Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Early Star Formation Traced by Water Masers

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Abstract. In this study, the correlation between 22 GHz water masers and other maser species with far infrared/submillimeter (FIR/sub-mm) sources is investigated. Comparing luminosity to mass ratio (L/M) of FIR/sub-mm clumps linked to different maser species, 22 GHz water masers have significantly lower L/M values than 6.7 GHz methanol and 1665 MHz OH masers. This suggests 22 GHz water masers may precede them in the evolution timeline of SFRs. The close association between water masers and FIR/sub-mm sources provides insight into maser pumping conditions and evolutionary stages.

Keywords. Masers, star formation region, Hi-GAL, ATLASGAL, evolution timeline

1. Introduction

Water maser emission has been widely recognized as a valuable tool for investigating high-mass and low-mass star formation in the Galaxy. Extensive studies have established the presence of a collisional mechanism responsible for the interstellar 22 GHz and other H2O maser lines, as well as their association with shocks. Such shocks can be generated by various mechanisms, including protostellar jets, large-scale shocks, and disks. In contrast, class I methanol (cIM) masers, which are also shock-driven, tend to appear at a distance from radiation sources and trace the edges of outflows in star-forming clumps.

This study presents a comparative analysis between 22 GHz water maser emission and infrared/submillimeter sources from the Herschel infrared Galactic Plane Survey (Hi-GAL) and APEX Telescope Large Area Survey of the Galaxy (ATLASGAL). The majority of water maser sources associated with star formation regions are found to be connected to submillimeter and infrared sources.

2. Maser evolution in star formation region

In a study by Ellingsen (2007), a model called the "straw-man" model was proposed to depict the evolutionary sequence of masers in star-forming regions (SFRs). According to this model, methanol masers (both class I and II) are associated with the earliest stage of evolution, followed by water masers, and OH masers appear only in evolved sources with H II regions. Billington et al. (2020) examined this model using the luminosity-to-mass ratio (L/M) of ATLASGAL clumps. The L/M and dust temperature serve as indicators of the evolutionary state of star-forming clumps.

In this study the water maser archive from MaserDB database (Ladeyschikov et al. 2022) were used, consisting of 1007 masers associated with Hi-GAL sources and 960 associated with ATLASGAL sources. The sample of cIM masers at 95 GHz, class II methanol (cIIM) masers at 6 and 12 GHz and OH masers with 383, 678, 388 and 126 ATLASGAL-associated sources were also used, respectively.

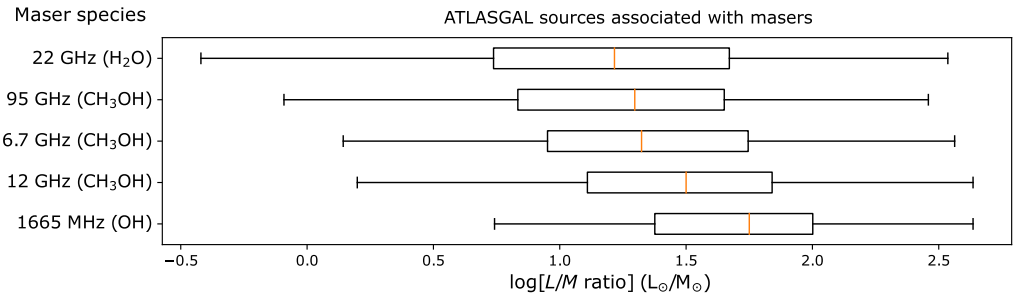

Figure 1. Box plot presenting the central 95 per cent distributions of luminosity to mass ratio for the ATLASGAL sources associated with different maser species and transitions ordered according to their mean value with lowest values at the top and largest value at the bottom.

To ensure reliable associations, the author applied certain constraints for maser associations. The beam size of the maser observations had to be smaller than 70", and the maximum distance between a maser and an ATLASGAL or Hi-GAL source was set at 30". These criteria aimed to exclude false-positive associations resulting from detections using large beam sizes, which could lead to less reliable associations.

The results of the L/M ratio analysis depicted in Figure 1, revealed that 22 GHz H2O masers appear earlier in the evolutionary sequence than cIIM masers at 6.7, 12 GHz, and 1665 MHz OH masers. The K-S test showed significant ($\sigma < 0.0013$) differences in L/M between sources associated with 22 GHz water masers and 6 GHz CH_3OH, 12 GHz CH_3OH, and 1665 MHz OH masers.

From the presented data author conclude that 22 GHz water masers arise before 6.7 GHz methanol masers in the evolutionary sequence. This conclusion is consistent with study Breen & Ellingsen (2011), but differed from several other studies (Ellingsen et al. 2007; Breen et al. 2010; Jones et al. 2020) that suggested water masers appear after the onset of 6.7 GHz methanol masers in the evolution timeline.

Water and cIM masers may reside in shock waves of the outflows from the protostars, indicating the earliest evidence of ongoing outflow activity in a star-forming region. Thus collisionally pumped water and cIM masers should exist before radiatively pumped cIIM masers. However, cIM and water masers exhibit significant differences in their variability timescales.

It is important to note that the results of this analysis could be influenced by the sample size and selection, and the detection of more masers in the future may alter the appearance of the presented figures. Additionally, limitations in sensitivity and the availability of interferometric positions for all known H2O masers might introduce some false associations, particularly in crowded regions.

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