Maser Misto

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with thanks to


- Traditional circumstellar envelope model
- Maser segregation in shells
- Red Supergiant deviants
- Maser segregation in clumps
- Role of star v. local microphysics
- What about AGB stars?
- New EVN+MERLIN results
- Why don't all OH1665-7/H$_2$O masers overlap?
- Beware transience, asphericity ...
- Unsolved problems - e-MERLIN legacy, EVN
'Onion shell' model for O-rich Circumstellar Envelopes

A) Form molecules (SiO, H$_2$O etc.) at high-n close to photosphere

B) Grains reach final size at ~5 $R_\star$ just inside H$_2$O maser shell

C) Dissociation by IS UV at a few 100 $R_\star$ forms OH
VX Sgr acceleration

Distance from centre of expansion (mas)

Expansion velocity increases with distance from first explored by Chapman & Cohen 1986
VX Sgr masers at mas resolution

- **OH 1612 MHz masers at 800-2000 au (65-170 R\(\ast\))**
- **H\(_2\)O masers at 95-325 au (8-27 R\(\ast\))**
- **SiO masers within 3 R\(\ast\)**
- **OH mainlines overlap H\(_2\)O and 1612 MHz**
VX Sgr 3D model

- Measure $V_{LSR}$ and angular position in orthogonal directions
- Solve quartic equation including acceleration
- Display and rotate using VO tool TopCat

MERLIN

X 1612 MHz OH
○ Mainline OH
• MERLIN H$_2$O
○ VLBI OH mainline
Measure VLSR and angular position in orthogonal directions

Solve quartic equation

Display and rotate using VO tool TopCat

VX Sgr 3D model

340 AU

MERLIN H$_2$O

VLBI OH mainline
RSG OH mainlines interleave H$_2$O

- MERLIN H$_2$O (blue)
- EVN/global mainline OH (contours)
  - Masheder et al.
- OH mainlines interleave H$_2$O
  - Near-by, but not identical distribution
- Only ground-state OH detected
  - $T_{\text{OH}} \sim 500$ K max?
  - $T_{\text{H}_2\text{O}} \sim 1000$ K?
RSG overlapping maser shells

- OH reaches >25 km/s
- Inner OH mainlines overlap $H_2O$!!
- VX Sgr similar
  - Double OH mainline shells
3/4 RSG overlap

- **VY CMa** OH 1667 (& 1612) MHz shell huge
  - \( v_0 > 40 \text{ km/s} \)
  - \( r_0 > 7000 \text{ AU} \)
- H\(_2\)O overlaps OH \( r_i \)
- Only **NML Cyg** shells are well-separated
  - H\(_2\)O and OH bipolar
  - Double OH mainline shell
  - Inner shell faster
  - Star 'recently' got brighter? (Etoka & Diamond 03)
Measuring 'true' maser cloud size

Cloud properties

Cloud $D=18$ AU at 1 kpc

1.2 km/s total line width

Channel maps every 0.2 km s$^{-1}$

Component measurements

Largest angular separation across all channels is actual cloud size ($18 \pm 5$ mas) (to limits of sensitivity)
Water masers concentrated in dense clouds

- Masers span 1-2 km/s, few mas
- Typical $R_{\text{cloud}}$:
  - AGB 1-2 AU
  - RSG 10-15 AU
    - $R_{\text{cloud}} \propto R_{\star}$
    - Cloud size set at stellar surface?
- Many RSG clouds:
  - $2R_{\text{cloud}} > \text{maser gain length}$
  - $\Delta V_{\text{cloud}} > \Delta V_{\text{th}}$
  - Clouds defined by density/composition
RSG water maser cloud density

- Inner $r_i$ where collision rate quenches maser (Cooke&Elitzur 85)
  - $n_q(r_i) \sim 5 \times 10^{15} \text{ m}^{-3}$
  - $>> n(r_i) \dot{M}(\text{CO, IR})$
  - H$_2$O clouds 10-100x overdense
Clumpy, inhomogenous CSE

- Water maser clouds dusty, rapidly accelerated
  - Require $n \approx [5 \times 10^{15}, 10^{14}]$ m$^{-3}$, $T \approx [1300, 500]$ K (Cooke & Elitzur)
- Water maser clouds over-dense: $n_{(\text{H}_2\text{O cloud})} \sim 50x \ n_{(\text{OH gas})}$
  - Consistent with better acceleration, tangential beaming
- OH mainlines emanate from surrounding gas
  - Require $n < 10^{14}$ m$^{-3}$, $T < 500$ K (Gray)
- Over-dense, over-temperature clumps survive shell crossing times of decades (AGB stars)/a century (RSG)??
- Water clumps have stronger magnetic field
  - $B_{\text{H}_2\text{O}}$ (Vlemmings et al.) $\sim 5 \times B_{\text{OH}}$ @ equivalent distance
    - Frozen-in $B \propto n^{-0.3 - 0.5}$ (Mouschouvias 87)
- Cloud radius $\sim 1$ AU (AGB), 10 AU (RSG) ($\sim R\star$)
  - Extrapolating to stellar surface would imply birth size $\sim 0.1 R\star$
More melon than onion?

A) $\text{H}_2\text{O}$ clumps dustier, better accelerated
   - Tends to tangential beaming

B) Interleaving gas supports $\text{OH}$ mainlines near star
   - Mixed, mainly radial beaming

C) Some $\text{H}_2\text{O}$ & $\text{OH}$ mainlines reach high velocities
   - Can overshoot $\text{OH} 1612$
   - At different latitudes?

D) $\text{OH} 1612$ further out
   - Needs ~steady velocity
   - Radial beaming
RSG and AGB

H₂O masers

- RSG $M_\star \geq 10 \, M_\odot$
  - End up as SNe
- AGB lower mass
  - Most end as PNe
- H₂O shell outer radii
  several tens of $R_\star$
End up as SNe

AGB lower mass

Most end as PNe

H\textsubscript{2}O shell outer radii several tens of \(\text{R} \approx 10 \, \text{M} \odot\)

H\textsubscript{2}O masers 100 AU
AGB maser cloud density

- Fit maser shell limits
- Inner radius $r_i$
  - $\sim 5$ AU (AGB)
  - $\sim 50$-100 AU (RSG)
- $n_q$ at H$_2$O $r_i$ implies $\dot{M}$
  - 10-100 x CO, IR values
- H$_2$O clouds $\sim 50x$ overdense
- 20-100 per shell
  - Filling factor $\lesssim 1\%$
  - 1-few clouds / period
- $r_o$ 25 - 500 AU

Separation from star vs. $V_{LSR}$
**H$_2$O maser cloud size/Star mass**

- **H$_2$O cloud $R \propto M_\star$**
- Cloud size determined by star size (not wind microphysics)
- Origins in convection cells, star spots, chemical inhomogeneities?

\[
\log M_\star = (-2.7 + 1.94 \log R_\star - \log P)/0.9
\]
(Wood in FMPN, 1989)

\[
R_\star: \text{Skinner+88, Mennesson+02, Monnier+04, Ragland+06}
\]

\[
P: \text{AAVSO, GCVS, Etoka+01}
\]
OH mainline/H$_2$O overlap on AGB?

- RT Vir SRb at 133 pc
- MERLIN resolves overlap

H$_2$O  ★ OH mainlines
Hint of overlap in IK Tau 1667 MHz

IK Tau: Sum emission for sensitivity: by velocity ...
Hint of overlap in IK Tau 1667 MHz

IK Tau: Sum emission for sensitivity: by velocity ... and by angle
Hint of overlap in IK Tau 1667 MHz

IK Tau: Sum emission for sensitivity: by velocity ...
Inner 1667 MHz still there!
IK Tau

- EVN OH at edge of H$_2$O
- Much resolved out?
- But MERLIN 2001 << 1993

- Mira - but very bipolar OH?
- OH 1612 MHz still outside

![Graph showing V$_{LSR}$ vs. offset from centre of expansion, with data points at 1665 MHz OH, 1667 MHz CO, and 22 GHz H$_2$O. The right side shows a spectral map of OH 1612 MHz.]
U Ori MERLIN

- Mira, 266 pc, OH mostly mainline
- Transient 1612-MHz probably a flare from inner CSE
U Ori MERLIN

- Fairly well-filled, stable OH mainline shell (Chapman+91)
- **Trace of inner emission**
U Ori MERLIN+EVN

- MERLIN+EVN observed OH within 3 months
- Several MERLIN runs - little variability

Combined data show a little overlap?
W Hya separate?

- SRa, ~100 pc
- Dec -28
  - MERLIN $\sigma_{pos}$ large!
- MERLIN OH
  * Szymczak+ 1998
- EVN confirms (if assume aligned)
- H$_2$O *Yates*
  - More epochs to come
  - Ovelap in velocity but probably not in position
CSEs with water/OH mainline overlap

<table>
<thead>
<tr>
<th>RSG AGB</th>
<th>$dM/dt$ CO/IR (M$_\odot$ yr$^{-1}$)</th>
<th>H$_2$O shell $r_i$ (AU)</th>
<th>OH shell $r_i$ (AU)</th>
<th>H$_2$O shell $r_o$ (AU)</th>
<th>$dM/dt$ H$<em>2$O $n_q$ (M$</em>\odot$ yr$^{-1}$)</th>
<th>Number of H$_2$O clouds</th>
<th>H$_2$O cloud size $&lt;L&gt;$ (AU)</th>
<th>H$<em>2$O cloud mass yr$^{-1}$ (M$</em>\odot$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Per</td>
<td>3–60</td>
<td>55</td>
<td>80</td>
<td>165</td>
<td>(930)</td>
<td>100</td>
<td>18 (44)</td>
<td>15–20</td>
</tr>
<tr>
<td>VX Sgr</td>
<td>5–80</td>
<td>95</td>
<td>130</td>
<td>320</td>
<td>(190)</td>
<td>100</td>
<td>21</td>
<td>10–15</td>
</tr>
<tr>
<td>VY CMa</td>
<td>70–115</td>
<td>75</td>
<td>300</td>
<td>600</td>
<td>(3220)</td>
<td>54+</td>
<td>--</td>
<td>&gt;60?</td>
</tr>
<tr>
<td>U Ori</td>
<td>~0.08</td>
<td>9</td>
<td>25</td>
<td>32.5</td>
<td>(8.3)</td>
<td>14</td>
<td>3</td>
<td>~0.03</td>
</tr>
<tr>
<td>RT Vir</td>
<td>~0.05</td>
<td>6</td>
<td>15</td>
<td>25.6</td>
<td>(5.1)</td>
<td>55</td>
<td>2.2</td>
<td>~0.05</td>
</tr>
</tbody>
</table>

- H$_2$O clouds much denser than surroundings
- $n_{H_2O\text{cloud}}$ 30-100x $n_{OH\text{gas}}$
- OH mainline $r_i < H_2O\ r_o$
- H$_2$O maser cloud filling factor less than a few %
- Solves mass loss rate discrepancy
- OH comes from less dense gas around and outside H$_2$O clouds
Why don't OH mainlines overlap H₂O around all RSG/AGB stars?

Four RSG: VX Sgr, S Per, VY CMa, NML Cyg
- All with SiO, H₂O, OH mainline and 1612-MHz masers
- VX Sgr, S Per, VY CMa overlap
- NML Cyg H₂O bipolar, inner OH faster, no overlap
  - More evolved? Excited OH detected.

Four AGB: SR: RT Vir, W Hya Mira: U Ori, IK Tau
- RT Vir-U Ori-IK Tau-W Hya: strong-some-little-no overlap
- Only IK Tau has well-resolved outer OH 1612-MHz
  - Others show faint/flaring emission (e.g. Etoka et al. 03)
- IK Tau had strong, biconical OH mainlines, now fading
- IK Tau, RT Vir bright H₂O with persistent? asymmetries
  - U Ori, W Hya H₂O no obvious preferred direction
  - W Hya outer detached OH mainline shell? (Etoka+00)
Observational requirements

- Clumping scales, cloud survival determine:
  - Wind chemistry, ionisation, magnetisability, acceleration
  - Molecular structure of material returned to ISM, future SF
  - Accuracy of mass-loss estimates

- Multiple epochs
  - Proper motions for 3D structure
  - Transient excitation effects v. persistent asymmetry

- High resolution and sensitivity
  - Resolve sub-mas components for maser physics
  - 100-mas scale weak extended emission (as in SFR)

- e-MERLIN+EVN ideal
  - +Global VLBI for RSG
  - +EVLA for close AGB
  - Good N-S baselines - Noto - invaluable

- Phase-referencing - align different species/epochs

- Full polarization at <100 m/s spectral resolution

- Adequate velocity span & resolution
e-MERLIN is coming

- MERLIN since 1992
  - 10-200-mas resolution @1.2-25 cm
  - Full polarization, >20' f.o.v. @ 21 cm
  - Max. b/w 16 MHz - 60 μJy/12 hr

- e-MERLIN 2 GHz opt fibre b/w
  - New receivers, hard/software
    - Lovell upgrade
  - 10-30x continuum sensitivity
    - $\sigma_{\text{rms}}$ 2 μJy/beam/12 hr around $\lambda$ 6 cm
    - $\sigma_{\text{rms}}$ 15 μJy/beam/12 hr around 1.3 cm
    - ~Filled aperture @ $\lambda$ 4cm!

- Sub-mas ICRF astrometry
- Rapid frequency changes
- 1000s km/s, multiple spectral lines

- Run by JBCA, Manchester University
- Funded by STFC, NWDA, other Uni's

- Incremental development
- Full ops 2009-10
Mass loss from the stellar surface

- α Ori lumpy, aspherical
- RSG clouds 5-10% $R_\star$ at birth
  - Star spots?
  - Chemical inhomogeneity?

- e-MERLIN, EVLBI
  - Image the star and its masers
- ALMA
  - Track the dust as it forms

HST

MERLIN+VLA 5GHz

VLA 43 GHz

Atmosphere of Betelgeuse

Morris et al.

Lim et al.
Track AGB/RSG wind from photosphere to ISM
(part of 'radio H-R' legacy group)

- 1612 MHz masers
- e-MERLIN, EVN
- OH 1665/7 MHz masers
- e-MERLIN, EVN
- H$_2$O masers
- e-MERLIN
- Dust
- ALMA, VLTI
- SiO masers
- VLBA
- Star radio photosphere
- e-MERLIN (+ALMA, VLTI...)

α Ori Lim+ Nature 1998
<table>
<thead>
<tr>
<th>Where</th>
<th>What</th>
<th>How study</th>
<th>What with</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>R· few AU, spots R·/10?</td>
<td>Photosphere 2500 K, star spots</td>
<td>Optical, IR, 5-25 GHz</td>
<td>eMERLIN/EVN, ALMA, VLTI</td>
<td>0</td>
</tr>
<tr>
<td>SiO masers 2-5 R·</td>
<td>2000 K gas small clumps</td>
<td>43, 86 GHz polarization</td>
<td>VLBA (Diamond)</td>
<td>1 – 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(monthly)</td>
</tr>
<tr>
<td>Dust forms 4 – 5  R·</td>
<td>1000 – 1500 K clumps? shells?</td>
<td>IR/sub-mm polarization</td>
<td>ALMA, VLTI, MROI</td>
<td>4 – 15?</td>
</tr>
<tr>
<td>H2O masers 5-25 R·</td>
<td>500 – 1500 K dense clumps</td>
<td>22 GHz polarization</td>
<td>eMERLIN/ EVN</td>
<td>5 – 25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(few mn)</td>
</tr>
<tr>
<td>OH mainline 8 – 100 R·</td>
<td>200 – 500 K diffuse gas</td>
<td>1.6 GHz polarization</td>
<td>eMERLIN/EVN/ global VLBI</td>
<td>8 and later</td>
</tr>
<tr>
<td>OH 1612MHz 50 – 100 R·</td>
<td>50 – 150 K tranquil gas</td>
<td>1.6 GHz polarization</td>
<td>eMERLIN/ EVN</td>
<td>Follow outer H2O</td>
</tr>
</tbody>
</table>