Masers around evolved stars
from kinematics to physics

Anita Richards
UK ARC, JBCA, Manchester

with thanks to

Al-Muntafki, Bains, Bartkiewicz, Diamond, Elitzur, Etoka, Gray, Humphreys, Murakawa, Rosa-Gonzalez, Szymczak, van Langevelde, Yates et al.

photos: Diah Gunawan
Overview

• Water maser 3-D kinematics
  – Radial acceleration
• AU-scale resolution
  – Water maser clumps in OH gas
  – Implies density, temperature contrast
  – Need e-MERLIN plus VLBI for full picture
• Test models of maser beaming
  – Spherical clouds or shocked slabs?
• How does star lose mass?
• ALMA+e-MERLIN+EVN submm to cm at mas resl'n
  – Star/masers/thermal lines/dust
  – Reconstruct detailed physical conditions
  – Suitable targets for early science/mm VLBI
Proper motions – expansion, acceleration

- MERLIN well-resolves 22-GHz water masers, detects all emission
  - Proper motion velocities consistent with Doppler acceleration
  - No significant rotation
- RT Vir clouds 1-2 AU
  - Shell inner radius determined by quenching density
  - Clouds ~50x over dense
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Dust-driven wind acceleration

- Bounds of resolved maser shells
  - CO outer limits
- Wind accelerates to 100s AU
  - Dust absorption coefficient increases
  - $\kappa_D \propto r$ (Chapman & Cohen 86)
  - Why do OH mainlines have bigger scatter?
  - IR shows dust properties evolve
    - Verhoelst et al.

Data: Bains+ 2003 (incl. CO refs), MERLIN H$_2$O, MERLIN+EVN OH
OH in unexpected places

- **OH mainlines** interleave outer H$_2$O shell
  - Greater spatial extent but less acceleration
  - More evidence for lower density (less efficient coupling to dust-driven acceleration).

- No 4-6 GHz OH detection is problematic constraint
  - Temperature required for OH excitation $<<$ H$_2$O
  - Need VLBI to probe more distant sources
Projection effect?

- **U Her**
  - Interleaved like RT Vir
- **Is this just projection effect in axisymmetric outflow?**
Maser survival

- U Her $\text{H}_2\text{O}$ 2000-2001
  - 14 clouds matched
  - Expansion 2.7(0.1) km/s
  - Rotation 0.3(0.1) km/s
- 4 epochs EVN OH
  - 3 reduced
  - Hope to measure proper motions
  - Deduce 3D structure and hence location
  - Is the OH really as close to the star as it looks?
OH mainlines need e-MERLIN+EVN

- EVN resolves out 30%-95% of emission
  - MERLIN-only barely resolves
OH mainlines need e-MERLIN+EVN

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Maser components and cloud sizes

Spherical
\[ D = 18 \text{ AU} \@ 1 \text{ kpc} \]

Channel maps every 0.2 km s\(^{-1}\)

Component measurements

Individual component has beamed size
Largest angular separation across all channels is actual cloud size (18±5 mas)
Beaming from spherical clouds

• “Amplification-bounded beaming”
  - $L$ = Measured size of multi-chan clouds
  - Observed (beamed) size $s$
    • Measured component size per channel
    - Brighter maser (peak $I_v$), tighter beam
    - $s \propto 1/\sqrt{\ln(I_v)}$

• Slope $\sim -0.5$-$1.5$ for S Per, RT Vir, IK Tau (mostly)
  - Bright, well-filled maser shell
    • Steeper may be due to saturation
  - Small-amplitude, less regular optical periods

\[ \log(s) \text{ v. } \log[\ln(I_v)] \]
Amplification bounded spheres

- Brighter components near line peaks are smaller
- Coherent, curved spatial distribution
Beaming from shocked slabs

- Shock 'into page'
  - Maser propagates perpendicular to shock
  - Pump photons escape orthogonally
  - Entire surface emission is amplified
  - “Matter bounded” beaming
  - apparent size ~ actual size ($s \sim L$)

- Slope $>> 0$ or large scatter for U Ori, U Her
  - Other evidence for shocks:
    - Regular, deep pulsations (AAVSO)
    - OH and H\textalpha{} flares (Etoka, Rudnitskj etc.)
Matter-bounded shocked masers

- Peak components often as large as in wings
- Tangled spatial distribution
- Fainter, poorly filled maser shells
Maser properties reveal wind disturbances

- Distinguish between smoothly expanding regions and those affected by pulsations
  - Need to detect ~all the emission
- e-MERLIN+EVN for OH

Based on
Richards Elitzur & Yates 2010
Elitzur Hollenbach & McKee 1992,
R Cas SiO

- 21 epochs (2 stellar cycles)
  - See poster by Al-Muntafki
- Infall/outflow?
- Or new shells emerging/old shell fading?
  - Seems to come from half the star in turn
- ALMA+ e-MERLIN + VLBI trace mass loss from star to ISM

Stellar image Weigelt et al. 96

20 mas
671 nm, 9/1994
ALMA evolved star masers

<table>
<thead>
<tr>
<th>Band</th>
<th>θ_B(16km/1km) (mas)</th>
<th>H₂O (GHz)</th>
<th>SiO (GHz)</th>
<th>HCN (GHz)</th>
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<td>3</td>
<td>40 / 650</td>
<td>96</td>
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<tr>
<td>5</td>
<td>20 / 320</td>
<td>183</td>
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<td>10-15 / 160-240</td>
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<td>300, 302, 336*, 343, 345</td>
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<td>9 / 145</td>
<td>437, 439, 471</td>
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<td>6 / 100</td>
<td>658</td>
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<tr>
<td>10</td>
<td>5 / 80</td>
<td>*isotopomer</td>
<td></td>
<td>805, 891</td>
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</table>

- **Multiple lines constrain physics much better**
  - e.g. Humphreys 2007 and refs
- Early science - VLA-like resolution
  - Full ops - cm-wave-VLBI-like resolution
(Sub)mm water

- Multiple transitions detected in circumstellar envelopes
  - Menten 96; Menten+ 06
- Guess locations from line widths/variability/correlation with cm transitions
Vibrationally excited water

- Widespread, wide velocity 658 GHz emission
SiO masers

- Many lines detected
  - $\nu = 0$ to 4, $J=1-0 \ldots J=8-7$
- Higher rotational transitions weaker, more time variable
  - Faintest at $\phi 0.4 - 0.7$

Menten+06, Humphreys+ 96, 97, Grey+ 98, 99, Pardo+ 98
Sub-mmaser model predictions

- Vibrational ground-state:
  - 321 GHz peaks close to star (inside dust formation region?)
  - Anomalously wide in symbiotic R Aql ([Ivison+98](#))
  - 183 GHz peaks resemble 22 GHz
  - 325 GHz wide span
  - Humphreys+ 01
Properties of (sub-)mm water

- Compare with cm-wave images
  - 70% 22-GHz sources have 321, 325 GHz emission \((Yates+ 96)\)
- 325 GHz spectra resemble 22 GHz
- 321 GHz narrower, weaker, more variable
- 183 GHz less variable
  - \((Gonzales-Alfonso+98)\)
Where is vibrationally extd water?

- Excited state $v_2=1$:
  - Probably within a few $R_*$
  - 658 GHz commonly strong
  - Correlation with SiO maser zone
  - Hunter+ 07
Masers around C-stars

- HCN 805, 891 GHz
  - Schilke+ 00, 03
- SiS
  - More lines from SOFIA
Thermal lines and dust
Thermal lines and dust

• 3-6 antennas already MANY lines
  - Resolve outer CSE in early science
• Dust &/or star continuum seen
• ALMA early science: 1-km baselines
  - 100-mas resolution at 650 GHz
  - ~5 $R_\star$ for AGB stars at 100-200 pc, RSG at 1-2 kpc
    • Dust formation complete?
    - Longer wavelengths - dust composition/grain size
• Full ALMA: 7 to 10-mas resolution
  - Size of water maser clumps
    • Mass ~0.1 - 0.5 $M_\odot$ (AGB), 1 -- 10+ $M_\odot$ (RSG)
    • Dust fraction ~ 0.1 -- 5 $M_\odot$
    • Detectable in a day / few hr
Results and prospects

- Kinematics
  - 0.1 km/s or better velocity resolution
  - Position accuracy ~ 0.01 – 1 mas
  - VLBI – MERLIN – ALMA

- Proper motions in weeks: full 3D structure, distance

- Trace mass loss from the star:
  - Clumps = Convection cells?
  - Asymmetry = Magnetic fields (stellar origin?)

- Evolutionary stage (rapid post-AGB changes)

- Physical conditions (model-dependent)
  - Constrain density, temperature, \( \tau \) (pump/cascade photons)

- Helps to have multiple transitions
  - ALMA: excited H\(_2\)O around 180, 300, 658 GHz...

- Some inside dust completion radius, some outside

- Resolve details of dust clumps and radio photosphere
  - Thermal lines e.g. CO - test density contrast explanation

**ALMA TEST results NGC 253**

- Observations made to test performance and observing strategies
  - Not science!
    - 1-2 hr, 4-6 antennas
    - Not “1st ALMA images”

- Observations made to test performance and observing strategies
  - Band 7/345 GHz CO J=3-2
  - Band 9/690 GHz CO J=6-5

- 0.12 mm PWV
ALMA ‘fringe meeting” Thu lunch

- ALMA early science
  - Band 3, 6, 7 and 9; 4 and 8 where possible
  - 16 antennas, 0.25 – 1 km baselines