Kinematics of H$_2$O masers in high-mass star forming regions

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Star Forming Regions (SFRs)

**Theory:**
- Collapsing core
- Angular momentum conservation
- Accretion disk
- Jet

**Observations**

**Low-mass YSOs:** the existence of disk/jet systems *confirmed* by observations
- Distant from the Sun (≥1 kpc): high-angular resolution needed!

**High-mass YSOs:**
- On the ZAMS phase *enshrouded* in the placental cloud
- (M > 8 M☉, L > 10³ L☉)
  - Optical (and NIR) observations *impossible*

**A powerful diagnostic tool**

**VLBI observations of maser lines** (e.g., 22 GHz H₂O; 6.7 and 12 GHz CH₃OH):
- Linear resolution of few AU: disk/jet systems resolvable even at 1 kpc
- Multi-epoch observations: 3-d velocity distribution of the masing gas

The only technique able to derive the gas kinematics nearby the YSO!
Kinematics of 22.2 GHz $\text{H}_2\text{O}$ masers in high-mass SFRs

- **Collimated flows of gas:**
  e.g., IRAS 20126+4104

- **Accretion rotating disks:**
  AFGL 5142 (Goddi et al., 2004)

- **Expanding spherical shells:**
  e.g., W75N-VLA2

Proper motions are essential to derive the kinematics of the masing gas!

So far, only few (~10) high-mass YSOs studied with *multi-epoch VLBI* observations of water masers!
### The sample

Multi-epoch **VLBI** observations of the **22 GHz H$_2$O masers** towards a sample of candidates as **high-mass YSOs**:

- **EVN**: S255 IR, WB89-234, AFGL 5142
- **VLBA**: AFGL 5142

#### Observational parameters

<table>
<thead>
<tr>
<th><strong>EVN</strong></th>
<th><strong>VLBA</strong></th>
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<tbody>
<tr>
<td><strong>Antennas</strong>:</td>
<td>full array (10)</td>
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<tr>
<td>Medicina, Cambridge, Onsala, Noto, Effelsberg, Metsahovi, Jodrell and Shanghai</td>
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<td><strong>Observational epochs</strong>:</td>
<td>Oct and Nov 2003, Jan and Feb 2004 (separat ∼1 month)</td>
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<td>Oct 1996, and Jun, Sep, Nov 97</td>
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<td><strong>Bandwidth</strong></td>
<td>16 MHz</td>
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<tr>
<td><strong>Spectral channels</strong></td>
<td>1024</td>
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<tr>
<td><strong>Velocity resolution</strong></td>
<td>0.21 km s$^{-1}$</td>
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<td><strong>Correlator</strong></td>
<td>VLBA (Socorro, NewMexico)</td>
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<tr>
<td><strong>Phase-reference</strong></td>
<td>ABSOLUTE position</td>
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</table>

Bandwidth = 1-2 MHz
Spectral channels = 112
Velocity resolution = 0.12 km s$^{-1}$
Correlator = MKIII (Bonn, Germany)
Observational results on single source: S255 IRS1

Howard et al. 1997
Brγ (2.17 μm) – continuum

H₂ ν = 1–0 (2.12 μm) jet

Cesaroni (unpubl.)
VLA 22 GHz maser

Rengarajan (1996)
+ VLA 15 GHz cont.
Observational results on single source: S255 IRS1

Howard et al. 1997

Brγ (2.17 µm) − continuum

$H_2$ ν = 1–0 (2.12 µm) jet
Observational results on single source: AFGL 5142

Hunter et al. 1999
OVRO HCO$^+$ (1→0) outflow
OVRO SiO (ν=0, 2→1) jet
OVRO 88 GHz cont.
VLA 22 GHz water

Hunter et al. 1995
VLA 8.4 GHz cont.
VLA 22 GHz water
Observational results on single source: AFGL 5142
Observational results on single source

AFGL 5142

Group I

Group II

HCO⁺ outflow

OVRO SiO (ν = 0, 2 → 1) jet

OVRO 88 GHz cont.

VLA 22 GHz water

Group II

Hunter et al. 1999

Hunter et al. 1995

VLA 8.4 GHz cont.
Observational results on single source:

Group I

Group II

YSO position
Kinematics of the masing gas

Common features between the studied YSOs:

- A large-scale molecular outflow detected towards each of the studied SFRs
- Good agreement of LOF velocities between outflows and H$_2$O masers
- Measured proper motions consistent with a general expansion.

Simple interpretation:

The detected masers are tracing the innermost portion of the molecular outflow

BUT:

The overall spatial and velocity distribution of the H$_2$O masers seems not in agreement with a model of collimated flow
Kinematical Models

Conical outflow

Keplerian disk

Hubble motion: \( v = a \cdot r \)

Keplerian Motion: \( V = (GM/R^2)^{1/2} \)

Results:

- Conical outflow: a solution for S255 and WB89-234
- Keplerian disk: a solution for AFGL 5142
S255 IRS1 and WB89-234

Best fit solutions of conical model

- Estimated parameters in agreement with large-scale outflows
- Modeled conical jets with large opening angles
  - wide-angle winds
Two distributions of masers nearly perpendicular to each other:

- **Multiple outflows**
  - supported by the measured proper motions
  - evidence in other massive (proto)stars (eg, Beuther2003)
  - binary/multiple star system
  - higher sensitivity and resolution observations (from radio to NIR frequencies) needed to confirm

- **Disk/jet system**
  - **Group I** fitted with the *keplerian disk* model:
    - Disk *edge-on* and parallel with the maser elongation axis
    - Disk radius: $\geq 800$ AU
    - $M_{\text{YSO}} = 14 M_\odot$: in agreement with $L_{\text{bol}}$ ($4 \times 10^3 L_\odot$)
  - **Group II** proper motion orientation:
    - close to the HCO$^+$ outflow axis
    - indicating outflow motion from the YSO
Conclusions

• **S255 IRS1** and **WB89-234**
  - Masers trace preferably outflow rather than rotation
  - Jets driven possibly by wide-angle winds

• **AFGL 5142**
  - **massive YSO** associated with a disk/ jet system
    ➔ Star formation process is similar for low and high-mass stars?
  - **Multiple star** system associated with distinct outflows

Follow-up observations

✓ Multi-frequency *radio continuum* with the **VLA** for **AFGL 5142**
✓ **22 GHz water masers** with the **VLBA** for **WB89-234** and **S255**