Simultaneous observations of the H2O and SiO masers toward the late-type stars using KVN

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Late-type stars (from AGB to PPN)

- low- and intermediate-mass stars (1–8 \(M_\odot\))
Late-type stars (from AGB to PPN)

- low- and intermediate-mass stars (1-8 $M_\odot$)
- Stellar pulsation $\rightarrow$ shock wave $\rightarrow$ mass-loss
• **Spatial distributions of the different masers**
  - H$_2$O and SiO masers
  - SiO masers of different rotational states (J = 1-0, J = 2-1, J = 3-2)
  - SiO masers of different vibrational states (v = 1, v = 2, v = 3)

• **To study**
  - Physical environments of CSEs
  - Dynamical links between the inner and outer parts of CSEs
  - Maser-variability driven by the stellar pulsation
  - Pumping mechanisms of the stellar masers
  - Mass-loss processes and stellar evolution

Scientific goals
KVN
Four band receivers
Simultaneous observations at four frequency-bands

- 22 GHz H2O maser
- 42, 43 GHz SiO maser
- 86 GHz SiO maser
- 129 GHz SiO maser
KVN observation under SFPR scheme

Target source @low & high freq.

Reference source @low & high freq.

Several degrees OK

Multi-frequency simultaneous observation
For one source A

High: \( \Phi_A = \Phi_{A,GEO} + \Phi_{A,TRO} + \Phi_{A,ION} + \Phi_{A,STR} + \Phi_{A,INST} + 2\pi n_A \)

Low: \( \Phi_A = \Phi_{A,GEO} + \Phi_{A,TRO} + \Phi_{A,ION} + \Phi_{A,STR} + \Phi_{A,INST} + 2\pi n_A \)

Non-dispersive errors:
\( \Phi_{A,TRO} - R \cdot \Phi_{A,TRO} \approx 0 \)
\( \Phi_{A,GEO} - R \cdot \Phi_{A,GEO} \approx 2\pi v/c(D \cdot \Theta_{A,SHIFT}) \)

Dispersive errors:
\( \Phi_{A,ION} - R \cdot \Phi_{A,ION} = (1/R-R) \cdot \Phi_{A,ION} \)

\( \Phi_A - R \cdot \Phi_A = \Phi_{A,STR} - 2\pi v/c(D \cdot \Theta_{A,SHIFT}) + IONO_A + INST_A \)
For one source A
\[ \Phi_A - R \cdot \Phi_A = \Phi_{A,STR} - 2\pi v/c (D \cdot \Theta_{A,SHIFT}) + \text{IONO}_A + \text{INST}_A \]

For another source B
\[ \Phi_B - R \cdot \Phi_B = \Phi_{B,STR} - 2\pi v/c (D \cdot \Theta_{B,SHIFT}) + \text{IONO}_B + \text{INST}_B \]

Source/ Frequency referenced visibility phase:
\[ \Phi_{A,STR} + 2\pi v/c (D \cdot \Theta_{A,SHIFT} - D \cdot \Theta_{B,SHIFT}) \]
Calibration solutions determined from the lower frequency data are transferred to the higher frequency data.
Calibration solutions determined from the lower frequency data are transferred to the higher frequency data.

Schematic of data reduction using SFPR method
# Introduction to Key Science Program (KSP) of KVN

## Target sources of KSP

<table>
<thead>
<tr>
<th>Target</th>
<th>Reference</th>
<th>Sep. (deg)</th>
<th>Observation frequency</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>22/43 GHz</td>
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<tr>
<td>IK Tau</td>
<td>J0345+1453</td>
<td>4.04</td>
<td>3</td>
</tr>
<tr>
<td>NV Aur</td>
<td>J0514+5602</td>
<td>3.19</td>
<td>4</td>
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<tr>
<td>R Cas</td>
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<tr>
<td>R Crt</td>
<td>J1048-1909</td>
<td>3.06</td>
<td>2</td>
</tr>
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<td>R Leo</td>
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<td>5.52</td>
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<td>V627 Cas</td>
<td>J2231+5922</td>
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<td>V1111 Oph</td>
<td>J1824+1044</td>
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<td>V1366 Aql</td>
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<td>1</td>
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<td>V5102 Sgr</td>
<td>J1833-2103</td>
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<tr>
<td>VX Sgr</td>
<td>J1833-2103</td>
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<tr>
<td>VY CMa</td>
<td>J0731-2341</td>
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<td>W Hya</td>
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<td>WX Psc</td>
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<tr>
<td>χ Cyg</td>
<td>J2015+3710</td>
<td>6.65</td>
<td>1</td>
</tr>
</tbody>
</table>

Monitoring observations have been performed since August 2014.
Example of KSP observations

• Target source: WX Psc
• Obs. date: 2015.12.30 (~7 hours)
• Fringe finder: J0136+4751
• Position reference source: J0121+1149 (3.81° from TS)
• Scan pattern: TS (2 min.) – PR (2 min.) – TS (2 min.)
• Obs. frequencies: 22/ 43/ 86/ 129 GHz
Frequency setting of BBCs (base band channels)

WX-PSC (blue=USB, green=LSB)

K-band: 6 IFs

Q-band: 6 IFs

W-band: 2 IFs

D-band: 2 IFs
Frequency setting of BBCs (base band channels)

- **Widely separated IFs**
  - Group delay can be precisely determined.

- **Randomly distributed IFs**
  - To avoid the frequency redundancy.
Phase transfer from LOW to HIGH frequency band

WX-PSC (blue=USB, green=LSB)

From K-band

From Q-band
Frequency phase transfer from K-band to Q-band

Phase of K-band

Phase of Q-band
Final image of H2O and SiO masers at four bands

- **22 GHz**
  - H2O $6(1,6)-5(2,3)$

- **42 GHz**
  - SiO $v=2$, $J=1-0$

- **43 GHz**
  - SiO $v=1$, $J=1-0$

- **86 GHz**
  - SiO $v=1$, $J=2-1$

- **129 GHz**
  - SiO $v=1$, $J=3-2$
Final image of H₂O maser (22 GHz)
Superposed map of H2O and SiO masers at four bands

Location of the central star
→ Center of the SiO maser ring

Asymmetric morphology of the H2O maser@22 GHz
→ Outflow (bipolar?) motion in CSEs

Spatial distribution of SiO masers
→ Similarity and difference imply the pumping mechanisms of the SiO masers.
→ Important information of the physical environments of the CSEs
Superposed map of SiO masers

Location of the central star
→ Center of the SiO maser ring

SiO $v=1$ and $v=2$, $J=1-0$ masers
→ Largely overlapped
→ Slightly different
→ Radiative/ collisional pumping

SiO $v=1$, $J=2-1$ and $J=3-2$ masers
→ Different spatial distribution from 42/43 GHz SiO masers
Superposed map of H2O and SiO masers at four bands
Superposed map of H2O and SiO masers at four bands

**IK Tau (2016.4.30)**

- H2O 61,6-52,3
- SiO v=1, J=1-0
- SiO v=2, J=1-0
- SiO v=1, J=2-1

SiO v=1, J=1-0
SiO v=2, J=1-0
SiO v=1, J=2-1
Superposed map of H2O and SiO masers at four bands

VY CMa (2016.3.27)

- H2O $6_{1,6}^{3}2_{1,3}$
- SiO $v=1$, $J=1-0$
- SiO $v=2$, $J=1-0$
- $^{29}$SiO $v=0$, $J=1-0$
- SiO $v=1$, $J=2-1$
- SiO $v=1$, $J=3-2$
Superposed map of H2O and SiO masers at four bands
• Simultaneous observations of KVN at four frequency-bands have succeeded and are now very promising for studying the stellar masers.

• Relative spatial distributions between the SiO masers obtained from the KVN observations can give a good evidence for the maser pumping study.

• Monitoring-observational results of the SiO masers and the H2O masers can be used to trace the dynamical evolution of the CSEs together with the stellar pulsation.

• POSTER section of #15 shows more information of this study.

Come and enjoy KVN!