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ATLASGAL – relationship between dense star-forming clumps and interstellar masers

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ABSTRACT

We have used catalogues from several Galactic plane surveys and dedicated observations to investigate the relationship between various maser species and Galactic star-forming clumps, as identified by the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL) survey. The maser transitions of interest are the 6.7 and 12.2-GHz methanol masers, 22.2-GHz water masers, and the masers emitting in the four ground-state hyperfine structure transitions of hydroxyl. We find clump association rates for the water, hydroxyl and methanol masers to be 56, 39, and 82 per cent, respectively, within the Galactic longitude range of $60^\circ > \ell > -60^\circ$. We investigate the differences in physical parameters between maser associated clumps and the full ATLASGAL sample, and find that clumps coincident with maser emission are more compact with increased densities and luminosities. However, we find the physical conditions within the clumps are similar for the different maser species. A volume density threshold of $n(\text{H}_2) > 10^{4.1} \text{ cm}^{-3}$ for the 6.7-GHz methanol maser found in our previous study is shown to be consistent across for all maser species investigated. We find limits that are required for the production of maser emission to be $500 L_\odot$ and $6 M_\odot$, respectively. The evolutionary phase of maser associated clumps is investigated using the L/M ratio of clumps coincident with maser emission, and these have similar L/M ranges ($\sim 10^{0.2} - 10^{2.7} L_\odot/M_\odot$) regardless of the associated transitions. This implies that the conditions required for the production of maser emission only occur during a relatively narrow period during a star's evolution. Lower limits of the statistical lifetimes for each maser species are derived, ranging from $\sim 0.4 - 2 \times 10^4 \text{ yr}$ and are in good agreement with the ‘straw man’ evolutionary model previously presented.

Key words: Stars: formation – Stars: massive – ISM: molecules – submillimetre: ISM.

1 INTRODUCTION

Masers exist across the Galaxy and the different species of masers have been shown to trace certain physical processes and are associated with particular celestial objects (e.g. late-type stars, H II regions, star-forming regions; Elitzur 1992). Over the last decade, research has been devoted to the study of maser emission, where large-scale surveys have resulted in the production of large, comprehensive, and statistically representative catalogues of the various maser species (e.g. Caswell et al. 2010; Walsh et al. 2014; Qiao et al. 2016, 2018; Beuther et al. 2019). Catalogues of maser species have driven detailed investigations and theoretical studies into the environments

and conditions required for their production (Sobolev, Cragg & Godfrey 1997; Norris et al. 1998; Cragg et al. 2001; Breen et al. 2010; Urquhart et al. 2013). Masers have been shown to be good chemical probes of star-forming environments (Menten 1997) and different species have been regularly shown to be coincident with each other in positional space (Forster & Caswell 1989; Menten et al. 1992; Menten 1997).

The Class II 6.7- and 12.2-GHz methanol (CH_3OH) masers, first reported by Menten (1991) and Batrla et al. (1987), respectively, have been found to be exclusively associated with intermediate- and high-mass young stellar objects (YSO; Minier et al. 2003; Xu et al. 2008; Breen et al. 2013; Urquhart et al. 2015; Billington et al. 2019). Therefore, the 6.7- and 12.2-GHz methanol masers provide a simple and convenient method for identifying potential regions of massive star formation. A number of observations have been made towards

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these maser species and in-depth studies have been conducted (e.g. Menten et al. 1992; Phillips et al. 1998; Szymczak et al. 2002; Błazzkiewicz & Kus 2004; Goedhart, Gaylard & Van Der Walt 2005; Green et al. 2009). It is thought that the Class II methanol masers are produced in the accretion discs around young massive stellar objects (Norris et al. 1998), and are radiatively pumped in small, confined regions with temperatures of ~ 150 K, methanol column densities of $> 10^{15} \text{ cm}^{-2}$ and volume densities of $> 10^8 \text{ cm}^{-3}$ (Sobolev et al. 1997; Cragg et al. 2001). However, other studies have proposed different scenarios, such as the existence of these maser species within expanding shock waves or protostellar outflows (Walsh et al. 1998). Although, it could in fact be true that methanol masers exist in all of these situations (Minier 2000).

There also exist other maser species that are known to be associated with regions of star formation, such as the 22.2-GHz maser emission produced by water (H_2O ; Cheung et al. 1969), and the four ground-state transitions of hydroxyl (OH; Weinreb et al. 1963) at 1612, 1665, 1667, and 1720-MHz. Observations of water masers indicate that these are found in outflows as well as circumstellar discs of both low- and high-mass YSOs (Claussen et al. 1996; Codella et al. 2004; Titmarsh et al. 2014, 2016), and are associated with regions of ongoing star formation. Elitzur, Hollenbach & McKee (1989) presented a model for H_2O masers in star-forming regions, where masers are produced in post-shocked gas with initial densities of $n \sim 10^7 \text{ cm}^{-3}$ and temperatures of ~ 400 K. Hydroxyl masers are known to trace a number of different environments. The most abundant transition at 1612-MHz is typically found in the expanding shells of evolved stars (Wilson & Barrett 1968; Elitzur, Goldreich & Scoville 1976), while the emission lines of 1665 and 1667-MHz have generally been found towards regions of star formation (Argon, Reid & Menten 2000; Qiao et al. 2014; Qiao et al. 2016). The 1720-MHz is the least frequently found and is generally observed towards shock excited regions within star formation sites and supernovae remnants (Claussen et al. 1999; Caswell 2004). However, none of these associations is exclusive and all four transitions can be found within different environments and even toward the same region (Caswell, Green & Phillips 2013; Walsh et al. 2016; Beuther et al. 2019). Cragg, Sobolev & Godfrey (2002) produced models of the OH masers, and found that OH masers require temperatures of ~ 100 K, moderately high densities of $n = 10^5 - 10^8 \text{ cm}^{-3}$, conditions which are likely to be met in all regions where OH masers are found.

As these three maser species are capable of tracing different physical conditions and processes, studies have been undertaken to investigate the relationship between the masers and environments where high-mass stars are born (e.g. Beuther et al. 2002; Breen et al. 2010; Breen & Ellingsen 2011; Urquhart et al. 2013, 2015). Studies have also investigated the relationship between different maser species (e.g. Forster & Caswell 1989; Menten 1997; Szymczak, Pillai & Menten 2005; Jones et al. 2020), and it has been shown that different maser transitions are often spatially associated with one another (within 15 arcsec). Ellingsen et al. (2007) presented a ‘straw man’ model for the evolution and relative time-scales of different maser species (water, methanol, hydroxyl) within regions of star formation. This model was further refined by Breen et al. (2010), who estimated relative lifetimes for each of the maser species. The sequence of events as described by this model state that during star formation, Class I (collisionally pumped) methanol masers occur first, followed by the appearance of water masers, produced in the post-shocked gas due to outflows associated with these objects. Class II (radiatively pumped) masers are then produced in accretion discs due to the thermal output of the natal star. Finally, hydroxyl masers are seen towards developing H II regions, and as these H II regions

evolve, they disrupt and disperse their environments, destroying the conditions necessary for any type of maser emission to exist (as indicated by the decreased detection rate of all maser types in the late evolutionary phases).

In three previous papers (Urquhart et al. 2013, 2015; Billington et al. 2019), we have presented a detailed analysis of the 6.7-GHz methanol masers, as identified by the Methanol MultiBeam survey (MMB; Green et al. 2009), and submillimetre dust emission, as identified by the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL; Schuller et al. 2009). These works identified the almost ubiquitous association between the 6.7-GHz maser and dust emission (~ 99 per cent), and showed that this maser species has a well-defined turn-on and termination point, existing for a distinct amount of time in the evolutionary time-scale of massive star formation, with a statistical lifetimes of 3.3×10^4 yr (Billington et al. 2019). The findings of this study support the theoretically derived value (Van Der Walt 2005; $2.5 - 4.5 \times 10^4$ yr). Given the availability of large-scale water and hydroxyl surveys, it is possible to extend our previous work and fully test the ‘straw man’ model presented by Ellingsen et al. (2007) and Breen et al. (2010) by investigating the lifetimes and evolutionary time-scales of multiple maser species.

This study will extend the work of Billington et al. (2019) by investigating the physical properties of dense Galactic clumps associated with each maser transition, for which catalogues have been produced from a number of Galactic surveys. The Galactic surveys of interest are: the MMB survey (Caswell et al. 2010, 2011; Green et al. 2010, 2012; Breen et al. 2015), The H I/OH/Recombination line survey (THOR; Beuther et al. 2016, 2019), the Southern Parkes Large-Area Survey in Hydroxyl (SPLASH; Dawson et al. 2014; Qiao et al. 2014, 2016), the H_2O southern Galactic Plane Survey (HOPS; Walsh et al. 2011, 2014) and observations of 12.2-GHz methanol masers undertaken by Breen et al. (2012a, 2012b, 2014, 2016). These surveys are described in Section 2. Along with investigating the physical properties of maser associated clumps, we derive statistical lifetimes for each of the masers species and identify their positions in the evolutionary time-scales of star formation.

The structure of this paper is as follows: In Section 2, we describe the archival survey data that will be used throughout the study. In Section 3, we describe the matching procedure used for the maser species of interest. Section 4 presents the derivation of the various physical parameters of maser associated dust clumps, along with the corresponding uncertainties. In Section 5, we discuss various aspects of the different maser samples, along with presenting the statistical lifetimes for each maser species. A summary of our findings is given in Section 6.

2 SURVEY DESCRIPTIONS

Fig. 1 shows the survey coverages for each of the surveys that are utilized in this study. In Table 1, we present a summary of the coverages for each survey.

2.1 Descriptions of maser surveys

2.1.1 The HOPS

The HOPS (Walsh et al. 2011) is an unbiased survey of 100 deg^2 of the Galactic plane ($30^\circ \geq \ell \geq 290^\circ$, $|b| < 0.5^\circ$). HOPS was performed using the Australia Telescope National Facility (ATNF) Mopra 22-m radio telescope and detected 540 sites of 22.2-GHz H_2O maser emission (Walsh et al. 2011). Walsh et al. (2014) performed follow-up observations of these maser sites using the

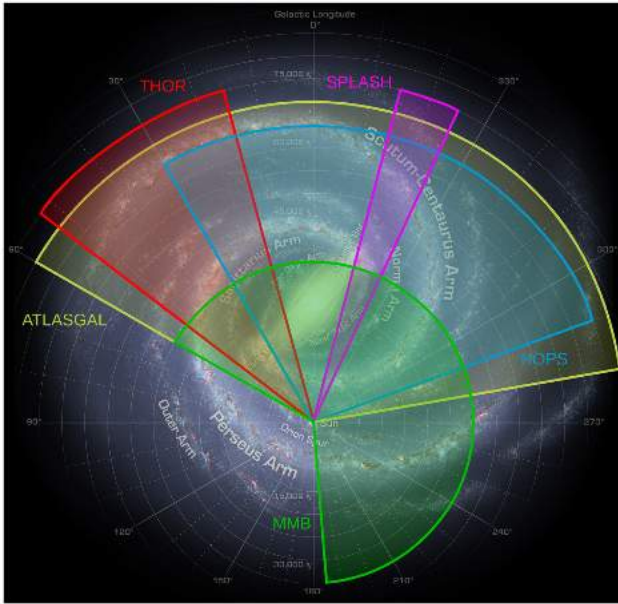


Figure 1. Image depicting the Galactic longitude coverages for the Galactic plane surveys that are utilized in this study (courtesy of NASA/JPL-Caltech/R. Hurt (SSC/Caltech)). The approximate coverage of each survey is shown along with each survey's corresponding name. The length of each sector is arbitrary.

Table 1. Galactic Longitude coverages for each survey presented in this study.

Survey name	Maser species	Sensitivity (mJy)	Survey coverage
HOPS	H ₂ O	15–167	$30^\circ \geq \ell \geq 290^\circ$
THOR	OH	~10	$66:8 \geq \ell \geq 14:5$
SPLASH	OH	~65	$344^\circ \geq \ell \geq 334^\circ$
MMB	Class II CH ₃ OH	~170	$60^\circ \geq \ell \geq 186^\circ$
ATLASGAL	870- μ m continuum	~60	$60^\circ \geq \ell \geq 280^\circ$

Australia Telescope Compact Array (ATCA), to provide accurate positions for individual maser spots within 1 arcsec. The typical noise for these observations was 15–167 mJy. The higher resolution observations identified 631 maser sites (collections of maser spots) in the 540 regions detected by Mopra; these consisted of 2790 individual spectral features (maser spots).

Out of the 631 maser sites detected in Walsh et al. (2014), 433 were identified as being associated with star formation, 121 sites with evolved stars and the remaining 77 were classified as unknown. They also found that evolved stars tend to have more maser spots than those associated with star formation. Furthermore, they found that maser sites associated with evolved stars are much more clustered around localized positions than the full area of star formation regions. The linear positions of maser spots within star formation regions present features that are both parallel and perpendicular to known outflows, where H₂O masers are thought to originate.

2.1.2 THOR line survey

THOR (Beuther et al. 2016) line survey of the inner Milky Way has surveyed $14:5 \leq \ell \leq 66:8$ and $|b| < 1:25$ of the Galactic plane using the Karl Jansky Very Large Array in the C-array configuration. The THOR survey has observed a number of different spectral lines, including the H I 21 cm, 19 of the H α radio recombination lines and

the four ground-state transitions of the hydroxyl maser, as well as continuum emission between 1 and 2-GHz (Bihl et al. 2016; Wang et al. 2018). The survey has angular resolutions of ~ 12.5 –19 arcsec, with a spectral resolution of 1.5 km s^{-1} , and typical rms noise levels of $\sim 10 \text{ mJy}$.

Recently, THOR has produced an unbiased catalogue of the four OH maser emission lines at 1612, 1665, 1667, and 1720-MHz (Beuther et al. 2019). The catalogue is comprised of OH maser sources in the northern hemisphere, tracing a number of different astronomical phenomena, as previously described in Section 1. We do note here that within the THOR survey, the 1667-MHz maser was not covered in ~ 50 per cent of the survey (below $\ell = 29:2$, between $31:5$ and $37:9$ and between $47:1$ and $51:2$), however, this will not affect the results and statistics presented in this study.

2.1.3 The SPLASH

The SPLASH is an unbiased southern Galactic plane survey of the four ground-states transitions of the hydroxyl molecule, undertaken using the Parkes 64-m telescope and utilizing the H–OH receiver. The first results of this survey are presented in Dawson et al. (2014) and covers the Galactic plane between longitudes 334° and 344° and latitudes $|b| < 2^\circ$. Within this region, the SPLASH survey has detected a total of 495 masers, across the four ground transitions of hydroxyl.

Qiao et al. (2016) presented accurate positions of the masers identified within the pilot region. These observations were undertaken using the ATCA, with angular resolutions of between 4 and 13 arcsec, spectral resolution of 0.09 km s^{-1} and typical rms noise levels of $\sim 65 \text{ mJy}$. The catalogue presented in Qiao et al. (2016) provides a further sample of hydroxyl masers in the southern Galactic plane and we use these to supplement the THOR survey maser catalogue.

2.1.4 Class II Methanol masers (6.7 and 12.2 GHz)

The MMB (Green et al. 2009) survey has surveyed the Galactic plane between $60^\circ \geq \ell \geq 186^\circ$ and $|b| < 2^\circ$, and has produced a catalogue of 972 emission sites of the Class II 6.7-GHz methanol maser across the Galaxy (Caswell et al. 2010, 2011; Green et al. 2010, 2012; Breen et al. 2015). Initial detections were made using the ATNF Parkes 64-m radio telescope, and were followed up with ATCA or the Multi-Element Radio Linked Interferometer Network (MERLIN; Thomasson 1986) to determine accurate positions (< 1 arcsec) to maser emission sites if those positions were not available in the literature. The average noise in survey cubes was 170 mJy. It is likely that the MMB survey accounts for the majority of 6.7-GHz methanol masers across the Galaxy, as it has been shown that away from the Galactic plane, 6.7-GHz maser emission is rare (Yang et al. 2017, 2019). This is also consistent with them being only associated with high-mass star formation.

Breen et al. (2012a, 2012b, 2014, 2016) have produced a number of MMB follow-up observations towards sites of 6.7-GHz methanol masers, searching for the class II 12.2-GHz methanol maser transition. The 12.2-GHz maser is the strongest and most widespread class II methanol maser line after the 6.7-GHz transition, and over the same coverage as the MMB survey ($60^\circ \geq \ell \geq 186^\circ$), Breen et al. detected 432 12.2-GHz masers. Breen et al. (2012a, b, 2014, 2016) also concluded that the 12.2-GHz maser occurs within star formation regions at a slightly later stage of evolution than regions that are only associated with the 6.7-GHz transition. This was explained due to the 12.2-GHz methanol masers being associated with 6.7-GHz masers that have relatively higher flux densities and peak luminosities.

Furthermore, 12.2-GHz methanol masers are also more likely to be found towards 6.7-GHz methanol masers with associated OH masers (Breen et al. 2010). The estimated lifetime of the 12.2-GHz masers is estimated to be in the range 1.5×10^4 and 2.7×10^4 yr (Breen et al. 2010).

It is worth noting that as the 12.2-GHz maser observations are targeted towards known positions of 6.7-GHz masers, this sample may not be regarded as an independent sample. However, no previous studies have resulted in the serendipitous detections of 12.2-GHz methanol masers, and all currently known 12.2-GHz masers have been found with a 6.7-GHz counterpart. Also, previous searches (Caswell et al. 1995; Błazzkiewicz & Kus 2004) have shown that 12.2-GHz methanol maser emission is rarely brighter than any associated 6.7-GHz methanol maser emission. Therefore, it is not unreasonable to assume that the observations conducted by Breen et al. (2012a, 2012b, 2014, 2016) account for the majority of the 12.2-GHz methanol masers within the MMB survey coverage ($60^\circ \geq \ell \geq 186^\circ$).

2.2 ATLASGAL survey

ATLASGAL (Schuller et al. 2009) has mapped dust emission at 870- μ m across 420 deg² of the Galactic plane, between Galactic longitudes $60^\circ \geq \ell \geq 280^\circ$ and latitudes $|b| < 1.5^\circ$. ATLASGAL is the largest and most sensitive ground-based submillimetre survey to date and has produced a catalogue of over 10 000 dense clumps within the Galaxy (Contreras et al. 2013; Csengeri et al. 2014; Urquhart et al. 2014b). The Large APEX Bolometer Camera (LABOCA; Siringo et al. 2009) was used to conduct the survey. The APEX telescope has a dish size of 12 m allowing for a full width at half-maximum (FWHM) resolution of 19.2 arcsec at this wavelength.

Urquhart et al. (2018) produced a catalogue of physical parameters for a large fraction of the ATLASGAL compact source catalogue (~ 8000), outside of the Galactic centre region ($5^\circ < |\ell| < 60^\circ$ and $|b| < 5^\circ$). The Galactic centre region was omitted from this study to reduce source confusion and difficulty in determining reliable kinematic distances. This catalogue includes representative samples of all of the earliest stages of massive star formation. Following the procedures first established for a representative sample of ~ 100 ATLASGAL sources (König et al. 2017), emission maps from the HiGAL survey (Molinari et al. 2010) were used to fit the spectral energy distributions (SEDs) in order to derive dust temperatures and bolometric luminosities of embedded objects. Follow-up molecular line observations of the ATLASGAL emission maps (e.g. CO, NH₃, N₂H⁺; see table 1 of Urquhart et al. 2018 for a complete list of observations) have determined radial velocities which, along with the Galactic rotation curve, have been used to derive distances to ~ 8000 regions (~ 79 per cent of the full ATLASGAL sample). These distances have been used to determine the properties of dense clumps across the Galaxy as presented in Urquhart et al. (2018). Every ATLASGAL source has been classified into one of four evolutionary groups based on infrared or radio counterparts and are defined as quiescent, protostellar, YSO, and H II region (König et al. 2017).

3 MASER ASSOCIATIONS

This study will only focus on the Galactic coverage between $5^\circ < |\ell| < 60^\circ$ and $|b| < 1.5^\circ$, the same coverage as Urquhart et al. (2018), to ensure we have accurate determinations for the physical properties of clumps associated with any maser transition.

By using the catalogues of the surveys mentioned in the previous section, we have attempted to associate multiple maser transitions to dense clumps as found in the ATLASGAL survey. These maser

transitions are the 6.7-GHz and 12.2-GHz methanol maser, 22.2-GHz water maser and the four hydroxyl maser emission lines at 1612, 1665, 1667, and 1720-MHz. We have utilized the 6.7-GHz methanol maser matches with the ATLASGAL survey reported in Urquhart et al. (2013) and Billington et al. (2019) but have not included clumps identified from the JCMT Plane Survey (JPS; Moore et al. 2015; Eden et al. 2017; Billington et al. 2019) as the data from JPS will provide no further information for this study. We have also chosen not to utilize the targetted observations towards sites of 6.7-GHz methanol maser emission presented in Urquhart et al. (2015) that were beyond the boundaries of the ATLASGAL survey.

When referring to a specific maser species or transition in this study, the corresponding frequency of that maser will always be given, in contrast, the term ‘maser’ used independently will refer to all the maser transitions.

3.1 Spatial matching

Initial matches were identified using a 90 arcsec search radius between maser emission and the 870- μ m peak dust emission. This radius is the 3σ value of the effective radius distribution for ATLASGAL sources and so 99.7 per cent of dust continuum sources have a radius of less than this size. Images have been created from the ATLASGAL 870- μ m emission maps, so that each match could be confirmed visually. A match was confirmed if the maser source was within the 3σ boundary of the 870- μ m emission and all masers found beyond this boundary have been removed from any further analysis, as these are unlikely to be associated with star formation. We find 549 OH (429 from THOR and 120 from SPLASH), 359 water and 392 12.2-GHz masers sites that are spatially coincident with dust emission (within 3σ). A cumulative distribution function of the angular offsets for each of the maser species can be found in the upper panel of Fig. 2. It can be seen from this figure that the majority of masers (~ 90 per cent) lie within 10 arcsec of a dust continuum peak. As the majority of star formation is concentrated towards the highest column density regions in the centre of clumps (Urquhart et al. 2014a), this provides further confirmation that the masers are associated with star formation. It can also be seen from the upper panel in Fig. 2 that there are no significant differences in the spatial offsets between the various maser species. However, they may be differences on scales less than 10 arcsec but the resolution of the data is not sufficient to investigate this.

3.2 Velocity offsets

Molecular line velocities of the dense clumps are available for the majority of masers and for a large portion of the ATLASGAL survey (see table 1 of Urquhart et al. 2018 for a complete list of observations and references). We use these measurements to examine the correlation between the masers and the dense clumps to confirm their associations. The difference between maser median velocity and clump median velocity has been calculated for all of the maser species that are spatially coincident. The cumulative distribution functions of these distributions can be found in the lower panel of Fig. 2. It can be seen from this Figure that water masers appear to have larger velocity offsets, which is consistent with this type of maser being associated with protostellar outflows.

In Fig. 3, we show the velocity offsets for the different maser species and these have been fitted with Gaussian profiles. The Gaussian fits appear to be a reasonable model for all of the velocity distributions. To confirm our maser associated sample, we have opted to only include clumps with a maser source that has a median velocity

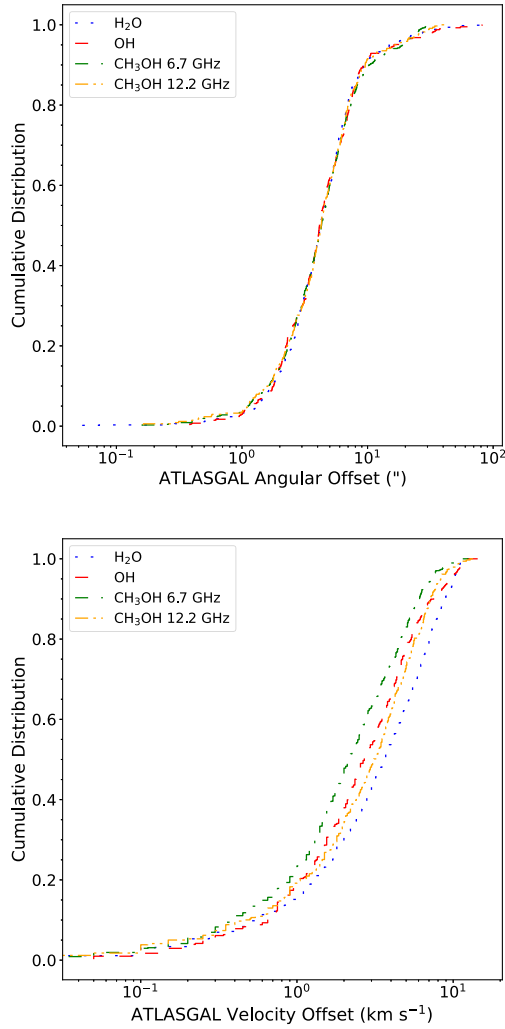


Figure 2. Cumulative distribution functions of the maser-ATLASGAL angular and velocity offsets in the upper and lower panels respectively. Each coloured line represents a different maser species as shown by the legend in the top left-hand corner of each plot. Both panels present the same maser associated clump sample, i.e. those that are within the spatial and velocity matching criteria as explained in the text.

difference of less than 3σ , which is calculated from the Gaussian models. This likely accounts for any possible line-of-sight alignments between masers and clumps that may not be spatially coincident. It is likely that masers with a high-velocity difference compared to a spatially aligned clump, may in fact not be associated with each other. Since the focus of this study is on the dense clumps associated with maser emission and not the masers themselves, this will help to refine the true sample of maser associated clumps. The 3σ values for the different distributions are 11.56, 11.92, and 13.89 km s^{-1} for the H_2O , OH, and 12.2-GHz methanol masers, respectively. The 3σ value for the 6.7-GHz methanol masers is taken from Billington et al. (2019) as 13.5 km s^{-1} .

3.3 Total matched sample

We have matched a number of different maser species to dense clumps across the Galaxy as identified by the ATLASGAL survey. Our sample has been constrained using the positional and velocity

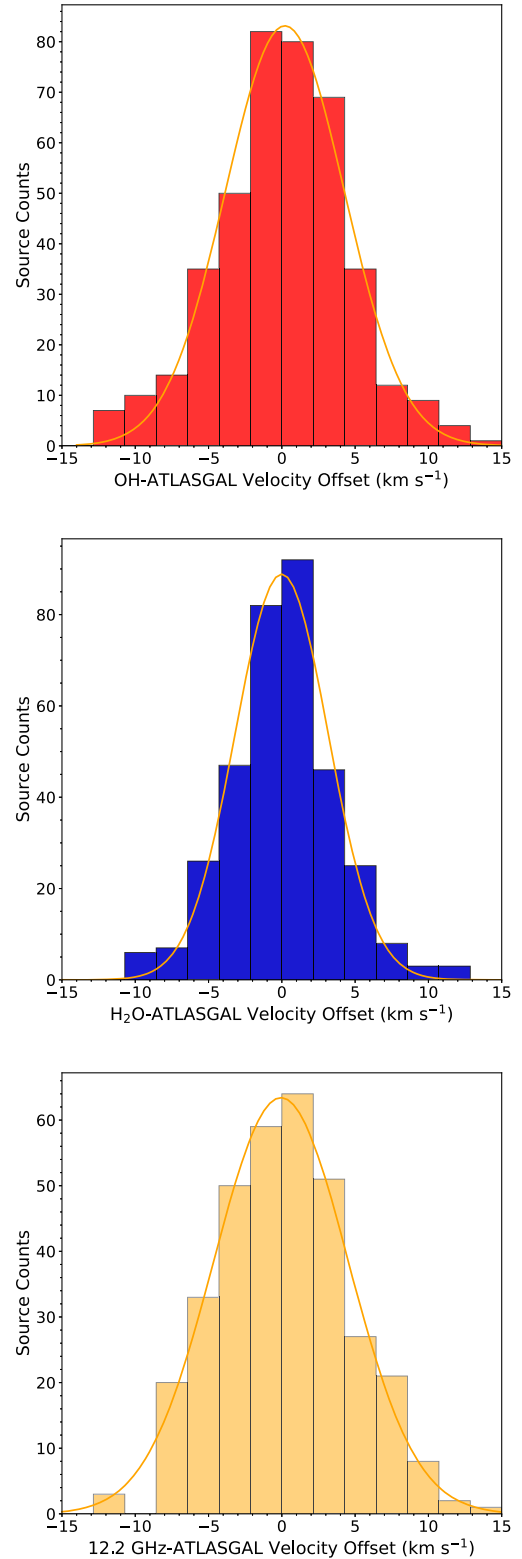


Figure 3. Histograms presenting the velocity offsets between the median maser velocities and the ATLASGAL molecular line velocities. The panels present the hydroxyl, water, and 12.2-GHz methanol maser velocity distributions in the upper, middle, and lower panels, respectively. The distributions have been truncated at -15 and 15 km s^{-1} . A Gaussian profile has been fitted to each histogram and is shown as the solid yellow lines in each panel.

Table 2. Total matches for each maser species and the ATLASGAL catalogue between Galactic longitudes $60^\circ > \ell > -60^\circ$, where all matches are below our 3σ threshold in both positional and velocity space. The percentage of associated dust clumps within each survey coverage is also given. Errors have been calculated using Binomial statistics.

Maser transition	Maser–dust associations	Percentage of associated dust clumps ^a
CH ₃ OH 6.7-GHz	839/918 ($91 \pm 0.9\%$)	8.5%
CH ₃ OH 12.2-GHz	340/414 ($82 \pm 1.9\%$)	3.2%
H ₂ O 22.2-GHz	345/614 ($56 \pm 1.4\%$)	2.0%
OH 1612-MHz	43/1378 ($3 \pm 0.5\%$)	0.9%
OH 1665-MHz	238/394 ($60 \pm 2.5\%$)	3.6%
OH 1667-MHz	96/226 ($42 \pm 3.2\%$)	1.2%
OH 1720-MHz	31/63 ($49 \pm 6.3\%$)	0.7%

^aNumber of ATLASGAL sources with an associated detected maser.

offsets as previously described. The number of maser associations for each maser transition can be found in Table 2.

We find that there is no difference in the spatial offsets between each maser species and their associated dust clump. The average offset between any maser species and the peak dust emission is ~ 6 arcsec with the 90 per cent range of the maser samples having offsets between 1.7 and 10.3 arcsec. The absolute velocity differences for all of the maser species range between 2.8 – 4.3 km s^{−1} with the 6.7-GHz methanol maser having the smallest average velocity offset of 2.8 km s^{−1}.

Out of the 807 hydroxyl maser sites identified by the THOR survey, we have matched 294 to 141 individual dense clumps identified by the ATLASGAL survey. This is an association rate of 36 per cent with 2.1 maser sources per clump on average. The majority of clumps contain more than two maser sources (75/141), and the remaining 66 sources are only associated with a single maser. Of the 75 clumps with multiple maser associations, there exist four clumps with five maser sources and also another four which contain more than five maser sources. As the average number of masers per clumps is 2.1, we find that only three of these eight sources have a significantly¹ large number of masers (G030.703–00.067 and G031.412+00.307 with nine and G030.823–00.156 with eight; these three regions are associated with the W43 star-forming complex; Motte, Schilke & Lis 2002). For the 495 OH maser sites identified by the SPLASH survey, we have matched 114 of these to 24 individual ATLASGAL sources, giving an average number of maser per clump of five and association rate of 23 per cent. Five clumps have a significant number of masers (G338.876–00.084 with 8, G339.986–00.426 with 10, G340.054–00.244 with 12, G340.784–00.097 with 13 and G344.227–00.569 with 8), with the maximum number of masers being 13, associated with G340.784–00.097.

As both surveys cover all four hydroxyl emission lines, we find the 1612, 1665, 1667, and 1720-MHz transitions to have corresponding association rates with 165 dust clumps of 3, 60, 42, and 51 per cent, respectively. Fig. 4 presents a Venn diagram of the matches between clumps and the four different hydroxyl transition lines. We find that 145 of the 165 dust continuum sources are associated with a 1665-MHz maser, with only 26 dense clumps containing a 1720-MHz maser, showing that the 1665-MHz are more commonly found towards regions of star formation. The mean association rates for 1665, 1667, and 1720-MHz are all roughly 50 per cent, however, the 1612-MHz has an association rate of 3 per cent. The lower number of associated 1612-MHz masers is expected due to this maser transition

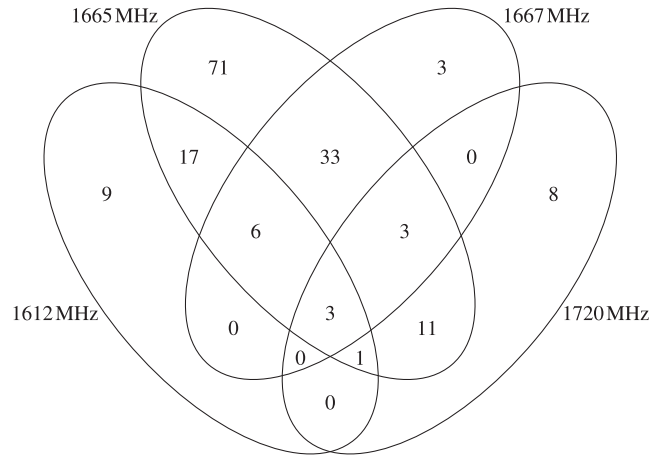


Figure 4. A Venn diagram presenting the number of ATLASGAL sources associated with the different transition lines of the hydroxyl maser.

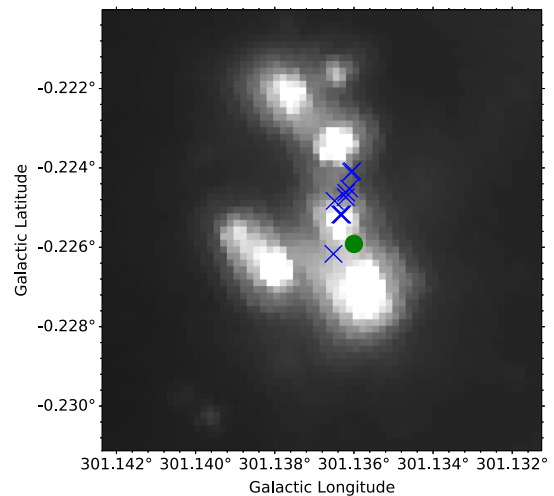


Figure 5. An example GLIMPSE 8- μ m image of the region G301.136–00.226. The positions of water masers associated with this region have been overlaid as blue crosses and the associated 6.7-GHz methanol masers as green filled circles. It is likely that these masers are associated with a known protostellar outflow in the region (see the text for details).

being larger associated with the expanding shells of AGB stars. Furthermore, we find the majority of hydroxyl masers that are associated with a clump (96 per cent) to be associated with either a YSO or H II region as identified by the ATLASGAL survey. We only find eight clumps that are coincident with a hydroxyl maser (1665 or 1667-MHz) and that are associated with a protostellar object (identified by a weak mid-infrared counterpart in the ATLASGAL survey).

We have matched 345 water maser sites (978 maser spots), presented in Walsh et al. (2014), to 291 dust continuum sources, an association rate of 55 per cent with a mean maser number of spots per clump of 1.2, which is lower than the overall rate found for the hydroxyl masers. We find that out of the 291 matched dust continuum sources, there is one source with 10 maser spots (G301.136–00.226), a significant number of maser spots, which is also associated with a 6.7-GHz methanol maser. An 8- μ m infrared GLIMPSE legacy survey (Churchwell et al. 2009) image of this region is presented in Fig. 5. A linear alignment between the water masers can be seen, likely due to an outflow originating in the region (Henning et al. 2000; Guzmán

¹Significance is based on the 3σ value calculated using Poisson statistics.

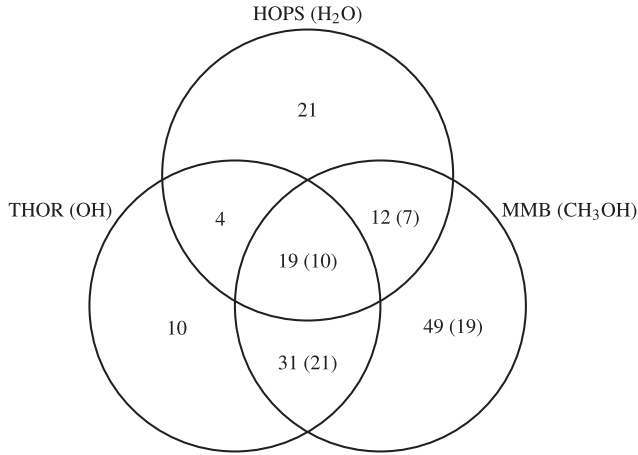


Figure 6. A Venn diagram presenting the number of ATLASGAL sources and the corresponding associated masers between Galactic longitudes, $14^{\circ}.5 < \ell < 30^{\circ}$, and Galactic latitudes, $|b| < 0.5^{\circ}$. The values in brackets are the values for the 12.2-GHz methanol masers, all of which are associated with a 6.7-GHz maser counterpart.

et al. 2012). This is consistent with the idea that the morphology of water masers trace outflows (e.g. Claussen et al. 1996).

For the 432 emission sites of the 12.2-GHz, as identified by Breen et al. (2012a, 2012b, 2014, 2016), we find that 340 are associated with 330 ATLASGAL sources. The majority of clumps (320; 96 per cent) that are associated with a 12.2-GHz methanol maser only host a single maser, with the remaining clumps (10; 3 per cent) hosting two masers. No clumps are associated with more than two 12.2-GHz methanol masers. Matching statistics for the 6.7-GHz methanol masers are taken unchanged from Billington et al. (2019). This study produced a sample of 839 6.7-GHz methanol masers (identified by the MMB survey) that are associated with dust continuum emission, also with an average of 1 maser site per clump. The percentage of the number of dust clumps associated with each maser species can be found in Table 2.

3.4 Common Spatial Area

Each of the surveys presented in this study has differing Galactic coverages and while this has no impact on the fractional associations between individual masers species and the dust emission, to be able to compare associations rates for different sources, we need to investigate a common region. Fortunately, due to the coverages of the presented surveys, there exist two windows on the Galactic plane where all four maser species were observed in at least one survey. The first window is positioned between Galactic longitudes of $14^{\circ}.5 < \ell < 30^{\circ}$ and Galactic latitudes of $|b| < 0.5^{\circ}$, and the second is between Galactic longitudes of $334^{\circ} < \ell < 335^{\circ}$ and Galactic latitudes of $|b| < 0.5^{\circ}$ (see Fig. 1). Due to the superior sensitivity of the THOR survey, we have chosen to use this first common spatial area to investigate the relationships between the maser species themselves and how they relate to the dust continuum.

Within this window, we find that there are 1263 ATLASGAL sources, however, only 146 (12 per cent) of these are associated with maser emission. This low association rate may suggest that masers are not always present within clumps or they may only be associated with a particular stage of star formation. The matches between this subsample of clumps and the various maser transitions are shown in Fig. 6 in the form of a Venn diagram. As all of the 12.2-GHz masers will have a 6.7-GHz counterpart, due to the nature of the observations,

they are included in brackets with the 6.7-GHz matching values. We find that within this overlapping coverage window there are 64, 56, 57, and 111 clumps associated with hydroxyl (at least one transition), water, 12.2-GHz methanol and 6.7-GHz methanol masers, respectively.

Out of the 146 maser associated clumps in this window, 47 ± 4 per cent of them are associated with multiple maser species. We find that 76 ± 4 per cent of the clumps are associated with a 6.7-GHz methanol maser, significantly higher than the number of clumps associated with water (38 ± 4 per cent) and hydroxyl masers (44 ± 4 per cent). It can also be seen that 12.2-GHz methanol masers are present in 39 ± 4 per cent of clumps, showing that only approximately half of 6.7-GHz maser have a 12.2-GHz counterpart. This result was found in the 12.2-GHz maser follow-up catalogues (e.g. Breen et al. 2012a) but which differs from previous studies of this association rate, e.g. Błazzkiewicz & Kus (2004), who found a rate of 19 per cent. This is likely due to the improved sensitivity of the Breen et al. (2012a, 2012b, 2014, 2016) observations and the relative dimness of 12.2-GHz methanol masers compared to the 6.7-GHz methanol masers. The 6.7-GHz methanol maser also accounts for the majority of masers that are found in isolation at 58 ± 4 per cent, while the water and hydroxyl masers are only found in isolation (no association with other masers in the same clump) 25 ± 4 and 12 ± 4 per cent of the time, respectively.

It appears to be quite rare to find only a water maser and hydroxyl maser to be associated with the same source (only 4 out of 146 clumps), whereas the majority of these masers are always found with a methanol maser counterpart. Beuther et al. (2002) used a sample of 29 star-forming regions and found that ~ 62 per cent of 6.7-GHz methanol masers are associated with water emission and that ~ 65 per cent of water masers are associated with a 6.7-GHz methanol maser. Our results differ slightly in that we find only 28 ± 6 per cent 6.7-GHz methanol masers are associated with water emission, and 55 ± 7 per cent of water masers are associated with 6.7-GHz methanol emission. Breen et al. (2018) presented a comparison between the MMB and HOPS catalogues, and while they also found that 28 per cent of methanol masers have a water counterpart, they only found that 40 per cent of water masers are seen coincident with methanol masers (both 6.7 and 12.2-GHz). Although, this disparity is likely due to the matching parameters used in each study and their associated observing sensitivities. Furthermore, Titmarsh et al. (2014, 2016) conducted studies towards known positions of 324 6.7-GHz methanol masers and found that ~ 46 per cent and ~ 50 per cent of the 6.7-GHz methanol masers have a water emission counterpart, respectively. The differences in the association rates between the water and methanol masers is likely due to the differing sensitivities for each set of observations and the intrinsic variability of water masers (due to accretion and outflows associated within young stars and protostellar objects). However, the differences could also be due to the smaller sample sizes in previous studies.

4 PHYSICAL PARAMETER CALCULATIONS

In the following subsections, we describe how the physical parameters of our sample are derived and present the statistics for each in Table 3. The ATLASGAL catalogue provides an effective radius for each clump larger than the beam size of the survey; this radius is the intensity weighted flux density distribution (Contreras et al. 2013) scaled by a value of 2.4, which gives a reasonable approximation of the observed clump size (Rosolowsky et al. 2010). However, it was shown by Urquhart et al. (2018) that evolving clumps appeared to be associated with increasing radius, mass and

Table 3. Total statistical parameters for all maser associated clumps, determined within our matching criteria, within the Galactic longitude range $5^\circ < |\ell| < 60^\circ$. The values in brackets show the statistics from a distance-limited sample between 2 and 5 kpc.

Parameter	Number	Mean	Standard deviation	Standard error	Median	Minimum	Maximum
Distance (kpc)							
Maser sample	804 (273)	5.80 (3.07)	3.84 (0.48)	0.14 (0.03)	4.60 (3.10)	0.10 (2.10)	24.20 (3.90)
ATLASGAL	7743 (3014)	4.90 (3.10)	3.31 (0.46)	0.04 (0.01)	3.60 (3.10)	0.00 (2.10)	24.20 (3.90)
Radius (pc)							
Maser sample	768 (263)	0.35 (0.20)	0.27 (0.08)	0.01 (0.00)	0.26 (0.18)	0.01 (0.08)	1.85 (0.53)
ATLASGAL	5478 (2108)	0.41 (0.27)	0.31 (0.11)	0.00 (0.00)	0.32 (0.25)	0.00 (0.07)	2.89 (0.93)
Temperature (K)							
Maser sample	830 (258)	23.91 (23.78)	5.26 (5.66)	0.18 (0.35)	23.42 (23.16)	11.76 (12.13)	51.23 (51.23)
ATLASGAL	9928 (2952)	19.40 (18.93)	5.72 (5.89)	0.06 (0.11)	18.44 (17.76)	5.87 (7.89)	59.96 (51.23)
$\log[\text{Luminosity } (L_\odot)]$							
Maser sample	780 (258)	3.99 (3.65)	1.00 (0.84)	0.04 (0.05)	4.00 (3.53)	− 0.22 (1.74)	6.91 (5.83)
ATLASGAL	7601 (2952)	2.95 (2.66)	1.03 (0.89)	0.01 (0.02)	2.89 (2.56)	− 0.28 (0.55)	6.91 (5.93)
$\log[\text{Clump mass } (M_\odot)]$							
Maser sample	768 (256)	2.63 (2.30)	0.68 (0.41)	0.02 (0.03)	2.71 (2.32)	− 1.05 (1.23)	4.40 (3.28)
ATLASGAL	7460 (2909)	2.52 (2.32)	0.61 (0.34)	0.01 (0.01)	2.53 (2.33)	− 1.05 (1.03)	4.40 (3.43)
$\log[\text{L/M ratio } (L_\odot/M_\odot)]$							
Maser sample	768 (256)	1.38 (1.36)	0.63 (0.65)	0.02 (0.04)	1.35 (1.30)	− 0.43 (− 0.43)	3.25 (3.25)
ATLASGAL	7460 (2909)	0.44 (0.34)	0.89 (0.91)	0.01 (0.02)	0.42 (0.29)	− 2.40 (− 2.40)	3.30 (3.30)
$\log[\text{Volume density } (\text{cm}^{-3})]$							
Maser sample	744 (248)	4.86 (5.06)	0.54 (0.43)	0.02 (0.03)	4.83 (5.02)	3.40 (4.11)	6.90 (6.90)
ATLASGAL	5354 (2052)	4.59 (4.72)	0.48 (0.39)	0.01 (0.01)	4.56 (4.70)	2.95 (3.67)	6.90 (6.90)
$\log[\text{Free-Fall Time (yr)}]$							
Maser sample	744 (248)	5.27 (5.17)	0.27 (0.22)	0.01 (0.01)	5.28 (5.19)	4.25 (4.25)	6.00 (5.64)
ATLASGAL	5354 (2052)	5.41 (5.34)	0.24 (0.20)	0.00 (0.00)	5.42 (5.35)	4.25 (4.25)	6.22 (5.86)

decreasing volume density measurements. They determined that this was due to an observational bias. As Galactic clumps evolve their average temperature increases, which in turn, results in the extended envelope of these regions becoming bright enough to be detected by the ATLASGAL survey. Therefore, the apparent size and mass of sources appeared to increase (and density decreasing proportionally) during evolution. Billington et al. (2019) eliminated this bias by only considering the flux from within the FWHM contour of each 870- μm source. It was shown that this technique effectively removed the observational bias (see fig. 8 of Billington et al. 2019).

Throughout this study, we also use a distance-limited sample, from 2 to 5 kpc, to reduce any distance-related biases that may exist within the sample.

4.1 FWHM radius, clump mass, and volume density

The FWHM radius and mass values used in this study are taken directly from Billington et al. (2019) and are scaled from the values found in Urquhart et al. (2018) by using the ratio between the FWHM flux and the total flux of each clump.

The FWHM volume densities have also been calculated using the FWHM radii and FWHM masses in the same way as described in Billington et al. (2019):

$$n(\text{H}_2) = \frac{3}{4\pi} \frac{M_{\text{fwhm}}}{\mu m_p R_{\text{fwhm,pc}}^3}, \quad (1)$$

where $n(\text{H}_2)$ is the hydrogen number density of clumps, μ is the mean molecular weight of the gas (taken here to be 2.8), and m_p is the mean proton mass. M_{fwhm} and R_{fwhm} are the FWHM mass and

FWHM radius, respectively. Here, the clumps are assumed to be spherical and not extended along the line of sight. Fig. 7 presents the distributions of the clump FWHM radius, FWHM mass, and FWHM volume density in the upper, middle, and lower panels respectively. It can be seen from the upper panels of this Figure that maser associated clumps are significantly more compact. Although as shown in the middle panels, the masses of these clumps are similar to the overall distribution of clump masses within the ATLASGAL survey. As the clumps hosting a maser are smaller than the full ATLASGAL clump sample, but have similar masses, the derived volume densities for maser associated clumps are significantly larger.

4.2 Stability and free-fall times

To test the stability of individual clumps, we can derive the virial parameter, which is defined as (Bertoldi & McKee 1992)

$$\alpha_{\text{vir}} = \frac{5\sigma_v^2 R_{\text{fwhm,pc}}}{GM_{\text{fwhm}}}, \quad (2)$$

where σ_v^2 is the velocity dispersion of the NH_3 inversion transition emission observations (e.g. Urquhart et al. 2011; Wienen et al. 2012, 2018) and the other parameters are as previously defined. The virial parameter is a measure of the balance between gravitational collapse and internal energy that can counteract this collapse. A value of less than 2 generally indicates that an individual clump is unstable (Kauffmann et al. 2013) and is likely to be undergoing global gravitational collapse in the absence of any supporting magnetic fields.