Hidden bipolarity in cool supergiant circumstellar envelopes

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- **Using MERLIN, EVN/Global VLBI and VLBA maser observations**
  - **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

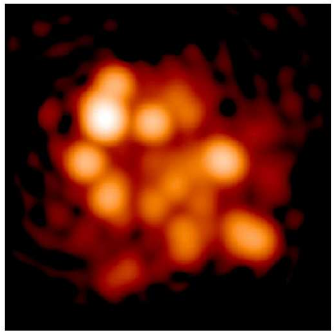
undetectable surface/wind rotation

- **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}
    - $R_☆$ ~ 10+ au
    - Cloud r_{H2O} ~10 au
    - dM/dt >10^{-6} $M_\odot$ /yr
- Most SNR (incl. Type 2) axisymmetric
  - RSG winds partly biconical
  - Magnetic fields
  - **No degenerate core!**

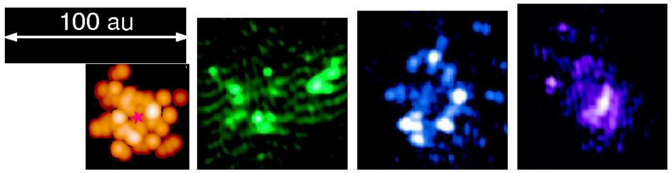
- **Low mass: ~1- a few $M_\odot$**
  - SR and Mira variables
    - Late M, T 2000 - 3000 K
    - P ~ 1+ yr
    - V_{wind} 3 - 15 km s^{-1}
    - $R_☆$ ~ 1+ au
    - Cloud r_{H2O} ~1au
    - dM/dt ~10$^{-8\,-\,-6+}$ $M_\odot$/yr
- Most (P)PNe axisymmetric
  - Asymmetry starts on AGB
  - Dectectable magnetic field
  - WD core spin + convection?

Masers in AGB & RSG CSEs

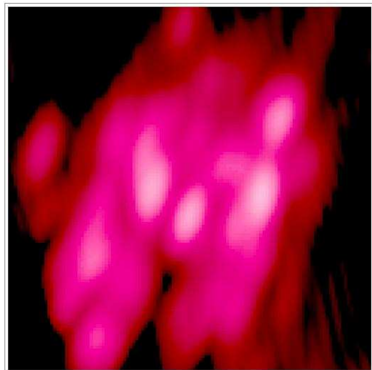
- SiO within few $R_☆$
- H_2O R_{dust} - tens $R_☆$
- Molecular chemistry
- Dust annealing
- OH outside H_2O?



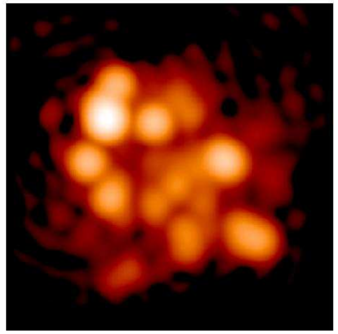
SPER



RT VIR IK TAU U HER U ORI



VX SGR



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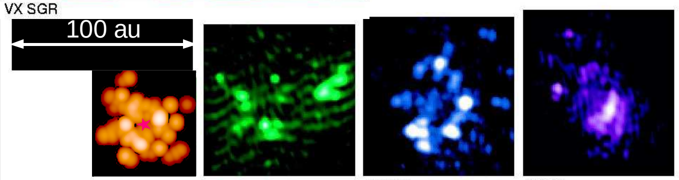
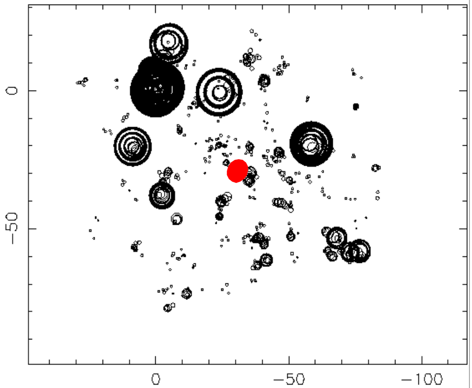


RT VIR IK TAU U HER U ORI

S Per maser shell shapes

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



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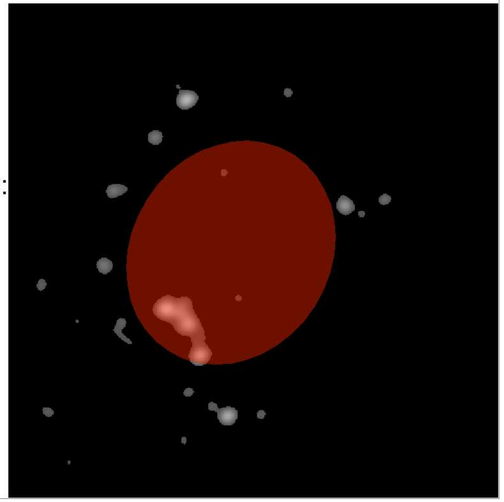
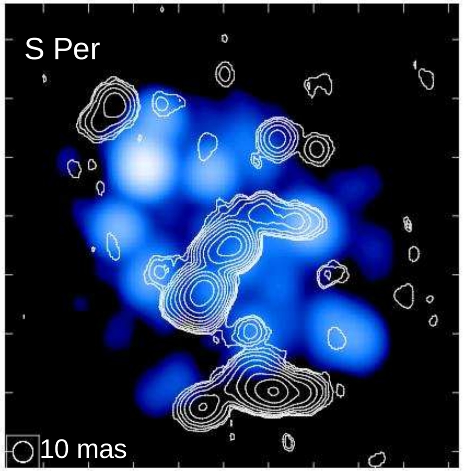
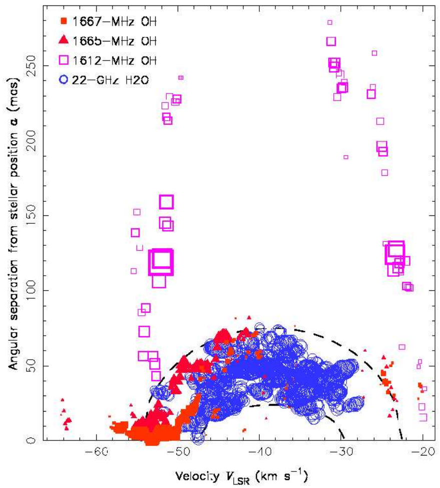


OH mainline masers interleave H_2O



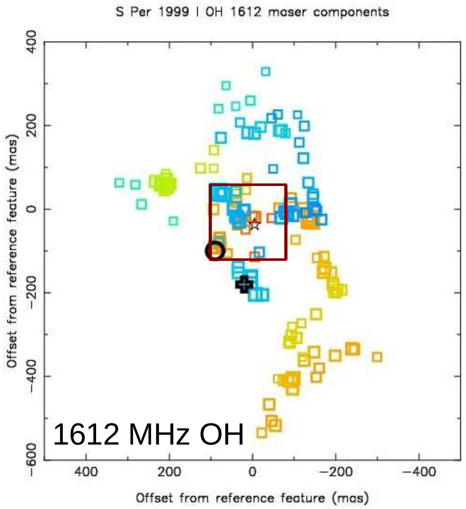
- MERLIN H_2O (blue)
- EVN/global mainline OH (contours)
- OH mainlines inter-leave H_2O
- Clump radii
  - r_{OH}~9 au
  - r_{H2O}~9 au
- OH masers so close to star!
  - T_{OH}~500 K max?
  - T_{H2O}~1000 K

Dust-driven winds



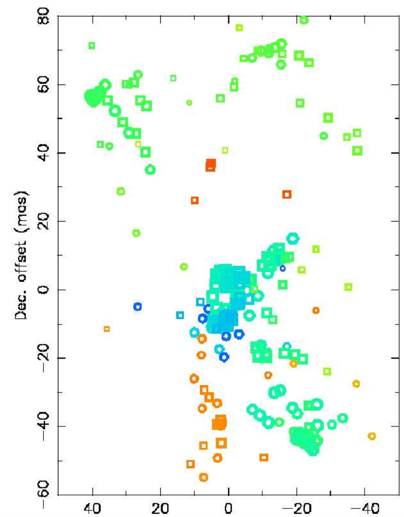
- Some H_2O & OH mainlines reach high velocities
- Some, especially OH 1612, slower
- H_2O clumps dustier, better accelerated
  - Tangentially beamed
- Interleaving gas supports OH mainlines near star
  - Radially beamed
- OH 1612 further out
  - Needs ~steady velocity

OH Asymmetry



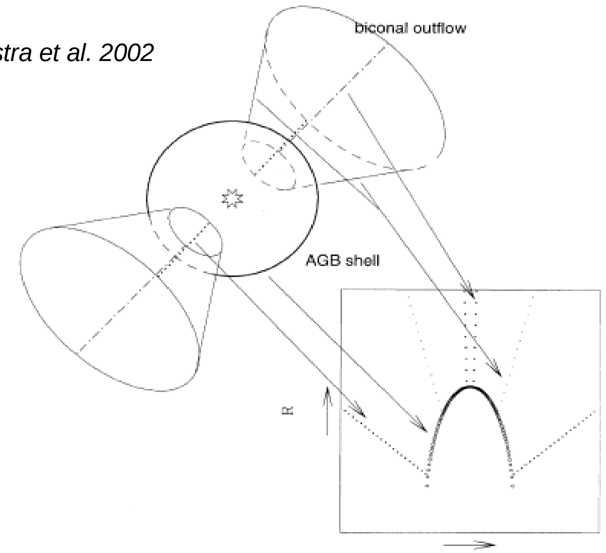
- 1999 MERLIN
- OH 1612 MHz
  - Axisymmetry for several centuries
- Box shows H_2O/ mainline OH region

OH Asymmetry

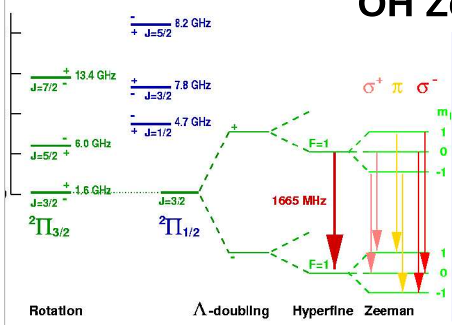


- 1999 MERLIN
- OH 1612 MHz
  - Axisymmetry for several centuries
- Box shows H_2O/ mainline OH region
- O/☐ 1665/7 MHz
  - Similar shape
  - Different velocities along limbs
- R&B $\pm V_{LSR}$ extremes offset 50-70 au about ☆
- Bicone? (*Zijlstra+02*)
  - S and N limbs seen at various angles?

Zijlstra et al. 2002



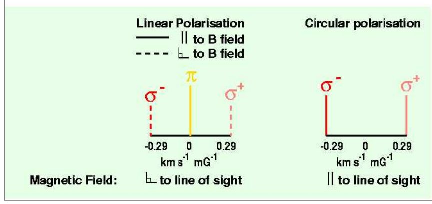
OH Zeeman Splitting



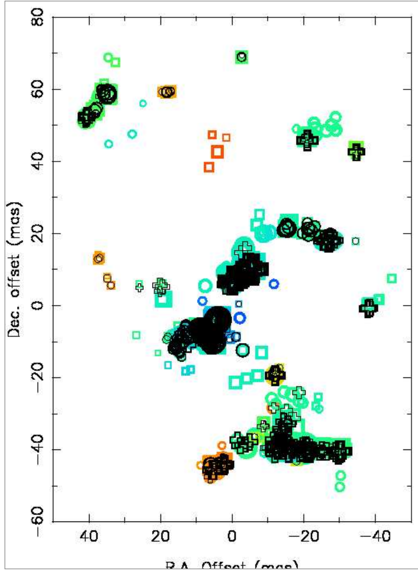
- Circular $V = (RR\text{-}LL)$
- $B \propto \Delta V_Z (= \Delta V_{LSR(RR\text{-}LL)})$

MHz	µT/km s^{-1}
1665	0.17
1667	0.28

- If $\Delta V_Z < \Delta V_{th}$ $V \propto dI / dV_{LSR}$
  - Only measure $B_{||}$
  - Mitigate by measuring $\Delta V_{LSR(I(RR)-I(LL))}$

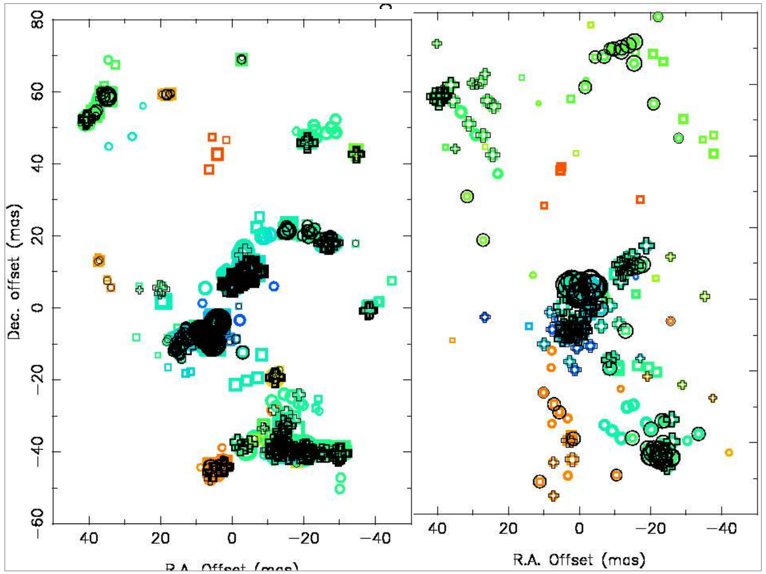


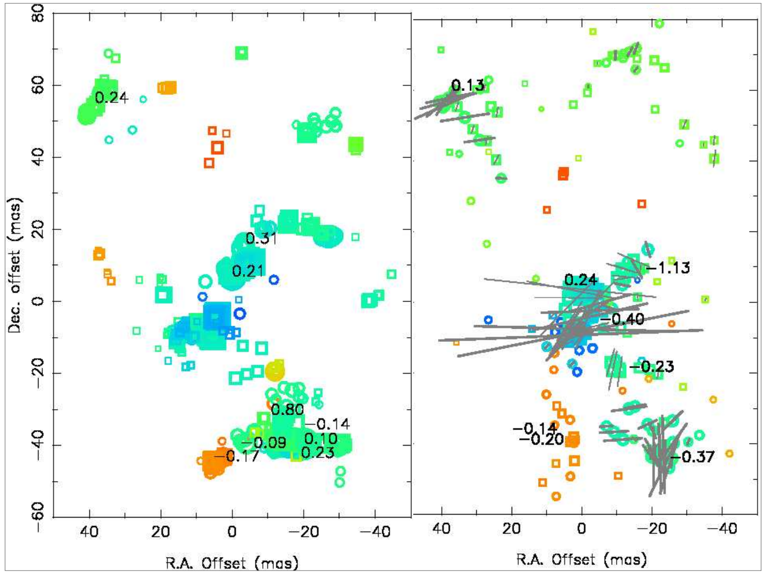
- Linear $P = \sqrt{(Q^2+U^2)}$
- Pol. angle $\chi = \mathrm{atan}(U/Q)$
  - Δm=0 :- π :- B II χ
  - Δm≠0 :- σ :- $B \perp \chi$
- If $\Delta V_Z < \Delta V_{th}$ & i (***B***) >55°
  - then $B \perp \chi$ (?)

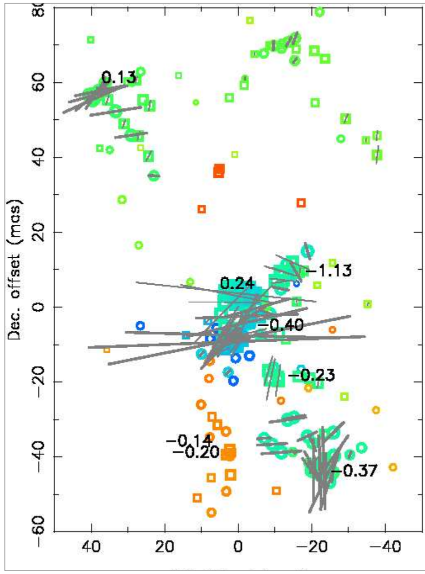


Zeeman components

- Circular polarization direction (>25% pol.)
  - Stokes *V* +/- ≡ ✚/◎
  - Some clumps dominated by single direction
- Zeeman pairs in EVN data
  - 7/2 @ 1665/7 MHz
- Typical ΔV_Z ~ 1 km s^{-1}
  - 0.1< B < 0.8 μT
  - 1 alternative ΔV_Z 12 km s^{-1}
    - B~3.4 μT
- 8 pairs in MERLIN data
- Mean B from all data:
  - magnitude 0.3 μT





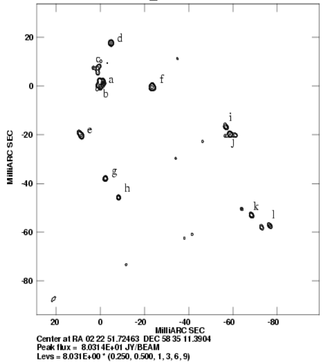


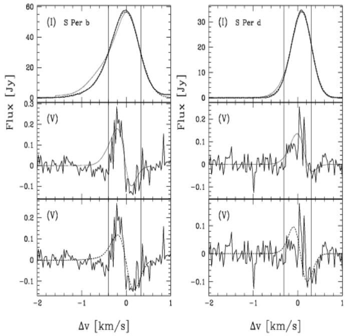
Linear Polarization

- Seen in near side only
- Pol. vector angles χ
  - Mostly ⊥ outflow
- Mean Δχ across clump 16°
- Interpretation:
  - σ components?
    - Implies χ ⊥ ***B*** axis
      - ***B*** axis || biconical outflow
    - But χ changes in S
      - ***B*** ~55° to l.o.s (*Elitzur*)?
      - χ || ***B*** axis
  - Or π component?
    - (but $V \neq 0$)
  - Or partial conversion *P*→*V*?

H_2O Zeeman splitting

- S Per VLBA (*Vlemming, Diamond & van Langevelde 02*)
- $B_{||}$ 7 - 20 µT (70- 200 mG) (model-dependent)
- Brightest H_2O masers @ R~90 au (2.3 kpc) - take B ~15 µT





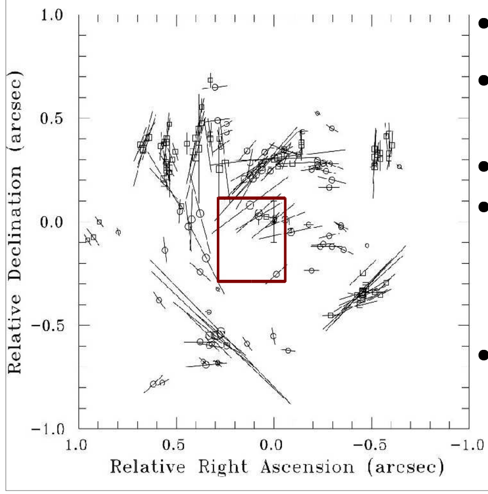
Faraday rotation & magnetic pressure

- Estimate electron density n_e from Faraday rotation
- $\Delta\chi^o = 0.15 B_{||}$ (T) n_e(m^{-3}) r_{OH}(cloud size, au)
  - $|B_{OH}|$~0.3µT (circ. pol), r_{OH} ~9 au, $\Delta\chi$ typically 16°
    - $n_e \leq\sim 4\times10^7$ m^{-3} (fractional ionisaton $\leq\sim10^{-6}$)
- Shell inner radius R_{OH} ~ 80 au, $\Delta\chi$(back-front)>180°
  - Far side depolarised by inhomogenous n_e or Alfven waves
  - Consistent with OH depolarisation in R Crt, W Hya, VX Sgr
- Thermal/magnetic pressure $\beta = 10^{-7} 8\pi\, n\, k_B T / B^2$
- Typical region densities OH n~10^{13} m^{-3} , H_2O n~10^{15} m^{-3}
  - $\beta(H_2O)$ ~0.1 (T~1000 K) - strong mag. pressure
  - β(OH) ~ 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

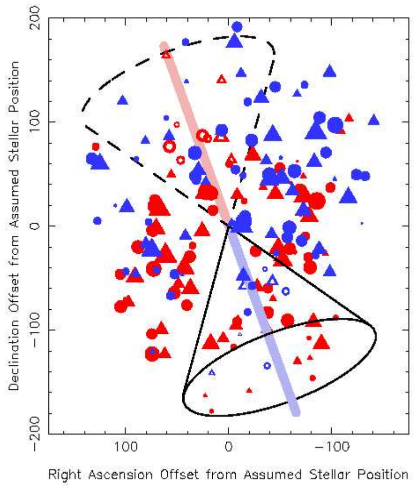
- OH mainlines B ~0.3 µT at up to 140 au
- H_2O B ~ 15 µT at ~90 au (brightest masers)
- Stretched dipole? $B \propto R^{-2}$, expect 6 µT @ 140 au **X**
  - 6 µT would split OH by~18-30 km/s; aligments ambiguous
- Selection effect?
  - Only strongest/weakest splitting detectable in H_2O/OH?
- H_2O clumps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

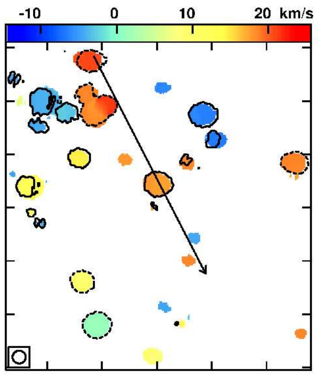
VX Sgr OH/H_2O axisymmetry



- OH 1612 polarization vectors
- Dipole magnetic field
  - Axis p.a. ~20°
  - S approaching
- *(Szymczak+)*
- H_2O ~spherical
  - Lower density bicone (△ ○)
  - Aligned about mag. axis
- *(Murakawa+)*

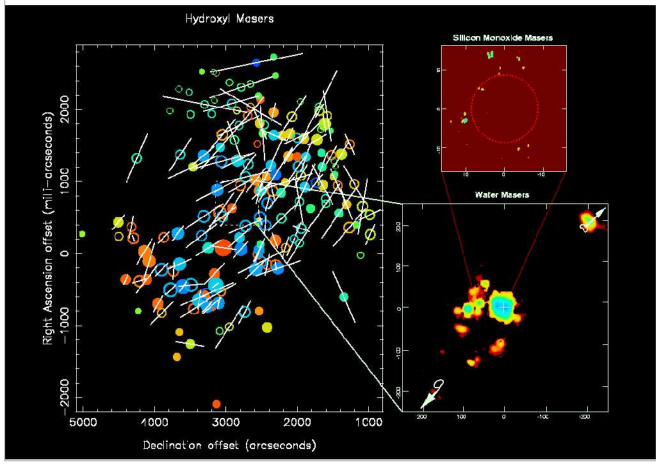
VX Sgr OH/H_2O axisymmetry



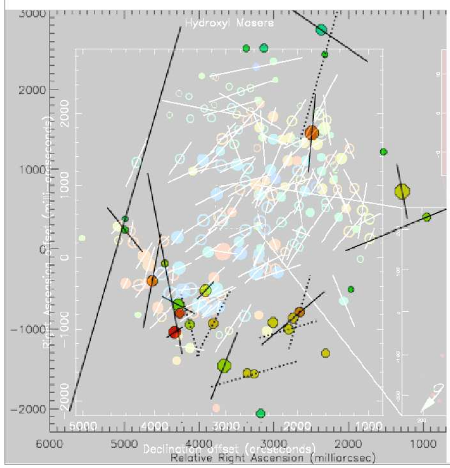


- EVN OH mainlines
  - In H_2O shell
  - No obvious pattern

Wind evolution - bipolarity increases?

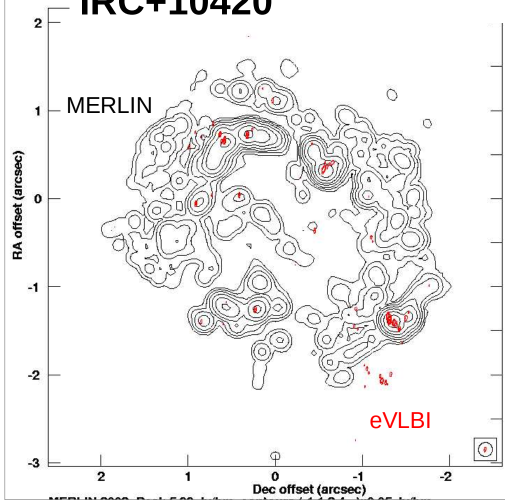


Wind evolution - bipolarity increases?



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

First spectral-line real-time VLBI IRC+10420

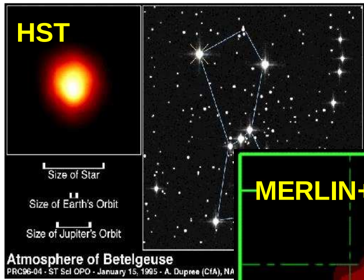


- 10 M⊙ RSG
  - heading for WR
- 1970's G0-F8
- Now A5 - 8500K!
  - (Klochkova et al.)
- No H_2O masers
- ?Fossil? molecular shell with OH masers
  - *r* ~7500 au @ 5kpc
  - 200xsolar system
- OH *Vexp* 40 km/s
  - Shell shows 900 yrs of wind history
- OH 1612 spherical?

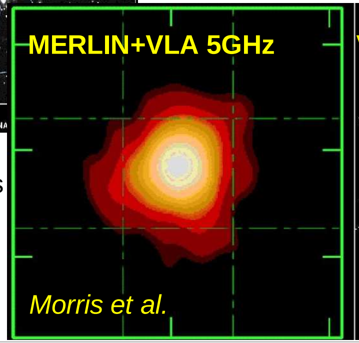
What is magnetic field origin? How does it act on the wind?

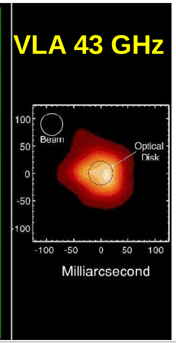
- Negligible stellar surface rotation
- Bipolarity in winds, magnetic field
- *Blackman+ 01*: α–ω dynamo?
  - Differential rotation in layers, fast core, convection
  - Dipole field in wind channels dust grains?
- No degenerate core in RSG
- S Per B not consistently r^{-2}/ r^{-3}
  - Neutral dust not 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 :* α^2 turbulent dynamo
  - Not strong enough to influence whole wind
  - Could produce cool spots => enhance dust formation
  - Shock compression enhances radial magnetic field
    - Field frozen in to maser clumps (*Hartquist & Dyson 97*)?

The stellar surface



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





- α Ori *Freytag+ 02*
  - 1-3 large starspots
  - Giant convection cells
- Local magnetic field enhanced
  - u_B ~$\exp^{time}$