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Kinematics of H_2O and CH_3OH masers at VLBI scales in two high-mass YSOs

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Introduction

Both 6.7 GHz methanol and 22.2 GHz water masers are known to trace the earliest evolutionary stages of the high-mass star forming process [1] and are often associated with outflows, hot molecular cores, and UC HII regions [2, 3].

Combination of maser Very Long Baseline Interferometry (VLBI) and thermal interferometry allows to study the physical conditions and the gas kinematics on scales of 10–10000 AU from the massive Young Stellar Object (YSO). Such a technique has the potentiality to address open problems of massive star formation such as determining the mass accretion process (disk-mediated or coalescence?), the ejection and collimation mechanisms of protostellar outflows, and the YSO evolutionary stage.

In this poster, we present a VLBI study of H_2O and CH_3OH masers in two high-mass YSOs, AFGL 5142 and G24.78+0.08, towards which previous (IR, mm, and radio) interferometric observations have provided a very detailed description of the circumstellar gas on scales ~0.01-0.1 pc.

Observations

22 GHz H_2O

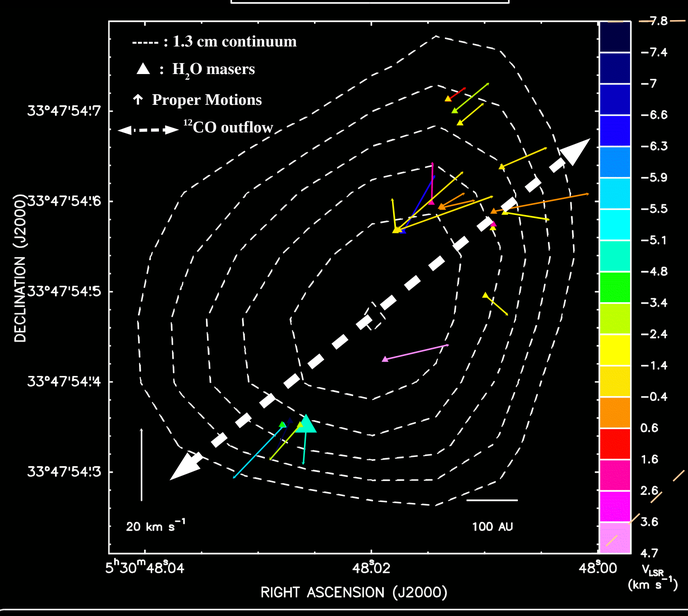
AFGL 5142 : 4 epochs (Oct & Nov 03, Jan & Feb 04)
G24.78+0.08 : 4 epochs (Sep & Nov 03, Feb & Jun 04)
FWHM~0.5-1 mas, RMS~2-40 mJy/beam
Phase-reference: absolute position accuracy ~0.5 mas

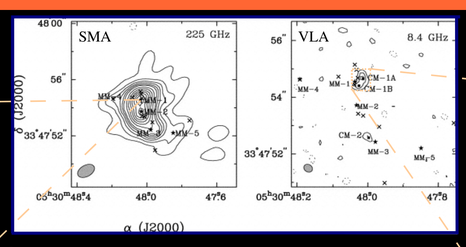
6.7 GHz CH_3OH

AFGL 5142 : 2 epochs (Jun 04 & Mar 07)
G24.78+0.08 : 2 epochs (Jun 03 & Mar 07)
FWHM~7-9 mas, RMS~4-60 mJy/beam
Phase-reference: absolute position accuracy ~5 mas

AFGL 5142 (L ~ 4×10^3 $L_\odot$, D ~ 1.8 kpc)

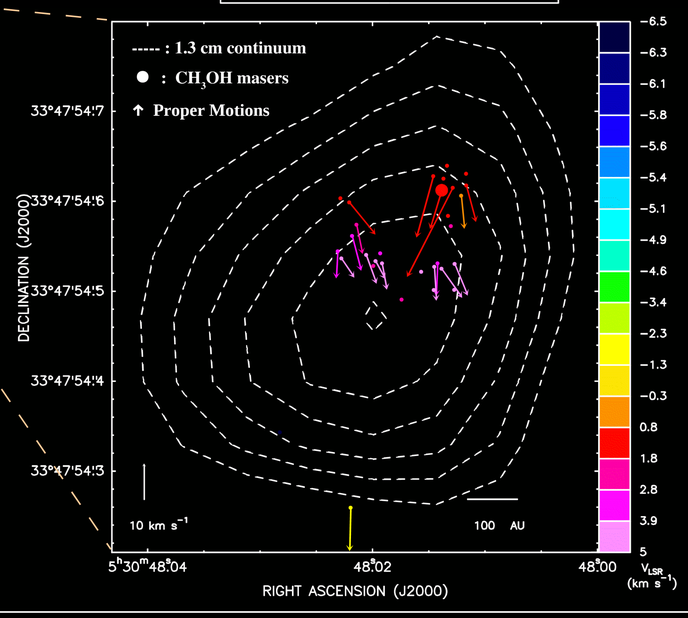
22GHz H_2O Masers





AFGL 5142 is located at a distance of 1.8 kpc and has a bolometric luminosity of 4000 $L_\odot$. The figure shows the (SMA) 225 GHz and (VLA) 8.4 GHz continuum emissions [4]. Five mm peaks (MM-1, MM-2, MM-3, MM-4, MM-5 – marked by stars) and three cm peaks (CM-1A, CM-1B, CM-2 – marked by squares) were detected in the region [4]. The H_2O and CH_3OH masers are associated with the MM-1 / CM-1 source, excited by a B1 ZAMS star .

6.7 GHz CH_3OH Masers



Observational features:

- H_2O masers (*filled triangles*) show a bipolar spatial and LOS velocity distribution
- The spatial distribution and the mean proper motion (*colour arrows*) orientation is elongated along the axis (*dashed arrow*) of a CO outflow observed with the SMA [4]
- The proper motions clearly trace expansion from the 22 GHz continuum peak [2]

Interpretation: *Water masers trace the innermost portion of the ^{12}CO outflow.*

Kinematical model: Conical outflow

Fitting positions and 3D velocities of H_2O spots with a conical outflow model, we derived an expansion velocity: V_{exp} = 20 km/s and an opening angle: θ = 70° [2].

CONCLUSIONS for AFGL 5142

- Water masers trace expansion at the base of a molecular outflow, whilst methanol masers trace infalling gas.
- Accretion onto the star can proceed along the plane perpendicular to the outflow traced by water masers.

Observational features:

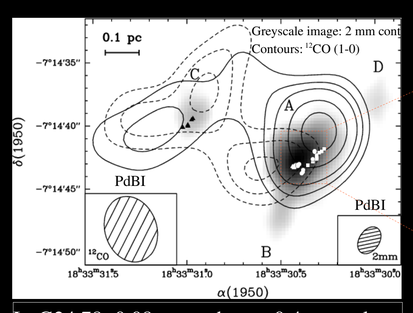
- The CH_3OH (*filled circles*) masers have strongly red-shifted LOS velocities
- They are seen in projection against the HC HII region, which is optically thick at 6.7 GHz, indicating that they must be located in the foreground of the HII region
- Their proper motions are mainly directed towards the peak of the radio continuum

Interpretation: *Methanol masers trace gas infalling toward the YSO*

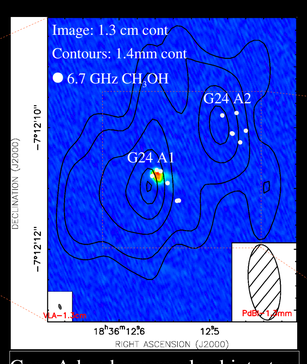
Kinematical model: Spherical infall [$V(r) = -(2\,G\,M/r^3)^{1/2}\,r$] [3]

Fitting positions and LOS velocities of CH_3OH spots with a spherical infall model, the following parameters were derived: r_s=540 AU, M_s=24 $M_\odot$, v_{inf}=9 km/s, $dM_{inf}/dt=2\times10^{-5} n_6 M_\odot yr^{-1}$

G24.78+0.08 (L ~ 7×10^4 $L_\odot$, D ~ 7.7 kpc)

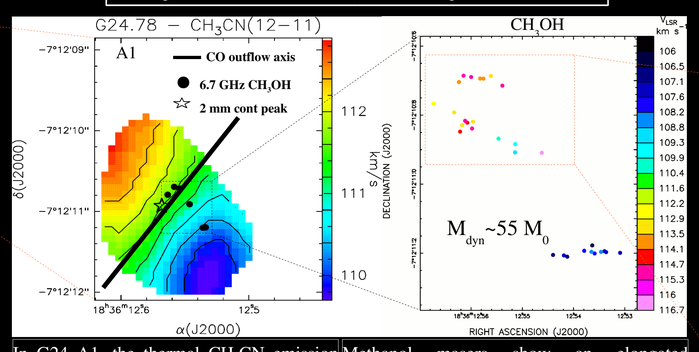


In G24.78+0.08, spread over 0.4 pc, at least 4 distinct centers of massive star formation are active, labeled A, B, C, and D, which power two CO molecular outflows (black contours) [5] (see also the Furuya's talk).



Core A has been resolved into two cores, G24 A1 and A2, by 1.4 mm PdBI observations (*contours*) [6]. G24 A1 is associated with a HC HII region, excited by a O9.5 star [7] (see also the Beltran's talk) .

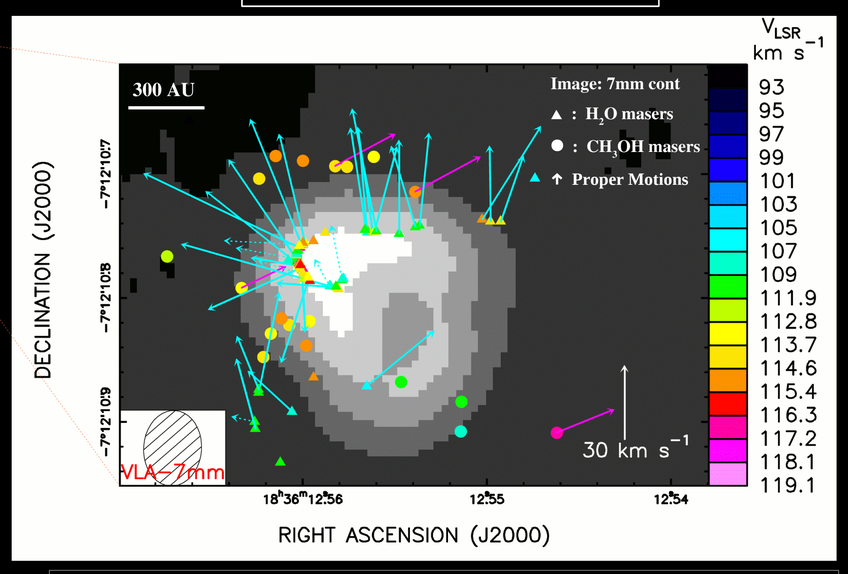
$CH_3CN(12-11)$ + 6.7 GHz CH_3OH Masers



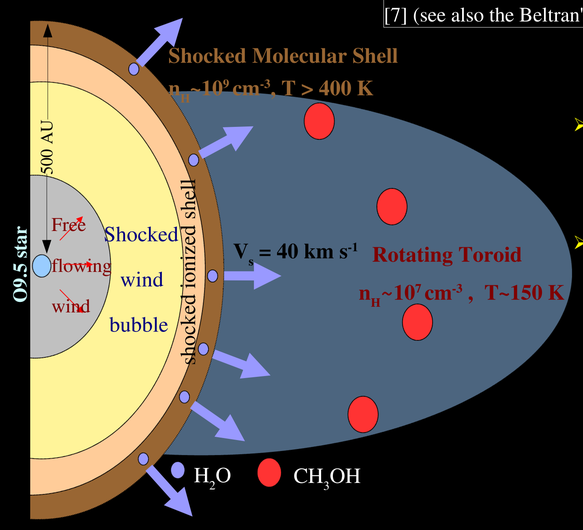
In G24 A1, the thermal CH_3CN emission shows a velocity gradient along a direction perpendicular to the axis of the CO outflow, interpreted in terms of a rotating toroid [6].

Methanol masers show an elongated distribution and a LSR velocity variation in agreement with the axis of the velocity gradient measured in the CH_3CN 1.4 mm line.

7mm cont + CH_3OH + H_2O Masers



- H_2O masers distribute along an arc at the border of a HC HII region (r~500 AU) and expand from its center with high velocities (~40 km s^{-1})
- CH_3OH masers distribute at larger distances from the HII region center than H_2O masers and have proper motions nearly perpendicular to H_2O masers



Schematic Model for the G24 A1 core

- CH_3OH masers emerge from a rotating toroid surrounding the HC HII region: from v_{rot} = 5 km s^{-1} and r=0.04 pc, one obtains M_{kep} = 55 $M_\odot$.
- H_2O masers expand in a molecular shell driven by a strong stellar wind ejected by a ZAMS O9.5 star (M_{wind}~10^{-6} $M_\odot$ yr^{-1}, V_{wind}~2000 km s^{-1}, L_{wind}~1-5 10^{36} erg s^{-1}).

For a molecular shell with V_s~ 40 km s^{-1} and R_s ~ 500 AU, pressure and momentum-driven solutions require: t_{exp}≈40 yr, n_H~10^7 cm^{-3} [8].

CONCLUSIONS for G24 A1:

In the depicted scenario, the rotating material in the toroid (on scales of 0.01-0.1 pc) cannot reach the star, but it is halted at the shock front at the surface of the HII region (r~0.003 pc): that means that the accretion phase is over.

Summary

Using EVN (two epochs) and VLBA (four epochs) phase-referenced observations, we have derived the absolute positions and velocities for 6.7 GHz methanol and 22.2 GHz water masers, respectively, in two high-mass YSOs, AFGL 5142 and G24 A1. AFGL 5142 and G24 A1 are so far the only sources for which CH_3OH 6.7 GHz and H_2O 22.2 GHz maser association on scales of 10-100 AU has been established by phase-referenced VLBI observations (but see also the poster from Sanna et al. for another interesting case in G16.59-0.06).

Three main conclusions can be drawn:

1. water and methanol masers can trace a common stage in the evolution of a forming high-mass star;
2. they appear to trace different kinematic structures: water masers trace *expansion* in jets or winds ejected by the YSO, whilst methanol masers *infalling/rotating gas* in a molecular envelope/toroid;
3. these results give support to models of accretion and jet ejection related to the formation of high-mass stars.

References

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