<sub>3</sub> v<sub>LSR</sub>.

<sup>j</sup> The longitude and velocity of this source indicate that it is likely in the near 3 kpc arm (see, for example, Figure 1 of Green et al. 2009). Following Green & McClure-Griffiths (2011), we place this source on a circle of radius 3.4 kpc around the Galactic Center, and adopt a distance uncertainty of ±0.2 kpc.

<sup>l</sup> Maser parallax distance. References: G14.33−0.64, Sato et al. (2010). G23.01−0.41, Brunthaler et al. (2009). G34.39+0.22 and G34.41+0.24, Kurayama et al. (2011). G35.20−0.74, Zhang et al. (2009).

<sup>m</sup> Maser parallax distance. References: G14.33−0.64, Sato et al. (2010). G23.01−0.41, Brunthaler et al. (2009). G34.39+0.22 and G34.41+0.24, Kurayama et al. (2011). G35.20−0.74, Zhang et al. (2009).

<sup>n</sup> Source that meets 4σ detection criterion for NH<sub>3</sub>(1,1) and (3,3), but not (2,2); hence, T<sub>kin</sub> is treated as an upper limit as for other (2,2) nondetections. See also Section 3.1.2.

<sup>n</sup> NH<sub>3</sub> nondetection. G49.42+0.33: distance estimated using H<sub>13</sub>CO+ velocity from C09. G53.92−0.07: distance estimated using H<sub>2</sub>O maser peak velocity. G57.61+0.02: distance estimated from velocity of weak (3.9σ) NH<sub>3</sub>(1,1) emission below our 4σ detection threshold. The distance for G57.61+0.02 is included here and in Figure 4 for completeness, but this source is otherwise excluded from our analysis. See also Section 3.2.1.

<sup>n</sup> This temperature limit is likely excessively low because the criteria of least-squares fitting are failing and the error distributions are non-Gaussian.

(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.)
Figure 4. Histograms showing distributions of observed NH$_3$ properties and physical properties obtained from the NH$_3$ modeling. Bin sizes are 0.2 K for the NH$_3$ peak temperatures, 0.2 km s$^{-1}$ for $\sigma_v$, 0.5 for $\tau_{1,1}$, 0.02 for $\eta_{ff}$, 0.1 dex for the NH$_3$ column density, and 2 K for $T_{\text{kin}}$. All EGOs detected in NH$_3$(1,1) are included in the first five panels ((1,1) peak, $\sigma_v$, $\tau_{1,1}$, $\eta_{ff}$, and column density). Sources for which $T_{\text{ex}} = T_{\text{kin}}$ (the upper limit, for $\eta_{ff} = 1$) are excluded from the filling fraction plot. EGOs detected in both NH$_3$(1,1) and (2,2) are included in the $T_{\text{kin}}$ and (2,2) peak histograms, and EGOs detected in all three NH$_3$ transitions are included in the (3,3) peak plot.
Figure 5. Observed NH₃ spectra with best-fit two-component model overlaid. Model spectra for each component are shown (dashed line: warmer component; dotted line: cooler component), as well as their sum (solid line). A “D” in the upper right corner of a panel indicates that our 4σ detection criterion was met for that transition. (An extended version of this figure is available in the online journal.)

Table 4
NH₃ Properties: Two-component Fits

| Source Name | T_{kin} | v_{LSR} | σ_v | T_{ex} | N(NH₃) |
|-------------|---------|---------|-----|--------|--------|
|             | (K)     | (km s^{-1}) | (km s^{-1}) | (K)    | (cm^{-2}) \times 10^{14} |
| G10.29−0.13 | 15.93(0.32) | 14.16(0.02) | 0.89(0.02) | 4.19(0.06) | 15.6(0.7) |
|             | 32.91(0.98) | 13.31(0.06) | 1.73(0.04) | 3.23(0.12) | 30.2(2.8) |
| G10.34−0.14 | 15.62(0.78) | 12.05(0.03) | 0.70(0.04) | 4.04(0.17) | 6.5(1.1) |
|             | 41.51(2.42) | 12.05(0.05) | 1.43(0.05) | 3.32(0.23) | 21.3(2.7) |
| G11.11−0.11 | 13.90(0.58) | 29.40(0.04) | 0.45(0.03) | 3.70(0.25) | 10.6(1.1) |
|             | 14.07(0.64) | 30.33(0.14) | 0.65(0.06) | 3.72(0.22) | 8.8(1.2) |
| G11.92−0.61 | 13.55(0.20) | 36.10(0.01) | 0.73(0.01) | 5.16(0.07) | 19.3(0.6) |
|             | 54.06(1.38) | 35.89(0.06) | 3.43(0.07) | 54.06(0.00) | 3.4(0.1) |
| G12.68−0.18 | 14.19(0.48) | 56.42(0.01) | 0.73(0.01) | 5.16(0.07) | 19.3(0.6) |
|             | 31.47(0.78) | 54.99(0.04) | 1.08(0.03) | 3.33(0.10) | 36.7(2.0) |

Note. a Uncertainties estimated from the model optimization are given in parentheses; values of 0.00 indicate cases where the model is poorly constrained (see Section 2.2). (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.)

3.2.1. Kinematic Distances

We calculate kinematic distances based on the NH₃ velocities in Table 3 and the prescription of Reid et al. (2009), using updated input parameters (M. Reid 2012, private communication; Galactic: \( R_O = 8.40 \) kpc, \( \Theta_0 = 245.0 \) km s^{-1}, \( d\Theta/dr = 1.0 \) km s^{-1} kpc^{-1}; Solar: \( U_0 = 10.00 \) km s^{-1}, \( V_0 = 12.00 \) km s^{-1}, \( W_0 = 7.20 \) km s^{-1}; Source peculiar motions: \( U_S = 5.00 \) km s^{-1}, \( V_S = -6.00 \) km s^{-1}, \( W_S = 0.00 \) km s^{-1}; and an assumed \( v_{LSR} \) uncertainty of 7 km s^{-1}). For sources with distance ambiguities, the near kinematic distance is listed in Table 3, unless otherwise noted. The angular extent of EGOs on the sky supports adopting the near kinematic distance, as does the association of EGOs, as a population, with IRDCs (see C08, C09). In their H1 self-absorption study of 6.7 GHz CH₃OH masers, Green & McClure-Griffiths (2011) have recently suggested assigning the far distance to masers associated with a few (eight) of our targets. Most of these assignments are “Class B” in their scheme, reflecting uncertainty in the classification. For these sources, we adopt the far distance calculated from the NH₃ velocity. Maser parallax distances are adopted when available, as noted in Table 3.

Three sources are undetected in NH₃(1,1), and so present special cases for calculating kinematic distances. For G49.42+0.33, we use the H¹³CO+(3–2) velocity from C09 (see also Section 3.1.3). For G53.92−0.07, the H₂O maser emission is very narrow (\( \Delta v = 1.3 \) km s^{-1}), and we calculate a kinematic distance using the H₂O maser peak velocity (Table 6). In G57.61+0.02, we detect weak NH₃(1,1) emission at \( \sim 3.9 \sigma \), just below our formal detection limit. The fitted \( v_{LSR} \) of 37.4 \pm 0.1 km s^{-1} gives a kinematic distance of 4.50 \pm 1.96 kpc. For completeness, we include this source in the distance histogram shown in Figure 6, but not in the subsequent analysis. The mean(median) distance for our sample is 4.3 kpc (4.2 kpc).
As discussed in Section 3.1.2, detection rates for the higher-excitation NH$_3$ transitions differ for various EGO subsamples. We consider seven pairs of EGO subsamples: (1) “likely”/“possible” outflow candidates; (2) sources associated/not associated with IRDCs; (3) H$_2$O maser detections/nondetections in our survey; (4) Class I CH$_3$OH maser detections/nondetections (regardless of Class II association); (5) Class II CH$_3$OH maser detections/nondetections (regardless of Class I association); (6) EGOs associated with only Class I/only Class II CH$_3$OH masers; and (7) EGOs associated with both Class I and II CH$_3$OH masers/EGOs associated with neither CH$_3$OH maser type. To assess whether the NH$_3$ properties of these subsamples exhibit statistically significant differences, we ran two-sided K-S tests of eight parameters: the NH$_3$ column density, $\sigma_v$, and the beam filling fraction, $\eta_{ff}$. EGOs associated with IRDCs have stronger NH$_3$ (1,1) emission (higher NH$_3$ (1,1) peak temperatures) and narrower NH$_3$ line widths (Figure 8). We note that the distance distributions for EGOs associated/not associated with IRDCs are statistically indistinguishable based on our K-S tests (K-S significance $0.21$, median distance $4.0$ and $4.3$ kpc, respectively; see also Section 3.2.1). Pillai et al. (2006b) found that IRDCs had, on average, narrower NH$_3$ line widths than IRAS-selected high-mass protostellar objects or UC H II regions. It is perhaps surprising, however, that we see a difference in the line width distributions for IRDC/non-IRDC EGOs, since we are specifically targeting active star-forming regions within IRDCs. The effect may be attributable to emission from more quiescent regions of IRDCs being included within the Nobeyama beam ($73'' \sim 1.4$ pc at a typical distance of $4$ kpc). As shown in Figure 13, EGOs associated with IRDCs also generally have larger (though still small, $<0.2$) beam filling fractions. This is consistent with numerous studies that show NH$_3$ emission overall follows $8\mu$m extinction indicative of molecules in high-resolution Karl G. Jansky Very Large Array (VLA) observations of one of the EGOs in our sample, Brogan et al. (2011) detect a hot ($220$ K), blueshifted outflow component in NH$_3$ emission, coincident with redshifted H$_2$O masers. In our survey, EGOs with H$_2$O masers are also generally found in clumps with higher NH$_3$ column densities and higher kinetic temperatures than H$_2$O maser nondetections.

The populations of EGOs associated and not associated with IRDCs show statistically significant differences in three NH$_3$ properties: NH$_3$(1,1) peak, $\sigma_v$, and the beam filling fraction, $\eta_{ff}$. EGOs associated with IRDCs have stronger NH$_3$(1,1) emission (higher NH$_3$ (1,1) peak temperatures) and narrower NH$_3$ line widths (Figure 8). We note that the distance distributions for EGOs associated/not associated with IRDCs are statistically indistinguishable based on our K-S tests (K-S significance $0.21$, median distance $4.0$ and $4.3$ kpc, respectively; see also Section 3.2.1). Pillai et al. (2006b) found that IRDCs had, on average, narrower NH$_3$ line widths than IRAS-selected high-mass protostellar objects or UC H II regions. It is perhaps surprising, however, that we see a difference in the line width distributions for IRDC/non-IRDC EGOs, since we are specifically targeting active star-forming regions within IRDCs. The effect may be attributable to emission from more quiescent regions of IRDCs being included within the Nobeyama beam ($73'' \sim 1.4$ pc at a typical distance of $4$ kpc). As shown in Figure 13, EGOs associated with IRDCs also generally have larger (though still small, $<0.2$) beam filling fractions. This is consistent with numerous studies that show NH$_3$ emission overall follows $8\mu$m extinction indicative of molecules in high-resolution Karl G. Jansky Very Large Array (VLA) observations of one of the EGOs in our sample, Brogan et al. (2011) detect a hot ($220$ K), blueshifted outflow component in NH$_3$ emission, coincident with redshifted H$_2$O masers. In our survey, EGOs with H$_2$O masers are also generally found in clumps with higher NH$_3$ column densities and higher kinetic temperatures than H$_2$O maser nondetections.

### Table 5

| Subsample          | Property | K-S Significance |
|--------------------|----------|------------------|
| Likely/Possible    | NH$_3$(1,1) peak ($T_{MB}$) | 8.4E-03 |
| Likely/Possible    | NH$_3$(2,2) peak ($T_{MB}$) | 7.6E-03 |
| IRDC/no IRDC       | NH$_3$(1,1) peak ($T_{MB}$) | 1.5E-05 |
| IRDC/no IRDC       | $\sigma_v$ | 8.2E-04 |
| IRDC/no IRDC       | $\eta_{ff}$ | 1.7E-03 |
| H$_2$O maser detections/nondetections | $\sigma_v$ | 5.5E-08 |
| H$_2$O maser detections/nondetections | $\eta_{ff}$ | 1.7E-03 |
| H$_2$O maser detections/nondetections | $\eta_{ff}$ | 1.7E-03 |
| Class I/Class I ND | NH$_3$(1,1) peak ($T_{MB}$) | 3.0E-03 |
| Class I/Class I ND | $\sigma_v$ | 5.1E-03 |
| Class I/Class I ND | $\eta_{ff}$ | 4.5E-03 |
| Class I/Class I ND | $T_{kin}$ | 5.1E-03 |
| Class II/Class II ND | NH$_3$(1,1) peak ($T_{MB}$) | 3.2E-03 |
| Class II/Class II ND | $\sigma_v$ | 4.0E-03 |
| Class II/Class II ND | $\eta_{ff}$ | 2.7E-06 |
| Class II/Class II ND | $T_{kin}$ | 6.8E-03 |
| Class II/Class II ND | NH$_3$(2,2) peak ($T_{MB}$) | 3.9E-03 |
| Class II/Class II ND | NH$_3$(3,3) peak ($T_{MB}$) | 3.5E-03 |
| Both Class I and II/Neither | NH$_3$(1,1) peak ($T_{MB}$) | 8.9E-04 |
| Both Class I and II/Neither | $\sigma_v$ | 1.6E-03 |
| Both Class I and II/Neither | $\eta_{ff}$ | 3.9E-05 |

### 3.2.2. Comparison of EGO Subsamples

and $0.80$ km s$^{-1}$ for H$_2$O maser detections and nondetections, respectively ($\sigma_v = \text{FWHM}/\sqrt{8 \ln 2}$). This is in agreement with previous single-dish studies of H$_2$O masers in star-forming regions. In their NH$_3$(1,1) survey of $164$ H$_2$O masers ($\theta_{FWHP} \sim 14'$), Anglada et al. (1996) found a correlation between $L_{H_2O}$ and the NH$_3$ line width; comparing their data with other NH$_3$ surveys, they found increased NH$_3$ line widths toward star-forming regions with H$_2$O masers. Both our results and those of Anglada et al. (1996) are consistent with the H$_2$O masers being excited in outflows, which also contribute to gas motions in the surrounding clump, increasing the NH$_3$ line width. Indeed, in high-resolution Karl G. Jansky Very Large Array (VLA) observations of one of the EGOs in our sample, Brogan et al. (2011) detect a hot ($220$ K), blueshifted outflow component in NH$_3$ emission, coincident with redshifted H$_2$O masers. In our survey, EGOs with H$_2$O masers are also generally found in clumps with higher NH$_3$ column densities and higher kinetic temperatures than H$_2$O maser nondetections.

Table 5 lists the subsample/parameter combinations that have significantly different distributions, adopting a moderately conservative threshold of $<0.01$ for the significance of the K-S statistic. Note that K-S tests involving the CH$_3$OH maser subsamples are limited by small sample sizes, particularly for parameters that require (2,2) or (3,3) detections. While we ran K-S tests in all cases where the subsamples being compared each have $>4$ members, we interpret the small-$n$ results with caution. Statistically significant differences are seen most often in the NH$_3$(1,1) peak temperature, $\sigma_v$, the NH$_3$ column density, and the kinetic temperature. The distributions of these properties for the various subsamples are shown in Figures 7–12.

The most dramatic difference is between the $\sigma_v$ distributions for EGOs that are/not detected in H$_2$O maser emission in our survey (Figure 9). The NH$_3$ lines are broader toward EGOs associated with H$_2$O masers, with median $\sigma_v$ of $1.18$ km s$^{-1}$ and $0.80$ km s$^{-1}$ for H$_2$O maser detections and nondetections, respectively ($\sigma_v = \text{FWHM}/\sqrt{8 \ln 2}$). This is in agreement with previous single-dish studies of H$_2$O masers in star-forming regions. In their NH$_3$(1,1) survey of $164$ H$_2$O masers ($\theta_{FWHP} \sim 14'$), Anglada et al. (1996) found a correlation between $L_{H_2O}$ and the NH$_3$ line width; comparing their data with other NH$_3$ surveys, they found increased NH$_3$ line widths toward star-forming regions with H$_2$O masers. Both our results and those of Anglada et al. (1996) are consistent with the H$_2$O masers being excited in outflows, which also contribute to gas motions in the surrounding clump, increasing the NH$_3$ line width. Indeed, in high-resolution Karl G. Jansky Very Large Array (VLA) observations of one of the EGOs in our sample, Brogan et al. (2011) detect a hot ($220$ K), blueshifted outflow component in NH$_3$ emission, coincident with redshifted H$_2$O masers. In our survey, EGOs with H$_2$O masers are also generally found in clumps with higher NH$_3$ column densities and higher kinetic temperatures than H$_2$O maser nondetections.
**Figure 7.** NH$_3$ property distributions for EGOs classified as “likely” and “possible” MYSO outflow candidates by C08. “Likely” and “possible” sources are plotted as horizontally and diagonally hatched histograms, respectively. Bin sizes are the same as in Figure 4.

**Figure 8.** NH$_3$ property distributions for EGOs associated/not associated with IRDCs, plotted as horizontally and diagonally hatched histograms, respectively. Bin sizes are the same as in Figure 4.
Figure 9. NH$_3$ property distributions for EGOs that are not detected in H$_2$O maser emission in our survey, plotted as horizontally and diagonally hatched histograms, respectively. Bin sizes are the same as in Figure 4.

Figure 10. NH$_3$ property distributions for EGOs that are not associated with Class I CH$_3$OH maser emission (in CE11; see also Section 3.1.1), plotted as horizontally and diagonally hatched histograms, respectively. Bin sizes are the same as in Figure 4.
Figure 11. NH$_3$ property distributions for EGOs that are/are not associated with Class II CH$_3$OH maser emission (in CE11; see also Section 3.1.1), plotted as horizontally and diagonally hatched histograms, respectively. Bin sizes are the same as in Figure 4.

Figure 12. NH$_3$ property distributions for EGOs associated with both Class I and II CH$_3$OH masers (green), only Class I CH$_3$OH masers (blue), only Class II CH$_3$OH masers (red), and neither type of CH$_3$OH maser (orange) (CH$_3$OH maser associations from CE11; see also Section 3.1.1). Bin sizes are the same as in Figure 4. (A color version of this figure is available in the online journal.)
CH$_3$OH maser detections associated with both Class I and II CH$_3$OH masers. Similarly, (lowest K-S significance) is between the NH$_3$(1,1) peak temperatures), broader NH$_3$ line widths, and higher NH$_3$ column densities than Class I CH$_3$OH maser nondetections (Figure 10). Class II CH$_3$OH maser detections/nondetections show the same trends in the same properties (Figure 11). EGOS associated with both Class I and II CH$_3$OH masers likewise show stronger NH$_3$(1,1) emission and increased NH$_3$ line widths and column densities compared to EGOS associated with neither type of CH$_3$OH maser. Too few EGOS with neither CH$_3$OH maser association are detected in NH$_3$(2,2) to run a K-S test on $T_{kin}$, but Figure 12 shows that the kinetic temperature is indeed also higher toward EGOS with Class I and II CH$_3$OH masers. Of the CH$_3$OH maser subsamples, the most significant difference (lowest K-S significance) is between the $N$(NH$_3$) distributions for EGOS with/without Class II CH$_3$OH masers.

The majority of our sample of Class II CH$_3$OH maser detections (21/28), and about half of our sample of Class I CH$_3$OH maser detections (21/41), are comprised of EGOS associated with both Class I and II CH$_3$OH masers. Similarly, the majority of the Class II nondetections (15/23) and $\sim$1/2 the Class I nondetections (15/28) are EGOS with neither type of CH$_3$OH maser. Thus, it is not surprising that the Class I detection/nondetection, Class II detection/nondetection, and both (Class I and II)/neither EGO subsamples show similar patterns in their NH$_3$ properties. The sample sizes of EGOS known to be associated with only Class I or only Class II CH$_3$OH masers are small (Table 2). Nonetheless, there are no indications of systematic differences in the NH$_3$ properties of Class I-only and Class II-only EGOS, either in the K-S test results or in the plots shown in Figure 12.

### 3.3. Water Maser Properties

For each EGO with detected H$_2$O maser emission in our survey, Table 6 lists the rms, peak flux density, velocity of peak maser emission, minimum and maximum velocities of maser emission ($>4\sigma$; see also Section 3.1.1), integrated flux density, and isotropic maser luminosity. Spectra are presented in Figure 14 (available online in its entirety), with the minimum and maximum velocities of detected maser emission plotted as dotted lines. In the absence of precise positions, the extreme variability of H$_2$O masers makes it very difficult to establish with confidence whether or not a newly observed maser is identifiable with one previously reported (as discussed in Breen & Ellingsen 2011, and references therein). The present study is, to our knowledge, the first systematic search for H$_2$O maser emission toward EGOS. We note in Table 6 H$_2$O masers detected in high-resolution studies targeting other samples that fall within the polygonal EGO apertures from C08, but do not attempt to correlate our Nobeyama spectra with previous single-dish detections. As in similar studies (e.g., Anglada et al. 1996; Urquhart et al. 2011), we estimate the isotropic H$_2$O maser luminosity, $L$(H$_2$O), as

$$\left[ \frac{L(\text{H}_2\text{O})}{L_\odot} \right] = 2.30 \times 10^{-8} \left[ \frac{\int S_\nu dV}{\text{Jy k}\text{m s}^{-1}} \right] \left[ \frac{D}{\text{kpc}} \right]^2,$$

### Table 6

| Source Name | $\sigma$ (Jy) | $V_{\text{min}}$ (km s$^{-1}$) | $V_{\text{max}}$ (km s$^{-1}$) | $V_{\text{peak}}$ (km s$^{-1}$) | $V_{\text{range}}$ (km s$^{-1}$) | $S_{\text{peak}}$ (Jy) | $\int S_\nu dV$ (Jy km s$^{-1}$) | $L_{\text{iso}}$(H$_2$O) ($L_\odot$) | Notes$^a$ |
|-------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| G10.29-0.13 | 0.08           | 5.3             | 16.1            | 12.3            | 10.8            | 14.0            | 0.7             | 1.548           | 8.98E-08        | BE11            |
| G10.34-0.14 | 0.11           | -13.1           | 49.8            | 19.8            | 62.8            | 12.0            | 11.1            | 64.044          | 2.45E-06        | BE11            |
| G11.92-0.61 | 0.14           | 18.2            | 43.8            | 39.9            | 25.6            | 36.1            | 53.1            | 151.44          | 4.06E-05        | BE11            |
| G12.29-0.03 | 0.11           | 47.3            | 47.6            | 47.3            | 0.3             | 51.2            | 0.5             | 0.242           | 7.62E-07        | BE11            |
| G12.42-0.50 | 0.11           | 4.5             | 11.2            | 5.8             | 6.7             | 18.1            | 2.9             | 7.828           | 6.30E-07        | BE11            |
| G12.48-0.18 | 0.11           | 8.3             | 109.7           | 59.5            | 101.4           | 55.7            | 629.0           | 1381.320        | 6.32E-04        | BE11            |
| G12.91-0.03 | 0.11           | 13.2            | 16.9            | 16.7            | 3.8             | 56.8            | 0.7             | 1.327           | 6.13E-07        | ...             |
| G12.91-0.26 | 0.14           | 40.4            | 49.3            | 40.7            | 8.9             | 37.1            | 1.0             | 1.010           | 2.70E-07        | *               |
| G14.33-0.64 | 0.13           | 14.3            | 32.3            | 27.2            | 18.1            | 22.5            | 35.8            | 108.120         | 3.12E-06        | S10             |
| G14.63-0.58 | 0.14           | 21.8            | 22.6            | 22.3            | 0.8             | 18.6            | 1.7             | 1.452           | 1.00E-07        | ...             |

Notes:

$^a$ References are for previously reported H$_2$O masers with accurate positions from interferometric observations that fall within the polygonal aperture for the EGO published by C08 (Section 3.3). B02: Beuther et al. (2002). B11: Bartkiewicz et al. (2011). BE11: Breen & Ellingsen (2011). CG11: Caswell & Green (2011). FC99: Forster & Caswell (1999). H96: Hofner & Churchwell (1996). S10: Sato et al. (2010). W06: Wang et al. (2006). “∗” indicates no H$_2$O maser reference meeting these criteria was found in a SIMBAD search.

“Outflow-only” source in C08. The published polygonal aperture does not include the “central” source, which is associated with H$_2$O maser emission (G12.91-0.26; G34.26+0.15; G37.55+0.20: Breen & Ellingsen 2011, Forster & Caswell 1999; Beuther et al. 2002, respectively).

(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.)

![Figure 13](image-url) Distribution of the beam filling fraction, $\eta_B$, for EGOS associated/ not associated with IRDCs, plotted as horizontally and diagonally hatched histograms, respectively. The bin size is 0.01. Sources for which $T_{ex} = T_{kin}$ and $\eta_B = 1$ are not shown.
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Figure 14. H$_2$O maser spectrum. The minimum and maximum velocities of detected maser emission (>4σ; Table 6) are shown as dotted vertical lines. The velocity range shown for each EGO extends from $V_{\text{min,water}} - 30$ km s$^{-1}$ to $V_{\text{max,water}} + 30$ km s$^{-1}$.
(An extended version of this figure is available in the online journal.)

where $D$ is the distance to the source (Section 3.2.1, Table 3) and $\int S_\nu dV \sim \sum_i (S_i \Delta v_i)$ is calculated over all channels that meet our 4σ detection criterion. For H$_2$O maser nondetections, Table 7 lists the rms and upper limit for the isotropic H$_2$O maser luminosity (calculated from Equation (3) for 4σ and two channels). The distributions of H$_2$O maser peak and integrated

flux densities, luminosity, and velocity range for H$_2$O maser detections in our sample are shown in Figure 15.

3.3.1. High-velocity Features

H$_2$O masers are known for their wide velocity ranges and high-velocity features, as compared to other masers found in MSFRs (e.g., CH$_3$OH and OH). The velocity of the strongest H$_2$O maser emission in a given source is nonetheless generally well correlated with the $v_{\text{LSR}}$ of the dense gas (e.g., Churchwell et al. 1990; Anglada et al. 1996; Urquhart et al. 2011). Notably, for the Red MSX Source (RMS)$^{15}$ sample of MIR-bright MYSOs and UC H II regions, the distribution of $V_{\text{H$_2$O,peak}} - V_{\text{NH$_3$}}$ is skewed toward negative velocities. The offset (from zero) is statistically significant, and indicates that blueshifted masers are stronger and more prevalent than redshifted masers (Urquhart et al. 2011). In our sample of 62 sources detected in both H$_2$O maser and NH$_3$(1,1) emission, the mean offset $V_{\text{H$_2$O,peak}} - V_{\text{NH$_3$}}$ is $-2.43$ km s$^{-1}$ and the median offset $-0.54$ km s$^{-1}$. However, in our (smaller) sample, the offset from zero is not statistically significant (standard errors 1.37 and 1.72, respectively). The distribution of $V_{\text{H$_2$O,peak}} - V_{\text{NH$_3$}}$ for our EGO sample is shown in Figure 16.

The relative frequency of blueshifted and redshifted emission can also be accessed by examining high-velocity maser features (generally defined as $V - V_{\text{LSR}} \geq 30$ km s$^{-1}$, e.g., Caswell & Breen 2010; Urquhart et al. 2011). Caswell & Breen (2010) recently analyzed high-velocity emission in numerous H$_2$O

$^{15}$ For additional details on the RMS sample, see Hoare et al. (2005); Urquhart et al. (2008).

Figure 15. Histograms showing the distributions of H$_2$O maser properties for all H$_2$O maser detections in our sample. The panels show (clockwise from upper left): peak flux density, integrated flux density, isotropic H$_2$O maser luminosity, and velocity range of maser emission (>4σ) (Section 3.3). Bin sizes are 0.5 dex (peak and integrated flux densities and luminosity) and 10 km s$^{-1}$ (velocity range).
Figure 16. Distribution of the difference between the NH$_3$ $v_{\text{LSR}}$ and the velocity of peak H$_2$O maser emission for all sources with both H$_2$O maser and NH$_3$(1,1) detections. The bin size is 2 km s$^{-1}$.

Table 7

| Source Name      | $\sigma$ (Jy) | $L_{\text{int}}$(H$_2$O) (L$_\odot$) |
|------------------|---------------|-------------------------------------|
| G11.11-0.11      | 0.14          | <1.09E-06                           |
| G12.02-0.21      | 0.10          | <1.41E-07                           |
| G16.58-0.08      | 0.10          | <5.04E-08                           |
| G16.61-0.24      | 0.10          | <5.68E-08                           |
| G19.36-0.03      | 0.16          | <3.40E-08                           |
| G21.24+0.19      | 0.10          | <1.89E-08                           |
| G24.11-0.17      | 0.09          | <9.87E-08                           |
| G24.11-0.18      | 0.10          | <1.09E-07                           |
| G28.28-0.36      | 0.17          | <8.07E-08                           |
| G28.83-0.25      | 0.17          | <2.01E-07                           |
| G28.85-0.23      | 0.12          | <1.73E-07                           |
| G29.84-0.47      | 0.14          | <1.09E-07                           |
| G29.89-0.77      | 0.16          | <1.74E-07                           |
| G29.91-0.81      | 0.17          | <1.87E-07                           |
| G29.96-0.79      | 0.06          | <6.52E-08                           |
| G35.04-0.47      | 0.12          | <5.82E-08                           |
| G35.83-0.20      | 0.13          | <2.10E-08                           |
| G36.01-0.20      | 0.10          | <1.50E-07                           |
| G40.28-0.27      | 0.08          | <8.94E-08                           |
| G40.60-0.72      | 0.10          | <9.26E-08                           |
| G44.01-0.03      | 0.10          | <1.16E-07                           |
| G48.66-0.30      | 0.16          | <4.68E-08                           |
| G49.27-0.32      | 0.15          | <2.18E-07                           |
| G54.11-0.04      | 0.16          | <1.09E-07                           |
| G54.11-0.05      | 0.11          | <7.35E-08                           |
| G56.13-0.22      | 0.06          | <6.80E-08                           |
| G57.61-0.02      | 0.11          | <1.11E-07                           |
| G58.09-0.34      | 0.06          | <1.69E-09                           |
| G58.79-0.63      | 0.07          | <6.48E-08                           |
| G62.70-0.51      | 0.06          | <4.15E-08                           |

Note. $^a$ All limits are 4$\sigma$.

maser subsamples and proposed that an excess of sources showing only blueshifted high-velocity emission is an indicator of youth. For H$_2$O masers associated with Class II CH$_3$OH but not OH masers (from the sample of Breen et al. 2010a), they find a “blue” (blueshifted high-velocity emission only) fraction of 16%, a “red” fraction of 8%, and a “red+blue” (both blueshifted and redshifted high-velocity H$_2$O maser features) fraction of 7%. Interestingly, Urquhart et al. (2011) find a similar ratio of “blue”:“red” sources in their much larger sample of RMS YSOs and UC H II regions, though a smaller overall fraction (22%) of their detected H$_2$O masers show some high-velocity emission. Twelve of our EGO targets (∼19%) have high-velocity H$_2$O maser features (offset by ≥30 km s$^{-1}$ from the NH$_3$ $v_{\text{LSR}}$): 6 “blue,” 1 “red,” and 5 “red+blue.” Of these 12 EGOs, 5 are associated with both Class I and II CH$_3$OH masers, 4 are associated with Class I CH$_3$OH masers and are classified as Class II “no information” in CE11, 1 is associated with Class I but not Class II CH$_3$OH masers, and 2 are not included in CE11. Our sample sizes and those of Caswell & Breen (2010) are too small to warrant detailed comparisons; however, the “blue”:“red” excess we observe is generally consistent with their results for CH$_3$OH maser sources.

3.3.2. Comparison of EGO Subsamples

To look for differences in the properties of H$_2$O masers associated with the various EGO subsamples, we ran two-sided K-S tests for four parameters: velocity range, peak flux density, integrated flux density, and isotropic maser luminosity. The subsample pairs considered were the same as outlined above (Section 3.2.2), with the exception of H$_2$O maser detections/nondetections (since we are investigating H$_2$O maser properties, only detections are considered). We find no evidence for statistically significant differences. As an example, Figures 17 and 18 show histograms of the H$_2$O maser luminosity, shaded by subsample, for the six subsample pairs.

3.4. Properties of Associated Dust Clumps

Of the 94 northern EGOs in our survey, 82 fall with the coverage of the 1.1 mm BGPS (resolution 33′′; Aguirre et al. 2011; Rosolowsky et al. 2010), and 77 are associated with BGPS...
Figure 17. Distributions of the H$_2$O maser luminosity for different EGO subsamples. Upper left: divided by association with IRDCs. EGOs associated and not associated with IRDCs are plotted as horizontally and diagonally hatched histograms, respectively. Upper right: divided by “likely”/“possible” outflow candidates. EGOs classified as “likely” and “possible” by C08 are plotted as horizontally and diagonally hatched histograms, respectively. Lower left: divided by Class I CH$_3$OH maser association (regardless of Class II association information). Class I detections/nondetections are plotted as horizontally and diagonally hatched histograms, respectively. Lower right: divided by Class II CH$_3$OH maser association (regardless of Class I association). Class II detections/nondetections are plotted as horizontally and diagonally hatched histograms, respectively. The bin size is 0.5 dex, as in Figure 15. The significance of the K-S statistic (low values indicate different cumulative distribution functions) is 0.98 (IRDC/no IRDC), 0.06 (likely/possible), 0.51 (Class I/no Class I), and 0.51 (Class II/no Class II), indicating no statistically significant differences in the distributions of the H$_2$O maser luminosities.

Figure 18. Distribution of H$_2$O maser luminosity for EGOs associated with both Class I and II CH$_3$OH masers (green), only Class I CH$_3$OH masers (blue), only Class II CH$_3$OH masers (red), and neither type of CH$_3$OH maser (orange). The bin size is 0.5 dex.

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

sources. The BGPS source extraction algorithm, Bolocat, uses a seeded watershed approach to identify the boundaries of BGPS sources, and outputs “label maps” in which each pixel assigned to a source has a value of that source’s BGPS catalog number (see Rosolowsky et al. 2010; Dunham et al. 2011a, for more details). If the position of an EGO from C08 falls within the Bolocat-defined boundary of a BGPS source, we consider the EGO and BGPS source to be associated.

We calculate clump gas masses from the 1.1 mm dust continuum emission

$$M_{\text{gas}} = \frac{4.79 \times 10^{-14} R S_{\nu} (\text{Jy}) D^2 (\text{kpc})}{B(v, T_{\text{dust}}) \kappa_{\nu}},$$

where $S_{\nu}$ is the integrated flux density from the BGPS catalog corrected by the recommended factor of 1.5 ± 0.15 (Aguirre et al. 2011; Dunham et al. 2010), $D$ is the distance to the source (Section 3.2.1, Table 3), $B(v, T_{\text{dust}})$ is the Planck function, $R$ is the gas-to-dust mass ratio (assumed to be 100), and $\kappa_{\nu}$ is the dust mass opacity coefficient in units of cm$^2$ g$^{-1}$.

We follow recent BGPS studies (e.g., Dunham et al. 2010, 2011a) is because we consider G19.01−0.03 as a single EGO, while they treat this EGO and its northern and southern outflow lobes (for which separate photometry is given in C08) as three objects.
assignments are “B” classifications in their scheme (see also Section 3.2.1). We adopt the far kinematic distance estimated from the NH3 McClure-Griffiths (2011), we place this source on a circle of radius 3.4 kpc around the Galactic Center, and adopt a distance uncertainty of

(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.)

| Source Name       | BGPS Cat. ID | $S_{1.1\, \text{mm}}^d$ (Jy) | Distance$^e$ (kpc) | Radius$^d$ ($\degree$) | Radius (pc) | Single Component$^b$ | Two Component$^c$ |
|-------------------|--------------|------------------------------|--------------------|------------------------|-------------|----------------------|------------------|
|                   |              |                              |                    |                        |             | Clump Mass ($M_\odot$) | Log($n_{H_2}$) (Log(cm$^{-3}$)) | Clump Mass ($M_\odot$) | Log($n_{H_2}$) (Log(cm$^{-3}$)) |
| G10.29−0.13       | 1474         | 9.0(0.7)                     | 1.58(+0.86, −1.13) | 68.1                   | 0.52        | 427 $^{+774}_{-398}$ | 4.1$^{+6.2}_{-4.1}$ | 585                  | 4.2                |
| G10.34−0.14       | 1483         | 8.6(0.6)                     | 1.29(+0.92, −1.23) | 84.9                   | 0.43        | 179 $^{+441}_{-179}$ | 3.7$^{+8.2}_{-3.7}$ | 361                  | 4.0                |
| G11.11−0.11       | 1589         | 2.3(0.2)                     | 12.67(+0.48, −0.41)$^f$ | 56.7                   | 4.18        | 11740 $^{+1341}_{-2679}$ | 3.1$^{+2.7}_{-2.6}$ | 7967                  | 2.9                |
| G12.02−0.21       | 1668         | 1.0(0.1)                     | 5.30(+0.20, −0.20)$^f$ | 38.0                   | 1.75        | $>1024^{+301}_{-292}$ | $>3.7^{+3.4}_{-3.2}$ | ...                  | ...               |
| G12.20−0.03       | 1682         | 2.1(0.2)                     | 11.70(+0.31, −0.27)$^f$ | 52.8                   | 3.86        | 5732 $^{+1674}_{-1373}$ | 3.0$^{+2.5}_{-2.4}$ | ...                  | ...               |

Notes.

$^a$ Properties calculated as described in Section 3.4 using nominal distances from Table 3. For EGOs matched to a BGPS source but undetected in NH3 emission, the BGPS clump ID and radius are listed, but no clump mass and density are calculated. Uncertainties in $n_{H_2}$ are also in units of log(cm$^{-3}$).

$^b$ Calculated from the integrated flux density in the BGPS catalog assuming isothermal dust emission and $T_{\text{dust}} = T_{\text{kin}}$ from Table 3. Quoted ranges include the uncertainties in the integrated flux density from the BGPS catalog, the recommended BGPS flux correction factor, and the distance. See also Sections 3.4 and 4.1.2.

$^c$ Calculated for sources fit with two NH3 components as described in Section 3.4. Because the systematic uncertainties in this estimate are difficult to quantify, only nominal values are listed (which assume a BGPS correction factor of 1.5 and the nominal integrated flux from the BGPS catalog).

$^d$ Integrated flux density taken directly from the BGPS catalog, Rosolowsky et al. (2010). The recommended correction factor is applied when calculating clump masses and densities (Section 3.4).

$^e$ These data are identical to those in Table 3, and are replicated here for convenience.

$^f$ Associated with a 6.7 GHz CH3OH maser assigned the far distance by Green & McClure-Griffiths (2011). Except for G12.20−0.03 and G45.80−0.36, all far distance assignments are “B” classifications in their scheme (see also Section 3.2.1). We adopt the far kinematic distance estimated from the NH3 emission.

$^g$ The longitude and velocity of this source indicate that it is likely in the near 3 kpc arm (see, for example, Figure 1 of Green et al. 2009). Following Green & McClure-Griffiths (2011), we place this source on a circle of radius 3.4 kpc around the Galactic Center, and adopt a distance uncertainty of ±0.2 kpc.

$^h$ It is unclear if this source is at the near or the far distance (e.g., Green et al. 2011a; Green & McClure-Griffiths 2011). Maser parallax distance. References: G23.01−0.41; Brunttner et al. (2009), G34.39+0.22 and G34.41+0.24; Kurayama et al. (2011).

$^i$ NH3 nondetection. G49.42+0.33: distance estimated using H13CO+ velocity from C09. G53.92+0.33: distance estimated using H2O maser peak velocity. G57.61+0.02: distance estimated from velocity of weak (3.9σ) NH3(1,1) emission below our 4σ detection threshold. See also Section 3.2.1.

$^j$ The density range is not constrained because the lower end of the distance range is 0.0 kpc. (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.)

2011a, 2011b) in adopting $\kappa_{271\, \text{GHz}}/R = 0.0114\, \text{cm}^2\, \text{g}^{-1}$. Our NH3 observations provide a measurement of the clump-scale gas kinetic temperature, $T_{\text{kin}}$, and we assume $T_{\text{dust}} = T_{\text{kin}}$ in calculating the clump masses. To estimate the volume-averaged number densities of the clumps, we use the clump gas mass from Equation (4) and the deconvolved angular source radius from the BGPS catalog (Rosolowsky et al. 2010), assuming spherical geometry. For consistency with Hill et al. (2005; see Section 4.2), we adopt a mean mass per particle $\mu = 2.29\, m_{\text{H}}$. The 1.1 mm flux densities, radii, gas masses, and volume-averaged number densities for the clumps associated with our target EGOs are listed in Table 8. For the three BGPS sources in our sample that could not be stably deconvolved (listed as “null” radii in the BGPS catalog), we adopt half the BGPS beam size as an upper limit to the source radius, e.g., $R < 16.5$. The derived number densities for these sources are thus lower limits, and are indicated as such in the tables and figures. We regard this radius upper limit as conservative because source radii can sometimes be determined for source diameters smaller than a beam width. However, given the substantial uncertainty in relating an emission distribution to a true radius, particularly at low signal-to-noise ratio, a more aggressive limit could be incorrect (e.g., Rosolowsky et al. 2010; Rosolowsky & Leroy 2006). If we instead adopted an upper limit of half the BGPS beam size for the source diameter, this would increase the density limits by a factor of eight.

To estimate clump parameters consistently for the largest possible number of sources in our sample, we first calculate $M_{\text{gas}}$ and $n_{\text{H}_2}$ as described above using the gas kinetic temperatures derived from the single-component NH3 fitting. For EGOs undetected in NH3(2,2), we treat the best-fit $T_{\text{kin}}$ as an upper limit (see also Section 3.2); the derived clump mass and density are thus lower limits. The clump masses estimated using well-determined kinetic temperatures are in the range of hundreds to thousands of solar masses (Figure 19), with a mean (median) of $\sim 1850\, M_\odot$ ($\sim 1010\, M_\odot$). The range of EGO dust clump masses is consistent with expectations for MYSOs based on bolometer studies of other samples. For example, Rathborne et al. (2006) find a median IRDC mass of $\sim 940\, M_\odot$. 

Figure 19. Distribution of clump masses estimated from 1.1 mm dust continuum emission for sources with well-determined kinetic temperatures (Section 3.4). For clarity, only nominal mass values from Table 8 are plotted. The bin size is 0.2 dex.
possible that these EGOs are associated with mm dust clumps that would have been detected elsewhere in the BGPS. The distances of G49.27−0.32 and G62.70−0.51 are typical of our sample (D = 5.5 and 3.9 kpc, respectively, Table 3), and their properties are generally consistent with those of EGOs detected only in NH$_3$(1,1) emission and matched to BGPS sources. The increased noise of the BGPS at the locations of these EGOs thus seems to be a likely explanation for their lack of BGPS counterparts. G58.09−0.34, however, may be an example of a nearby, low-mass YSO: it has a near kinematic distance of 0.74+0.06$^{−0.03}$ kpc and exceptionally narrow NH$_3$(1,1) emission ($\sigma_v$ ∼ 0.23 km s$^{-1}$).

Examining the BGPS images suggests that the two other unmatched EGOs (G50.36−0.42 and G29.89−0.77) are associated with 1.1 mm emission, despite not being matched to BGPS catalog sources. G50.36−0.42 appears to be associated with faint 1.1 mm emission that fell below the threshold for extraction as a BGPS source (Rosolowsky et al. 2010). A C08 “possible” outflow candidate (D = 3.0 kpc), G50.36−0.42 also has detected H$_2$O maser emission in our survey. G29.89−0.77 is immediately adjacent to a BGPS source, but the C08 position falls outside the BGPS source boundary defined by the label maps. Also a C08 “possible” outflow candidate, G29.89−0.77 has the strongest NH$_3$ emission of the unmatched EGOs; though the (2, 2) line is formally undetected by our 4σ criterion, weak NH$_3$(2, 2) emission is evident in the spectrum. Taken together, this evidence suggests G29.89−0.77 and G50.36−0.42 are likely similar in nature to EGOs that are matched to BGPS sources.

4. DISCUSSION

4.1. EGOs in Context

4.1.1. Comparison with Other Samples

A notable feature of EGOs, compared to other samples of young massive (proto)stars, is their very strong association with both Class I and II CH$_3$OH masers, reflected in remarkably high detection rates in CH$_3$OH maser surveys to date (e.g., C09, CE11). Since H$_2$O maser and NH$_3$ observations are common tools for studying massive star formation, our Nobeyama survey allows us to better place EGOs in their broader context, by comparing their molecular environments to those of MYSOs selected using other criteria/tracers. Table 9 summarizes H$_2$O maser and NH$_3$(1,1) detection rates toward a variety of MYSO samples from the literature, chosen to cover a range of sample selection criteria, survey parameters, and proposed evolutionary state of the target objects. The strong correlation of EGOs with 6.7 GHz CH$_3$OH masers and with dust clumps (Section 3.4) suggests these as natural comparison samples (indeed, the samples of Breen & Ellingsen 2011 and of Bartkiewicz et al. 2011 include some EGOs; see also discussion therein). “Active” IRDC cores in Chambers et al. (2009) are defined by the presence of “green fuzzy” and 24 µm emission. They define “green fuzzy” broadly, compared to C08 EGOS; still, one might expect these sources to be similar to EGOs associated with IRDCs. In contrast, MYSO and UC H II samples compiled using the IRAS or MSX point-source catalogs comprise sources that are brighter than EGOs in the MIR and so likely more luminous and/or more evolved (see also C08).

As illustrated by Table 9, H$_2$O maser detection rates toward massive (proto)star samples span a broad range, from <20% to >80%: our overall detection rate of 68% is toward the upper end of this range. Notably, our H$_2$O maser detection rate toward EGOs associated with both Class I and II CH$_3$OH
masers (95%) exceeds, to our knowledge, any reported in the literature. Our much lower detection rate toward EGOs with neither CH$_3$OH maser type (33%) is nonetheless higher than those toward quiescent dust clumps or IRDC cores. In general, the H$_2$O maser associations of EGO subsamples are similar to those of the most comparable subsamples in Table 9. For example, our detection rate for EGOs associated with Class II CH$_3$OH masers (regardless of Class I association) is roughly comparable to those for Class II CH$_3$OH maser and dust clump/Class II CH$_3$OH maser samples. Sensitivity is of course an important consideration, particularly in light of recent evidence that H$_2$O maser flux density increases as sources evolve, then turns over at a late (UC H ii region) stage (Breen & Ellingsen 2011). While H$_2$O masers are variable, the fact that we fail to detect H$_2$O maser emission toward EGO G11.11−0.11, where a weak (~0.3 Jy) H$_2$O maser was reported by Pillai et al. (2006a), indicates that some EGOs are associated with H$_2$O masers below the detection limit of our survey. Most of the surveys in Table 9 have sensitivity comparable to or better than our Nobeyama data.

The properties of the H$_2$O masers detected toward EGOs are typical of H$_2$O masers detected toward MYSOs. For example, the distributions of the velocity range of detected masers and of the velocity offset between dense gas and peak maser emission (Figures 15 and 16; see also Section 3.3.1) are generally similar to those reported in the literature, including for more evolved UC H ii region samples (e.g., Churchwell et al. 1990; Anglada et al. 1996; Urquhart et al. 2011). Based on their study of
MIR-bright MYSOs and UC H\textsc{ii} regions from the RMS sample with the Robert C. Byrd Green Bank Telescope (GBT), Urquhart et al. (2011) argue that H\textsubscript{2}O maser properties (in particular, \(L_{\text{iso}}\)) are driven by the bolometric luminosity of the central MYSO (see also Section 4.2). The distributions of H\textsubscript{2}O maser peak and integrated flux densities and isotropic luminosity for the MIR-bright RMS sample have high-end tails (e.g., Figure 8 of Urquhart et al. 2011); the strongest RMS H\textsubscript{2}O masers are several orders of magnitude brighter and more luminous than the strongest H\textsubscript{2}O masers we detect toward EGOs. However, two-sided K-S tests on these parameters indicate that the differences are not statistically significant (K-S significance 0.055, 0.249, and 0.027 for \(S_{\text{peak}}, S_{\text{iso}},\) and \(L_{\text{iso}},\) respectively). The K-S tests are consistent with the RMS and EGO water masers being drawn from the same parent distribution.

As discussed in Sections 3.2.2 and 3.3.2, we find evidence for statistically significant differences among EGO subsamples in NH\textsubscript{3} but not in H\textsubscript{2}O maser properties. Other NH\textsubscript{3} studies of large MYSO samples similarly find significant internal variations. The mean kinetic temperature, NH\textsubscript{3} line width, and NH\textsubscript{3} column density of BGPS sources increase with the number of associated MIR sources (albeit with considerable scatter, particularly in \(T_{\text{kin}}\), e.g., Figure 23 of Dunham et al. 2011b). In the RMS sample, Urquhart et al. (2011) find that the mean kinetic temperature, NH\textsubscript{3} column density, and NH\textsubscript{3} line width are higher for UC H\textsc{ii} regions than for MYSOs. Overall, the clump-scale NH\textsubscript{3} properties of EGOs are roughly comparable to those of other MYSO samples. Comparing Figure 4 to Figure 4 of Urquhart et al. (2011), for example, the line width, \(T_{\text{kin}}\), and \(N(\text{NH}_3)\) distributions are broadly similar (accounting for the conversion between \(\sigma_v\) and FWHM line width), though our sample is considerably smaller. The distribution of NH\textsubscript{3} column density extends to lower values for EGOs than for the RMS sample; however, this is a beam-averaged quantity, and the Nobeyama beam (\(\sim 73''\)) is considerably larger than that of the GBT (\(\sim 30''\)). For BGPS sources, the low end of the NH\textsubscript{3} column density range (based on GBT observations) extends to \(\sim 1.7 \times 10^{13}\), more comparable to our EGO results. The EGO \(T_{\text{kin}}\) distribution (from the single-component fitting, for consistency with other studies) lacks the high temperature (\(>40\) K) tail seen in RMS, UC H\textsc{ii} region, and even BGPS samples (Urquhart et al. 2011; Dunham et al. 2011b; Churchwell et al. 1990). The mean \(T_{\text{kin}}\) for the EGO sample (23.6 K) is higher than that of the Dunham et al. (2011b) sample (17.4 K, for their “\(T'_K\) subsample” consisting of (2,2) detections) and similar to that of the RMS sample as a whole (\(\sim 22\) K).

These general comparisons illustrate that the H\textsubscript{2}O maser and clump-scale NH\textsubscript{3} properties of EGOs are consistent with their being a population of young MYSOs. However, we emphasize that the differences within samples (EGOs, RMS sources, BGPS sources) are often as great or greater than the differences between them. These \textit{intra}-sample differences emphasize the importance of studying multiple star formation tracers across wavelength regimes.

### 4.1.2. Comparison with Star Formation Criteria

By combining our Nobeyama NH\textsubscript{3} data with the BGPS, we can also consider the dust clumps associated with EGOs in the context of proposed star formation thresholds. Unlike purely mm-selected samples (e.g., Dunham et al. 2011b), all of the clumps we consider are associated with EGOs, and thus demonstrably star forming (many are also associated with other MIR sources). Figure 20 shows a mass–radius plot for clumps with well-determined (non-limit) \(T_{\text{kin}}\) and \(r_{\text{clump}}\), with the clump masses estimated assuming \(T_{\text{dust}} = T_{\text{kin}}\) from the single-component NH\textsubscript{3} fits. The errors bars shown in Figure 20 indicate the range in radius associated with the distance uncertainty from Table 8, and the range in mass associated with the combined uncertainties in the BGPS integrated flux density, the BGPS flux correction factor, and the distance. The star formation thresholds of Krumholz & McKee (2008), Heiderman et al. (2010) and Lada et al. (2010), and Kauffmann & Pillai (2010) are indicated as dot-dashed, dashed, and dotted lines, respectively. Only sources for which the \(T_{\text{kin}}\) and radius are well-determined (non-limit) are plotted. H\textsubscript{2}O maser detections are plotted in green, and H\textsubscript{2}O maser nondetections in red.

(A color version of this figure is available in the online journal.)
observations of EGOs, and of other MYSOs, provide ample evidence for substructure (e.g., cores and (proto)clusters) and variations in gas temperature on much smaller scales (e.g., Cyganowski et al. 2011a; Brogan et al. 2011).

Having placed clumps on the mass–radius plot using (primarily) the BGPS data, we use our Nobeyama survey data to look for differences in the properties of clumps above/below the HL and KP thresholds. As in our comparison of EGO subsamples (Section 3.2.2), we ran two-sided K-S tests on eight NH3 parameters (the NH3 (1,1), (2,2), and (3,3) peaks (TMB), σν, T(1,1), ηH, N(NH3), and Tkin). We find statistically significant differences only for the NH3 (1,1) and (2,2) peak temperatures and the filling fraction ηH,17 with clumps below the HL and KP thresholds having lower values of these parameters. The K-S tests indicate no statistically significant differences in the distributions of the physical properties σν, Tkin, and N(NH3) for clumps above/below the thresholds. Interestingly, and perhaps counterintuitively, the H2O maser detection rates are higher for EGOs associated with clumps below the HL and KP thresholds (Figure 20). The H2O maser detection rate is 0.74(±0.07) for sources that meet the KP criterion, and 0.93(±0.06) for sources that do not (uncertainties in detection rates calculated using binomial statistics). Similarly, the H2O maser detection rates are 0.76(±0.07) and 0.92(±0.08) for sources that do/do not meet the HL criterion, respectively.

The nature of the EGOs associated with clumps that fall below the KP threshold requires further investigation. The higher H2O maser detection rate toward clumps below the KP threshold is surprising, and the lack of difference in NH3 properties suggests a continuum, rather than a sharp distinction. Additionally, one source that falls below the KP threshold, G24.94+0.07, is associated with 6.7 GHz Class II CH3OH maser and cm continuum emission (C09, C11b), both indicative of the presence of an MYSO. We note that the placement of clumps on a mass–radius plot is sensitive to assumptions about clump temperature structure (or lack thereof). For EGOs in our study fit with warm and cool components, the warm component constitutes a small fraction of the clump mass; the bulk of the material generally has temperature Tcool < Tsingle comp., and so the isothermal assumption usually underestimates the clump mass (Section 3.4, Table 8). Interferometric NH3 observations show significant temperature structure on scales within the Nobeyama beam for G35.03+0.35 (Figure 3 of Brogan et al. 2011), a source that did not require two temperature components to fit its Nobeyama NH3 spectra (Figure 21). On larger scales, many of the BGPS sources associated with EGOs (and plotted in Figure 20) extend beyond the Nobeyama beam. If isothermal clump masses for EGOs tended to be underestimated—due to temperature structure on small or large scales—this would move points up in Figure 20, and increase the proportion of sources above the KP threshold. Additional data—such as NH3 maps with sufficient resolution to probe the temperature structure of the BGPS clumps—are needed to address this issue. Interferometric (sub)mm observations, to resolve the dust continuum emission and detect individual cores, and improved constraints on bolometric luminosity (e.g., from HiGal) will also help to clarify the nature of the driving sources.

4.2. Correlations between H2O Maser and Clump Properties?

Over the past decades, numerous authors have investigated possible correlations amongst clump, H2O maser, and driving source properties in MYSO samples (e.g., Churchwell et al. 1990; Anglada et al. 1996; Breen & Ellingsen 2011; Urquhart et al. 2011). Recently, two studies have reported correlations between H2O maser luminosity and the properties of the driving source or surrounding clump. For their sample of ∼300 RMS sources with H2O maser detections, Urquhart et al. (2011) find that H2O maser luminosity is positively correlated with bolometric luminosity for both MYSOs and H II regions. In contrast, Breen & Ellingsen (2011) report an anticorrelation between clump H2 number density and H2O maser luminosity, which they attribute to an evolutionary effect: more evolved sources have more luminous water masers and are associated with lower-density clumps. All of these studies have combined H2O maser and either NH3 or (sub)mm dust continuum data. Breen & Ellingsen (2011), in particular, caution that the clump densities used in their study (from Hill et al. 2005) were calculated assuming a single temperature for all clumps, and that temperature differences could create the apparent density

17 We note ηH is mildly degenerate with TMB(1,1).
trend. Our NH3 and H2O maser survey, in combination with the BGPS, provides the necessary data to fully explore correlations between maser and clump properties, and test evolutionary interpretations.

Figure 22 shows that when clump densities are calculated for our sample using measured clump temperatures, there is no correlation between H2O maser luminosity and clump density: the log–log plot of $L_{\text{H}_2\text{O}}$ versus number density is a scatter plot. This remains the case even when accounting for the contributions of warm and cool gas for sources that require two-component NH3 fits. The partial correlation coefficients, computed with the distance squared as an independent
Figure 23. Top: isotropic H$_2$O maser luminosity vs. $T_{\text{kin}}$ from single-component NH$_3$ fitting. "*" indicates EGOs with H$_2$O maser and NH$_3$(2,2) detections in our survey (e.g., $T_{\text{kin}}$ well determined). Filled downward-pointing triangles indicate 4$\sigma$ $L$(H$_2$O) upper limits for EGOs undetected in H$_2$O maser emission but detected in NH$_3$(2,2). EGOs undetected in NH$_3$(2,2)—for which the best-fit $T_{\text{kin}}$ is treated as an upper limit—are represented as open triangles: open left-facing triangles indicate H$_2$O maser detections, and open downward-pointing triangles 4$\sigma$ $L$(H$_2$O) upper limits for H$_2$O maser nondetections. Bottom: same as top, except for sources fit with two NH$_3$ components, $T_{\text{kin(cool)}}$ is plotted in blue and $T_{\text{kin(warm)}}$ in red.

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

parameter, are 0.04 and 0.06 for the one- and two-temperature component density estimates, respectively (only sources with H$_2$O maser detections and non-limit densities are included in the calculation). These low values confirm that H$_2$O maser luminosity and clump number density are uncorrelated in our data.

In contrast, H$_2$O maser luminosity is weakly correlated with clump temperature, as shown in Figure 23. For EGOs detected in both H$_2$O maser and NH$_3$(2,2) emission, the partial correlation coefficient is 0.36 for $T_{\text{kin}}$ derived from the single-component fits (again computed with the distance squared as an independent parameter). Interestingly, if we recompute the partial correlation
coefficient using the $T_{\text{kin}}$ of the warm component for sources that require two-component fits (and the single-component $T_{\text{kin}}$ for all other sources), the value is reduced to 0.22. This is somewhat surprising, since the warm component traces gas nearer to, and heated by, the central MYSO.

We also find a weak positive correlation between H$_2$O maser luminosity and clump mass (Figure 24). Calculating clump masses assuming $T_{\text{dust}} = T_{\text{kin}}$ from the single-component NH$_3$ fits, the partial correlation coefficient is 0.44 (for EGOs detected in both H$_2$O maser and NH$_3$(2,2) emission, so that $T_{\text{kin}}$...
is well determined). The calculated partial correlation coefficient is very similar (0.43) if the presence of two temperature components is accounted for when estimating the clump mass (Section 3.4). A K-S test indicates no statistically significant difference between the mass distributions of clumps with/without H$_2$O masers, in contrast to earlier studies (Chambers et al. 2009; Breen & Ellingsen 2011). The significance of the K-S statistic is 0.26 using the isothermal clump masses (for EGOs with $(2,2)$ detections and so well-determined $T_{\text{kin}}$, as above), and increases to 0.45 if clump masses are estimated accounting for the two temperature components. Both previous studies assumed dust temperatures, and Chambers et al. (2009) found that the probability that their cores with/without H$_2$O masers were drawn from the same distribution increased dramatically (by a factor of $>50$, to 0.11) if they assumed a higher temperature for active cores (compared to assuming a single temperature for all cores). The $\delta_{\text{FWHM}}$ of the BGPS data ($\sim 33''$) is larger than that of the SIMBA data used by Breen & Ellingsen (2011) ($\sim 24''$; Hill et al. 2005) or the IRAM 30 m data used by Chambers et al. (2009) ($\sim 11''$; Rathborne et al. 2006). Additional data (such as temperature measurements for the Chambers et al. 2009 and Breen & Ellingsen 2011 sources) would be required to assess whether this difference in scale contributes to the difference in findings.

Our results are consistent with the positive correlation between H$_2$O maser and bolometric luminosity reported by Urquhart et al. (2011) for RMS sources. In this picture, the key factor is the bolometric luminosity of the driving MYSO, with more luminous MYSOs exciting more luminous H$_2$O masers. The observed correlations of H$_2$O maser and clump properties (temperature and mass) are then understood in terms of the relationship between a clump and the massive star(s) it forms. The final mass of an actively accreting MYSO is limited by the available mass reservoir, and studies of more evolved sources (UCH ii regions) indicate that higher-mass clumps form higher-mass (and thus more luminous) stars (e.g., Johnston et al. 2009). The more luminous an MYSO, the more energy it will impart to its environs, and the more it will heat the gas and dust of the surrounding clump.

4.3. NH$_3(3,3)$ Masers

While NH$_3(3,3)$ maser emission in an MSFR was first reported several decades ago (DR21(OH); Mangum & Wootten 1994), the number of known examples—all detected with the VLA—has remained small (e.g., W51, NGC 6334I, IRAS 20126+4106, G5.89−0.39: Zhang & Ho 1995; Kraemer & Jackson 1995; Zhang et al. 1999; Hunter et al. 2008). Two recent, large-scale single-dish surveys each report a single NH$_3(3,3)$ maser candidate: a blind survey of 100 deg$^2$ of the Galactic plane (HOPS; Walsh et al. 2011), and a targeted survey of ~600 RMS sources (Urquhart et al. 2011). This paucity of candidates led Urquhart et al. (2011) to suggest that bright NH$_3(3,3)$ masers are rare.

One of our targets, G35.03+0.35, was recently observed in NH$_3$(1,1)-(6,6) with the VLA (Brogan et al. 2011). In addition to complex thermal NH$_3$ emission from a (proto)cluster, nonthermal NH$_3(3,3)$ and (6,6) emission are clearly detected (Brogan et al. 2011, Figure 2; peak (3,3) intensity <70 mJy beam$^{-1}$). Figure 21 shows our Nobeyama NH$_3$ spectra of G35.03+0.35: while there is a narrow NH$_3(3,3)$ emission feature that is not well fit by the model, the signal-to-noise ratio is insufficient to identify it as a candidate maser from the single-dish data. This comparison demonstrates that single-dish surveys readily miss weak NH$_3(3,3)$ masers detected with interferometers; sensitive interferometric observations are required to assess the prevalence of NH$_3$ masers in MSFRs, and their association with other maser types (see also Brogan et al. 2011, 2012).

4.4. Future Work

Our analysis of our Nobeyama EGO survey shows that the presence of NH$_3$(2,2) and (3,3) emission, H$_2$O masers, and Class I and II CH$_3$OH masers are strongly correlated. These star formation indicators tend to occur in concert (at least on the scales probed by single-dish surveys), and identify a (sub)population of EGOs in which central MYSO(s) are substantially affecting their environments, heating the surrounding gas and exciting maser emission. Notably, maser emission and warm dense gas appear to pinpoint such sources more effectively than MIR indicators such as the “likely”/“possible” classification of C08 or the presence/absence of IRDCs. These sources are excellent targets for high-resolution follow-up observations aimed at understanding the importance of different (proto)stellar feedback mechanisms in MSFRs, as demonstrated by the SMA, CARMA, and VLA studies of Cyganowski et al. (2011a, 2011b) and Brogan et al. (2011). These EGOs are also important testbeds for proposed maser evolutionary sequences, as discussed in more detail below.

Less clear is the nature of those EGOs detected only in NH$_3$(1,1) emission in our survey. An examination of their GLIMPSE images suggests they are a heterogeneous group, including both EGOs in IRDCs (e.g., G12.02−0.21) and EGOs adjacent to 8 and 24 $\mu$m bright nebulae (e.g., G29.91−0.81). Some examples of each of these MIR source types are detected in H$_2$O maser emission, while others are not. The MIR morphologies of EGOs without detected H$_2$O masers in our survey are similarly heterogeneous, and some H$_2$O maser nondetections are associated with NH$_3$(2,2) and (3,3) emission. Higher-resolution observations are required to localize the NH$_3$ and H$_2$O maser emission detected in our Nobeyama data with respect to the MIR emission.

We emphasize that high-resolution observations are crucial for building an evolutionary sequence for MYSOs, and placing EGOs within it. In general, multiple MIR sources are present within the Nobeyama beam, and detailed studies of EGOs to date reveal mm and cm-\lambda multiplicity on ~0.1 pc scales. Furthermore, the members of (proto)clusters associated with EGOs exhibit a range of star formation indicators, suggestive of a range of evolutionary states (e.g., Cyganowski et al. 2011a; Brogan et al. 2011).

EGOs are notably rich in maser emission, and maser studies have and continue to provide key insights into the nature of EGOs; their copious maser emission likewise provides opportunities to use EGOs to advance our understanding of masers in MSFRs. H$_2$O, Class I and II CH$_3$OH, and OH masers are ubiquitous in regions of massive star formation, and much effort has been devoted to placing these different maser types into an evolutionary sequence. Of particular interest is which maser type appears first—and thus pinpoints the earliest stages of massive star formation. In most proposed sequences, Class I CH$_3$OH masers are identified with the earliest stages of MYSO evolution, with the youngest sources being those associated only with Class I CH$_3$OH masers (e.g., Ellingsen 2006; Ellingsen et al. 2007; Breen et al. 2010b). However, recent work suggests that Class I CH$_3$OH masers may be excited by shocks driven by expanding H ii regions as well as by outflows (e.g., Voronkov...
et al. 2010), such that Class I CH$_3$OH masers may outlast the Class II maser stage and/or arise more than once during MYSO evolution (e.g., Chen et al. 2011; Voronkov et al. 2012). Breen & Ellingsen (2011) and Caswell & Breen (2010) have also recently proposed that H$_2$O masers—particularly those with blueshifted high-velocity features—may be the earliest signposts of MYSO formation, preceding the Class II CH$_3$OH maser stage.

Statistical comparisons of “Class I only” and “Class II only” EGOs based on our data are limited by the small sample sizes. It is notable, however, that the NH$_3$(2,2) and H$_2$O maser detection rates toward these subsamples are comparable, particularly considering the small number statistics. Likewise, Figures 12 and 18 show no clear patterns in their NH$_3$ or H$_2$O maser properties that would suggest a trend in evolutionary state. The parameter space occupied by Class I-only and Class II-only sources in these plots also largely overlaps with that occupied by EGOs associated with both CH$_3$OH maser types. Though the comparison is again limited by small-number statistics, the difference in the NH$_3$(3,3) detection rates (63%/14% for Class I/II-only sources) is intriguing, particularly given the association of Class I CH$_3$OH and NH$_3$(3,3) masers (e.g., Brogan et al. 2011).

Progress in our understanding of masers as evolutionary indicators for MSF requires identifying candidate youngest sources, and studying them in detail (see also Cyganowski et al. 2012). The (small) samples of EGOs with H$_2$O+Class I CH$_3$OH and H$_2$O+Class II CH$_3$OH masers identified in our survey will be promising targets for such studies, as will the samples of H$_2$O-only, Class I CH$_3$OH-only, and Class II CH$_3$OH-only sources. Sensitive, high-resolution maser observations are needed: (1) to localize the maser emission, and determine whether or not all maser species are associated with the same MYSO and (2) to search for weak masers and establish whether maser types undetected in single-dish surveys are truly absent. The expanded capabilities of the Karl G. Jansky VLA are well suited to such studies. High-resolution cm-(sub)mm wavelength line and continuum observations will also constrain the properties of compact cores and outflows, allowing maser activity to be correlated with other signposts of star formation at the scale of individual active sources.

5. CONCLUSIONS

We have surveyed all 94 GLIMPSE EGOs visible from the northern hemisphere ($\delta \gtrsim -20^\circ$) in H$_2$O maser and NH$_3$(1,1), (2,2), and (3,3) emission with the Nobeyama 45 m telescope. Our results provide strong evidence that EGOs, as a population, are associated with dense gas and active star formation, and also reveal statistically significant variation amongst EGO subsamples:

1. H$_2$O masers, which are associated with outflows and require high densities ($n$(H$_2$) $\sim 10^8$–$10^{10}$ cm$^{-3}$), are detected toward $\sim$68% of EGOs surveyed.
2. The NH$_3$(1,1) detection rate is $\sim$97%, confirming that EGOs are associated with dense molecular gas.
3. Two-component models provide a significantly improved fit for $\sim$23% of our NH$_3$ spectra, indicating contributions from both warm inner regions and cooler envelopes along the line of sight.
4. H$_2$O maser emission is strongly correlated with the presence of warm, dense gas, as indicated by emission in the higher-excitation NH$_3$ transitions. The H$_2$O maser detection rate is 81% toward EGOs detected in NH$_3$(2,2) and (3,3) emission, and only 44% toward EGOs detected only in NH$_3$(1,1). We find statistically significant differences in the distributions of NH$_3$ column density, kinetic temperature, and NH$_3$ line width for EGOs with/without H$_2$O maser detections: EGOs with H$_2$O masers have higher median N(NH$_3$), $T_{\text{kin}}$, and $\sigma_v$.
5. H$_2$O maser and NH$_3$(2,2) and (3,3) detection rates are higher toward EGOs classified as “likely” outflow candidates based on their MIR morphology than toward EGOs classified as “possible” outflow candidates. However, statistical tests show significant differences only in the distributions of NH$_3$(1,1) and (2,2) peak temperatures ($T_{\text{MB}}$), not in physical properties.
6. EGOs associated with IRDCs have higher NH$_3$(2,2) and (3,3) detection rates than EGOs not associated with IRDCs. We find statistically significant differences in the distributions of NH$_3$(1,1) peak ($T_{\text{MB}}$), NH$_3$ line width, and NH$_3$ beam filling fraction: EGOs associated with IRDCs have higher median NH$_3$(1,1) $T_{\text{MB}}$, and lower median $\sigma_v$, than EGOs not associated with IRDCs.
7. The H$_2$O maser, NH$_3$(2,2), and NH$_3$(3,3) detection rates toward EGOs with both Class I and II CH$_3$OH masers are the highest of any EGO subsample we consider: 95%, 90% and 81%, respectively. In contrast, we detect H$_2$O masers and the higher-excitation NH$_3$ lines toward only 33% (H$_2$O), 20% (2,2) and 7% (3,3) of EGOs with neither type of CH$_3$OH maser. We find statistically significant differences in the distributions of NH$_3$(1,1) peak temperature ($T_{\text{MB}}$), NH$_3$ column density, and NH$_3$ line width for EGOs associated with both types/neither type of CH$_3$OH masers: EGOs associated with both Class I and II CH$_3$OH masers have higher median NH$_3$(1,1) $T_{\text{MB}}$, N(NH$_3$), $\sigma_v$, and $T_{\text{kin}}$.
8. While H$_2$O maser detection rates vary across EGO subsamples, we find no evidence for statistically significant differences in the properties of detected H$_2$O masers.

Our H$_2$O maser and NH$_3$ survey, in combination with the 1.1 mm continuum BGPS, provides the necessary data to explore connections between H$_2$O maser and clump properties: H$_2$O maser spectra, clump-scale $T_{\text{kin}}$, and $N$(H$_3$) measurements from NH$_3$, and clump masses and densities from the 1.1 mm dust continuum emission and $T_{\text{kin}}$ measurements. These combined data show no correlation between isotropic H$_2$O maser luminosity and volume-averaged clump density. H$_2$O maser luminosity is weakly positively correlated with clump temperature and with clump mass, consistent with reported correlations between H$_2$O maser luminosity and the bolometric luminosity of the driving source.

We interpret the observed correlations of H$_2$O maser and clump properties in terms of the relationship between a clump and the massive star(s) it forms. For more evolved sources (UC H II regions), studies indicate that higher-mass clumps form higher-mass (and thus more luminous) stars (e.g., Johnston et al. 2009). For an actively accreting MYSO, the available mass reservoir sets the limit on its final, stellar mass. The more luminous (and massive) an MYSO, the more energy it will impart to its environs, and the more it will heat the gas and dust of the surrounding clump.

We find that NH$_3$(2,2) and (3,3) emission, H$_2$O masers, and Class I and II CH$_3$OH masers are strongly correlated, at least on the scales probed by single-dish surveys. These star formation indicators pinpoint EGOs in which the central MYSO(s) are substantially affecting their environments, more effectively than...
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