Water masers and the physics of stellar winds

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Masers round cool late-type stars

- RSG VX Sgr Stellar disc at 2 μm Chiavassa+ 2010
  - $R_{\star}$ 4 mas ~ 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 $R_{\star}$ ~1 AU
  - Periods ~1 yr (RSG longer), $T_{\text{eff}}$ ~2300–3300 K
  - Mass loss $10^{-7} - 10^{-5} M_{\odot}/yr$
Masers resolve winds on AU scales

- **SiO >42 GHz (\(T_E >2000\) K) < 4 \(R_\star\)**
- **H\(_2\)O 22GHz (\(T_E \sim 650\) K), 5-30 \(R_\star\)**
- **OH 1612 MHz (\(T_E\) few K, long column depth), at >50 \(R_\star\)**
- **OH mainlines (1665-7 MHz) can overlap H\(_2\)O and/or extend as far as 1612 MHz masers**
What accelerates the wind?

- Water maser shell limits show $V_{\text{exp}} \propto r$
  - Relationship holds for $M_* \sim 1$ to $>10 \, M_\odot$
- $\tau$ or momentum coupling changes?
  - Ivezic & Elitzur'10
- Dust absorption efficiency evolves?
  - Chapman & Cohen 86; Verhoelst+
- Also seen in other lines incl. Herschel
  - Decin + '10
Mass loss problems

- Can pulsation drive mass loss from the star's surface?
  - Pulsation shocks \( \lesssim 5 \text{ km/s} \) (\( \lesssim 10 \text{ km/s} \) in RSG)

- Can radiation pressure on dust drive O-rich winds?
  - No: Woitke 2006
  - Yes: Alumina nucleation Wittkowski+ 2007
    - Large grains at 2 \( R_\star \) Barnaby+ 2012 (Nature)
  - SiO masers reach \( \sim 7 \text{ km/s} \) but also infall
  - \( \text{H}_2\text{O} \) masers show acceleration past escape velocity

- Who made all the dust?
  - Clumping scales – can it survive into the ISM?

- Do solitary stars produce axisymmetric PNe?
  - OH (and other) masers polarized, asymmetric
    - What is role of magnetic field?
22 GHz $\text{H}_2\text{O}$ channel maps

- MERLIN images
  - Compact front and back caps
  - Extended emission in plane of sky
- Accelerating radial outflow
- 10 mas beam $\theta$
- 2D Gaussian components
  - $\sigma_{\text{pos}} \sim \theta / (S/\sigma_{\text{rms}})$
  - 0.2 mas @ 10 Jy
Cloud measurements

- Each component beamed size
  - 1-2 km s\(^{-1}\) series
    - Gaussian spectra
      - \( \Delta V_c \geq \Delta V_{th} \)
  - Series = discrete clouds
    - \( R_{c\text{AGB}} \) 1 - 2 AU
    - \( R_{c\text{RSG}} \) 10-15 AU
      - \( 2R_c \geq \) gain length
    - Density/temperature/composition determines cloud size
      - Not just velocity coherence
Initially assume clouds $\sim$ spherical

- Linear strings of components indicate velocity gradient
  - Not necessarily elongated maser

- Internal gradients vary at $\sim$ sound speed

- Beaming angle
  $\Omega \sim \frac{\text{feature FWHM}}{\text{feature size}}^2$
Shrinking of brighter masers

- Brighter components near line peaks are generally smaller
- Coherent, curved spatial distribution
  - S Per, some AGB
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 \( \sim -0.5 \) to \( -1.5 \) for S Per, RT Vir, IK Tau (mostly)
  - Bright, well-filled maser shells
  - Small-amplitude, less regular optical periods

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

S Per
But sometimes brighter = bigger

- Spectral peak components swell
- Disorderly 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 $\gg 0$ or large scatter for U Ori, U Her
  - Other evidence for shocks:
    - OH 1612 MHz flares
      - Pataki+74; Chapman+85; Etoka+97
    - Regular, deep pulsations

\[
\log(s) \text{ v. } \log [\ln(I_v)]
\]
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?
  - Rapid maser variability
  - Stars with deepest periods
    - Shocked slabs

\[ \text{Spatial intensity profiles in a single velocity channel} \]

\[ \text{Amplification-bounded beaming} \]

\[ \text{Matter-bounded beaming} \]

\[ \text{Richards Elitzur & Yates 2011} \]
\[ \text{Elitzur Hollenbach & McKee 1992} \]
Water maser clumps scale with $\star$

- 22 GHz maser thick shell
  - $\sim 5 - 50 \ R_\star$
    - Ten-fold range of $R_\star$, SRs to RSG
- Cloud radius $\sim 1 \ R_\star$
  - Assuming radial expansion, birth radius 5%-10% $R_\star$
- Must be determined by stellar properties
  - Not dust cooling or other microphysics
    - Would be same scale for all stars
Cloud density

- **H$_2$O** 22 GHz maser $r_i$
  - Collision rate $<$ masing rate Cooke & Elitzur '85
  - Quenching density
    $\sim5\times10^{15}$ m$^{-3}$
- $\sim50x$ average wind density
  - Clouds 50-90% wind mass
    - Filling factor $\lesssim$1%
  - **H$_2$O** shell crossing times:
    - Few decades (AGB stars); $\lesssim$ century (RSG)
    - Imaged clouds last $\lesssim$2 yr (AGB), $\lesssim$10 yr (RSG)
      - Pushchino monitoring shows masers blink, clouds persist
- Overdense, probably hotter – how can clouds survive?
  - Frozen-in magnetic field?
S Per maser clumps

- MERLIN H$_2$O masers 22 GHz  
  - 10-mas beam
- EVN/Global VLBI 1.6 GHz OH mainlines  
  - Same resolution  
  - Interleave H$_2$O  
  - Extended OH resolved-out
Lower density surroundings

- **OH mainlines** interleave 22 GHz $\text{H}_2\text{O}$ clouds
  - Need $\sim 1/50$ $\text{H}_2\text{O}$ gas density, $T<500$ K
  - Seen for most RSG, about half AGB
- **OH 1612 MHz** further out where they belong
Modelling (sub-)mm water

- Vibrational ground-state models (*Humphreys*+01):
  - 325 GHz wide span
  - 321 GHz peaks close to star (inside dust formation region?)

- 183 GHz peaks resemble 22 GHz
  - Less variable (*Gonzales-Alfonso*+98)
(Sub)mm water maser spectra

Yates, Cohen & Hills '95, 96

VY CMa 325 GHz ALMA TEST spectrum

Menten+06
Observations of (sub-)mm water

- Compare spectral extent
  - 70% 22-GHz sources have 321, 325 GHz emission
    - (Yates+ 96)
- 325 GHz spectra resemble 22 GHz
- 321 GHz narrower, weaker, more variable
Tracing different conditions

- **Toy IK Tau model**
  - 658, 321 GHz peaks inside 22-GHz $r_i$
  - 325 GHz outside
  - 183 GHz spans dust formation
    - Neufeld+ 91, Humphreys+ 01
  - 325 GHz traces 22-GHz clumps?
  - 321 GHz excited state maser from inter-clump gas?
    - Equatorial density enhancement? biconical outflow?

- Gray, Baudry, Yates, Humphreys developing models
Proper motions

- 22-GHz masers identifiable ~1 yr
  - 5 km/s~4 mas/yr @ 250 pc
    - Trackable with MERLIN/ ALMA
- SiO near star has shorter life
  - 0.3 mas/month – VLBA
- Need VLBI for 321 (& 325?) GHz kinematics
  - Strong acceleration?
    - Dense clumps
  - Weak radial acceleration?
    - Surrounding gas
  - Outflow and infall like SiO?
    - Possible for 321-GHz masers
sub-mm maser physics

- Extended ALMA resolution similar to e-MERLIN
  - Resolve 325-GHz clumps if they are similar to 22 GHz
  - 321-GHz masers probably closer to star
    - Also from similar, radially expanding clouds?
      - More compact – need higher resolution
    - Or emanate from inter-cloud gas?
- \( R_{\text{cloud}} \sim 2 \text{ AU} @ 15 \, R_*; 0.4 \text{ AU} @ 3 \, R_* \) (1 mas @ 250 pc)
- Need to measure sub-mas component separations
  - Are brighter sub-mm masers smaller?
    - Emission from stable clouds is tightly beamed
  - Bright emission random-sized/more extended?
    - Suggests shocked material
Shocks and Turbulence

• How far does the stellar pulsational influence reach?
  – Why are SiO maser motions so disordered?

• Direct measurements of turbulence:
  – Line width fluctuations
  – Maser proper motions

• Fractal scales
  – Incompressible/ Kolmogorov within clumps
  – Shallower slope on larger scales suggests supersonic dissipation

• Need full range of scales
  – Strelniski+’02, Silant’ev+06, Gray’12
  – Richards, Lekht+’04
Copropagation

- Conditions for excitation of 321 and 325-GHz masers overlap
- Copropagation or segregation constrains temperature, density, velocity gradient
- Need positions to <<1 mas
- Only maser VLBI can achieve this in CSE
Band 7 GHz water masers

Observed Frequency

321.244 GHz
325.153 GHz

Goodish PWV

0.913mm (3rd Octile)

~10% transmission
VLBI sensitivity

- $\lambda \sim 0.9$ mm, $>6000$ km baselines
  - $<30 \mu$as resolution
  - Say, collecting area/conditions $\sim 1/2$ ALMA (32 ants)
    - $1$ mm PVW
  - Declination $-26^\circ$
- Sensitivity at $325$ GHz $\sim 0.2$ Jy in $2$ hr
  - $0.2$ km/s bandwidth, $30 \mu$as beam
  - $5\sigma$ $1$ Jy $\sim 1.3 \times 10^{10}$ K
  - $321$ GHz: $5\sigma$ $0.04$ Jy $\sim 5 \times 10^8$ K
- Maximum resolution $\sim 15 \mu$as, $0.03$ km/s
  - $325$ GHz needs $1.4 \times 10^{11}$ K for $5\sigma$ detection in $2$ hr
VLBI detectability

- Typical 22-GHz maser 0.1 – few mas
  - Resolved by MERLIN, VLBA
  - Peaks $10^9$ – $10^{14}$ K
- 325 GHz > 1000 Jy in VY CMa, 100 Jy in AGB stars
  - Likely to exceed $1.3 \times 10^{10}$ K
- 321 GHz masers often ~1/10 strength
  - But noise limits are better than 1/10 lower
- What about calibration?
  - Compact QSO continuum 1 Jy?
    - Bandpass dynamic range per 0.2 km/s ~10 in 10 hr 😞
  - Can this be mitigated?
  - Accurate delay vital to align lines
    - Reasonable amplitudes, especially for physics
Missing flux

- R Cas SiO 43 GHz, 176 pc
- Over half flux missed by VLBA
  - Scales > 5 mas
    - NB some polarization >100% - smaller-scale structure!
- VLBI likely to resolve out 90% of sub-mm masers
  - Still measure kinematics, fractals, co-propagation...
    - Total flux densities needed for full maser modelling
      - Need within weeks? Ideally days.
- ALMA will detect all the flux, separate clouds
  - Interpolate assuming Gaussian beamed profiles?
  - Detect star, provide astrometry?
- Can ALMA alone also help bandpass calibration?
  - e.g. half array phased, half extended?
Summary

• 321/5 GHz VLBI tests CSE clumpy mass loss model
  – Location:
    • Does 325 GHz trace 22 GHz?
    • 321 GHz from sub-AU clouds close to star?
      – and/or inter-clump gas further out?
    – Masers from ~spherical clouds or shocked slabs?
      • High-resolution beaming properties differentiate
    – Are clouds internally ~incompressible, but with large-scale motions like dissipative turbulence?
      • Different fractal degrees on μas v. mas scales
  – ALMA half & half VLBI, extended configuration
    – Detect all flux, star for astrometry
    – Per-phased-array bandpass calibration?