Understanding the magnetic field structure in the star formation to the Galactic scales through the maser observations for Zeeman splitting and polarization

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0. Brief introduction for masers
Interstellar masers

✓ Masers in the star-forming regions
  • Major: OH, H$_2$O, CH$_3$OH
  • Minor: NH$_3$, H$_2$CO, SiO, radio RL

✓ Characteristics
  • Much brighter than thermal lines
  • **Narrow line width**: $\Delta v \sim 0.2-0.5$ km s$^{-1}$
  • Compact size of spot: $\sim 1$-10 au
    - Some spots consist of core/halo (Minier+ 02)

👉 **very bright**: $T_B \sim 10^7$-$10^{12}$ K

European VLBI spectrum and map of the 6.7 GHz CH$_3$OH maser (Bartkiewicz+ 16).
Usable characteristics of masers

✓ Flux variability
  • Various times-scales: < 1 day – a few month – 1 year <
  • Provide information in 0.1-1 au spatial scales from Keplerian time-scale
  • Remarkable variation: Periodic, Flaring
    • Periodic: stellar pulsation / binary system?
    • Flaring: flare of exciting star / accretion burst / magnetic reconnection?
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- Proper motion with VLBI (a few milliarcsec (mas) spatial resolution)
  - Enable us to detect tiny motions of a few mas yr\(^{-1}\) on disk/outflow/jet
  - Reveal 3-D velocity structure with LSR velocity information
Wide-angle outflow and jet scenario observed in high-mass SFR Cepheus A (Torrelles+ 11). Proper motions of 22 GHz H$_2$O masers showed expanding motions emanated by wide-angle outflow, while a radio jet was observed by radio continuum observation.
Proper motion with Wide-angle outflow and jet scenario observed in high-mass SFR Cepheus A (Torrelles+ 11).

Proper motions of 22 GHz H$_2$O masers showed expanding motions emanated by wide-angle outflow, while a radio jet was observed by radio continuum observation.

Shock propagation formed by wide-angle outflow expanding shell of bow shock propagation

Shock propagation formed by wide-angle outflow

Expanding shell of bow shock propagation

Observed in high-mass SFR Cepheus A (Torrelles+ 11). Showed expanding motions emanated by wide-angle outflow continuum observation.
**Usable characteristics of masers**

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✓ **Magnetic field strength and 3D structure**
  - Circular polarization => Zeeman splitting
  - Linear polarization => Polarization vector
    - Convertible to the direction of the magnetic field axes
1. What’s advantages of maser obs. for magnetic ($B$) field?
Importance of $B$ field

✓ Launch outflow/jets and magnetic braking
  • Removal of angular momentum
  • Maintain accretion through disk

✓ Launch mechanism and morphology of outflow/jets affected by the strength and the configuration of the $B$ field (Machida+ 08)
  • Outflow: low-velocity and hourglass-like, caused by strong $B$ field and the magnetocentrifugal force
  • Jet: high-velocity and well-collimated, caused by weak $B$ field and the magnetic pressure gradient force

3D MHD simulations to understand the outflow/jet launching mechanism and morphology in the star-forming core (Machida+ 08). These figures show the relation among velocities, collimations, $B$ field strength, and morphology.
e.g.) Dust pol. obs.

- Aligned dust by $B$ field
- Measure polarization vector, convertible to the $B$ field on the plane of sky
  - e.g., “hourglass” shape (e.g., Girart+ 06)

- Weak points
  - Impossible to direct measurement of the strength of $B$ field
    - may be estimated by comparing the gravitational force as an upper limit at collapse phase
  - Hard to trace high-density area ($> 10^8$ /cc)
e.g.) Zeeman splitting obs.

✅ Energy quantum state is split by the \( B \) field into multiple states

✅ Measure the strength of the \( B \) field directly!

✅ To date in thermal lines, measured from HI, OH, and CN (e.g., Crutcher+ 99; Falgarone+ 08)
  • Low-density (\(< 10^4 \) /cc) : HI, OH
  • High-density (\(10^4-10^6 \) /cc) : CN

✅ Weak points
  • Split coefficient is much smaller than thermal line-width : \(~1\) Hz/\(\mu G\)
  • Signal-to-noise ratio is not enough to detect circular polarized spectrum

☞ a few detections in the high-density tracer

![CN Zeeman spectra of Stokes \( I \) (top) and \( V \) (bottom) in W3(OH) (Falgarone+ 08).](image)
Advantages of the masers

i. Narrower line-width and brighter emission than thermal lines
   • Enable us to measure for small Zeeman split with high S/N

ii. Pumped in compact and high-dense cloud, called as “spot”
   • Enable us to trace higher-density area than thermal emissions

iii. Both linearly and circularly polarized emission
    • Full stokes parameters (I, Q, U, V) usable to determine 3D $B$ field structure

iv. Combined with dynamics (3D velocity structure) information
    • Understand dynamical motions and magnetic structures, simultaneously
ii. High-density tracer (> 10^6 /cc)

- \( n_{H_2} > 10^6 /cc \)
  - OH : 10^5-10^8 /cc (Cragg+ 02)
  - CH\(_3\)OH : 10^4-10^9 /cc (Cragg+ 05)
  - H\(_2\)O : 10^8-10^{11} /cc (Elitzer+ 92)

- \( B \propto n_{H_2}^{0.47 \pm 0.08} \) (Vlemmings 08)
  - Consistent with Crutcher (99) relation
  - Connect from low to high-density area

Zeeman splitting measurements extensible to high-density area!

Magnetic field strength \( B \) vs the number density \( n_{H_2} \) in high-mass SFR Cepheus A (Vlemmings 08).
iii. Full stokes (linear and circular)

- Masers linearly and circularly polarized
  - Linear: 2D pol. vector on the plane of sky
  - Circular: Strength and radial 1D pol. vector through Zeeman split

![3D B field structure]

**RCP definition**

Stokes \( V = RCP - LCP \) (the IAU convention)

the IEEE convention

Image credit: Green+ (14)
iv. Combined with 3D vel. structure

- Totally understanding through the compact gas cloud “spot”
  - Spatial distribution
  - Dynamics from 3D vel. structure
  - \( B \) field structure

- e.g.) evolved AGB star W43A case
  - 3D vel. structure well fitted by precessing jet model (Imai+ 02)
  - Toroidal \( B \) field structure measured through linear pol. of \( \text{H}_2\text{O} \) masers (Vlemmings+ 06a)

\[ \uparrow: \text{Proper motions detected for \( \text{H}_2\text{O} \) masers in the evolved AGB star W43A (Imai+ 02).} \]
iv. Combined with 3D vel. structure

↑: B field direction converted from linear pol. vector of the H$_2$O masers in W43A (Vlemmings+ 06a). ↓: Toroidal B field model inferred of H$_2$O maser results.

↑: Proper motions detected for H$_2$O masers in the evolved AGB star W43A (Imai+ 02). ↓: Precessing jet model fit to 3D velocity structure of H$_2$O masers.
2. Remarkable works of maser obs. for the magnetic field
**B field parameters of the masers**

<table>
<thead>
<tr>
<th></th>
<th>OH</th>
<th>CH$_3$OH</th>
<th>H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ [GHz]</td>
<td>1.6-1.7</td>
<td>6.7</td>
<td>22.2</td>
</tr>
<tr>
<td>Coefficient [Hz/$\mu$G]</td>
<td>2-3</td>
<td>$\sim$10$^{-4}$* (Jen 1951)</td>
<td>$\sim$10$^{-3}$</td>
</tr>
<tr>
<td>Trace</td>
<td>Edeg of HII region</td>
<td>Accretion disk</td>
<td>Outflow/jet</td>
</tr>
<tr>
<td>fraction L</td>
<td>$\sim$10-20%</td>
<td>&lt;1-20%</td>
<td>&lt;1-10%</td>
</tr>
<tr>
<td>fraction C</td>
<td>$\sim$50-60%</td>
<td>&lt;1-5%</td>
<td>&lt;1-5%</td>
</tr>
<tr>
<td>Strength</td>
<td>$\sim$10-50</td>
<td>$\sim$10-100 *</td>
<td>$\sim$10-1000</td>
</tr>
<tr>
<td>Note.</td>
<td>Strongly affected by RM</td>
<td>* Large uncertainty of coefficient</td>
<td></td>
</tr>
</tbody>
</table>

Ref. --- e.g., Szymczak & Gerard (09); Surcis+ (12, 15); Vlemmings (08, +11)
Case 1. W75 N

~ rapidly evolution of outflow morphology and $B$ field structures ~
High-mass star-forming region W75 N

- Part of Cygnus X region
- Distance: 1.30 kpc (Rygl+ 12)
- Three YSO candidates at different evolutionary phase (Carrasco-Gonzalez+ 10)
  - **VLA1**: oldest
    - Index: -0.4 ±0.1 => optically thin, free-free
  - **VLA2**: younger than VLA1
    - Index: 2.2 ±0.3 => optically thick, free-free
  - **VLA3**: youngest
    - Index: 0.6 ±0.1 => thermal jet
H$_2$O maser distributions and motions

- **VLA1**: elongated NE-SW direction
  - Bipolar motion toward NE-SW
- **VLA2**: spherical morphology
  - Spherically expanding motion
Rapidly change of spatial distribution and $B$ field structure of H$_2$O maser in VLA2

✔ Spatial distribution of H$_2$O maser in VLA2 in $\sim$8 yrs (Kim+ 13)
  - Spherical $\Rightarrow$ Elongated to NE-SW

VLBI maps at 3 epochs (Torrelles+ 03; Surcis+ 11; Kim+ 13).
Rapidly change of spatial distribution and $B$ field structure of H$_2$O maser in VLA2

- Surcis+ (14) detected rapidly changes of the $B$ field structure in 7 yrs
  - the direction of the $B$ field: $+18 \Rightarrow +57$ deg
  - the strength of the $B$ field: $345$ mG $\Rightarrow 128$ mG
Rapidly change of spatial distribution and $B$ field structure of $\text{H}_2\text{O}$ maser in VLA2

- Spatial distribution of $\text{H}_2\text{O}$ maser in VLA2 in $\sim 8$ yrs (Kim+ 13)
  - Spherical $\Rightarrow$ Elongated to NE-SW

- $B$ field structure of $\text{H}_2\text{O}$ maser in VLA2 in $\sim 7$ yrs (Surcis+14)
  - Direction: $+18 \Rightarrow +57$ deg
  - Strength: $345 \text{ mG} \Rightarrow 128 \text{ mG}$

- Short-lived, isotropic, ionized wind in the strong $B$ field predicted by MHD simulation (e.g., Machida+ 08; Seifried+ 12)
  - Collimated as being evolved

VLBI maps at 3 epochs (Torrelles+ 03; Surcis+ 11; Kim+ 13).
1.3 cm continuum distribution was also changed in ~20 yr in VLA2 (Carrasco-Gonzalez+ 15)

- Spherical $\Rightarrow$ Elongated to NE-SW

Verified short-lived, isotropic, ionized wind whose morphology evolves into elongated to NE-SW inferred from H$_2$O maser observations (dynamics & $B$)!!

Carrasco-Gonzalez+ (15)
Alignment of the $B$ direction?

- Surcis+ (14) detected alignment of $B$ field direction in VLA1 and VLA2
  - VLA1: $+49 \pm 15$ deg, VLA2: $+57 \pm 21$ deg
  - Nearly perpendicular filament structure traced by NH$_3$ emission.

$\checkmark$
Case 2. Statistical study in star-formation scale

~ relationship of the orientations between $B$ field and outflow axes ~
**B field vs outflow axes**

✓ Measured \( B \) field of \( \text{CH}_3\text{OH} \) masers in \( \sim 20 \) high-mass YSOs (Surcis+ 12, 13, 15)

✓ Orientation of the \( B \) field along the outflow axes, preferentially
  - At least, on scales of 10-100 au

Comparison of the \( B \) field orientation from \( \text{CH}_3\text{OH} \) maser obs. to the outflow axes (Surcis+ 13).

PDF and CDF of the projected angle between the \( B \) field and the outflow axes (Surcis+ 13).
Case 3. Statistical study in the Galactic scale

~ Galactic structure of the $B$ field ~
‘MAGMO’ project through Zeeman splitting of OH masers

- MAGMO: the Magnetic field of the Milky Way through OH masers (e.g., Green+ 12)
- Pilot survey: 6 high-mass sources 280<l<295°, |$B_\parallel$|~1-10 mG, Same orientation
4. Summary
Summary

✓ $B$ field observations of the masers is usable
  • Narrower line-width and brighter emission than thermal one
  • Pumped in compact dense cloud ($10^6$-$10^{11}$ /cc)
  • Both linearly and circularly polarized (full stokes $I$, $Q$, $U$, $V$)
  • Combined with dynamics (3D velocity structure) information

✓ Remarkable works of the maser $B$ field obs.
  • W75 N : short-lived, isotropic, ionized wind in the strong $B$ field whose morphology evolves into elongations (e.g., Surcis+ 14; Carrasco-Gonzalez+ 15)
  • Statistical study (e.g., Surcis+ 12, 13, 15; Green+ 12)
    • in the star formation scale : Alignment of the $B$ field along the outflow axes
    • in the Galactic scale : Zeeman splitting measurements throughout the Milky Way ‘MAGMO’