How do stellar winds break free from the star's gravity?

Anita Richards, UK ARC, Manchester

with thanks to ALMA and e-MERLIN/EVN colleagues

Acceleration of clouds
Inhomogenous mass loss
Shocks and turbulence
Mass loss from AGB/RSG stars

- Stellar pulsations lift photosphere
  - 5-7 km/s (Reid+’97)
  - Dissipated at >5R_✶_
- Wind cools, dust forms
  - Radiation drives grains

\[ \sim 5 \text{ stellar radii} \]

- SiO masers show infall/outflow at <5R_✶_
  - How can this lead to steady expansion?
  - Pressure on small O-rich grains not efficient Woitke06

- Scattering on larger grains (low-mass stars, Norris+12)?
- Radiation pressure on lines?

- How is matter ejected from the stellar surface?
  - Pulsation?
  - Convection/star spots?
  - Magnetic forces?
Water maser cloud measurements

- Fit 2D Gaussian component to each spot:
  - Measure beamed size
  - Spots in 1-2 km s\(^{-1}\) series
- Series = discrete clouds
  - Clouds 30-100 x overdense
    - Filling factor <1%
    - Contain 30-90% mass
  - Few formed per stellar P
- Beaming angle
  \[ \Omega \sim \left( \frac{\text{peak spot size}}{\text{feature size}} \right)^2 \]
OH masers interleave H$_2$O

- Mainline OH inner rim in 22-GHz H$_2$O shell
  - 22 GHz 400-1200K, $n \leq 5 \times 10^{15}$ m$^{-3}$ (quenching density)
  - OH needs <500K, lower density gas
- Abundance differences?
- 22 GHz H$_2$O masers concentrated in dense clumps
  - OH from gas in between
- Seen for other evolved stars
  - OH 1612 always outside H$_2$O
22 GHz cloud size depends on star size

$$R_{\text{cloud}} \sim (0.7 \pm 0.3) R_*^{1.0 \pm 0.1}$$

Richards+12+ refs therein

- Cloud properties determined at ejection from star
  - Not micro-physics of dust cooling
- If outflow expands as $r^{-2}$, birth radius $(5\text{–}10\%) R_*$

- VLTI etc. observations & convection cell models suggest stellar surface inhomogeneities on $\sim 10\%$ scale
  - Wittkowski+11; Chiavassa+
Shrinking of brighter masers

- Component size $s$
- Intensity $I_v$
- Brighter spots are smaller

$s \propto 1/\sqrt{\ln(I_v)}$

"Amplification-bounded" beaming from ~spherical clouds
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 ~ actual size
Maser properties reveal wind disturbances

- Brighter = smaller beamed size?
  - Smoothly expanding spheres
- Brightest emission often ~cloud size?
  - Rapid maser variability
  - Stars with deepest pulsation amplitudes
  - Unusual OH flares
    - Shocked slabs

Richards Elitzur & Yates 2011
Elitzur Hollenbach & McKee 1992
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: supersonic dissipation? Strelniski+'02, Silant’ev+06, Gray’12, Uscanga
• Need full range of scales
  – Inside and between clouds

SFR S128A (22 GHz)
  – Richards, Lekht+’04
Sub-mm water maser predictions

Humphreys+‘01
Neufeld+‘91,’10

22 GHz \( E_U \) 643 K

321 GHz \( E_U \) 1862 K

658 GHz \( E_U \) 2361 K
Expect to be even more compact (in SiO zone)

325 GHz \( E_U \) 470 K
ALMA SV observations of sub-mm masers

- Baselines up to 2.7 km
  - First resolved images
  - Locate VY CMa star

- 325-GHz most extended, as predicted
  - Moderate acceleration

- 321-GHz similar distrib. to 22 GHz
  - Strong acceleration

- 658-GHz starts at few $R_\star$, inside dust formation radius – OK
  - Extends to tens $R_\star$!
Spatial distribution

- 658 GHz starts inside dust formation zone
  - But at larger radii than SiO
  - Extend almost to where OH begins!!!
- At least 325-GHz is as predicted
  - Low excitation temperature, large inner radius
- 325-GHz some faint extreme-velocity emission
  - Close to line of sight to star
  - Moderate acceleration
• 325-GHz extends to lower wind densities than 22 GHz
  – But more easily quenched
• 321- inner overlap with 22-GHz
• First 658-GHz model
  – Hard to explain observed extension
• Different lines – different beaming?
Shocks and inhomogeneities

- 658- and 325-GHz masers appear to curve round 'C'
  - Wind colliding with dense clump?

Can shock heating explain extended high-excitation lines?
  - Rel'nship shocks/dust (Hoffner)

- Species separate 10-au scales
  - At similar radii but in different-density environment/clumps?
    - Not co-propagation
VLBI + ALMA for sub-mm masers

- Sub-mm VLBI needed to resolve proper motions, spots
  - Multiple species: constrain temperature, density, $V$ field
    - Maser physics, fundamental physics (non-Gaussianity)
  - Kinematics, fractals, (non)co-propagation...
    - Shock/turbulence diagnostics on sub-au scales
  - Similar sub-mm water maser science possible in SFR
- AGB/RSG spot at few 100s/1000s pc: $\leq 0.1$ – few mas
  - Whole clouds up to few tens mas
    - Total flux densities needed for full maser modelling
  - Need 0.5 km/s spectral resolution, if possible finer
    - But also continuum for calibration sources?
- ALMA subarray e.g. 0.5 -15 km to detect all the flux
  - Detect star, provide astrometry, help calibration
  - LLAMA? (~100s km South American baselines)
Spectral line VLBI at 321/325 GHz???

- Most telescopes with 230 GHz have 345 GHz band
- Masers few Jy per 40 μmas beam per 0.5 km/s
  - 1-hr sensitivity ten(s) mJy
  - RadioAstron (similar bm) detects 22 GHz masers
- Biggest challenge bandpass calibration?
- Next... 658 GHz VLBI?
  - Polarization?
    - Avoid Faraday rotation/beam depolarization!