Masers
Precision probes of molecular gas

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A. Baudry, L. Decin, M.D. Gray, S. Etoka, F. Herpin, E.M.L. Humphreys,
I. Marti-Vidal, A. Sobolev, W. Vlemmings, J.A. Yates and many more
Environments of compact masers

• Active galaxies \textit{Impellizzeri}
• Galactic structure, astrometry \textit{van Langevelde}
• Circumstellar envelopes of evolved stars
  – How is mass ejected from the stellar surface?
    • SiO masers overlap radio photosphere (\textit{Matthews})
  – How is wind driven?
    • Composition and acceleration of clumps
• Star-forming regions
  – Accretion, interaction, jet launching....
• Maser physics
  – Physical conditions
    • Flares
    • Turbulence
  – Basic physics
Zones around the star
CSE radius: log scale

- Infall and outflow
- Accelerating expansion
- Pulsational shocks
- Waves
- Pulsation
- Convection
- Masers: 
  - SiO
  - H$_2$O 22GHz
  - OH 1665/7MHz
  - OH 1612MHz

- How is matter ejected from star?
- What transforms outflow / infall to radial acceleration?
- ~50x denser
- Same clouds? Re-form when dust condenses fully?

Adapted from Woitke Vesc
Transport across radio photosphere

- $2 \rightarrow 5 \ R_\star$ radio photosphere
  - $\lambda \ 1 - 6+ \ cm$
- Compare VLBA/KVN monitoring of SiO masers
  - VLA/e-MERLIN stellar continuum
  - 6 GHz stellar size
  - Optical/IR interferometry &/or ALMA dust formation?
- As done with SiO masers + VLTI in S Ori
  - Wittkowski et al. 2007

W Hya
Color Vlemmings et al. 338 GHz
Reid & Menten 22 GHz disc
Contours Cotton et al. 43 GHz
SiO masers
What forces act on SiO at 2-5 $R_{\star}$?

VLBA monitoring

- Heating $\Rightarrow$ expansion $\Rightarrow$ convection
  - Inside $2R_{\star}$: fails once $\tau_{\text{NIR}} < 1$
    - But + pulsation = waves Freytag
- R Cas SiO feature proper motions
  - Many directions, small net outflow
    - Consistent with $\dot{M} \sim 4 \times 10^{-7} M_\odot/yr$
- Flow mostly not along B lines
  - Minority of matched features have consistent polarization angles
    - Minority of those close to outflow, but more than any other direction
  - Magnetic field has enough energy to shape but not drive outflow
- Scattering by heat-resistant grains?
- Magnetic buoyancy?
  - Obs. evidence for small-scale field complexity; Lopez Ariste model
Resolving 22 GHz H$_2$O masers

- Each channel: beamed components:
- Fit 2-D Gaussian, FWHM $s$ (0.01-10 mas)
  - Uncertainty $\sigma_{\text{pos}} \propto (\text{beamsize})/(S/N)$
- Series make features (e.g. A - D):
  - Gives 'true' cloud size $L$ (2-100 mas)

- $\theta_B < ($few$)100$ mas resolve $L$
- $\theta_B \lesssim 25$ mas also resolve $s$
  - Beaming angle $\Omega = s^2/L^2$
    - Shock v. quiescent clouds
    - Accurate $T_b$
- $\theta_B \lesssim 5$ mas resolve out?
  - If shortest spacing $\lesssim 80$ mas (1.5 M$\lambda$)
22 GHz maser clouds over-dense

- Filling factor (<1%), mass loss rate and quenching density suggest 22-GHz clouds are 30 - 80 x average wind density

- Birth size 5-10% $R_*$
  - If clouds expand radially in outflow

Richards+ 2012
Maser beaming

- Linear strings of components indicate velocity gradient
  - Not necessarily elongated maser
- Internal gradients vary at ~sound speed
- Symbol size \( \propto \) beamed component size \( s \)
- Beaming angle
  \[ \Omega \sim \frac{\text{feature FWHM}^2}{\text{feature size } L} \]
  - feature FWHM \( \sim s_{\text{peak}} \)
Shrinking of brighter masers

- Component size $s$
- Intensity $I_{\nu}$
- Brighter spots are smaller

$s \propto \frac{1}{\sqrt{\ln(I_{\nu})}}$

“Amplification-bounded” beaming from $\sim$ spherical clouds
But *sometimes* brighter = bigger

- Spectral peak components swell
- Disorderly spatial distribution
But sometimes brighter = bigger

- Spectral peak components swell

- Shock 'into page'
  - Maser propagates perpendicular to shock
  - Pump photons escape orthogonally
  - Entire surface emission is amplified
  - "Matter bounded" beaming
  - Apparent size \( \sim \) actual size
Maser (negative) optical depths for some of the ~50 lines of H$_2$O visible to ALMA as functions of kinetic temperature & o-H$_2$O number density.
VY CMa maser model (Gray)

- 658, 321, 325 GHz deeper shade = stronger maser $\tau$
- 22 (solid), 183 (dotted) GHz heavy contour at 50% max $\tau$
- Lowest contour at crude estimate of sensitivity limit
ALMA SV VY CMa multi-λ water masers

- 183 GHz masers very extended as predicted
  - Distribution similar to/within HST scattered light (as are OH)
  - Follows small, cool dust grains/extends to low densities

183 GHz masers over HST contours/grey Smith+2001

- 183 GHz also found close to star
- Excited in exceptionally wide range of parameter space
VY CMa sub-mm H$_2$O masers

Star, VY

- 658-GHz surprisingly extended round cold clump C
  - Shock?
  - OGorman+15

- 325 GHz furthest
- 658 GHz closest
- 321 GHz between
  - Clearest strong acceleration
  - Richards+14
Zoom in on 5 transitions

- $\text{H}_2\text{O}$ components
- Size $\propto \sqrt{\text{flux density}}$
- VY at (0, 0)

- 321, 325, 658 GHz obs 2013
- 183 GHz obs 2016
Angular separation-velocity

- Well-defined inner shell limits

- 22 GHz outer
- 658 GHz outer
- 183 GHz inner
- 22 GHz inner
- SiO outer
- 658 GHz inner
Temperature constraints

- Roughly supports Decin model (which includes dust formation feedback & variable mass loss rate)
Number density constraints

- Number density 50 or more \(n\) x higher often needed
  - Dense clumps?
Extending to 30-50 km baselines

- c. 50 predicted H$_2$O maser transitions in ALMA bands
  - $T_b \geq \text{few } 10^4 \text{ K (representative } \nu, \text{ good & bad transmission)}$

- Detectable at 10-20 mas resolution in 30-60 min
  - Resolve all maser emission, model physical conditions

<table>
<thead>
<tr>
<th>1st octile</th>
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<th>Resolution/3</th>
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Extending to 30-50-3000 km baselines

- c. 50 predicted H$_2$O maser transitions in ALMA bands
  - $T_b \gtrsim$ few $10^4$ K (representative ν, good & bad transmission)
  - Detectable at 10-20 mas resolution in 30-60 min
    - Resolve all maser emission, model physical conditions
    - GMVA/EHT-type baselines for proper motions of peaks

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Continuum detectable on 50 km b'lines

- Stellar/dust continuum extremely valuable, including:
  - Register masers
  - Self-calibration across the band in 20 sec solint
- Sufficient S/N simultaneous with masers at same resoln
THz water masers in CSE

- AGB W Hya, UHer;
- RSG VY CMa
  - Neufeld et al. 2017
- 1.278, 1.296, 1.885 THz, SOFIA GREAT
- Thermal, Maser, Quasi-thermal
- THz masers saturate at lower maser gain than 22 GHz
Resolving out

- MERLIN (200-km) gets all 22 GHz flux at >100 pc
- Even ground-based VLBI resolves-out more than half
  - Even at a few kpc
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  - How is wind driven?
    - Composition and acceleration of clumps
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- Maser physics
  - Physical conditions
    - Flares
    - Turbulence
  - Basic physics
Cepheus A RadioAstron

- SF region at 700 pc
- RadioAstron-Yebes
  - 3.3 Earth diameter baseline
- Fit 15 μas spot FWHM s ≲ 0.01 au
  - 0.6 km/s, 80, 40 Jy components
- $T_b > 2 \times 10^{14}$ K

Total power (Yebes)
~800 Jy peak
Detected RA-GB

Rapid variability Pushchino

Sobolev et al. 2018
Sun-sized spots in CepA

- High 22-GHz gain if gas:dust ratio v. high (or dust cool?)
  - IR radiation quenches collisional pumping
    - YSO circumstellar/protoplanetary discs e.g. dust has coagulated (low $n_{\text{grain}}$ density)?
    - Cloud overlap (Cep A needs complex distribution)?
    - Multiple turbulent vortices?

Compact components at $\sim0.6$ km/s

Ground-based baselines peak 540 Jy
SFR also resolved-out, weaker sub-mm?

- Cep A 321/22 GHz 1/700
- W49 321/22 GHz 1/60; 325/22 GHz 1/8 Menten'91
Some SFR strong (sub-)mm H$_2$O masers

- Orion KL:
  - 658/22 GHz > 1/2
  - Spatially distinct
  - Other masers much weaker
- 183 GHz strong, common
  - But extended?
    - Chernicharo '99
    - Test with ALMA

*Cernicharo+’90* Orion KL Hirota+’16
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Most likely SOFIA maser (stepped line spectrum) Matches e-MERLIN line from hottest part of IRS1 as expected for THz maser

22 GHz Effelsberg, e-MERLIN
1296 GHz SOFIA
1st THz maser in SFR
Herpin et al. 2017
Why are compact 22-GHz masers seen around YSO but not evolved stars?

- RadioAstron: 7 Galactic SF at 22 GHz, 22-180 μas resolution and 2 in OH at 1-few mas resolution. No evolved stars.
- Cep A: 0.6 km/s peak region $L \sim 1$ au; spot $s \sim 0.01$ au
  - Estimate beaming angle $\Omega \sim (s/L)^2 \sim 0.0001$ sr
  - More evidence for maser saturation so tighter beaming
- Evolved star CSE gas:dust $\sim 200$ at $>5R_*$
  - Dust probably hotter than gas in 22 GHz region
    - Weakens collisional pumping, suppresses radiative pump
  - 658 GHz also v. bright, less variable - more saturated?
  - 183 GHz worth investigating
  - Even brighter predicted $\text{H}_2\text{O}$ masers accessible from space
    - 120, 793, 899, 1077, 1486, 1689, 1849, 1873 GHz
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    - Flares
    - Turbulence
  - Basic physics
183 & 22 GHz blue-shifted flare 2013-16

- VY CMa \( V^* \) 22 km/s, 22-GHz peak \( \sim 18 \) km/s for decades
- 2016 183-GHz peak \( \sim -1 \) km/s as bright as \( \sim V^* \) peak
- 1994, 2000 weak 22 GHz \( \sim -1 \) km/s
- 2013 KVN 22 GHz \( \sim -1 \) km/s \( \sim 30\% \) of central peak
- 2016 22 GHz similar new peak: \( \sim -1 \) km/s \( \sim 90\% \) of central peak
Clump 'C' shock?

- Continuum contours
- 658-GHz masers appear to curve round 'C'
  - Wind collides with cold, dense clump?
    - O'Gorman+14
- All masers, many lines avoid 'C'
  - Only seen at velocities very different from $V_\star$ in that direction
Shocks round clump C?

- 2016: 183 and 22 GHz flares around -1 km/s
- 2013 (KVN): 22 GHz flare starts?
- Both lie between VY & Clump C
- Probably not co-spatial
  - 22 GHz aligned only by centre of expansion

*NB faint &/or extreme velocity emission not shown*
W Hya localised flare

- W Hya $>10x$ increase of 40 km/s peak ($\sim$3000 Jy)
  - Pushchino monitoring (Rudniskij)
  - MERLIN imaging
Cloud overlap

- Two spectrally and spatially discrete features
- Exchange places spatially during flare
- Foreground amplifies background
  - Predicted by e.g. Kartje, Konigel & Elitzur
Maser properties reveal wind disturbances

- Brighter = smaller beamed size?
  - $s \propto \frac{1}{\sqrt{\ln(I_v)}}$
  - Smoothly expanding spheres

- Brightest emission \sim cloud size?
  - Thinner shells/inner edges
  - Rapid maser variability
  - Stars with deepest periods
  - Shocked slabs/flares

Richards Elitzur & Yates 2011
Elitzur Hollenbach & McKee 1992
Fractal scale metric for turbulence

- Direct measurements of turbulence:
  - Line width fluctuations
  - Maser proper motions

- Fractal scales
  - Incompressible/Kolmogorov within clumps
  - Shallower slope on larger scales: supersonic dissipation?

- Need full range of separation scales
  - Inside & between clouds

SFR S128A (22 GHz) Richards, Lekht+ '04, Gray'12, Strelniski+ '02, Silant'ev+06,
Non-Gaussian statistics

- Saturated masers may show residual coherence due to stimulation of emission ([Gray'12](#))
- Spectral resolution $\sim 2$ Hz (Lorenz width) sampled at $\frac{1}{2}$ sec
  - Sample line widths - Fourier components of avg. 'line'
    - (tens) mas resolution to avoid blending
    - 1000s Jy 6 GHz methanol etc. bright enough for eMERLIN
- Time coherence test, $\mu$s sampling
  - Single dish, [Takefuji+'16](#)
  - Coherence scale 30$\mu$s for W49N
    - $\gg 5\mu$s expected for Gaussian stats
    - Can't correct atm that fast
      - Try from space
        - 22, 183 GHz
          - Need $\mu$s sampling
Summary: High-res/ space maser science

- Proper motions
  - Evolved star mass loss mechanisms
  - Star-formation jet launching, proto-planetary discs
- Physical conditions on au scales or less (multi-transition)
- Magnetic fields (avoid beam depolarization)
  - Polarized flux maybe less resolved-out than total intensity
- Beaming: distinguish shock v. overlap amplification
  - Test saturation state
- Turbulence: extreme amplification, fractal scales
- Non-Gaussian photon statistics
  - Very high time and spectral resolution
  - Maybe practical up to 183 GHz incl. single dish
What do we need?

• Few Earth-diameter baselines at cm wavelengths
  – Plus multiple scales down to ~100 km
• Polarization - circular and linear - often strong
• Rapid (weeks) response for flares
• Potentially highly beamed (sub-)mm masers
  – Test with spectral line VLBI $\lambda < 3\text{mm}$!
    • LLAMA and ALMA extended baselines needed
• Great single dish space potential for (sub-)mm masers
  – Meths has multiple transitions
    • Sample a range of SF conditions
• I volunteer for the servicing mission...