THE PROTOCLUSTER G18.67+0.03: A TEST CASE FOR CLASS I CH$_3$OH MASERS AS EVOLUTIONARY INDICATORS FOR MASSIVE STAR FORMATION

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Received 2012 September 20; accepted 2012 October 10; published 2012 November 5

ABSTRACT

We present high angular resolution Submillimeter Array and Karl G. Jansky Very Large Array observations of the massive protocluster G18.67+0.03. Previously targeted in maser surveys of GLIMPSE Extended Green Objects (EGOs), this cluster contains three Class I CH$_3$OH maser sources, providing a unique opportunity to test the proposed role of Class I masers as evolutionary indicators for massive star formation. The millimeter observations reveal bipolar molecular outflows, traced by $^{13}$CO(2–1) emission, associated with all three Class I maser sources. Two of these sources (including the EGO) are also associated with 6.7 GHz Class II CH$_3$OH masers; the Class II masers are coincident with millimeter continuum cores that exhibit hot core line emission and drive active outflows, as indicated by the detection of SiO(5–4). In these cases, the Class I masers are coincident with outflow lobes, and appear as clear cases of excitation by active outflows. In contrast, the third Class I source is associated with an ultracompact (UC) H II region, and not with Class II masers. The lack of SiO emission suggests that the $^{13}$CO outflow is a relic, consistent with its longer dynamical timescale. Our data show that massive young stellar objects (MYSOs) associated only with Class I masers are not necessarily young and provide the first unambiguous evidence that Class I masers may be excited by both young (hot core) and older (UC H II) MYSOs within the same protocluster.

Key words: ISM: individual objects (G18.67+0.03) – ISM: jets and outflows – ISM: molecules – masers – stars: formation – techniques: interferometric

Online-only material: color figures

1. INTRODUCTION

The lack of a detailed, observationally-based evolutionary sequence for massive young stellar objects (MYSOs) limits our understanding of the early stages of high-mass ($M_{\text{ZAMS}} > 8 M_\odot$) star formation. Massive stars form in (proto)clusters, with younger sources (such as hot cores), often found in close proximity to ultracompact (UC) H II regions (e.g., Hunter et al. 2006; Cyganowski et al. 2007 and references therein). Because massive protoclusters are generally distant ($D > 1$ kpc) and deeply embedded, most efforts to develop evolutionary sequences have focused on cm-wavelength maser transitions, which are amenable to high-resolution study and unaffected by extinction. Four types of masers are ubiquitous: Class I and II CH$_3$OH, H$_2$O, and OH. Class I CH$_3$OH and H$_2$O masers are collisionally pumped in shocked gas, while Class II CH$_3$OH and OH masers are radiatively pumped by infrared emission from warm dust (e.g., Elitzur et al. 1989; Cragg et al. 2002; Voronkov et al. 2006). CH$_3$OH masers are the key to proposed evolutionary sequences of masers in MYSOs, which posit that Class I CH$_3$OH masers appear first (e.g., Ellingsen et al. 2007; Breen et al. 2010), based in part on their observed association with outflows (e.g., Plambeck & Menten 1990; Kurtz et al. 2004; Cyganowski et al. 2009). Class I only sources have thus generally been interpreted as tracing the earliest stages of massive star formation (Ellingsen 2006). Recent work, however, suggests that Class I CH$_3$OH masers may also be excited in shocks driven by expanding H II regions (Voronkov et al. 2010), raising the possibility of multiple distinct epochs of Class I maser activity during MYSO evolution (Chen et al. 2011; Voronkov et al. 2012). The prevalence of Class I only sources is currently unknown, primarily due to the lack of substantial untargeted searches in Class I maser transitions (see also Voronkov et al. 2010).

Our studies of a new sample of MYSO outflow candidates (Extended Green Objects (EGOs), selected based on extended 4.5 μm emission in GLIMPSE images; Cyganowski et al. 2008) have identified a massive protocluster ($M_{\text{clump}} \sim 3510 M_\odot$; Schuller et al. 2009) that provides a unique opportunity to understand the evolution of Class I CH$_3$OH masers: G18.67+0.03. Cyganowski et al. (2009) detected 44 GHz Class I CH$_3$OH masers toward three mid-infrared (MIR) sources in this region: two (including the EGO) are also associated with 6.7 GHz Class II CH$_3$OH masers (Figure 1). The third—the only source in the region with a cm-wavelength continuum counterpart in deep Very Large Array (VLA) images (Cyganowski et al. 2011a)—has no Class II masers. Green & McClure-Griffiths (2011) assign both 6.7 GHz masers in G18.67+0.03 the far distance in their H I self-absorption study of Class II masers. Using the revised kinematic distance prescription of Reid et al. (2009) and thermal NH$_3$ data, Cyganowski et al. (2012) find a similar far distance of 10.8 kpc, which we adopt here.

In this Letter, we present a high-resolution Submillimeter Array (SMA)$^7$ study of the millimeter-wavelength dust continuum and molecular line emission toward G18.67+0.03, to constrain the evolutionary states of the maser sources and the

$^7$ 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.
presence/absence of active outflows. The SMA is well suited for deciphering MYSO relative evolutionary states (Beuther et al. 2009; Zhang et al. 2009; Wang et al. 2012). To provide kinematic information for the ionized gas, we include complementary 1.3 cm Karl G. Jansky Very Large Array (VLA) hydrogen recombination line as well as cm continuum observations.

2. OBSERVATIONS

SMA observations at 1.3 mm were obtained on 2010 June 18 with 7 antennas in compact configuration, in good weather ($\tau_{225\,\text{GHz}} \sim 0.07$). A three-pointing mosaic was used to cover the extent of the (sub)millimeter clump (Figure 1). The primary beam (FWHP) at 1.3 mm is $\sim 55''$. The largest angular scale recoverable from these data is $\sim 20''$. We observed $\sim 216.8$–220.8 GHz in the lower sideband (LSB) and $\sim 228.8$–232.8 GHz in the upper sideband (USB), each divided into $2 \times 2$ GHz intermediate frequencies (IFs), with a uniform channel width of 0.8125 MHz. The calibrators were J1733$-$130 and J1911$-$201 (complex gain), 3C454.3 (bandpass), and Neptune (absolute flux density). The LSB was flux-calibrated using a model of Neptune’s brightness distribution and the MIRIAD task smaflux. This direct approach cannot be used for the USB because of strong $^{12}$CO in Neptune’s atmosphere. Instead, the USB flux density calibration was bootstrapped from the LSB assuming a spectral index $\alpha = -0.85$ for 3C454.3 (based on SMA monitoring). Comparison of derived quasar flux densities with SMA monitoring suggests the absolute flux density calibration is accurate to better than $\sim 15\%$.

Initial calibration was performed in MIRIAD; the data were then exported to CASA for further processing. Each IF was processed independently, with the continuum estimated using line-free channels in the $uv$ plane, and separated from the line emission. The continuum was self-calibrated and the resulting solutions applied to the line data. The data were imaged using Briggs weighting and a robust parameter of 0.5. The final combined continuum image has a synthesized beam size of $3''\times2''$ and a $1\sigma$ rms of 1.5 mJy beam$^{-1}$. The line data were resampled to $\Delta v = 1.2$ km s$^{-1}$, then Hanning-smoothed; the typical rms per channel is $\sim 40$ mJy beam$^{-1}$. All measurements were made from images corrected for the primary beam response.

The NRAO$^8$ VLA observations of G18.67+0.03 were obtained in the C configuration on 2011 January 7 as part of

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$^8$ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
a 1.3 cm line and continuum survey of massive protostellar objects (program AB1346; Brogan et al. 2011). The calibrators were J1832−1035 (complex gain), J1924−2914 (bandpass), and 3C286 (absolute flux density). A single pointing was observed (α = 18h24m53.7s, δ = −12°39'20") in the primary beam (FWHP) ± 0.′′3. The data were calibrated and imaged in CASA. The full VLA data set will be described in a future publication; here we consider only the 24.50878 GHz continuum source designated F G18.67+0.03−0.02. The self-calibrated continuum image has a synthesized beamsize of 1′.46 × 1′.08 (P.A. = −174°) and a 1σ rms of 74 μJy beam−1. To improve the signal-to-noise ratio, we smoothed the H63α and H64α data (to Δνchannel = 4.8 km s−1, θbeam = 2′), then averaged to obtain a final radio recombination line (RRL) image cube with σ ∼ 0.29 mJy beam−1. All measurements were made from images corrected for the primary beam response.

3. RESULTS

3.1. Millimeter Continuum and Line Emission

As shown in Figure 1, we resolve four compact 1.3 mm continuum sources, arranged in a line of ∼ 50′ (2.6 pc) extent along the clump. All have 24 μm counterparts. For ease of reference, we designate them (from E to W): EGO, CM1-UCHII, non-EGO maser source (NEMS), and mid-infrared source (MIRS). CM1-UCHII refers to the millimeter counterpart of the cm-wavelength continuum source designated F G18.67+0.03−0.02 CM1 by Cyganowski et al. (2011a). Observed millimeter continuum properties are summarized in Table 1. The SMA image recoveries 19±6% of the 1.1 mm BGPS flux density (3.8±0.7 Jy; Rosolowsky et al. 2010, corrected as per Aguirre et al. 2011). The westernmost source (MIRS) falls outside the area searched for 44 GHz CH3OH masers by Cyganowski et al. (2009), so we do not discuss it further in this Letter.

Only a few species (including CO isotopes, SO, DCN, and low-excitation lines of H2CO and CH3OH) are detected toward all three maser sources. The LSR velocities of the sources, determined from compact molecular line emission, are within 3 km s−1 of each other (Figure 3(a), Table 1). Figures 2(a)–(c) present a comparison of the spectra at the EGO, CM1-UCHII, and NEMS 1.3 mm continuum peaks across 2 GHz of the SMA band. The EGO and NEMS both exhibit copious molecular line emission from classic hot core tracers, such as CH3CN, OCS, and high-excitation CH3OH. In contrast, CM1-UCHII is line-poor; none of these tracers are detected.

All three Class I CH3OH maser sources are associated with both redshifted and blueshifted 13CO(2–1) emission, with velocity extents of 23, 16, and 30 km s−1 for the EGO, CM1-UCHII, and NEMS, respectively (Figure 3(c)). In all cases, there is a clear spatial offset between the red and blue lobes, which are centered on a compact source. These characteristics indicate that the high-velocity 13CO(2–1) emission traces bipolar molecular outflows. The 44 GHz masers associated with the EGO and NEMS are coincident with outflow lobes. The CM1-UCHII 44 GHz masers are located, in projection, near the edge of its redshifted lobe. In addition to the N–S outflow, there is evidence for an E–W gradient in low-velocity molecular gas near the UCHII region (ν = νsystemic ≲ 1.5 km s−1; Figure 3(b)). This E-W velocity gradient could indicate a second, slower outflow, and/or large-scale rotation or infall. Importantly, the outflows associated with the EGO and NEMS are detected in SiO(5−4) emission, while the outflow(s) associated with CM1-UCHII is not (Figure 3(d)).

3.2. Temperatures and Dust Masses

We estimate gas temperatures for the EGO and NEMS by fitting the J = 12−11 CH3CN ladder using the method described in Cyganowski et al. (2011b). In brief, the model accounts for optical depth effects and emission from the CH3CN isotope: the temperature, source size (diameter), and CH3CN column density and line width are free parameters. Figures 2(d)–(e) show the best-fit models, overlaid on the observed spectra. The best-fit temperatures, source sizes, and CH3CN column densities are quite similar for the two sources: T = 175 K and 185 K, log[NCH3CN(cm−2)] = 16.66 and 16.58, and dsource = 0′′.45 (4900 AU) and 0′′.39 (4200 AU) for the EGO and NEMS, respectively.

Gas masses and (beam-averaged) column and number densities estimated from the 1.3 mm thermal dust emission, using the methodology of Cyganowski et al. (2011b), are presented in Table 1. The mass estimates for the EGO and NEMS

### Table 1

Properties of Millimeter Continuum Sources

| Source Name | J2000 Coordinates | Peak Intensity | Integ. Flux Density | T_dust | T_dust | M_gas | N_H2 | m_H2 | v_LSR |
|-------------|-------------------|----------------|--------------------|--------|--------|-------|-------|-------|--------|
| EGO         | 18 24 53.77       | −12 39 20.8    | 96                 | 175    | 0.003  | 30    | 0.7   | 2.8   | 79     |
| CM1-UCHII   | 18 24 52.59       | −12 39 20.0    | 36                 | 50     | 0.008  | 100   | 2.1   | 8.6   | 80     |
| NEMS        | 18 24 51.09       | −12 39 22.0    | 187                | 185    | 0.006  | 70    | 1.5   | 6.1   | 82     |
| MIRS        | 18 24 50.27       | −12 39 22.0    | 44                 | 92     | 32     | 718   |       |       |        |
| Total       |                   |                |                    |        |        |       |       |       |        |

Notes.

a As designated in Section 3.1.
b Coordinates of 1.3 mm continuum peak. The number of significant figures reflects a 1 pixel uncertainty.
c Integrated flux density within 3σ contour, measured using the CASAviewer program. Following the approach developed for the CORNISH survey (Purcell et al. 2008), we estimate uncertainties as √N/σsky(1 + (σsky/Nsky)), where N is the number of pixels in the source aperture, Nsky is the number of pixels in an off-source “sky” aperture, and σsky is the standard deviation over the “sky” aperture. The quoted uncertainties are averages for three choices of “sky” apertures.
d Beam-averaged.
e Determined from compact molecular line emission; Section 3.1.
f Physical properties calculated using the 1.3 mm flux density less the estimated free–free contribution of 5 mJy.
Figure 2. SMA spectra toward the (a) EGO, (b) CM1-UCHII, and (c) NEMS 1.3 mm continuum peaks, showing 2 GHz of the LSB. (d–e) SMA CH$_3$CN spectra (gray) overlaid with the best-fit model (dashed black line).

assuming $T_{\text{dust}} = T_{\text{CH}_3\text{CN}}$ (∼30 and 70 $M_\odot$, respectively) are likely lower limits; the CH$_3$CN-emitting regions are unresolved at the scale of our SMA observations ($\theta_{\text{syn}} \sim 33,000$ AU), while the 1.3 mm continuum emission appears somewhat more extended. For comparison, the gas masses of the CH$_3$CN-emitting regions, estimated from the best-fit source sizes and column densities, are ∼40 and 30 $M_\odot$ for the EGO and NEMS, for CH$_3$CN/H$_2 = 10^{-8}$. Since the CH$_3$CN/H$_2$ abundance in hot cores is uncertain, and values an order of magnitude higher/lower are plausible (see Cyganowski et al. 2011b), this is reasonable agreement.

Constraining the gas temperature of CM1-UCHII is more difficult because of the paucity of associated line emission: no CH$_3$CN is detected, and only one CH$_3$OH line. Most lines detected have $E_{\text{upper}} < 50$ K; the highest-excitation transitions have $E_{\text{upper}} \sim 68$ K (H$_2$CO). In addition, while the ionized gas is unresolved (Section 3.3), the millimeter-wavelength continuum emission is extended E–W, with a scale >0.5 pc. For the estimates in Table 1, we adopt a temperature of 50 K, and subtract the free–free contribution to the 1.3 mm flux density (extrapolated from the 1.2 cm integrated flux density assuming optically thin emission, $S_\nu \propto \nu^{-0.1}$).

3.3. Ionized Gas Properties

We detect the H63α and H64α recombination lines toward F G18.67+0.03-CM1 (Cyganowski et al. 2011a). The fitted RRL velocity (77.3 ± 0.9 km s$^{-1}$) is consistent with the molecular-gas velocity. From the line-to-continuum ratio of 0.48, the fitted FWHM line width of 27.0 km s$^{-1}$, and the fitted source size of 0.63 (from the continuum image), we derive an electron temperature of ∼5100 K and density of ∼1.9 × 10$^4$ cm$^{-3}$ (following the method of, e.g., Garay et al. 1986; Sewiło et al. 2011). If bulk motions (e.g., expansion) dominate the line width, this could explain the low derived $T_e$; however, the RRL emission is too weak to investigate this possibility. The cm-wavelength spectral index is consistent with optically thin free–free emission, and the ionizing photon flux (∼1 × 10$^{47}$ s$^{-1}$, calculated as in Cyganowski et al. 2011a) corresponds to a single ionizing star of spectral type B0.5V (Smith et al. 2002).

4. DISCUSSION

4.1. Evolutionary States of Class I Maser Driving Sources

All three maser sources in G18.67+0.03 are associated with massive (∼30 $M_\odot$), dense ($n_{H_2} > 10^5$ cm$^{-3}$) millimeter continuum cores, and with $^{13}$CO outflows. CO (and HCO$^+$) may trace relic outflows from MYSOs (e.g., Klaassen et al. 2006; Klaassen & Wilson 2007; Hunter et al. 2008). SiO emission, however, specifically indicates recent shocks and active outflows, since the gas-phase SiO abundance is enhanced by shocks and remains so for only ∼10$^4$ years (e.g., Pineau des Forets et al. 1997). The EGO and NEMS, which have both Class I and II CH$_3$OH masers, thus share two other key characteristics: (1) their outflows are active, as evidenced by SiO(5–4) emission and (2) the driving sources exhibit hot core line emission (e.g., CH$_3$CN, CH$_3$OH, OCS). In summary, the Class I masers in these sources appear as clear cases of excitation by outflows.
In contrast, the Class I-only maser source lacks indicators of youth: neither SiO nor hot core line emission are detected in our observations. The 44 GHz masers lie near a cm continuum source, detected in RRLs; its derived ionized gas properties are consistent with a UCHII region. Two mechanisms have been posited that could explain Class I maser emission associated with such a comparatively evolved source. Voronkov et al. (2006) suggested that Class I masers might be long-lived, persisting after the exciting shock had dissipated. More recently, Voronkov et al. (2010) noted the proximity of cm continuum emission to three of the four known examples of 9.9 GHz Class I CH$_3$OH masers. They suggested that shocks driven into the surrounding cloud by expanding HII regions were responsible for these masers, and that this mechanism should also apply to other Class I transitions. These two scenarios have somewhat different implications for maser evolutionary sequences: the first implies that Class I masers outlast the Class II phase; the second, that Class I masers may appear more than once, excited by young or evolved MYSOs (see also Voronkov et al. 2012).

In G18.67+0.03, the lack of associated SiO emission suggests that the CM1-UCHII 13CO outflow is a relic. It also has a smaller velocity extent than the EGO and NEMS 13CO outflows, despite being more spatially extended: additional evidence that the CM1-UCHII 13CO outflow is older ($t_{\text{dyn}} \sim 19,000, 26,000, \text{and } 66,000$ for the NEMS, EGO, and CM1-UCHII, respectively). In this picture, the CM1-UCHII 13CO outflow would have been driven by the now-ionizing source, prior to the creation of the UCHII region (analogous to the E-W outflow in G5.89−0.39; Hunter et al. 2008). The Class I masers are near the edge of the redshifted lobe, consistent with an association with the relic(?)
flow, and so supporting the scenario in which long-lasting Class I maser activity extends beyond the Class II maser lifetime. This interpretation, however, is not conclusive; the Class I masers are also near the UCHII region, and we cannot rule out their being excited by H II region-driven shocks. In either case, these Class I masers are clearly associated with a more evolved MYSO.

4.2. Class I Maser Excitation as a Key?

Probable maser emission in the Class I 229.759 GHz CH$_3$OH(8–7,8) transition is a conspicuous feature of recent SMA observations of MYSO outflows (e.g., Cyganowski et al. 2011b and references therein). In these outflows, 229 GHz emission is generally co-located (spatially and spectrally) with lower frequency Class I masers, and the brightest features in all transitions coincide (see also Fish et al. 2011). In G18.67+0.03, we detect strong 229.759 GHz emission coincident with the blueshifted, SiO-rich western outflow lobe. Like many previous 229 GHz studies, our beam is too large to establish masers coincidently with lower frequency Class I masers. However, the brightest features in all transitions coincide (see also Fish et al. 2011).

For G18.67+0.03, higher angular resolution observations are needed to confirm the maser nature of the 229 GHz emission and to spatially resolve the potential millimeter masers from the hot cores in the EGO and NEMS; high-resolution 36 GHz observations may also be helpful (e.g., Voronkov et al. 2012).

5. SUMMARY

Our high-resolution SMA and VLA observations provide the first unambiguous evidence of Class I CH$_3$OH masers being excited by both young and more evolved MYSOs within the same protocluster. The two hot cores, also associated with Class II CH$_3$OH masers, drive active outflows traced by SiO(5–4) emission and Class I masers. In contrast, the UCHII region is associated only with Class I CH$_3$OH masers and with an older (possibly relic) $^{13}$CO outflow; the UCHII shows neither SiO nor hot core line emission. These results further demonstrate the limitations of current evolutionary sequences for maser emission (see also Voronkov et al. 2010; Chen et al. 2011). In particular, our data show that MYSOs associated only with Class I CH$_3$OH masers (no Class II) are not necessarily young, in contrast to published sequences. This work highlights the importance of high angular resolution multwave-length observations for constraining MYSO evolutionary states, and disentangling an observation-based MYSO evolutionary sequence.

This research made use of NASA’s Astrophysics Data System Bibliographic Services, APLpy, an open-source plotting package for Python hosted at http://aplpy.github.com, and the myXCLASS program (http://www.astro.uni-koeln.de/projects/schilke/XCLASS), which accesses the CDMS (http://www.cdms.de) and JPL (http://spec.jpl.nasa.gov) molecular databases. C.J. Cyganowski is supported by an NSF AAPF under award AST-1003134.

REFERENCES

Aguirre, J. E., Ginsburg, A. G., Dunham, M. K., et al. 2011, ApJS, 192, 4
Beuther, H., Zhang, Q., Bergin, E. A., & Sridharan, T. K. 2009, AJ, 137, 406
Breen, S. L., Ellingsen, S. P., Caswell, J. L., & Lewis, B. E. 2010, MNRAS, 401, 2219
Brogan, C. L., Hunter, T. R., Cyganowski, C. J., et al. 2011, ApJ, 739, L16
Chen, X., Ellingsen, S. P., Shen, Z.-Q., Titmarsh, A., & Gan, C.-G. 2011, ApJS, 196, 9
Cragg, D. M., Sobolev, A. M., & Godfrey, P. D. 2002, MNRAS, 331, 521
Cyganowski, C. J., Brogan, C. L., & Hunter, T. R. 2007, AJ, 134, 346
Cyganowski, C. J., Brogan, C. L., Hunter, T. R., & Churchwell, E. 2009, ApJ, 702, 1615
Cyganowski, C. J., Brogan, C. L., Hunter, T. R., & Churchwell, E. 2011a, ApJ, 743, 56
Cyganowski, C. J., Brogan, C. L., Hunter, T. R., & Churchwell, E. 2011b, ApJ, 729, 124
Cyganowski, C. J., Whitney, B. A., Holden, E., et al. 2008, ApJ, 136, 2391
Cyganowski, C. J., et al. 2012, ApJ, in press (arXiv:1210.5528)
