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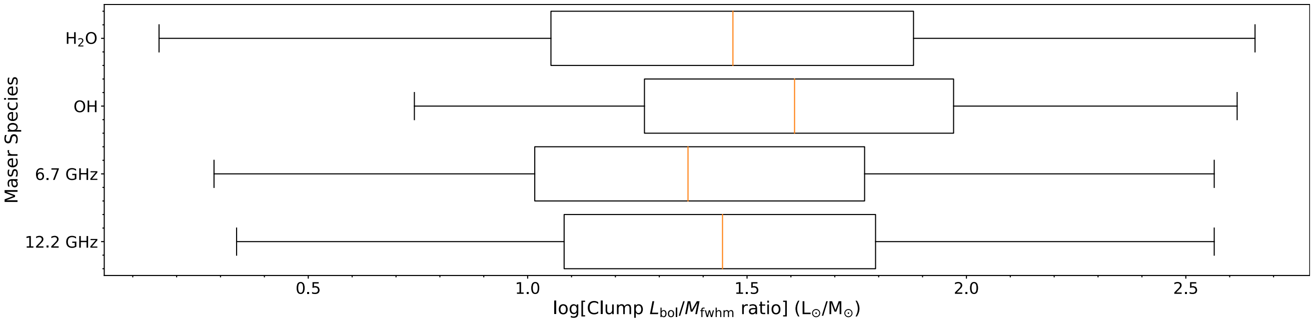

Figure 14. Box plot presenting the central 95 per cent distributions of L_{bol}/M_{fwhm} ratios for clumps associated with the various maser species. Each box extends from the lower to upper quartile with an orange line denoting the median value, the whiskers show the full range of the data.

parameter, $n > 10^{4.5}$ cm^{-3} (Billington et al. 2019). We find that the mean lifetimes of maser emission to be 1.6, 0.4, and 2.0 × 10^4 yr for the water, hydroxyl and 12.2-GHz methanol masers respectively. The statistical lifetime for the 6.7-GHz maser is taken from Billington et al. (2019) as 3.3 × 10^4 yr. The uncertainty on these calculations has been calculated using Poisson statistics and is shown in Fig. 13, with the mean error being found to be ∼10 per cent. As the Poisson errors rely on the number of clumps at each volume density (error = $\sqrt{N}$, where N is the number of sources), the errors for the lifetimes are greatly increased towards higher volume densities due to the small number of clumps that possess these increase volume densities.

5.3 'Straw man' model comparison

One of the main aims of this study is to investigate the Ellingsen et al. (2007) 'straw man' model using the physical properties presented in the ATLASGAL catalogue. This model is based on maser observations within regions of ongoing star formation and that, methanol masers (class I and II) are associated with a very early stage of formation, followed by water masers. Hydroxyl masers are then seen to be coincident with ultracompact H II regions. In Section 5.2.1, we show that all of the maser associated clumps have similar L_{bol}/M_{fwhm} ratios, which we are using as our gauge of protostellar evolution.

These differences between the L_{bol}/M_{fwhm} ratios of the maser associated clumps can be used to investigate the 'straw man' model. In Fig. 14, we present a box plot of the distribution of L_{bol}/M_{fwhm} ratios for the maser associated clumps. In general, there is a good agreement between the results presented in Fig. 14, and the previous model presented in Breen et al. (2010). However, a difference that can be noted is that water masers are seen towards regions of star formation before methanol masers and outlast hydroxyl masers, as predicted by the 'straw man' model. While these findings show that the 'straw man' model is fairly consistent with the L_{bol}/M_{fwhm} ratios of associated clumps, it can be seen from Fig. 14 that there is a considerably overlap between all of the maser species, which limits the power of this model as an evolutionary tracer for star formation.

We can also attempt to test the 'straw man' model using the calculated statistical lifetimes for each maser phases. Breen et al. (2010) predicted that the lifetime of the 12.2-GHz methanol maser to be between 1.5 × 10^4 and 2.7 × 10^4 yr. The statistical lifetime that we calculate for this maser does lie towards the centre of this range at ∼2 × 10^4 yr, and so our results are in good agreement with Breen et al. (2010). Along with the statistical lifetime for the 6.7-GHz methanol maser predicted by Van Der Walt (2005) (2.5−4.5 × 10^4 yr) and the result found in Billington et al. (2019) (∼3.3 × 10^4 yr) our results support the 'straw man' model in terms of the methanol masers. The model presented by Breen et al. (2010) predicts that the hydroxyl maser has a lifetime of ∼20 000 yr and the value found here is only a fifth of that prediction (∼0.4 × 10^4 yr). Finally, water masers were predicted to have relative lifetimes of ∼30 000 yr, while we find a lifetime of approximately one half of this at only 16 000 yr. One aspect that has not been included in this study is the approximate lifetime of ultracompact H II (UCHIIs) regions, and where the maser lifetimes lie in comparison to this. The 'straw man' model predicts that UCHII regions begin to develop after the onset of water and 6.7-GHz methanol masers, and exist throughout the lifetime of the 12.2-GHz methanol masers and the hydroxyl masers. Kawamura & Masson (1998) predicted the dynamical age of a W3(OH) to be approximately 2 300 yr, similar to our prediction of the hydroxyl maser lifetime but an order of magnitude less than the 12.2-GHz statistical lifetime. Therefore, the 'straw man' model and our results may be overestimating the lifetime of the 12.2-GHz. However, it is currently unknown whether a UCHII region is required for the production of 12.2-GHz methanol masers and for how long after the development of a UCHII region could methanol maser emission be sustained.

All of the lifetimes that are estimated in this study are only a lower limit to the true lifetimes for each maser species, as the lifetimes depend on the sensitivity and completeness of each of the maser surveys. As these lifetimes are a lower limit on the true maser lifetimes, we find that they are still in agreement with the Ellingsen et al. (2007) model. While these measurements give a good indication of lifetimes for each maser species, we find it difficult to secure where these lifetimes lie in relation to one another as the L_{bol}/M_{fwhm} ratios show no significant trends. Overall we find a good agreement with the 'straw man' model in terms of the statistical lifetimes of the maser species investigated, while having employed a different method to previous studies to calculate these lifetimes.

6 CONCLUSIONS

This study has investigated the correlations between the ATLASGAL catalogue and dense Galactic clumps that are associated with methanol, water and hydroxyl maser emission. We have used catalogues from the HOPS, THOR, SPLASH, MMB, and ATLASGAL surveys, along with 12.2-GHz MMB follow-up observations, to match maser emission to dense clumps located in the Galactic mid-plane ($|\ell| < 60^\circ$ and $|b| < 1.5^\circ$).

The association rates between maser emission and dust clumps for the 22.2-GHz water and 12.2-GHz methanol masers are found to be 56 and 82 per cent, respectively. The association rates for the hydroxyl masers were found to be: 3 per cent (1612-MHz), 60 per cent (1665-MHz), 42 per cent (1667-MHz), and 49 per cent (1720-MHz). Physical parameters for the maser associated clumps and the full ATLASGAL sample are taken from Urquhart et al. (2018) and Billington et al. (2019).

(i) We find that the majority of methanol and water maser emission across the Galactic plane is associated with dense clumps, as identified by the ATLASGAL survey. Where a maser match has been found, they appear to have tightly correlated systematic velocities as those found for their counterpart clumps. The majority of masers (∼90 per cent) are also found to be tightly correlated with the peak of the dust emission ($<$10 arcsec), where the highest densities are found. This implies that they are at least coincident if not directly associated with embedded star formation.

(ii) It is just as common to find clumps coincident with multiple maser species (∼45 per cent) as those associated with only a single maser species (∼55 per cent). The communality of multiple species and/or transitions being found in a large fraction of clumps may be due to multiple evolutionary stages being present in each clump or that the various maser species require similar physical conditions. This is supported by the fact that all maser associated clumps, regardless of the corresponding maser species, have similar properties (we find no statistical differences between the clumps that are associated with different maser transitions).

(iii) Clumps associated with a maser are significantly more compact and dense than those that do not host any maser emission. However, we find no differences in radius and volume density between clumps which are associated with different maser species.

(iv) There is a similar density threshold required for the production of all species of maser emission as found in Billington et al. (2019) (clump densities of greater than $10^{4.1}$ cm^{-3}), further justifying that volume density is an important factor for maser emission. Furthermore, the fraction of clumps with associated maser emission increases with volume density.

(v) The $L_{\rm bol}/M_{\rm fwhm}$ ratios of maser associated clumps, regardless of the associated maser emission, are shown to occupy the same distinct region of the parameter space, and so all types of maser emission can be seen to have similar turn-on and turn-off points in the evolutionary sequence. The 'straw man' model (Ellingsen et al. 2007) predicts that the different maser species turn on and off at different times, however, large uncertainties associated with our results have limited any detailed comparison with the model but the $L_{\rm bol}/M_{\rm fwhm}$ ratios are broadly consistent with previous findings.

(vi) We have constrained the physical properties required for maser emission and it is shown that masers only exist in clumps with volume densities above $10^{4.1}$ cm^{-3}, luminosities greater than ∼500 $L_\odot$ and also require a minimum protostellar mass, estimated to be ∼6 $M_\odot$. Maser species also have an approximate turn-on point in the evolutionary process of star formation (∼$10^{0.2}$ $L_\odot/M_\odot$).

(vii) Statistical lifetimes are calculated for the water, hydroxyl and 12.2-GHz methanol masers, and these lifetimes are found to be ∼1.6, 0.4, and 2.0 × 10^4 yr, respectively. We find that the lifetimes for the 6.7-GHz (as found in Billington et al. 2019) and 12.2-GHz methanol masers are in good agreement with the values predicted by Breen et al. (2010), whereas the statistical lifetimes determined for the water and hydroxyl masers are considerably shorter than those predicted, by one quarter and one half, respectively. The lifetimes calculated for all masers are a lower limit on the true lifetimes, and so, our results support the 'straw man' model (Ellingsen et al. 2007).

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DATA AVAILABILITY

The data underlying this paper will be shared on a reasonable request to the corresponding author.

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