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Class II 6.7 GHz Methanol Maser Association with Young Massive Cores Revealed by ALMA

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Abstract. The association of 6.7 GHz class II methanol (CH_3OH) masers with ATLASGAL/ ALMA 0.9 mm massive dense cores is presented in this work from a statistical viewpoint. 42 of the 112 cores (37.5%) detected with the Atacama Compact Array (ACA) excite 6.7 GHz CH_3OH masers. ACA cores have offsets $0''.17$ to $4''.79$ from the methanol multibeam survey (MMB), with a median of 2.”19. Approximately 90% of the MMB-associated cores are of masses > 40 $M_\odot$. Because all the cores show evidence of outflow activity, and only a fraction of the cores excited CH_3OH masers, we suggest that outflows precede the emergence of maser emission. This first ALMA survey of massive dense cores combined with the MMB survey along with other maser specie surveys is a promising tool to trace the evolutionary sequence of high-mass stars.

Keywords. stars: formation – stars: winds, outflows – ISM: H II regions – surveys

1. Introduction

Large surveys of massive young cores at various wavelengths are crucial for understanding the evolutionary sequence of high-mass stars, especially at their early formation stages. A number of surveys both in dust continuum and different maser species toward massive dense cores have been carried out (Breen 2010, 2011, 2013; Gerner *et al.* 2014; Urquhart *et al.* 2013a, 2013b; Codella *et al.* 2004; de Villiers *et al.* 2015), and could be statistically analysed to filter out information about high-mass star formation.

While 6.7 GHz CH_3OH are known to be exclusively associated with massive stars, $\sim$22 GHz H_2O masers as well as other maser species can also trace sites of star formation. The formative stages at which massive cores excite this masers remain an unsettled issue

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with Reid 2007 suggesting that H_2O maser excitation precede CH_3OH masers which precedes OH masers with some level of overlap in time.

de Villiers *et al.* (2015) suggested that outflows are launched prior to the excitation of 6.7 GH and this is supported by the results of Bayandina *et al.* (2012). To confirm the above results a statistical approach is required and this is the aim of this paper.

2. ALMA and MMB Data

The data used in this work was taken from Atacama Compact Array (ACA) Cycle 2 0.9 mm observations (Csengeri *et al.* 2017a contains the details of the observing setup and data reduction procedure; Chibueze *et al.* 2017). The primary beam was $28\farcs9$, while the synthesized (geometric mean of the major and minor axes) beam was $3\farcs5$ to $4\farcs6$.

The 6.7 GHz CH_3OH maser information was taken from the methanol multibeam (MMB) catalog of Green *et al.* (2012) [covering Galactic longitude $186° - 330°$], and Caswell *et al.* (2010, 2011) [covering Galactic longitude $330° - 6°$]. The Australia Telescope Compact Array (ATCA) astrometric accuracy for the MMB is $0\farcs4$ (an order of magnitude better angular resolution than the ACA observations).

To check for the presence of 44 GHz class I CH_3OH masers, we have used the class I methanol maser catalog of Bayandina *et al.* (2012), which contains 206 sources selected from the literature up to the end of 2011 (see Bayandina *et al.* 2012 and references therein). Maser information extracted from individual publications lack completeness but we found 13% of the ALMA sources to be associated with 44 GHz class I CH_3OH masers, and in addition 4 with large offsets ($> 5''$) from the ALMA cores.

H_2O maser information was taken from the H_2O Southern Galactic Plane Survey (HOPS) by Walsh *et al.* (2011). G351.4441+0.6579 [NGC 6334 I(N)] H_2O maser details was taken from Chibueze *et al.* (2014).

3. Association and Selection Criteria

With 6.7 GHz class II CH_3OH maser (MMB) association with the ACA cores as the primary focus, we crossed matched and determined association with the following conditions:

(1) distance to the core is < 5 kpc;

(2) angular offset of the ACA core peak and the MMB peak is $<5''$.

(3) difference between the $V_{\rm LSR}$ of the MMB peak and that of its associated ACA core is within ± 8 km s^{-1}.

4. Results and Discussions

Of the 125 ACA core, we confirmed 6.7 GHz observations toward 112 cores of the 42 ATLASGAL clumps (Csengeri *et al.* 2017b). 31 of the 42 ATLASGAL clumps (73.8%) were associated with one or more 6.7 GHz CH_3OH masers. 42 of the 112 (37.5%) ACA cores were found to be exciting 6.7 GHz CH_3OH masers. The ACA-MMB core with the lowest mass has a mass of ~ 12 $M_\odot$. Figure 1 shows the 0.9 mm continuum emission of G329.1835 with markers to indicate the positions of different maser species (see Chibueze *et al.* 2017).

We compare ACA and ATLASGAL dust continuum peak flux densities and found a good correlation of coefficient 0.56 with a significance value of 2×10^{-10}.

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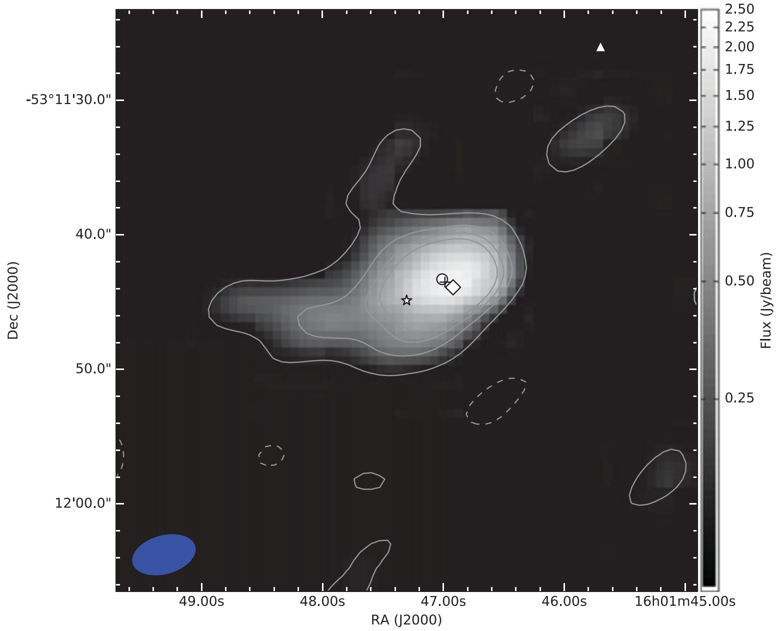

Figure 1. G329.1835. The white filled star, circle, triangle, and diamond with black edges represent the peak position of ATLASGAL clumps, 6.7 GHz CH_3OH masers, H_2O masers and 44 GHz CH_3OH masers, respectively (see Appendix of Chibueze *et al.* (2017).

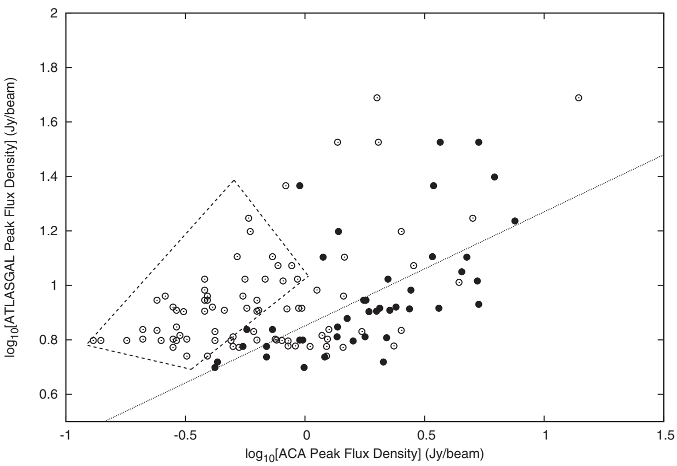

Figure 2. Plot of ATLASGAL clump peak flux densities against ACA core peak flux densities. Open circles represent sources without 6.7 GHz CH_3OH masers, while the filled circles are those associated with 6.7 GHz CH_3OH masers (*unflagged ACA-MMB*). The dotted line represents the best fit of the ATLASGAL-ACA flux relation of the 6.7 GHz CH_3OH maser associated cores only. The skewed square represent the ACA weak-continuum region which lack CH_3OH maser emissions.

Figure 2 is a plot of peak flux densities of the ATLASGAL clumps against those of their associated ACA cores. The filled circles represent cores/clumps associated with CH_3OH masers while the open circles are those with no CH_3OH maser association. The skewed box (drawn with dashed lines) in Figure 2 encloses cores/clumps that are massive, driving outflows but not associated with CH_3OH masers. This is likely an indication that

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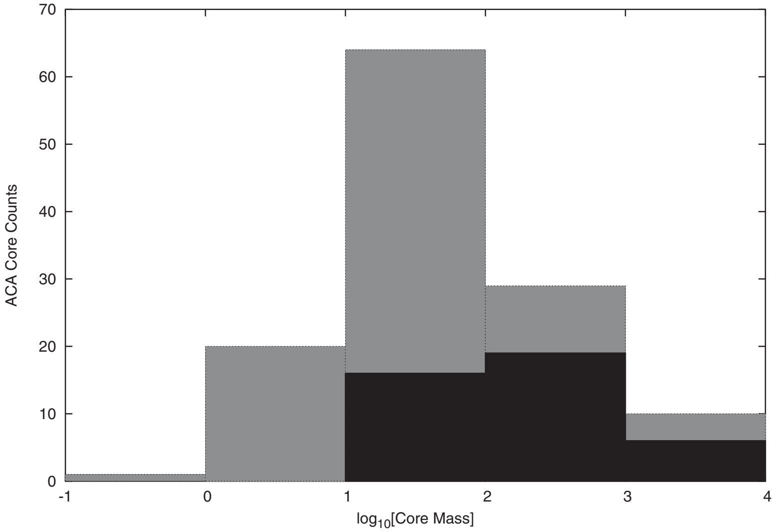

Figure 3. Mass distribution of all the ACA cores/clumps with 10 $M_\odot$ binning (gray: all core, black: 6.7 GHz CH_3OH maser associated cores).

the cores within the enclosed clump-to-core flux density relation represent the earlier phase of protostellar evolution. While these cores are driving outflows, absence of maser association could suggest that the cores do not have sufficient radiative power to pump CH_3OH masers.

Using the core masses of Csengeri *et al.* (2017a) derived with dust temperature of 25 K, we compared the mass distribution of ACA cores with 6.7 GHz CH_3OH masers (ACA-MMB). The mass range of the entire sample is 11.8 – 3876.3 $M_\odot$, and 11.8 – 403.4 $M_\odot$ for the more strictly selected sample of 27 cores. Figure 3 shows the distribution of the core masses.

Our statistical analysis supports the notion that outflows precede 6.7 GHz CH_3OH maser excitation in massive dense cores.

References

Bayandina, O. S., Val'tts, I. E., & Larionov, G. M. 2012, *Astron. Rep.*, 56, 553
Breen, S. L., Ellingsen, S. P., Caswell, J. L., & Lewis, B. E. 2010, *MNRAS*, 401, 2219
Breen, S. L., Ellingsen, S. P., Caswell, J. L., *et al.* 2011, *ApJ*, 733, 80
Breen, S. L., Ellingsen, S. P., Contreras, Y., *et al.* 2013, *MNRAS*, 435, 524
Caswell, J. L., Fuller, G. A., Green, J. A., *et al.* 2010, *MNRAS*, 404, 1029
Caswell, J. L., Fuller, G. A., Green, J. A., *et al.* 2011, *MNRAS*, 417, 1964
Chibueze, J. O., Omodaka, T., Handa, T., *et al.* 2014, *ApJ*, 784, 114
Chibueze, J. O., Csengeri, T., Tatematsu, K., *et al.* 2017, *ApJ*, 836, 59
Csengeri, T., Bontemps, S., Wyrowski, F., *et al.* 2017b, *A&A*, 601, A60
Csengeri, T., Bontemps, S., Wyrowski, F., *et al.* 2017a, *A&A*, 600, L10
Codella, C., Lorenzani, A., Gallego, A. T., Cesaroni, R., & Moscadelli, L. 2004, *A&A*, 417, 615
de Villiers, H. M., Chrysostomou, A., Thompson, M. A., *et al.* 2015, *MNRAS*, 449, 119
Gerner, T., Beuther, H., Semenov, D., *et al.* 2014, *A&A*, 563, A97
Green, J. A., Caswell, J. L., Fuller, G. A., *et al.* 2012, *MNRAS*, 420, 3108
Reid, M. J. 2007, Astrophysical Masers and their Environments, 242, 522
Urquhart, J. S., Moore, T. J. T., Schuller, F., *et al.* 2013, *MNRAS*, 431, 1752
Urquhart, J. S., Thompson, M. A., Moore, T. J. T., *et al.* 2013, *MNRAS*, 435, 400

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