Wind properties and clumping

Red Supergiants and Asymptotic Giant Branch stars
(with no obvious companions)
How are clouds formed?
What affects their journey to the ISM?

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Assaf, Baudry, Decin, Elitzur,
Etoka, Gray, Lekht, Lim,
Mendoza, Murakawa, Rudniskij,
vvan Langevelde, Yates

S Per water maser clouds
Total extent 350 AU ~ 43 R∗
Thanks for organising the meeting
nice of you to lay on the rain to make me feel at home...

What water masers round red supergiants really are???
Masers round cool late-type stars

- RSG VX Sgr Stellar disc at 2 μm Chiavassa+ 2010
  - $R_\star$ 4 mas $\sim$ 7 AU
  - SiO Chen+06 43 GHz 2—4 $R_\star$
  - $H_2O$ Murakawa03 22 GHz
    - Overdense clumps
    - 5 – 50 $R_\star$
- Red Supergiants $>\sim 8 M_\odot$
- Lower-mass AGB stars have $R_\star$ $\sim 1$ AU
  - Periods $\sim 1$ yr (RSG longer), $T_{\text{eff}}$ $\sim 2300$–$3300$ K
  - Mass loss $10^{-7}$ – $10^{-5}$ $M_\odot$/yr
Masers resolve winds on AU scales

- **OH 1612 MHz** \( (T_E \text{ few K, long column depth}), \text{ at } >50 R_\star \)
- **H_2O 22GHz** \( (T_E \sim 650 \text{ K}), \text{ 5-30 } R_\star \)
- **SiO >42 GHz** \( (T_E >2000 \text{ K}) < 4 R_\star \)
- **OH mainlines** (1665-7 MHz) can overlap H_2O and/or extend as far as 1612 MHz masers
Water maser channel maps

- MERLIN radio interferometry images
  - 22 GHz ($\lambda$ 1.3 cm)
  - 10 milliarcsec beam
- Compact front and back caps
- Bright extended emission in plane of sky with star
- Spherical, radially accelerating outflow
Cloud measurements

- Measure channel emission by fitting 2-D Gaussian components
  - Individual component beamed size
    - 1-2 km s\(^{-1}\) groups
- Series provide 'true' size of discrete clouds
  - RSG 10-20 AU
  - AGB 1-few AU
Beamed size – maser brightness

- S Per: component size $s$ smaller in line peaks than wings
- U Ori: many brighter spots are larger

\[
\log s \propto -\log[\ln(I_v)]
\]

\[
\log s \text{ v. log}[\ln(I_v)] \text{ random/positive}
\]
Maser properties reveal wind disturbances

- Brighter = smaller beamed size?
  - $s \propto 1/\sqrt{\ln(I_v)}$

Smoothly expanding spheres

- Brightest emission often $\sim$ cloud size?
  - Extreme variability
  - Deep stellar periods
  - Some OH flares

Shocked slabs

Richards Elitzur & Yates 2010
Elitzur Hollenbach & McKee 1992
Cloud survival, maser variability

- Specific RSG masers can be tracked for $\geq 5$ yr
- AGB masers survive $\leq 2$ yr
  - Similar to sound-crossing time
- Much less than shell crossing time
  - Decade(s) (AGB)
  - Up to a century (RSG)
Shell-crossing times

RSG VX Sgr
1700 pc

AGB IK Tau
266 pc
Masers blink, clouds survive

- Pushchino ~bimonthly spectral monitoring
- MERLIN imaging every few years (colour)
  - Matched features: black outlines
- Spectral variability between images
  - Peaks vanish, some reappear
- Clouds unlikely to reform if dispersed
  - Clouds survive as clumps
  - Masers turn on and off
    - Turbulence/beaming?
    - Shocks/excitation?
Whole shell tends to vary

- Change in flux density v. $r$
  - IK Tau, VX Sgr most matched features get fainter
  - At any distance from star
Variability faster than shocks

- U Her: most matched features dim in 1 yr
- U Ori: most brighten
- RT Vir: most brighten then fade over 10 weeks
- Propagation of pulsation shocks? (e.g. Shintani+'08)
  - V 100–300 km/s? not feasible
- Must be radiative mechanism
  - No obvious relationship with optical phase
  - Heating via IR? Lags optical by 0.1–0.2 P (Smith+'06)
Cloud density

- \( \text{H}_2\text{O} \) masers start at \( r_i \)
  - 40–70 AU RSG, 5–15 AU AGB
    - Where collision rate < masing rate (Cooke&Elitzur 85)
      - Quenching density \( \sim 5 \times 10^{15} \text{m}^{-3} \)
      - Clouds \( \geq 45 \times \) average (e.g. CO) wind density
        - Upper limit: surrounding gas density > 0
      - OH mainline masers interleave
        - Filling factor \( \lesssim 1\% \)
        - >90% mass loss in clouds
        - 2–6 clouds/stellar period
          - NB not all beaming towards us
Cloud size depends on star size
$R_{\text{cloud}}$ set by star properties?

- Measure stellar radius $R_*$ from opt/IR interferometry
  - Skinner+88, Mennesson+02, Monnier+04, Ragland+06
- Cloud radius is a function of stellar radius
  - In H$_2$O maser shell $R_c \sim (0.7\pm0.3) R_*^{1.0\pm0.1}$
  - Mass per cloud consistent with CO clump models
    - Bergman+93, Olofsson+96
- Suggests that cloud properties are determined when mass is ejected from star
  - Not e.g. due to cooling scales during dust formation
    - Such microphysics should not care about $M_*$
  - Birth radius (5–10)\% $R_*$ if outflow expands as $r^{-2}$
  - VLTI etc. observations suggest stellar surface inhomogeneities on ~10\% scale e.g. Wittkowski+11
Summary of wind properties from H$_2$O masers

- Properties of clouds derived from 22-GHz maser measurements
  - 7 stars, MERLIN & Pushchino monitoring \textit{Richards+2011,12}
  - Uncertainties, references therein for $R_{\odot}$ & $\dot{M}$

<table>
<thead>
<tr>
<th>Star</th>
<th>$R_{\odot}$</th>
<th>$R_{\text{cloud (average)}}$</th>
<th>$\dot{M}_{\text{total}}$</th>
<th>$\frac{n_{\text{cloud}}}{n_{\text{average}}}$</th>
<th>$\dot{M}_{\text{cloud (single)}}$</th>
<th>$\frac{\dot{M}<em>{\text{clouds}}}{\dot{M}</em>{\text{total}}}$</th>
<th>Filling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>VX Sgr</td>
<td>7.4</td>
<td>6.5</td>
<td>72</td>
<td>107</td>
<td>17</td>
<td>0.2</td>
<td>0.09%</td>
</tr>
<tr>
<td>S Per</td>
<td>8</td>
<td>7.5</td>
<td>38</td>
<td>43</td>
<td>14</td>
<td>1.3</td>
<td>0.95%</td>
</tr>
<tr>
<td>U Ori</td>
<td>1.5</td>
<td>1.9</td>
<td>0.23</td>
<td>72</td>
<td>0.24</td>
<td>1.8</td>
<td>0.95%</td>
</tr>
<tr>
<td>U Her</td>
<td>1.3</td>
<td>1.7</td>
<td>0.37</td>
<td>88</td>
<td>0.29</td>
<td>1.8</td>
<td>0.79%</td>
</tr>
<tr>
<td>IK Tau</td>
<td>2.8</td>
<td>1.4</td>
<td>2.6</td>
<td>75</td>
<td>0.16</td>
<td>0.2</td>
<td>0.10%</td>
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<tr>
<td>RT Vir</td>
<td>0.8</td>
<td>0.5</td>
<td>0.13</td>
<td>55</td>
<td>0.004</td>
<td>0.4</td>
<td>0.26%</td>
</tr>
<tr>
<td>W Hya</td>
<td>2.1</td>
<td>0.7</td>
<td>0.23</td>
<td>55</td>
<td>0.015</td>
<td>0.2</td>
<td>0.19%</td>
</tr>
</tbody>
</table>
OH mainlines interleave H$_2$O

- MERLIN H$_2$O (blue)
- EVN/global mainline OH (contours)
- OH mainlines interleave H$_2$O
  - Evidence for clumps
  - Only ground-state OH detected
  - $T_{\text{OH}} \sim 500$ K max?
  - $T_{\text{H}_2\text{O}} \sim 1000$ K ?
- 7 stars, multi-epoch EVN/MERLIN
  - Richards, Masheder, van Langevelde, Yates 2013??
'Old' MERLIN/VLA: $\alpha$ Ori at 5 GHz

- Davis, Morris, Skinner
  - MERLIN: 7-9 spots
  - 0.40 – 0.79 mJy/bm
    - (55x85) mas resolution
    - Sensitivity limited
    - Shortest spacing $\equiv >0''.5$
  - VLA 5 GHz barely resolved
  - MERLIN+VLA
    - $\sigma_{\text{rms}}$ 0.055 mJy/bm
    - 200 mas beam

- Lim+98
  - VLA image
  - JVLA projects Brown, Harper, O Gorman
EMERLIN capabilities

• Resolution matches HST/JWST/ALMA
• 1.3-1.7, 4-8, 21-26 GHz wavebands (≤2-GHz bw)
• 200 - 10 mas angular resolution
  - Sub-mas ICRF astrometry, in-beam calibration
• 6 μJy 3-σ sensitivity in 12 hr at 4-8 GHz
  - 40-mas resolution, up to 8-arcmin field of view
• Other bands ~15 μJy continuum sensitivity
• Spectral line: 7-20 mJy in 0.1 km/s
• Full polarization
• Dec ≳ -30° ~ 20°
• **Open skies**, 2nd proposal call imminent
  - Joint observations with EVN/Global VLBI
• [http://www.e-merlin.ac.uk](http://www.e-merlin.ac.uk)
α Ori e-MERLIN 5.75 GHz

- Richards, Davis, Decin, Lim, Etoka, Garrington, McDonald, Wittkowski
- 6-8 hr, 400 MHz b/w
  - Colour tapered to 180 mas resolution
    - $\sigma_{\text{rms}}$ 0.02 mJy/bm
    - 1.826 mJy/0.092 asec$^2$
    - $T_B$ 1220 (100) K
  - Contours (80x60) mas resolution
    - $\sigma_{\text{rms}}$ 0.009 mJy/bm
    - Peaks 0.789, 0.533 mJy/bm
    - $T_B \gtrsim 4000$ K?
      - (similar in 1992,5,6)
    - Total disc $T_B$ 1240 (100) K
\( \alpha \) Ori e-MERLIN 5.75 GHz

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**WARNING! PRELIMINARY RESULTS! Cols have not yet checked these images.**
α Ori e-MERLIN 5.75 GHz

- SW extension similar to plume of Kervella+09,11

- Also CO source 5" SW (O'Gorman+12)
\(\alpha\) Ori e-MERLIN 5.75 GHz

- Hotspots not aligned with 'pole' \textit{Uitenbroek+98}

- Nor with H-band peaks \textit{Haubois+09}

Contour: Partial uniform weighting, \((-1,2,4,8,16)\times 0.027\) mJy/beam
What initiates the wind? Does this determine clump size?

- Outer layers of AGB stars 2000 – 2500K
  - RSG up to ~3500 K

- α Ori convection model
  - Fits H-band VLTI

- VX Sgr also 'spotty'
  - Convection provides local cooling &/or lower gravity
  - Chemical or magnetic inhomogeneity?
Different ν's trace different layers

- $r_{22 \text{ GHz}} \sim 2r_{\text{photosphere}}$
- Cool free-free gas
  - Low chromospheric filling factor
- Betelgeuse (Harper, Lim, Chiavassa, Freytag...)
  - 2-3 main cells
    - Lifetime years
    - Scale height 5-10% $R_\star$
    - Correlated changes: pulsation?
    - Variegated changes: convection?

- $r (\tau \to 1) \uparrow$ as ν ↓
  - Radiosphere $V<5$ km/s
    - $r_{43} \to r_{24} \sim 1$ AU, $\sim 1$ yr
    - $r_{24} \to r_{21} \sim 2$ months
Masers (and the rest) with ALMA

- Multiple transitions trace different conditions
  - Models: Neufeld&Melnick'91, Humphreys+'01, Gray

- **183, 325 GHz**
  - 22-GHz clumps
  - or inter-clump gas nearer star?

- **321 GHz**, excited state
  - Straddles dust formation zone?

- **658 GHz** close to *
  - Eventually resolve dust clumps, star
Track wind from photosphere to ISM

- CO ALMA
- 1612 MHz masers
  - e-MERLIN, EVN
- OH 1665/7 MHz masers
  - e-MERLIN, EVN
- H$_2$O masers
  - e-MERLIN, ALMA
- Dust, chemistry
  - ALMA, VLTI
- SiO masers
  - VLBA, ALMA
- Star photo/radiosphere
  - e-MERLIN/ EVLA, ALMA, VLTI, MROI

- Different $\lambda \equiv$ different depths