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Maser polarization and Magnetic Fields

Probing B at the smallest scales during star formation

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Background: masers during SF

- OH masers
  - Typical densities: $n_{H2} = 10^{5-8}$ cm^{-3}
  - Several transitions found (1.6 GHz main-line and satellite-lines as well as higher excitation lines at 6 and 13 GHz)
  - Very high linear polarization and Zeeman pairs give magnetic field strength and structure.
- Methanol masers (CH_3OH)
  - Typical densities: $n_{H2} = 10^{6-9}$ cm^{-3}
    - Often found in similar regions as OH
  - Both 12.2 and 6.7 GHz masers observed, with especially 6.7 GHz masers strong and abundant tracers of high-mass star-formation
  - Likely originates in areas where high CH_3OH densities are generated by evaporation from dust grains
  - Linear polarization reasonably strong (few percent); tentative circular polarization detected
- H_2O masers
  - Typical densities: $n_{H2} = 10^8 - 10^{10}$ cm^{-3}
  - Likely occur in shocks in disks or outflows
  - Circular/linear polarization (both weak) provides magnetic field strength and direction
  - Shocks increase pre-shock magnetic field
- SiO masers
  - Extremely rare, mainly around Orion IRc2
  - Several tens of percent linearly polarized

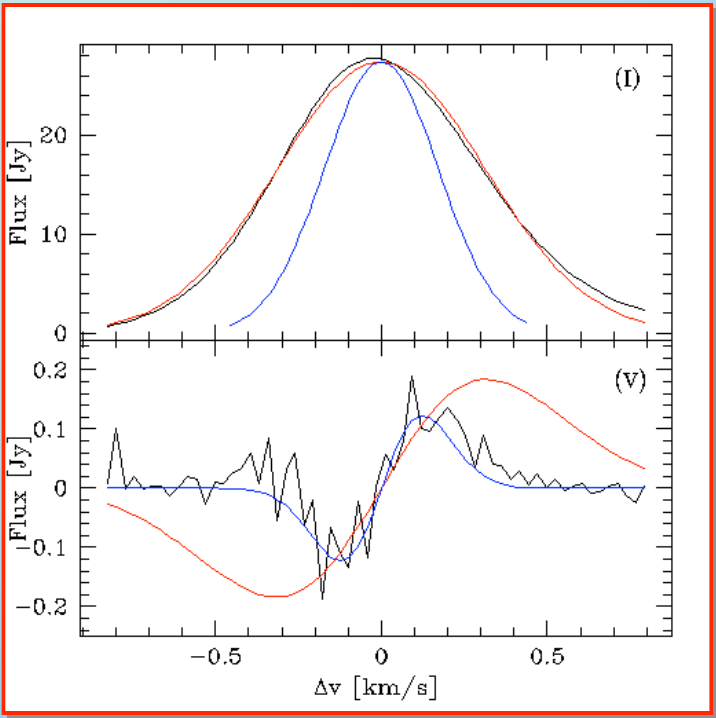
Theoretical Considerations

- Theory differs significantly when magnetic transitions overlap in frequency or are well separated:
  - Large splitting (typically OH; paramagnetic)
    - $r_Z > 1$ (or $r_Z \sim 1$)
    - B strength follows directly from measured splitting of Zeeman pairs
    - Linear polarization || or ⊥ to B depends on observation of σ (⊥) or π (||) compents
  - Small splitting (most others; non-paramagnetic)
    - $r_Z < 1$
    - $B_{||} \propto m_c$ (fractional circular)
    - *But:* depends on B-field angle to the l.o.s., maser saturation etc. and not always simply related to dI/dv !
  - See extensive modeling work by Goldreich, Keeley and Kwan (1973); Elitzur (1991 ff.); Watson and collaborators (1983 ff).
    - Gray 2003 MNRAS 343 L33 presents a comparison between polarization models

$$r_Z = \frac{\Delta\nu_Z}{\Delta\nu_D}$$

$$\Delta\nu_Z = Zeeman\ splitting$$

$$\Delta\nu_D = Doppler\ linewidth$$



S Per H_2O

(Vlemmings et al., 2001, A&A 375 L1)

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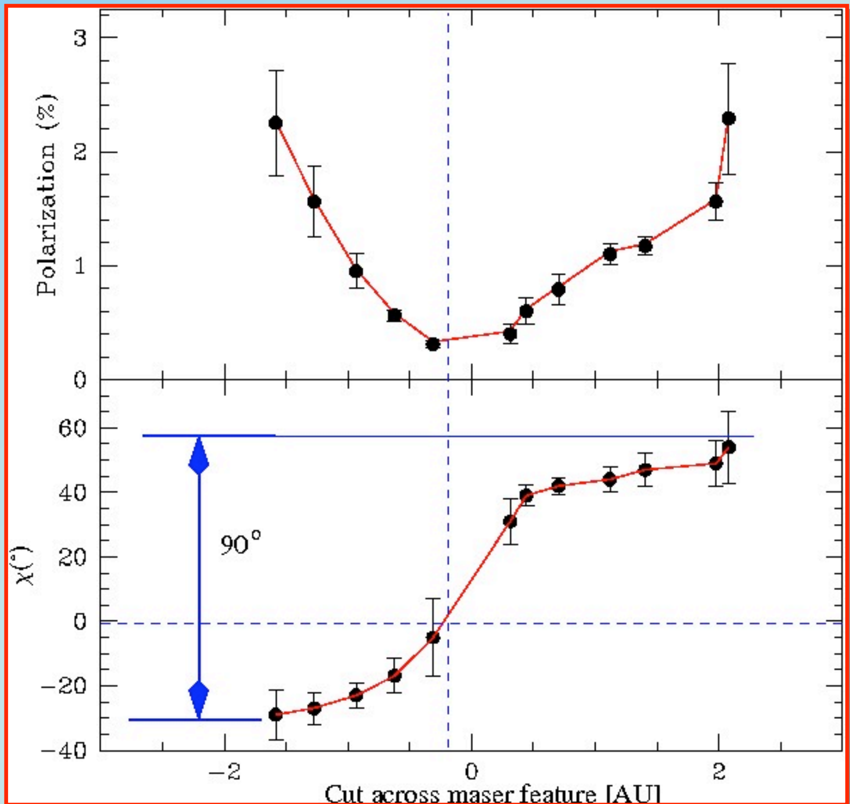
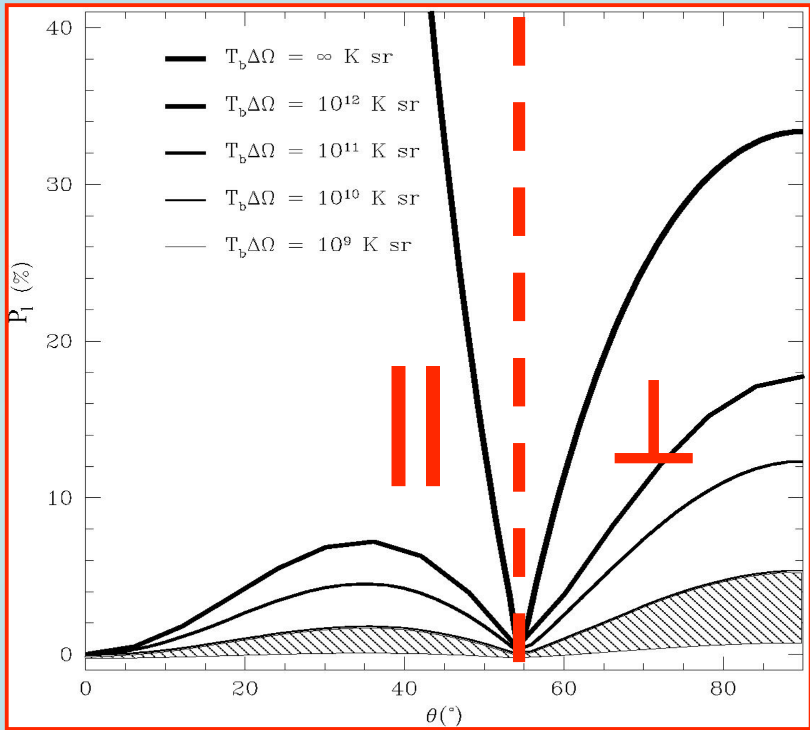
Linear polarization in the small splitting regime

- Polarization fraction strongly dependent on angle between magnetic field and line-of-sight (θ) as well as maser saturation level
- Either || or ⊥ to magnetic field direction on the sky, depending on θ
  - || when θ < 55°
  - ⊥ when θ > 55°





H_2O maser linear polarization

Theory predicted 90º flip with accompanying decrease in linear polarization fraction observed in W43A
(Vlemmings & Diamond 2006 ApJ 648 L59)

Other considerations

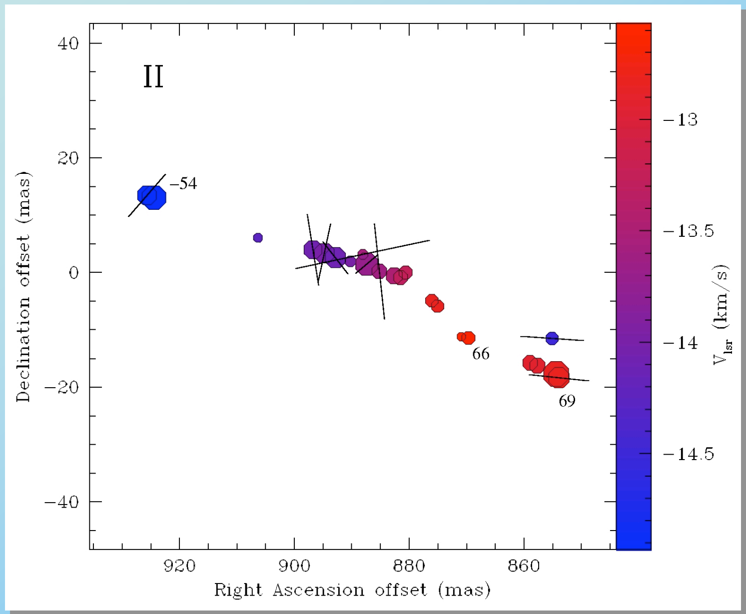
- Faraday rotation:

$$\Phi[^\circ] = 4.17 \times 10^6 D[\mathrm{kpc}] n_e [\mathrm{cm}^{-3}] B_{\parallel}[\mathrm{mG}] \nu^{-2}[\mathrm{GHz}]$$

  – Example: for typical ISM values Φ = 190º toward W3(OH) at 1.6 GHz
  – Internal faraday rotation along maser path
- Velocity gradients along maser propagation direction
  – Can lead to significant underestimate of the magnetic field strength
- Low spatial resolution observations suffer from blending and typically also underestimate field strength

Maser polarization observations and magnetic field in Star-forming regions

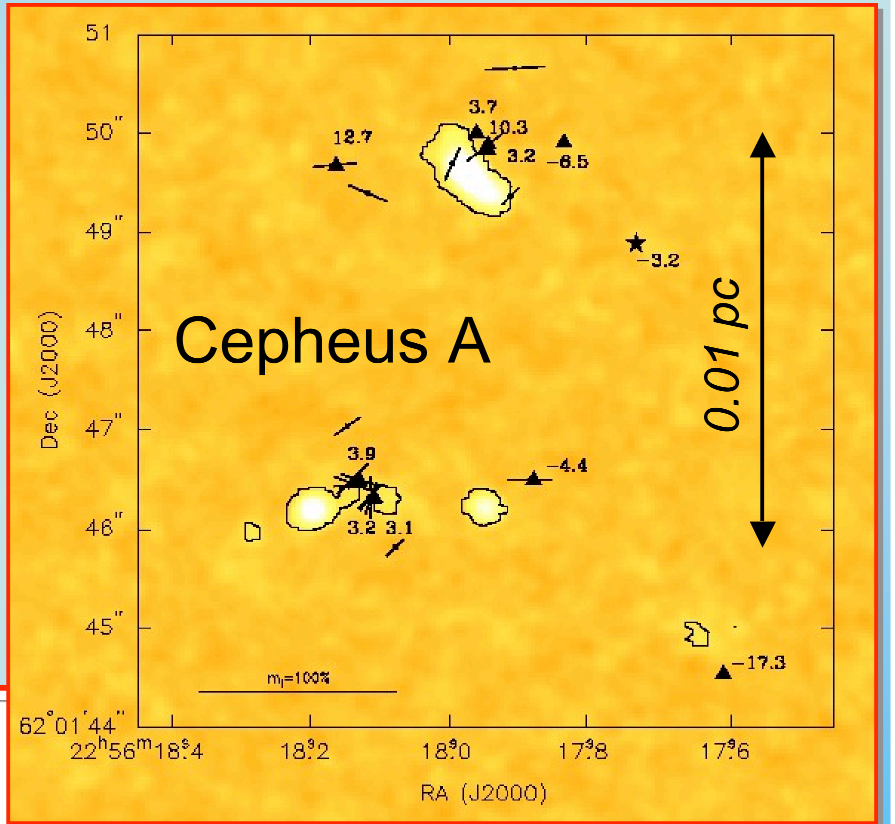
- *OH masers*
- *SiO masers*
  - *Thus far only in Orion*
- *Methanol masers*
- *H_2O masers*



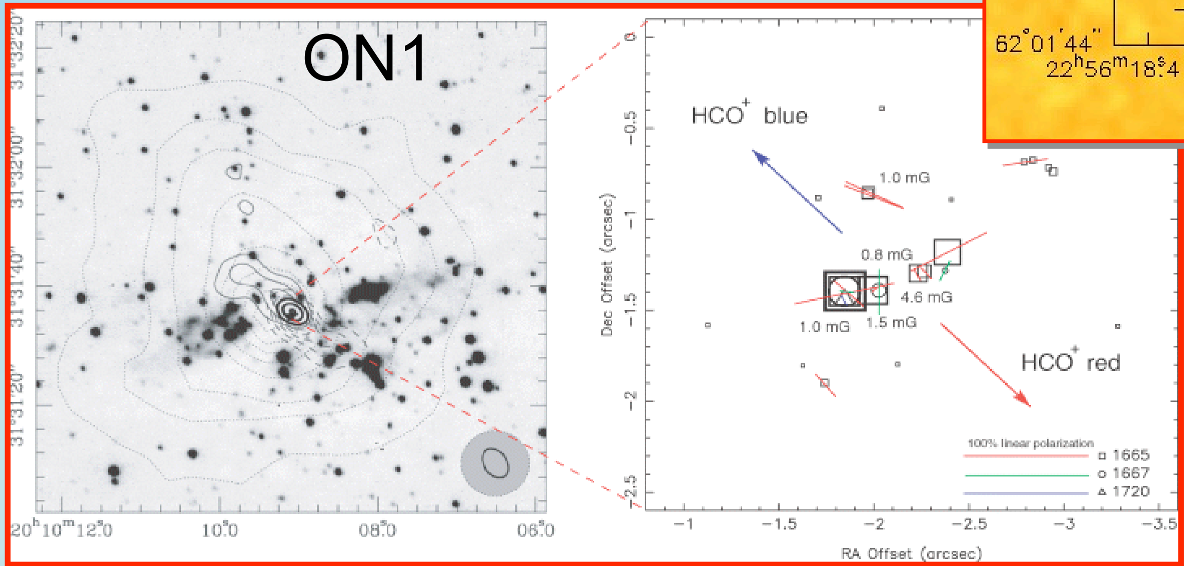
SF OH maser polarization

- OH Zeeman splitting gives |B| ≈ 1-10 mG
- Typically consistent l.o.s. direction or a single reversal across the entire source
  - Ambient B-direction preserved
- OH masers strongly (up to 100%) linearly polarized
  - Polarization vector often ⊥ to the magnetic field direction
- Both internal and external Faraday rotation makes determining 3D B-field structure difficult

(See discussion in Fish & Reid 2006, ApJS 164 99)



(Bartkiewicz et al. 2005 MNRAS 361 623)

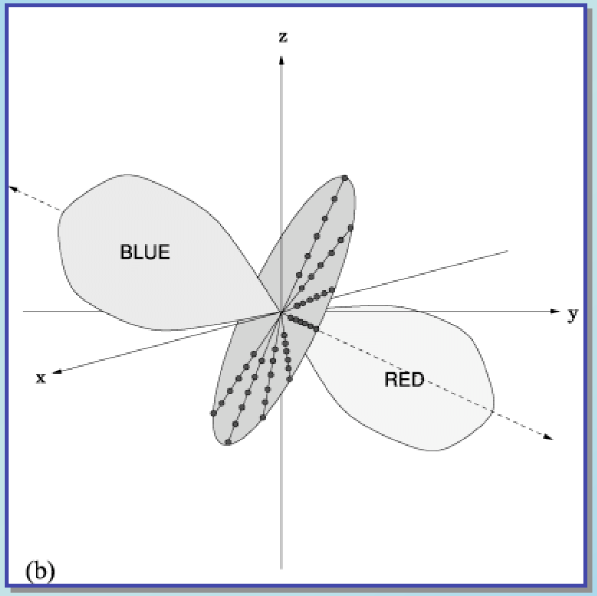


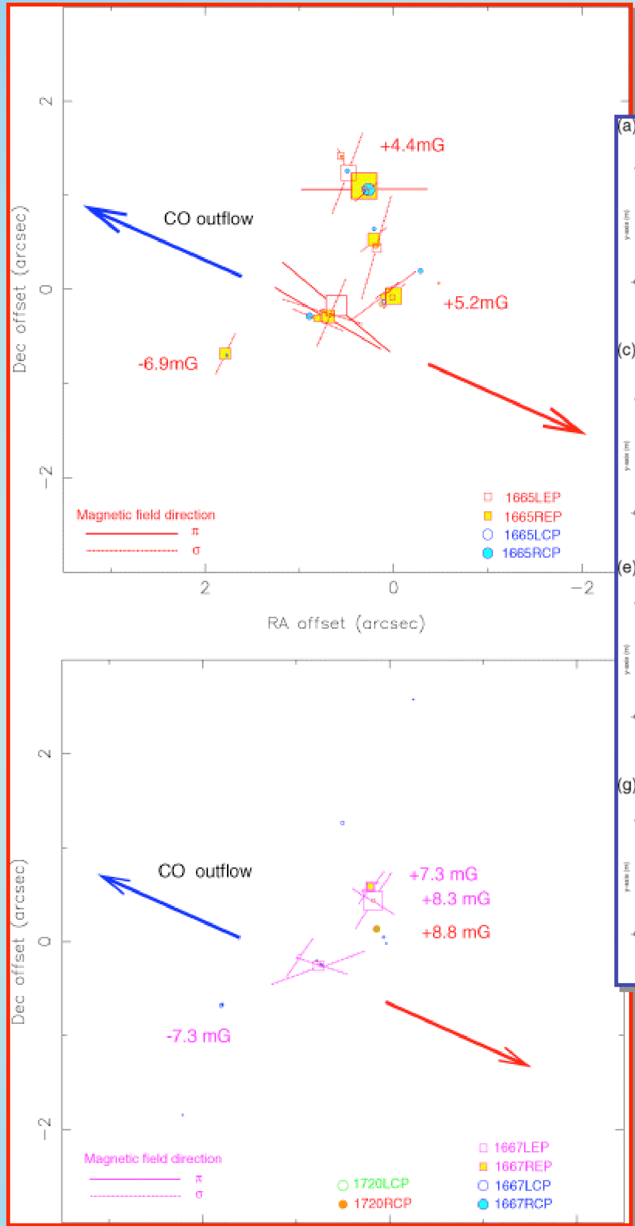
MERLIN OH polarization

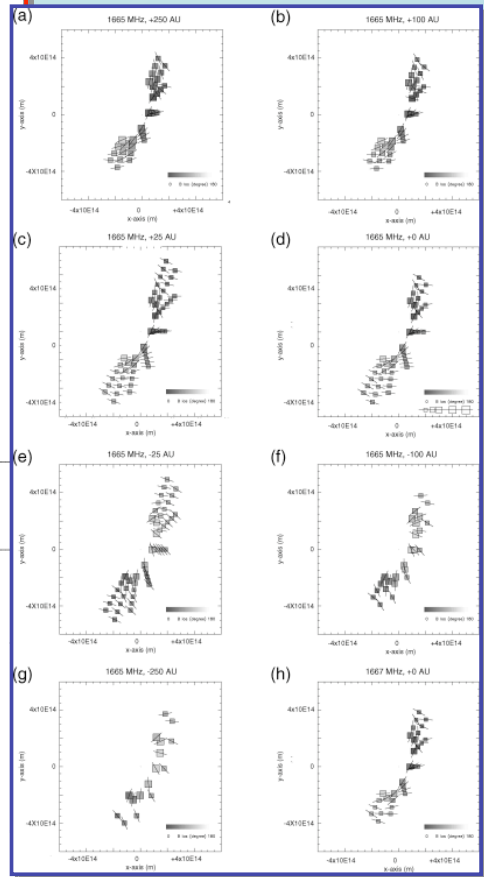
(Nammahachak et al. 2006 MNRAS 371 619)

More OH polarization

- Detailed modeling of OH maser polarization can enhance the understanding of the protostellar environment
  - Polarization observations combined with accurate maser radiative transfer models give physical conditions and morphology





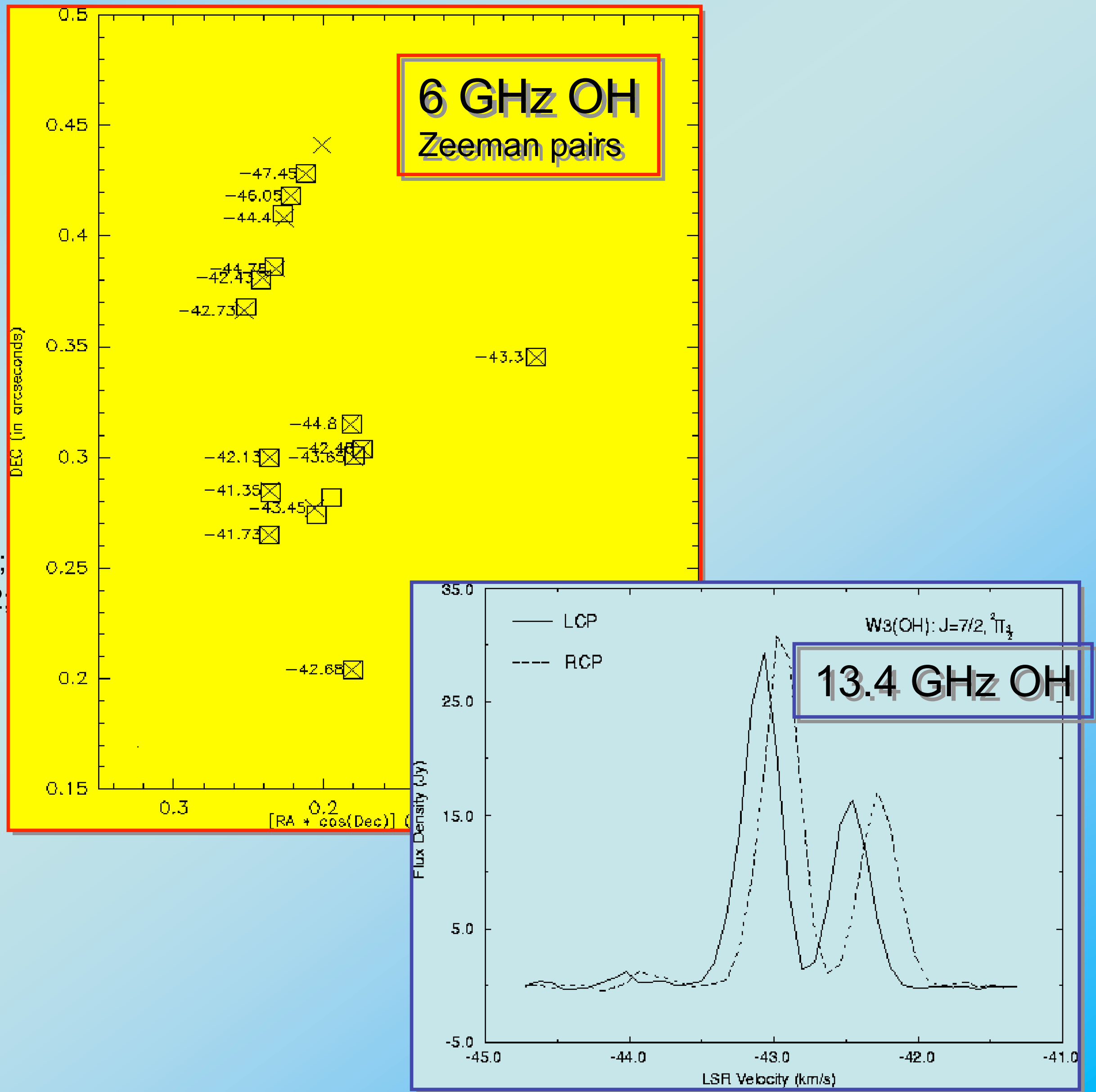


W75N

(Gray et al. 2003, MNRAS 343 1067; Hutawarakorn et al. 2002 MNRAS 330 340)

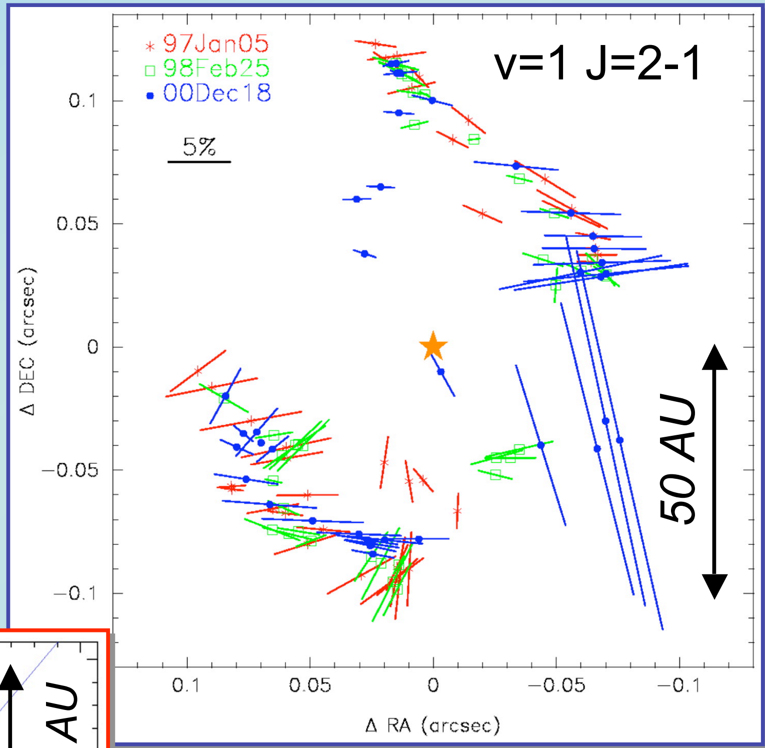
Higher OH transitions

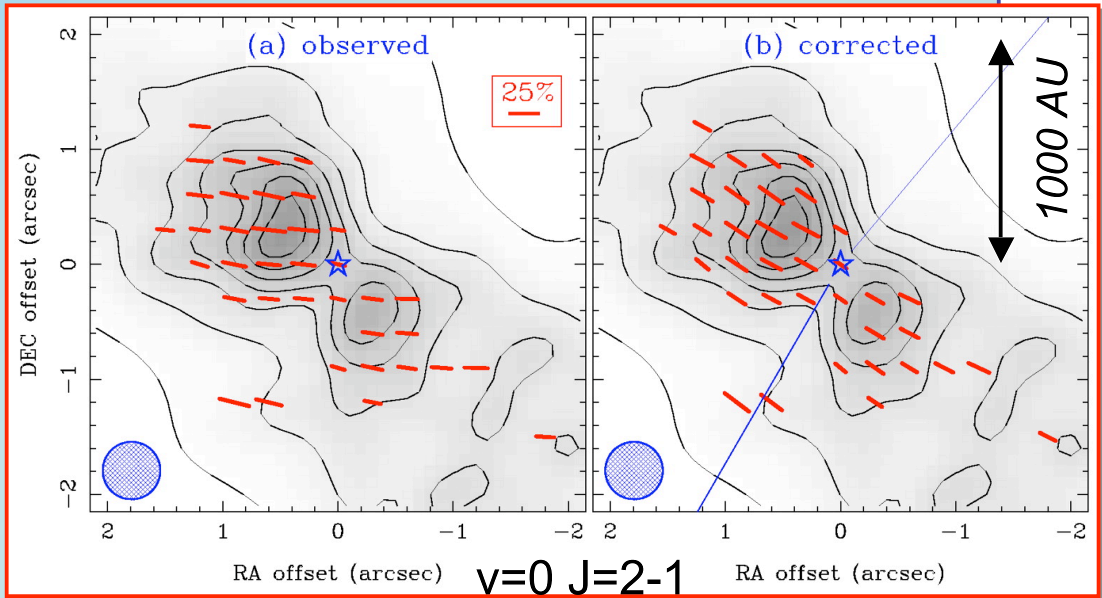
- Observations of excited OH:
  - OH 6 and 13.4 GHz observations also reveal magnetic fields of several mG
    (Caswell 2004 MNRAS 352 101;
    Desmurs et al. 1998 A&A 334 1085;
    Etoka et al. 2005 MNRAS 260 1162;
    Diamond et al. 2007 in prep.)



Orion SiO maser polarization

- 86 GHz SiO maser polarization of Orion IRc2
  - Up to 30% linear polarization
  - Faraday correction linear polarization direction parallel to the plane of the 'disk'
    - Discrepancy between J=1-0 (Barvainis 1984 ApJ 279 358) and J=2-1 direction likely due to foreground Faraday rotation
  - B-field likely perpendicular





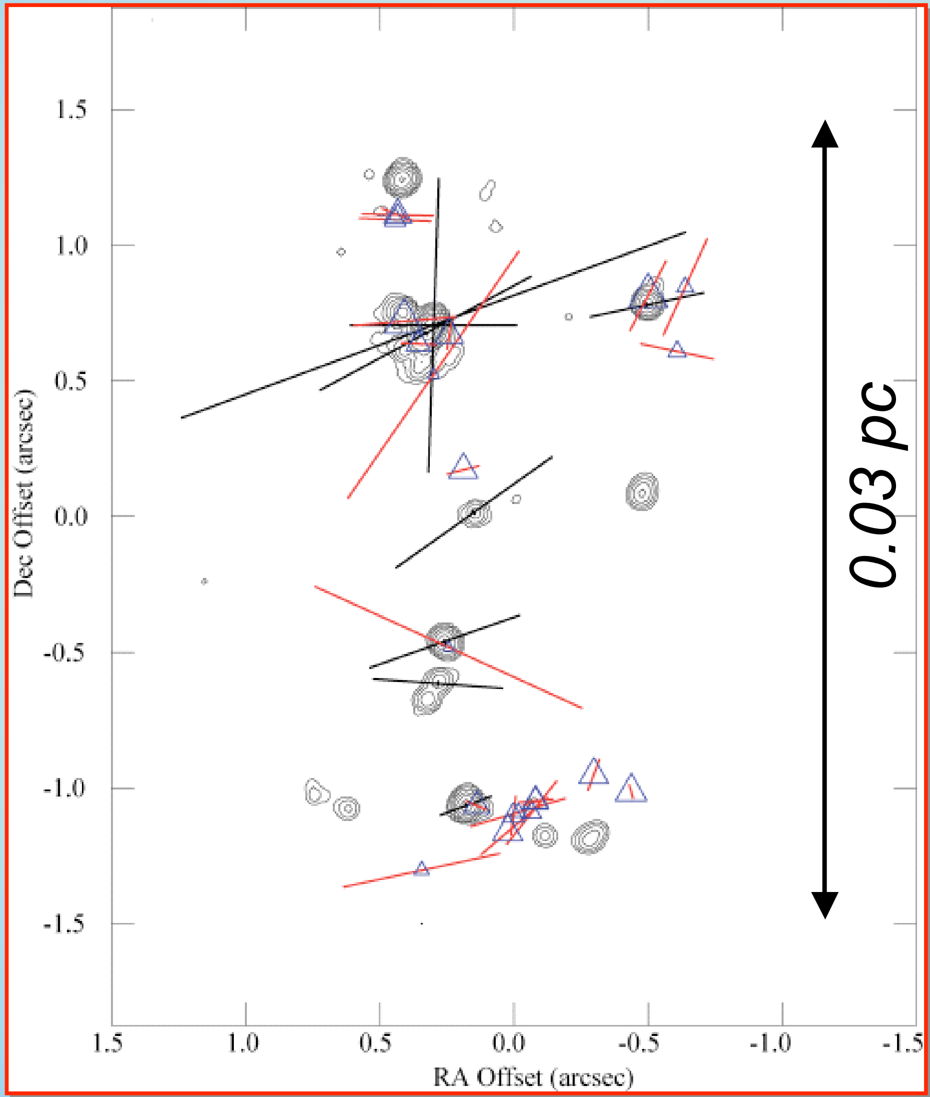
BIMA observations

(Plambeck et al. 2003 ApJ 594 911)

Methanol polarization

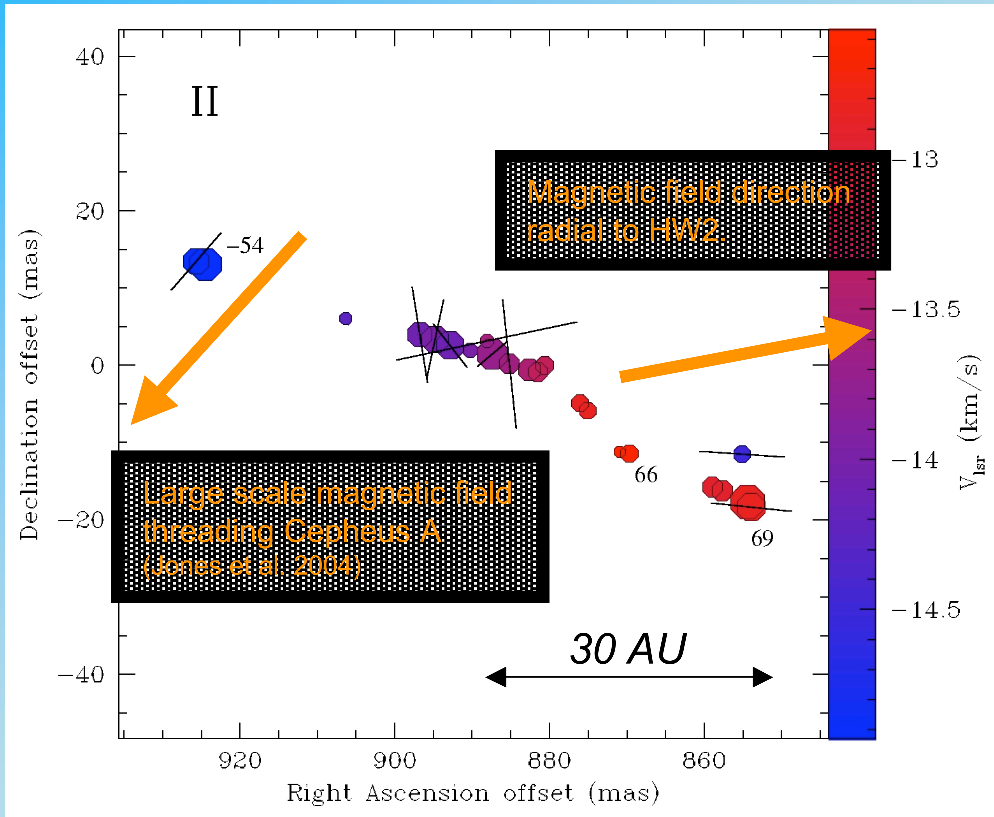
- Few linear polarization measurements reported
  - Up to ~10% linear polarization measured for 6.7 and 12.2 GHz masers
    - ATCA (Ellingsen IAU #206) and single dish (Koo et al., 1988 ApJ 326 931)
  - Up to ~40% linear polarization for mm masers (Wiesemeyer et al. 2004 A&A 428 479)
- First 6.7 GHz linear polarization map (MERLIN) made for W3(OH)
  - Pol. vectors perpendicular to large filament

    ⇒ magnetic field parallel to the filament
  - Zeeman splitting upper limit $B_{||}$ < 22 mG
- Tentative first detection of methanol Zeeman splitting for ON1 (18 ± 6 mG; Green et al. 2007 astro-ph/0709.0604)



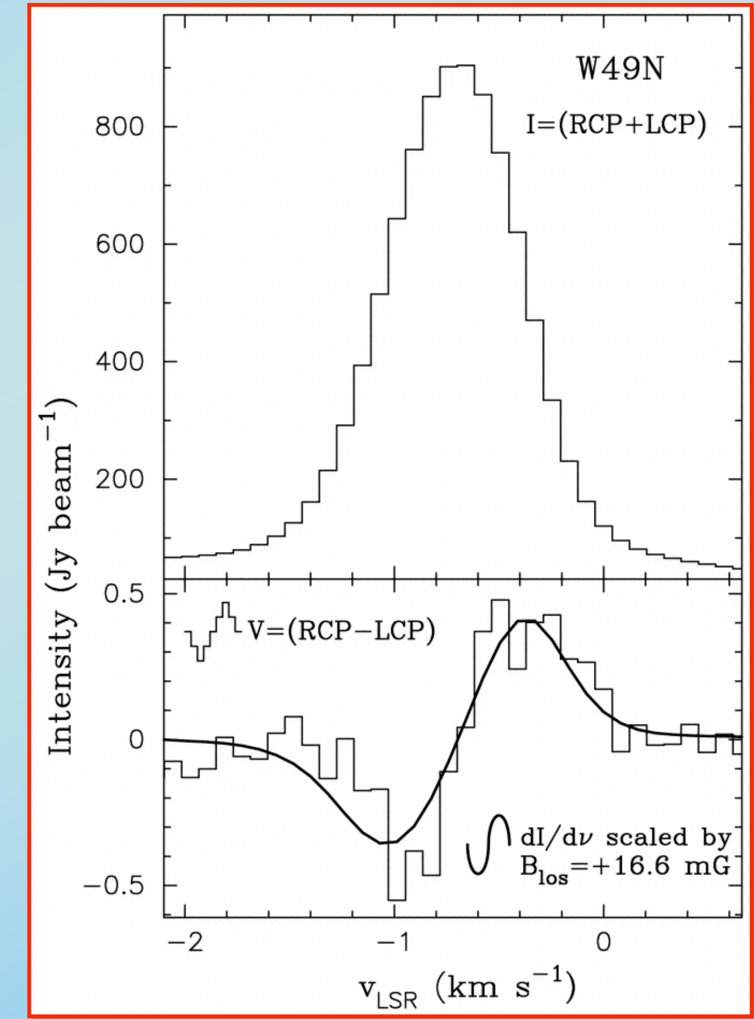
(Vlemmings et al. (2006) MNRAS, 371, L26)

SF H_2O maser polarization



Cepheus A VLBA observations of H_2O masers in shocked interaction region between protostellar outflow and molecular cloud.

(Vlemmings et al. 2006 A&A 448 597)



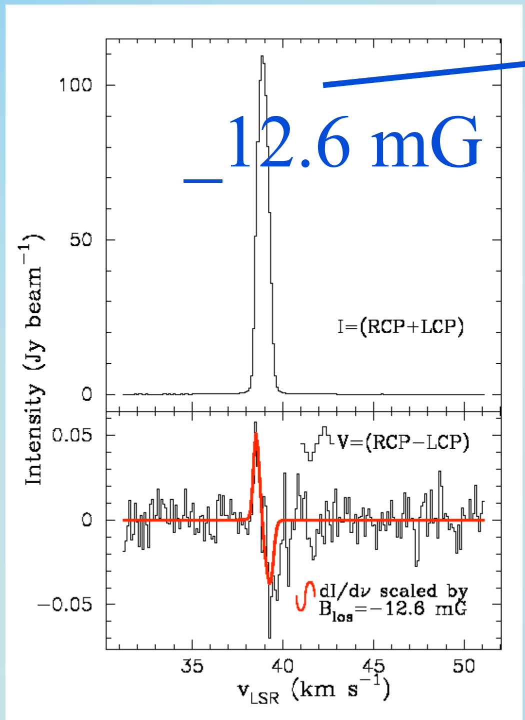
VLA observations

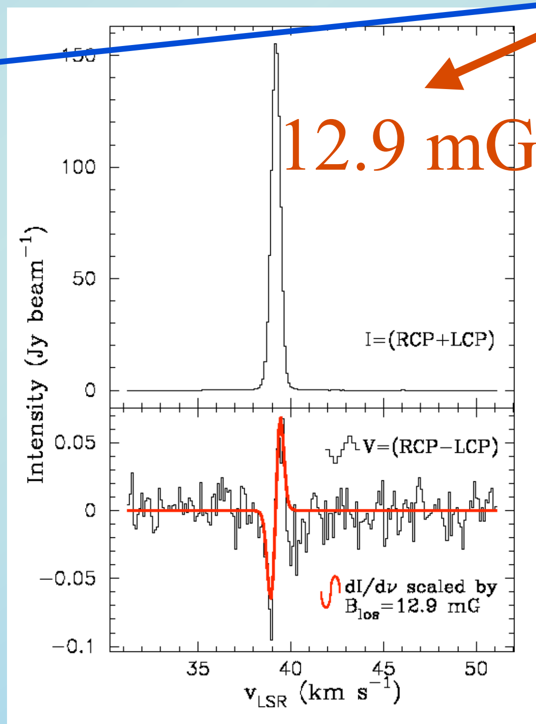
(Sarma et al. 2002 ApJ 580 928)

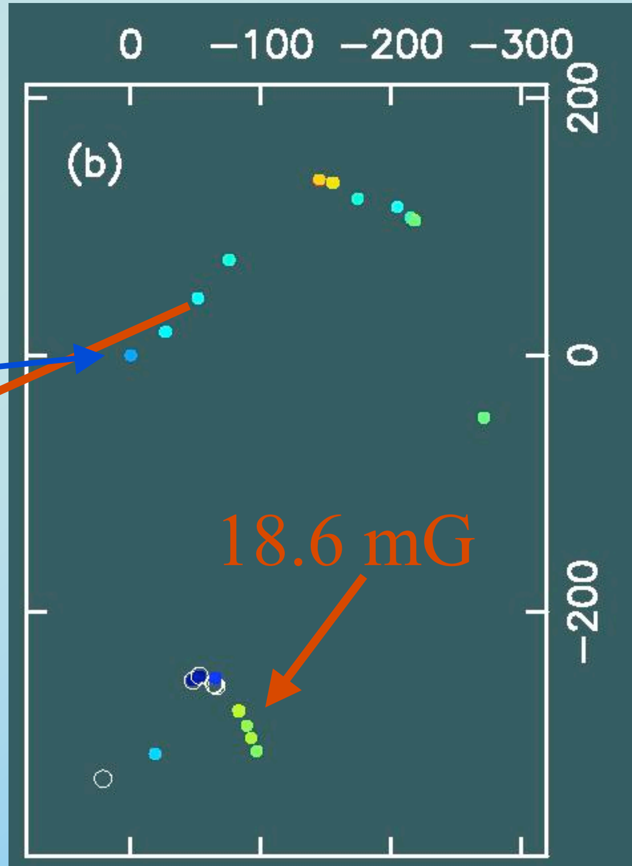
More H_2O

- H_2O maser polarization observations indicate |B| ~ 10-600 mG
  - With small scale field reversals
  - Magnetic pressure often almost equal to dynamic pressure
    ⇒ dynamically important
- Linear polarization of the order of 1%
  - Indicate complex structure but often clearly related to outflow/shock direction

OH43.8-0.1



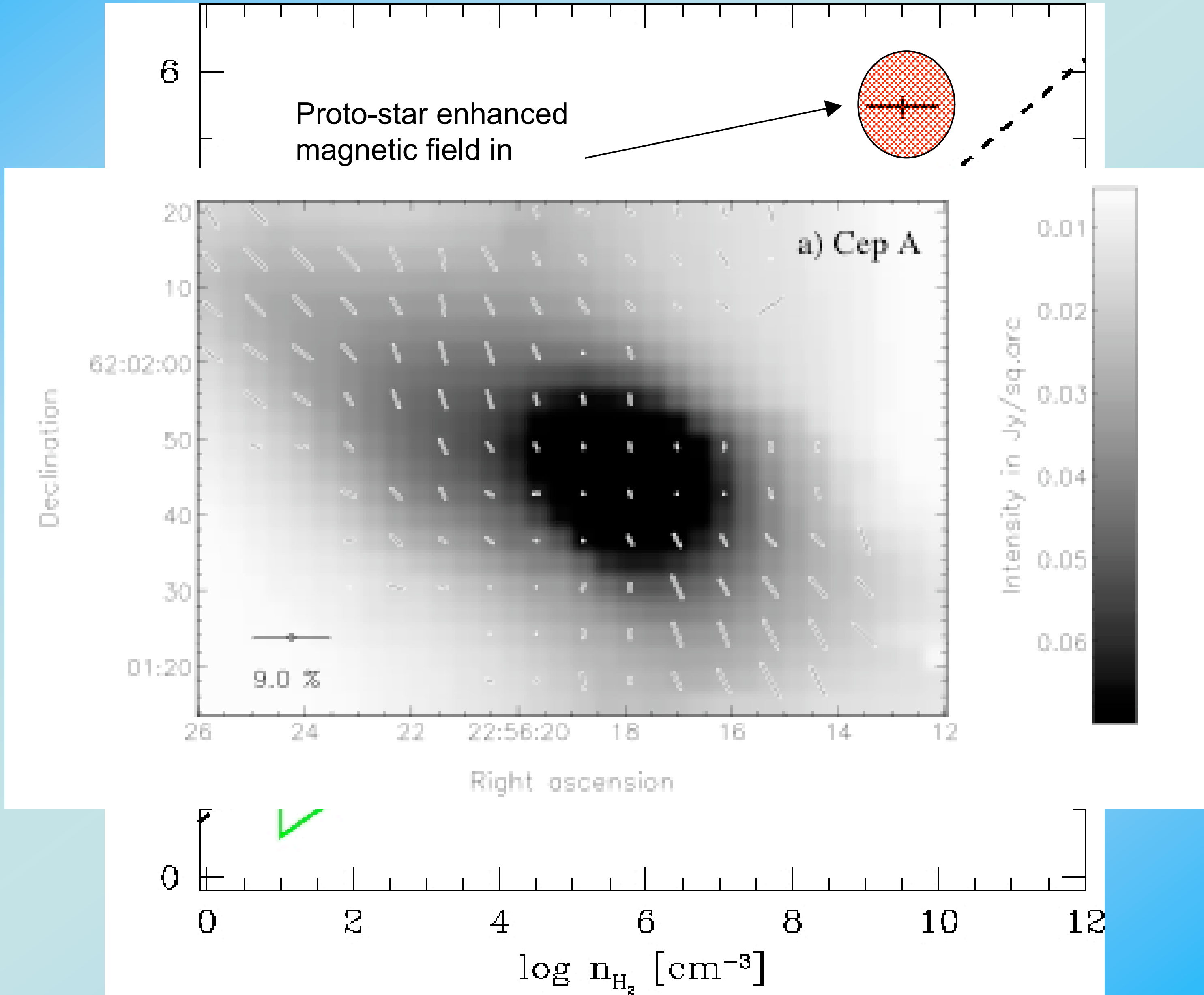




Sarma et al. (in prep.)

Color image from VERA: Honma et al. (2006)

SF Magnetic Fields



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0709.0256)

Enhanced Cepheus A B-Field

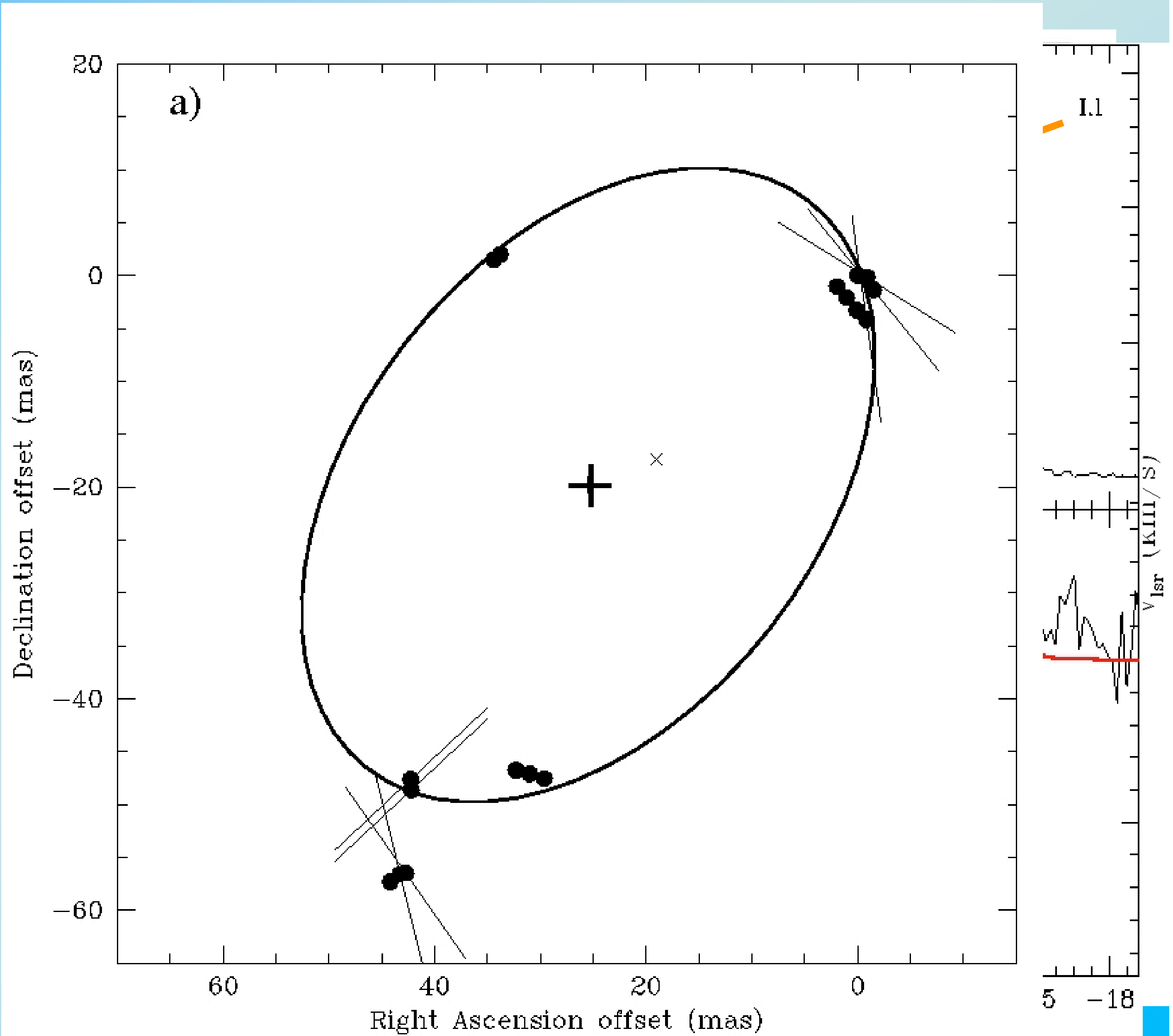
- Expanding shockwave through rotating proto-stellar disk with R~25 AU (Gallimore et al. 2003 ApJ 586 306)

- Strong magnetic fields (650mG) with small scale reversals

- Magnetic field direction follows disk (inclination 51º)
  - Toroidal field ?
  - Shock compression of field lines ?

- Field enhancement through nearby Dynamo
  - 1/r gives 2.5 G near protostar

(Vlemmings et al. 2006 A&A 448 597)



Conclusions

- OH and H_2O maser polarization observations reveals strong, dynamically important but complex magnetic fields during high-mass star-formation
- Methanol maser linear polarization is an ideal probe of magnetic field morphology
  - Less influenced by (internal/external) Faraday rotation compared to lower frequency OH
  - Very common and strong maser
- Magnetic field strength determination using methanol masers difficult (but extremely promising!)
- Maser magnetic field observations follow B-density scaling law for collapsing spherical cloud along the magnetic field lines, including ambipolar diffusion
  - Up to densities of 10^{10} cm^{-3}
  - H_2O maser timescales less than diffusion timescale
  - Outlying observed B values indicate local enhancements due to for example a nearby protostar