Cosmic Masers - from OH to H_0
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Masers in GLIMPSE Extended Green Objects (EGOs)

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Abstract. Large-scale *Spitzer* surveys of the Galactic plane have yielded a new diagnostic for massive young stellar objects (MYSOs) that are actively accreting and driving outflows: extended emission in the IRAC 4.5 μm band, believed to trace shocked molecular gas. Maser studies of these extended 4.5 μm sources (called EGOs, Extended Green Objects, for the common coding of 3-color IRAC images) have been and remain crucial for understanding the nature of EGOs. High detection rates in VLA CH_3OH maser surveys provided the first proof that EGOs were indeed MYSOs driving outflows; our recent Nobeyama 45-m survey of northern EGOs shows that the majority are associated with H_2O masers. Maser studies of EGOs also provide important constraints for the longstanding goal of a maser evolutionary sequence for MYSOs, particularly in combination with high resolution (sub)mm data. New SMA results show that Class I methanol masers can be excited by both young (hot core) and evolved (ultracompact HII region) sources within the same massive star-forming region.

Keywords. infrared: ISM– infrared: stars– ISM: jets and outflows– ISM: molecules– masers– radio continuum: ISM– stars: formation– techniques: interferometric

1. Introduction

What are GLIMPSE Extended Green Objects (EGOs)? GLIMPSE–the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (Churchwell *et al.* 2009)–is a *Spitzer Space Telescope* survey of the Galactic Plane in the four bands of the Infrared Array Camera (IRAC; Fazio *et al.* 2004): 3.6, 4.5, 5.8, and 8.0 μm. The broad IRAC bands include emission features from a range of interstellar species (e.g. Fig. 1 of Reach *et al.* 2006). All of the IRAC bands include H_2 lines; the 4.5 μm band also includes the CO (v = 1-0) bandhead and Brα. Notably, 4.5 μm is also the only IRAC band to *lack* polycyclic aromatic hydrocarbon (PAH) emission features. This combination of characteristics means that in massive star-forming regions, shock-excited gas in (proto)stellar molecular outflows can stand out as morphologically distinct, extended 4.5 μm emission. Thus, the ability to search for extended 4.5 μm emission in GLIMPSE images presented an exciting opportunity to compile a new sample of candidate massive young stellar objects (MYSOs) with *active* outflows, independent of previous CO imaging surveys based largely on IRAS point sources (e.g. Zhang *et al.* 2001). Because the 4.5 μm band is commonly coded as green in three-color IRAC images (RGB: 8.0, 4.5, 3.6 μm), these extended 4.5 μm sources are known as Extended Green Objects (EGOs; Cyganowski *et al.* 2008).

Cyganowski *et al.* (2008) cataloged over 300 EGOs in the GLIMPSE-I survey area ($10^\circ \leqslant |l| \leqslant 65^\circ$, $|b| \leqslant 1^\circ$). Based on their mid-infrared (MIR) colors and association with infrared dark clouds (IRDCs), Cyganowski *et al.* (2008) suggested that EGOs were specifically *massive* YSOs driving active outflows.

2. The Nature of EGOs (as revealed by CH_3OH masers)

The first step, after the identification of EGOs as a class of objects by Cyganowski *et al.* (2008), was to test whether GLIMPSE EGOs were in fact massive YSOs driving outflows. To do this, Cyganowski *et al.* (2009) conducted sensitive, high-angular resolution searches for two diagnostic types of CH_3OH masers towards a sample of EGOs with the Very Large Array (VLA)†: 6.7 GHz Class II CH_3OH masers, associated exclusively with *massive* YSOs (e.g. Minier *et al.* 2003) and 44 GHz Class I CH_3OH masers, associated with molecular outflows and outflow-cloud interfaces (e.g. Kurtz *et al.* 2004). An initial sample of 28 EGOs was selected to (1) cover a range of MIR properties, including morphology, angular extent of 4.5 μm emission, and the presence of 8 and/or 24 μm counterparts, and (2) be visible from the northern hemisphere. Due to technical problems, however, there is a bias in the final survey sample: only 19 sources with (strong) 6.7 GHz masers near the phase center were reobserved at 6.7 GHz, and only these 19 sources were observed at 44 GHz (see Cyganowski *et al.* 2009 for details). As a result, the Cyganowski *et al.* (2009) sample is, in essence, a 6.7 GHz CH_3OH maser-selected EGO subsample.

The detection rates for both 6.7 GHz Class II and 44 GHz Class I CH_3OH masers were extremely high: >64% (of the original 28 sources) and $\sim$ 90% (of the 19 observed sources), respectively. For 6.7 GHz CH_3OH masers, this detection rate was nearly twice that towards other MYSO samples (see also Cyganowski *et al.* 2009). The spatial distribution and kinematics of the two types of CH_3OH masers are strikingly different. The 6.7 GHz masers are centrally concentrated and usually coincident with 24 μm emission, while the 44 GHz masers are spatially distributed, often over tens of arcseconds, and coincident with 4.5 μm emission. To complement the maser surveys and provide information about the thermal gas emission, Cyganowski *et al.* (2009) used the James Clerk Maxwell Telescope (JCMT) ‡ to observe HCO^+(3-2), $H^{13}CO^+$(3-2), thermal CH_3OH ($5_{2,3}$-$4_{1,3}$), and SiO(5-4) emission. The velocities of the 44 GHz masers cluster near the systemic velocity (as measured from the dense gas tracers observed with the JCMT), consistent with their excitation at interfaces between outflows and the surrounding molecular gas. In contrast, the velocities of the 6.7 GHz masers exhibit every possible permutation with respect to the thermal gas v_{LSR}: different sources provide examples of 6.7 GHz masers at and near the systemic velocity, only redshifted, only blueshifted, and both red and blueshifted but *not* at the systemic velocity. This diversity suggests that the 6.7 GHz masers observed towards this EGO sample do not all arise in any single physical/dynamical structure.

The JCMT survey also provided further evidence, in addition to the Class I masers, that the target EGOs were associated with outflows. For all sources, the HCO^+ spectra

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showed broad line wings, and the detection rate for thermal SiO emission was very high: 90% (9 of a subset of 10 EGOs). Gas-phase SiO abundance is enhanced for only $\sim 10^4$ years after a shock (e.g. Pineau de Forets *et al.* 1997), so the SiO emission indicates that the outflows are being actively driven, as has been observationally confirmed in a survey comparing low-mass Class O and I sources (Gibb *et al.* 2004). High-resolution mm-λ followup observations have confirmed the presence of bipolar molecular outflows in EGOs. Submillimeter Array (SMA)¶ imaging of the EGOs G11.92−0.61 and G19.01−0.03 reveals high-velocity, well-collimated outflows traced by ^{12}CO(2-1) emission (Cyganowski *et al.* 2011a). The CO outflows are coincident with the extended 4.5 μm emission in these sources, and many of the 44 GHz Class I CH_3OH masers coincide with or trace the edges of the high-velocity CO outflow lobes.

In sum, the initial CH_3OH maser studies of EGOs provided strong evidence that the survey targets were young MYSOs with active outflows, and so presumably ongoing accretion. High resolution observations of direct tracers of molecular outflows and hot cores have confirmed this picture for EGOs observed to date (Cyganowski *et al.* 2011a), and further high-resolution mm-λ followup is ongoing.

It is worth emphasizing that extended 4.5 μm emission acts as an effective way to find MYSOs *in GLIMPSE*, and that this is to an important extent a function of the shallowness of the GLIMPSE-I survey. Outflows in nearby low-mass star-forming regions exhibit extended 4.5 μm emission in *Spitzer* images (e.g. Noriega-Crespo *et al.* 2004, Velusamy *et al.* 2007). However, the extended 4.5 μm emission from such low-mass outflows is too faint to be detected in GLIMPSE (see also discussion in Cyganowski *et al.* 2008). In deeper *Spitzer* Galactic Plane surveys (such as the GLIMPSE-360 survey of the outer Galaxy, and the ongoing Deep GLIMPSE), extended 4.5 μm emission will pick out outflows, including those from low- and intermediate- mass YSOs.

Millimeter Methanol Masers. The SMA observations of G11.92−0.61 and G19.01−0.03 also revealed probable CH_3OH maser emission in the 229.759 GHz Class I transition (Cyganowski *et al.* 2011a). The observed 229.759 GHz emission is spectrally narrow, and spatially and spectrally coincident with 44 GHz masers. While the angular resolution of the SMA data is not sufficient to definitively establish masing based on brightness temperature, the 229.759/230.027 line ratios indicate nonthermal emission. Our ongoing SMA observations of EGOs indicate that 229.759 GHz Class I masers may be common towards MYSO outflows. If so, such masers offer potential for self-calibrating very high-resolution 1.3 mm observations of MYSOs, e.g. with ALMA.

Evolutionary State. Constraining the evolutionary state of EGOs is crucial for placing maser studies of EGOs in the broader context of maser studies of massive star-forming regions. In particular, the presence of an ultracompact (UC) HII region signals a comparatively late stage of massive star formation, when a young O/B star has already ionized its environment. While it is important to remember that high resolution (sub)millimeter studies of UC HIIs typically reveal additional objects in a range of evolutionary stages (Hunter *et al.* 2008; Brogan *et al.* 2008; Hunter *et al.* 2004), the absence/presence of UC HIIs has been used in the past as a key divide between younger/older MYSO samples. To search for UC HIIs, shallow 44 GHz (7 mm) continuum data were obtained simultaneously during the 44 GHz maser survey. The *non*detection rate was 95%, but the sensitivity was sufficient to rule out only bright UC HII regions (Cyganowski *et al.* 2009). To better constrain the cm-λ emission of EGOs, Cyganowski *et al.* (2011b) carried out deep VLA

¶ The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

3.6 and 1.3 cm continuum observations of a sample of 14 EGOs associated with 6.7 GHz CH_3OH masers, 44 GHz CH_3OH masers, or both. The surveys had angular resolution of $\sim$1$''$ and $\sigma \sim 30$ μJy beam^{-1} (3.6 cm) and 250 μJy beam^{-1} (1.3 cm). The *non*detection rate of these VLA surveys was 57% (8/14). The cm-λ EGO counterparts that were detected were generally weak ($\lesssim$1 mJy at 3.6 cm), and not detected at 1.3 cm due to the higher noise. Only 2 EGOs are associated with ultracompact or compact HII regions; both show cm-λ multiplicity, with morphological evidence that a less evolved source may be driving the 4.5 μm outflow. One EGO is detected only at 1.3 cm; comparison with 1.4 mm data suggests that the 1.3 cm emission is free-free from an optically thick hypercompact (HC) HII region (Cyganowski *et al.* 2011b). This EGO (G11.92−0.61) in fact hosts a protocluster of 3 compact mm continuum cores (Cyganowski *et al.* 2011a). The 1.3 cm source is associated with a 1.4 mm continuum core, hot core line emission, 24 μm emission, and H_2O and 6.7 GHz CH_3OH masers.

3. Masers in EGOs: Insights for masers in massive star forming regions

In addition to constraining the nature of EGOs themselves, the wealth of multiwavelength data now available for many EGOs allows us to examine cross-correlations between different maser types and other star formation indicators (see also Brogan *et al.* 2011 and in this volume).

Class I CH_3OH Masers as Evolutionary Indicators? The EGO G18.67+0.03 is particularly interesting in the context of proposed maser evolutionary sequences, which posit that the youngest MYSOs exhibit only Class I CH_3OH maser emission (e.g. Ellingsen 2006, Ellingsen *et al.* 2007, Breen *et al.* 2010). Our VLA CH_3OH maser surveys revealed maser emission associated with 3 MIR sources in this region: two (including the EGO) have both 6.7 GHz Class II and 44 GHz Class I CH_3OH masers, while the third MIR source has only 44 GHz Class I masers (Cyganowski *et al.* 2009). The Class I maser-only MIR source has a cm-λ continuum counterpart, with properties consistent with a UC HII region (Cyganowski *et al.* 2011b). None of the other sources in the field have cm-λ continuum emission in our deep VLA surveys. The association of 44 GHz CH_3OH masers with a UC HII region in G18.67+0.03 is consistent with recent suggestions by Voronkov *et al.* (2010) that Class I masers may be excited by shocks driven by expanding HII regions. However, younger sources (such as hot cores) are often found in close proximity to UC HII regions (e.g. Hunter *et al.* 2006; Cyganowski *et al.* 2007 and references therein); therefore, additional multiwavelength information was needed. We conducted SMA 1.3 mm observations to determine the evolutionary states of the G18.67+0.03 maser sources based on their molecular line emission.

Our SMA observations reveal hot core line emission towards both Class II+Class I maser sources (Cyganowski *et al.* in prep.). In contrast, emission from only a few common species is detected towards the UC HII region/Class I maser-only source. All three maser sources are associated with molecular outflows traced by ^{13}CO (2-1) emission. However, the UC HII region outflow is *not* detected in SiO(5-4). As described above, SiO emission provides a discriminant between active (SiO present) and “relic” or “fossil” outflows (SiO absent). Thus, the lack of SiO emission is strong additional evidence that no younger YSO is present near the Class I-only maser source, and that these Class I masers are associated with the comparatively evolved UC HII region.

H_2O maser (and NH_3) Survey of Northern EGOs. Most maser studies of EGOs to date have focused on CH_3OH masers. For the broader picture of masers in high-mass star forming regions, H_2O masers in EGOs are an important missing piece of the puzzle. We

have recently completed a Nobeyama 45-m survey of all 94 northern EGOs ($\delta \gtrsim -20°$) for H_2O maser and NH_3(1,1), (2,2), and (3,3) emission (Cyganowski *et al.*, in prep.). The median rms of the H_2O maser survey is $\sim$0.11 Jy. The goals of this survey were (1) to evaluate the significance of the MIR categories from the Cyganowski *et al.* (2008) EGO catalog, (2) to compare the H_2O maser properties of EGO subsamples (for example, those associated with Class I/II CH_3OH masers), and (3) to compare H_2O maser properties with clump physical properties from other tracers (T_{kin}, density, etc.).

The overall H_2O maser detection rate in our Nobeyama survey is $\sim$68%. Cyganowski *et al.* (2008) classified EGOs as "likely" or "possible" outflow candidates based on MIR morphology; they also tabulated whether each EGO was or was not associated with an IRDC in the GLIMPSE images. The H_2O maser detection rate is somewhat higher towards EGOs that are "likely" outflow candidates, and roughly comparable towards EGOs that are and are not associated with IRDCs. We find little evidence of statistically significant differences in the H_2O maser properties (for example, the isotropic maser luminosity) of various EGO subsamples.

Recent studies have found correlations between the isotropic H_2O maser luminosity and the properties of the driving source or surrounding clump. Urquhart *et al.* (2011) found a positive correlation between H_2O maser luminosity and bolometric luminosity for both HII regions and MYSOs from the Red *MSX* Source (RMS) sample, while Breen & Ellingsen (2011) report an anticorrelation between H_2O maser luminosity and the H_2 number density of the associated clump. Breen & Ellingsen (2011) attribute this anticorrelation to an evolutionary effect, but caution that the clump densities were calculated assuming a single temperature for all clumps. Our Nobeyama survey and the 1.1 mm Bolocam Galactic Plane Survey (BGPS; Aguirre *et al.* 2011, Rosolowsky *et al.* 2010) together provide the data necessary to test this evolutionary interpretation and explore connections between H_2O maser and clump properties: H_2O maser spectra, T_{kin} measurements from NH_3, and clump properties from 1.1 mm dust continuum emission. Combining these datasets, we find no correlation between H_2O maser luminosity and clump density. There is a weak correlation between H_2O maser luminosity and clump temperature (T_{kin}). This is consistent with the correlation of maser luminosity with bolometric luminosity found by Urquhart *et al.* (2011): the more luminous the central source, the more it will heat the surrounding clump.

4. Conclusions

In sum, maser studies have been instrumental in showing that GLIMPSE EGOs are associated with MYSOs driving active, massive outflows. Sensitive VLA surveys yielded exceptionally high detection rates for CH_3OH Class I and II masers. In a somewhat less sensitive ($\sigma \sim 0.11$ Jy) Nobeyama 45-m H_2O maser survey, the detection rate is slightly higher than in similar searches towards other MYSO samples. By and large, cm continuum emission towards EGOs is weak, with most harboring an earlier phase of massive star formation than UC HII regions. Our SMA case study of G18.67+0.03 shows that Class I CH_3OH masers can be excited by both young (hot core) and older (UC HII) sources in the same massive star-forming region, indicating that simple evolutionary cartoons are probably not realistic. In our EGO H_2O maser survey, we see no trends in H_2O maser luminosity with clump density, association with IRDCs, or with CH_3OH maser type (Class I or II or both). There is a weak trend in H_2O maser luminosity with clump temperature, consistent with the L_{H_2O} vs. L_{bol} correlation.

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