Hidden bipolarity in cool supergiant circumstellar envelopes

- SiO with in few $R_\odot$
- $H_2O$ $R_{dust}$ - tens $R_\odot$
- Molecular chemistry
- Dust annealing
- OH outside $H_2O$?

Masers in AGB & RSG CSEs

- Using MERLIN, EVN/Global VLBI and VLBA
- Morphology at 0.1 - 1 au resolution
- Kinematics at 0.1 - 0.2 km/s resolution
- Circular and/or linear polarization
- Magnetic shaping of the wind
- Field configuration
- Origin of magnetic field

'Solitary' evolved stars undetectable surface/wind rotation

- Massive: progenitor $> 8 M_\odot$
  - Red Supergiants
    - Also M types, similar $T$
    - $P$ few yr, even less regular
    - $V_{wind}$ 6 - $> 30$ km s$^{-1}$
  - $R_c \sim 10 +$ au
  - Cloud $r_{proj} \sim 10$ au
  - $dM/dt > 10^8 M_\odot$/yr
- Low mass: $\sim 1$ - a few $M_\odot$
  - SR and Mira variables
    - Late M, $T$ 2000 - 3000 K
    - $P \sim 1$ yr
    - $V_{wind}$ 3 - 15 km s$^{-1}$
  - $R_c \sim 1$ + au
  - Cloud $r_{proj} \sim 1$au
  - $dM/dt \sim 10^7 - 10^8 M_\odot$/yr

- Most SNR (incl. Type 2) axisymmetric
- RSG winds partly biconical
- Magnetic fields
- No degenerate core!
S Per maser shell shapes

- Almost spherical?
- Elliptical distribution of hotspots
- Stellar asphericity:
  - Thompson & Creach-Eakman 03: 2.2μm interferometry
  - Minor axis PA 40°
- Also seen in SiO
- Diamond: ~monthly VLBA monitoring 1999/09-2000/04

OH mainline masers interleave H₂O

- MERLIN H₂O (blue)
- EVN/global mainline OH (contours)
- OH mainlines interleave H₂O
- Clump radii
  - r_OH~9 au
  - r_H₂O~9 au
- OH masers so close to star:
  - T_OH~500 K max?
  - T_H₂O~1000 K

Dust-driven winds

- Some H₂O & OH mainlines reach high velocities
- Some, especially OH 1612, slower
- H₂O clumps dustier, better accelerated
- Tangentially beamed
- Interleaving gas supports OH mainlines near star
- Radially beamed
- OH 1612 further out
- Needs ~steady velocity
**OH Asymmetry**

- 1999 MERLIN
- OH 1612 MHz
- Axisymmetry for several centuries
- Box shows H$_2$O/
  mainline OH region

**OH Zeeman Splitting**

- Circular \( V = (RR-LL) \)
- \( B \times \Delta V_2 = \Delta V_{LSR(RR-LL)} \)
  & MHz & \( \mu T/\text{km s}^{-1} \) & 1665 & 0.17
  & 1667 & 0.28
- If \( \Delta V_2 < \Delta V_{LSR} \times dl/dV_{LSR} \)
  & Only measure \( B \parallel \)
- Mitigate by measuring \( \Delta V_{LSR(LR-LL)} \)

**Observed:)**

- LL, RR, LR, RL Stokess
- I, Q, U, V Davie (74)
- Elitzur
- Watson
- Gray

**Contraversies...**

**Zijlstra et al. 2002**

- OH Zeean Splitting
- Linear \( P = \sqrt{Q^2 + L^2} \)
- Pol. angle \( \chi = \text{atan}(U/Q) \)
  & \( \chi \neq 0 \) & \( \parallel \) & \( B \parallel \chi \)
  & \( \chi \neq 0 \) & \( \perp \) & \( B \perp \chi \)
- If \( \Delta V_2 < \Delta V_{LSR} \) & \( i(B) > 55^\circ \)
  & then \( B \perp \chi \) (?)
**Zeeman components**

- Circular polarization direction (>25% pol.)
- Stokes $V \pm /-$ implies $\pm 90$
- Some clumps dominated by single direction
- Zeeman pairs in EVN data
- $7/2 @ 1665/7$ MHz
- Typical $\Delta V_2 \sim 1$ km s$^{-1}$
- $0.1 < B < 0.8$ $\mu$T
- 1 alternative $\Delta V_2$ 12 km s$^{-1}$
- $B \sim 3.4$ $\mu$T
- 8 pairs in MERLIN data
- Mean $B$ from all data:
  - magnitude 0.3 $\mu$T

**Linear Polarization**

- Seen in near side only
- Pol. vector angles $\chi$
  - Mostly $\perp$ outflow
  - Mean $\Delta \chi$ across clump $16^\circ$
- Interpretation:
  - $\sigma$ components?
  - Implies $\chi \perp B_{\text{axis}}$
  - $B_{\text{axis}} \parallel$ biconical outflow
  - But $\chi$ changes in S
  - $B \sim 55^\circ$ to l.o.s. (Elitzur)?
  - $\chi \parallel B_{\text{axis}}$
  - Or $\pi$ component?
  - (but $V \neq 0$)
  - Or partial conversion $P \rightarrow V$
**H₂O Zeeman splitting**

- S Per VLBA (Vlemming, Diamond & van Langevelde 02)
- \( B_{||} \approx 20 \mu T \) (70-200 mG) (model-dependent)
- Brightest H₂O masers @ \( R \approx 90 \) au (2.3 kpc) - take \( B \approx 15 \mu T \)

**Faraday rotation & magnetic pressure**

- Estimate electron density \( n_e \) from Faraday rotation
- \( \Delta \chi^2 = 0.15 B_{||} (T) n_e (m^3) r_{OH} \) (cloud size, au)
- \( |B_{OH}| \approx 0.3 \mu T \) (circ. pol.), \( r_{OH} \approx 9 \) au, \( \Delta \chi \) typically 16°
- \( n_e \approx 4 \times 10^7 \) m⁻³ (fractional ionisation \( \approx 10^{-6} \))
- Shell inner radius \( R_{OH} \approx 80 \) au, \( \Delta \chi \) (back-front) > 180°
- Far side depolarised by inhomogeneous \( n_e \), or Alfvén waves
- Consistent with OH depolarisation in R Crτ, W Hya, VX Sgr
- Thermal/magnetic pressure \( \beta = 10^{-8} \pi n k_B T / B^2 \)
- Typical region densities OH \( n \sim 10^{13} \) m⁻³, H₂O \( n \sim 10^{15} \) m⁻³
- \( \beta (H_2O) \sim 0.1 \) (7-1000 K) - strong mag. pressure
- \( \beta (OH) \sim 2 \) (T \~ 500 K) - significant but not dominant
- Pressure balance problem?
- Wind is supersonic...
- Dust-gas coupling better in magnetised clumps?

**S Per magnetic field**

- OH mainlines \( B \approx 0.3 \) µT at up to 140 au
- H₂O \( B \approx 15 \) µT at \(~ 90 \) au (brightest masers)
- Stretched dipole? \( B \propto R^2 \), expect 6 µT @ 140 au
  - 6 µT would split OH by \~ 18-30 km/s; aligns ambiguous
- Selection effect?
  - Only strongest/weakest splitting detectable in H₂O/OH?
- H₂O clumps \~ 50x denser than OH gas (Richards + 99)
  - Frozen-in \( B \propto n^{-0.3 \sim 0.5} \) (Mouschovias 87)
    - \( n \propto R^{-2 \sim 3} \) (no/strong acceleration) so frozen-in \( B \propto R^{-1 \sim 1.5} \)
  - \( B(H_2O) \) @ \( R \sim 30 \mu T \) where \( B(OH) \) would be \~ 4µT
- Extrapolate to 140 au (stretched dipole) \( B(OH) \approx 0.6 \) µT
  - This implies clump \( B \gg \) inter-clump \( B \) after dust forms

**VX Sgr OH/H₂O axisymmetry**

- OH 1612 polarization vectors
- Dipole magnetic field
  - Axis p.a. \~ 20°
  - S approaching
  - (Szymczak+)
- H₂O \~ spherical
  - Lower density bicone (\< 1)
  - Aligned about mag. axis
  - (Murakawa+)
**VX Sgr OH/H₂O axisymmetry**

- EVN OH mainlines
  - In H₂O shell
  - No obvious pattern

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**Wind evolution - bipolarity increases?**

- NML Cyg
  - Inner shell elongated
    - Polarization vectors \( || \)
  - Old 1612 MHz shell lower \( \epsilon \), tangential pol. vectors
  - Etoka & Diamond 04
  - Multiple elongated OH shells (Masheder, Diamond)
  - Multiple dust shells (Monnier et al.)

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**First spectral-line real-time VLBI**

**IRC+10420**

- 10 M\( \odot \) RSG
  - heading for WR
- 1970's G0-F8
- Now A5 - 8500K!
  - (Klochkova et al.)
- No H₂O masers
- ?Fossil? molecular shell with OH masers
  - \( r \approx 7500 \) au @ 5kpc
  - 200x solar system
- OH Vexp 40 km/s
  - Shell shows 900 yrs of wind history
- OH 1612 spherical?
**What is magnetic field origin? How does it act on the wind?**

- Negligible stellar surface rotation
- Bipolarity in winds, magnetic field
- *Blackman+ 01*: $\alpha - \omega$ dynamo?
  - Differential rotation in layers, fast core, convection
  - Dipole field in wind channels dust grains?
- No degenerate core in RSG
- S Per B not consistently $r^7/r^3$
  - Neutral dust not affected in CSE (hotter than gas)
  - Dust charged? Or field acts more on plasma fraction?
    - Observations show dusty clumps accelerated not braked
- *Soaker & Zoabi 02*: $\alpha^2$ turbulent dynamo
  - Not strong enough to influence whole wind
  - Could produce cool spots $\Rightarrow$ enhance dust formation
  - Shock compression enhances radial magnetic field
    - Field frozen in to maser clumps (Hartquist & Dyson 97)?

**The stellar surface**

- $\alpha$ Ori lumpy, aspherical
- RSG clouds 5-10% $R_\odot$ at birth
- Star spots?
- Chemical inhomogeneity?
- Convection cells?

*HST

$\alpha$ Ori Freytag+ 02

1-3 large starspots

Giant convection cells

Local magnetic field enhanced

$U_\parallel \sim \exp^t$*