Water masers

High resolution probes of physical conditions

Anita Richards (Manchester) & thanks to Liz, Wouter, Ivan, Sebastien, Sabine, Daniel, Ana, Lydia and all the rest of the B5 team and the chocolate shops of Kungsbacka

Mass loss, wind driving, shaping of circumstellar envelopes around evolved stars

Clumpy winds, density inhomogeneities

Survival of dust and molecules in late stellar evolution

See de Beck/Humphreys introduction

Vlemmings magnetic fields
Masers aren't just for kinematics, they are for physics

- Exponential amplification
  - Hard to reconstruct underlying environment from one line
- Multiple water transitions mase
  - Wide range of physical conditions for inversion
  - Water widespread in inner O-rich CSE – and elsewhere
- Gray et al. models for >50 lines accessible to ALMA
  - Also Yates, Sobolev, Humphreys, Nesterenok, Neufeld ...
    - Number density, Tk, Tdust/IR radiation field, vel. grad.
      - ortho:para 3:1
      - Some transitions radiatively pumped at high IR temp.
- Reconstruct physical conditions as well as kinematics
Maser (negative) optical depths for lines of H$_2$O visible to ALMA in bands 3–10 as functions of kinetic temperature & o-H$_2$O number density.

**o-H$_2$O**

- 321 GHz
- 658 GHz
- 922 GHz

**p-H$_2$O**

- 183 GHz
- 325 GHz
- 966 GHz

\[ n(H_2O) \]
VY CMa's CSE before ALMA

- Kaminski et al. 2013 (SMA), Shennoy, R. Humphreys (HST)
  - ~5" heart-shaped nebula
  - Mostly irregularly expanding
- Largest, longest-lived 22-GHz water maser features of any well-studied RSG
  - ~half features survived at least 9 yr from 1989 (Bowers et al. 1993, VLA) to 1994 (Richards et al. 1998, MERLIN)
  - Similar survival rate to 2000
VY CMa 22-GHz clouds

- Largest (~20-25au), longest-lived features of well-studied RSG
- Position of star uncertain

1985-1994

1994-2000
VY CMa ALMA SV

- 183-GHz see Liz's talk for observational details
- 321, 325, 658 GHz Richards+'14, O'Gorman+14, De Beck+15, Decin+16

Components fitted to 183-GHz masers
Some faint emission may be sidelobes or thermal
All masers avoid clump C

- Central 183-GHz masers overlying continuum contours
- Origin at stellar position VY
  - Brightest masers surround VY
- Clump C has strongest (sub-)mm continuum
  - No masers at all!
- Dust temperatures 970 K VY, <450 K C (O'Gorman+14)
- 183-GHz continuum consistent with VY, C sub-mm spectral indices (2.7, 1.9)
183 GHz extended

- Follow cold dust not detected by ALMA
- HST scattered light (Shennoy)
183 GHz extended

- Follow cold dust not detected by ALMA
- HST scattered light (Shennoy)

Thermal NaCl \((\text{Decin})\), TiO2 \((\text{De Beck})\) also associated with SW clump, but no other H2O masers
Water maser comparisons

<table>
<thead>
<tr>
<th>Line GHz</th>
<th>22</th>
<th>183</th>
<th>321</th>
<th>325</th>
<th>658</th>
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<tr>
<td>Eu K</td>
<td>521</td>
<td>200</td>
<td>1861</td>
<td>454</td>
<td>2360</td>
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</tbody>
</table>

- Similar shell to 22, 321, 325 GHz in inner few 100 mas
• 183-GHz spectral components resemble both 'hotter' masers and OH mainlines
Distance from star v. Vexpansion

Zoom of water masers 183 GHz red

OH masers + 183 GHz - uniquely extended among water masers
Comparison with thermal models

- Based on *Herschel* CO and other multi-transition single dish surveys *Decin*+ 2006, *Matsuura*+ 2013

- Assumes spherical symmetry

- Maser acceleration is more gradual than models predict
Gas temperature v. radius

- Decin variable mass loss rate
- Maser radii labels offset for clarity (not temperature)
Number density v. radius

- H$_2$O abundance depleted by photodissociation & freezeout
  - 22 GHz maser clumps ~x50 overdense
- Maser radii labels offset for clarity only
VY CMa maser model (Gray)

- Waiting for 183 GHz tailored to VY CMa
- Deeper shade = stronger maser inversion
- Contour at 50% maximum maser optical depth
Observed maser relationships

Zoom example 7 km/s channel averages
Observed maser relationships

Inner 3 arcsec
7 km/s channel averages
Ongoing work

- Physical conditions in inner CSE
  - Clump v. surroundings – $T$, density contrasts
  - Larger scale/axisymmetric inhomogeneities
  - Shock tracers
- Much higher resolution than thermal lines
  - Resolve 5-50 au clumps
- VY CMa least symmetric
  - Hard to use velocity as 3rd axis
- VX Sgr? Almost symmetric at least outside $r_{\text{dust}}$
  - Benchmark water maser models
VX Sgr cm and sub-mm

- 22 GHz slight axisymmetry
  
  *(Murakawa, Richards, Vlemmings)*

- Sub-mm spectra
  
  *(Yates, Hunter)*
  
  - No water maps yet
Need for high resolution

- MERLIN 10-20 mas res\textsuperscript{n} detects all 22 GHz emission,
  - Resolves spots
    - Maser physics
    - Shock diagnostics
- Need ALMA high resolution
- Disentangle clouds
  - Co-propagation v. avoidance
    - Constrains $T_k$, $T_{\text{dust}}$, $n$, $dV/dr$, $H_2O$ abundance...
- Central star 10s – 100s Jy in ALMA bands 3 – 10
  - Bright enough to self-calibrate
    - As are most water masers!
- Please give us long baselines at all bands!