Class I Methanol Masers in Low-Mass Star Formation Regions

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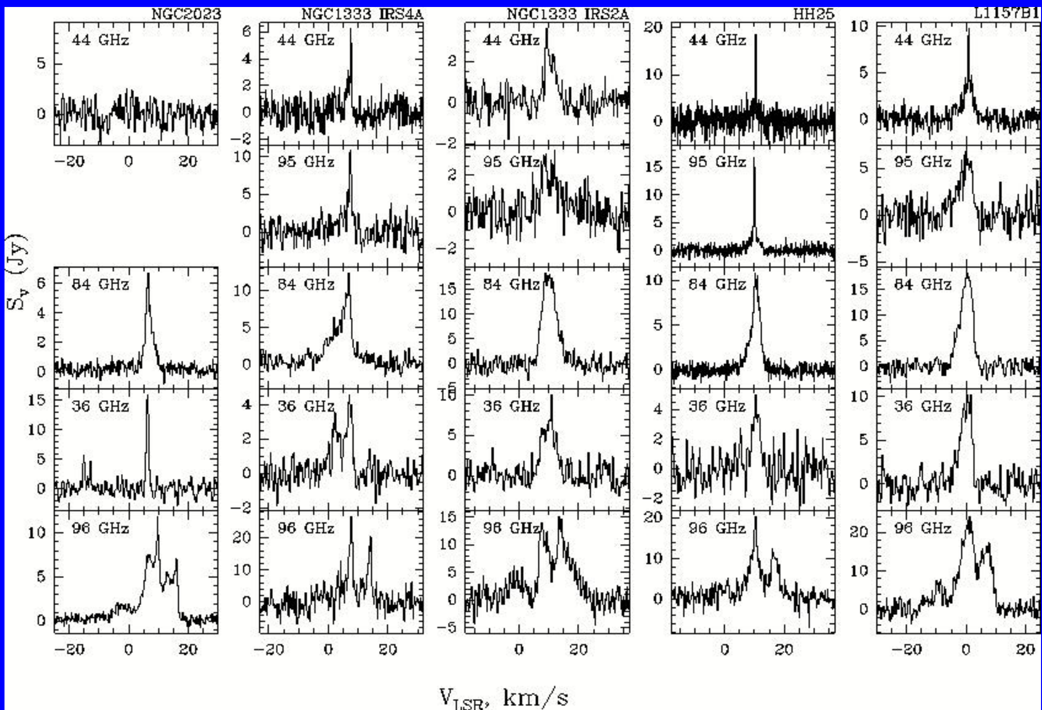
Introduction

In the past few years several Class I masers (MMIs) were found in nearby low-mass star formation regions (LMSFRs; Kalenskii et al., 2006,2010; Kang et al., 2013; Lyo et al., 2014). They were detected in Class I lines $4_{-1}-3_0E$ at 36 GHz, $7_0-6_1A^+$ at 44 GHz, $8_0-7_1A^+$ at 95 GHz, and $6_{-1}-5_0E$ at 132 GHz. In addition, Class I masers associated with low-mass protostars were found at 44 GHz in the HMSFR IRAS 20293+3952 (Rodriguez-Garza et al., 2017).



LMMI spectra at 44 GHz, 95 GHz, 84 GHz, and 36 GHz, taken at the Onsala Space Observatory. Thermal 2_K-1_K methanol lines at 96 GHz are shown in the bottom row. $\Longleftarrow$

MAIN PROPERTIES OF LMMIs.

- These masers are associated with chemically active bipolar outflows.
- Their flux densities are no higher than ~ 20 Jy, being much lower than those of strong HMMIs.
- Their radial velocities are close to the systemic velocities of associated regions.
- LMMI luminosities match the relation "maser luminosity–protostar luminosity", established earlier for HMMIs.
- No LMMI variability was detected in 2004–2011.

Thus, the main properties of LMMIs are similar to those of HMMIs. LMMIs are likely to be an extension of HMMI population toward low luminosities of both the masers and the associated YSOs.

Why should we study LMMIs?

Why should we study these few weak objects?

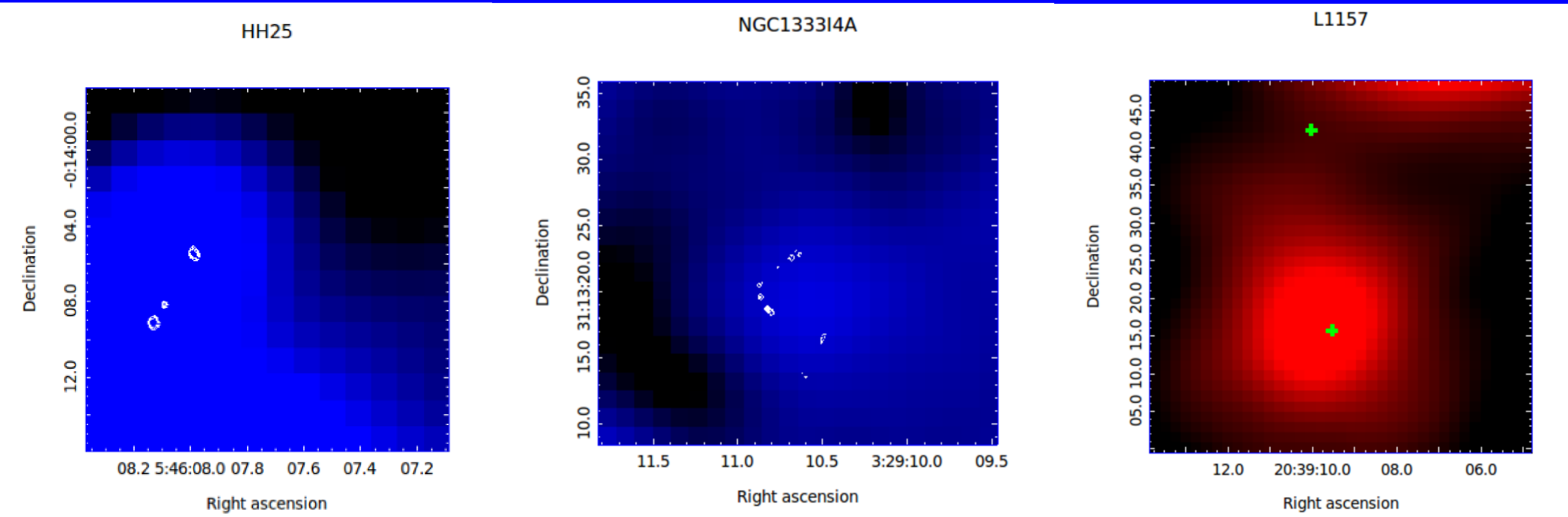
- Regions of low-mass star formation are much more widespread than MSFRs and many of them are only 200–300 pc from the Sun;
- they are less heavily obscured than MSFRs of high-mass star formation;
- there are many isolated low-mass protostars.

As a result, the study of masers in these regions might be more straightforward compared to that of high-mass regions. We continue to study MMIs in LMSFRs in order to better understand Class I methanol masers. Below we present the results of:

- Observations of three maser sources performed at 44 GHz with the EVLA in the B configuration;
- CARMA observations of thermal methanol lines $5_K - 4_K$ at 241 GHz.

EVLA observations

We observed HH25, NGC1333I4A, and L1157 at 44 GHz with an angular resolution of about $0.2''$. This corresponds to a linear resolution of about 60 AU at 300 pc.



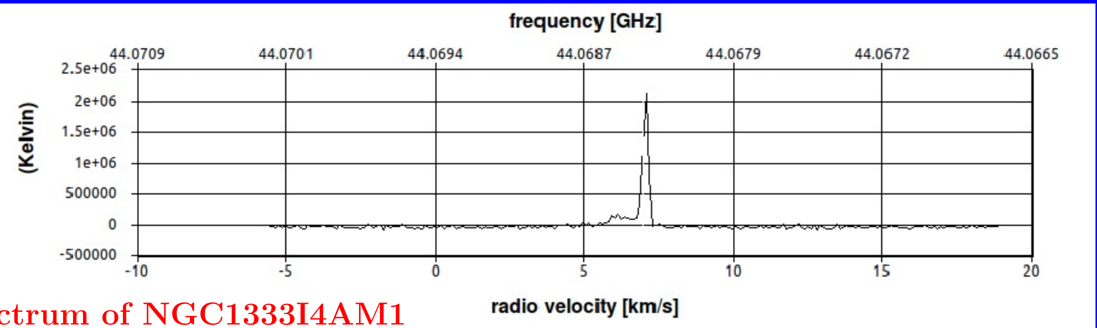
Maser maps at 44 GHz overlaid upon WISE images.

Results

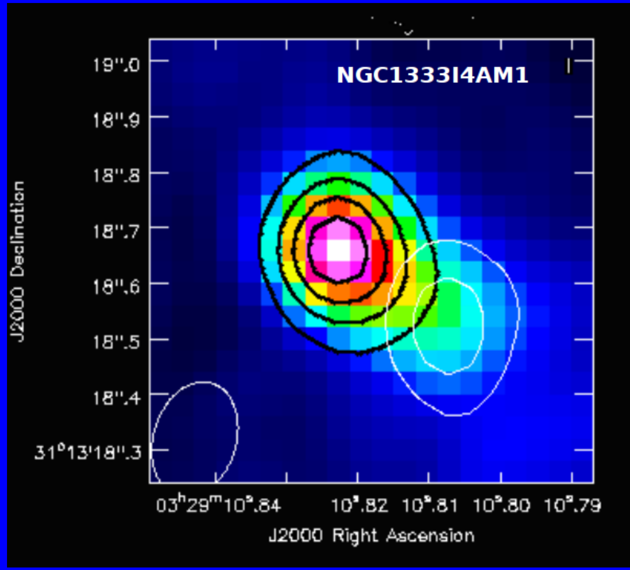
- Deconvolved spot sizes vary from $\sim 0.10''$–$0.15''$ for the stronger spots to $\sim 0.10''$–$0.3''$ for the weaker spots (30–45 AU and 30-90 AU, respectively)
- The brightness temperatures of the brightest spots are as high as 5×10^5 K.
- Masers in NGC1333IA form an arc around an object clearly seen in the 'blue' and 'green' WISE maps.
- Some spots consist of two closely spaced components.

Double spots

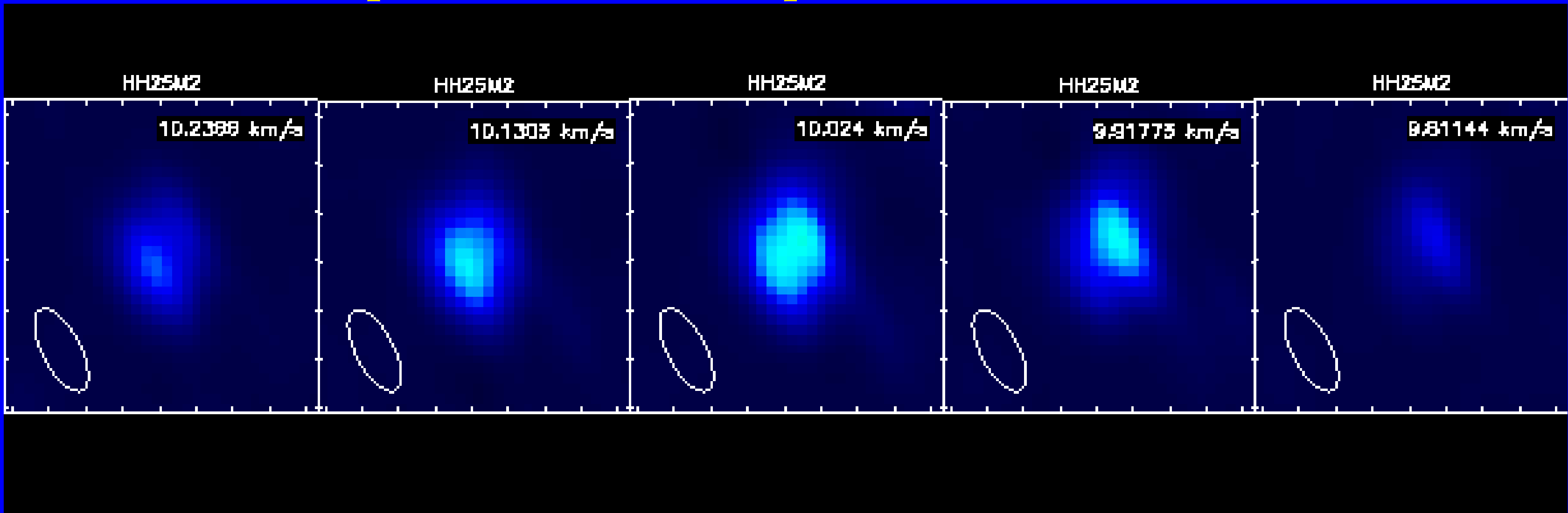
The strongest spot in NGC1333I4A: an example of a spot consisting of two closely spaced components.



Spectrum of NGC1333I4AM1



Another example of a double spot:

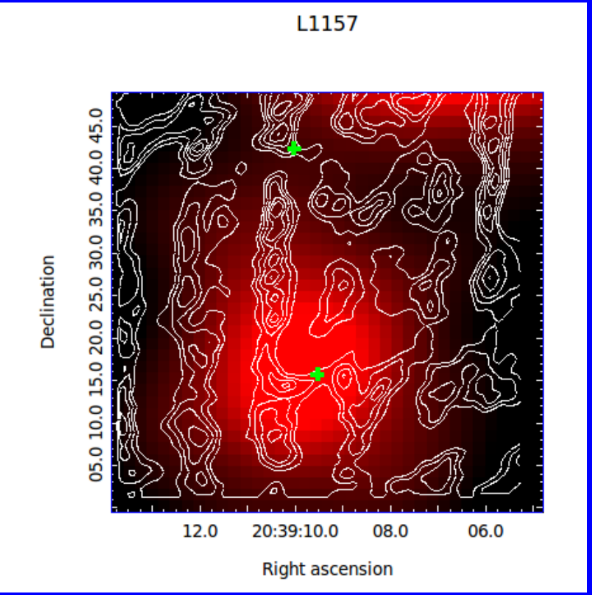


L1157

If masers are associated with turbulence, the map appearance depends on the maser regime:
Saturated maser amplification: large number of spots of comparable intensity;
Unsaturated maser amplification: small number of bright spots.
The map of maser emission in L1157 favors the unsaturated regime of maser amplification.

Unsaturated regime – discussed by Sobolev et al. (1998, 2003).
From the intensities of thermal lines $5_K - 4_K A^+$ towards M1 we estimated:

- $N_{CH3OH} \sim 10^{16}$ cm^{-2}; $n_{H_2} \geq 10^7$ cm^{-3}.
- Optical depth at 44 GHz in the absense of turbulence $\tau_0^{44} \sim 12$.
- Optical depth at 44 GHz $\tau^{44} \sim 7-8$ and $T_{br} \sim 10^4$ K.



An increase of N_{CH3OH} by a factor of less than 2 makes it possible to achieve the observed brightness temperature. Thus, the turbulence model "marginally" agrees with the observations.

SUMMARY

- Class I methanol masers in LMSFRs are associated with chemically active bipolar outflows.
- Their flux densities are no higher than ~ 20 Jy, being much lower than those of strong HMMIs.
- Their radial velocities are close to the systemic velocities of associated regions.
- LMMI luminosities match the relation "maser luminosity–protostar luminosity", established earlier for HMMIs.
- No LMMI variability was detected in 2004–2011.
- Deconvolved maser spot sizes fall within the range ~0.10″–0.3″ (30-90 AU, respectively)
- The brightness temperatures of the brightest spots are as high as 5×10^5 K.
- Maser spots often consist of two closely spaced components.
- Most likely, these masers are unsaturated.

Thank you very much for the attention!