SMA observations of Magnetic fields in Star Forming Regions

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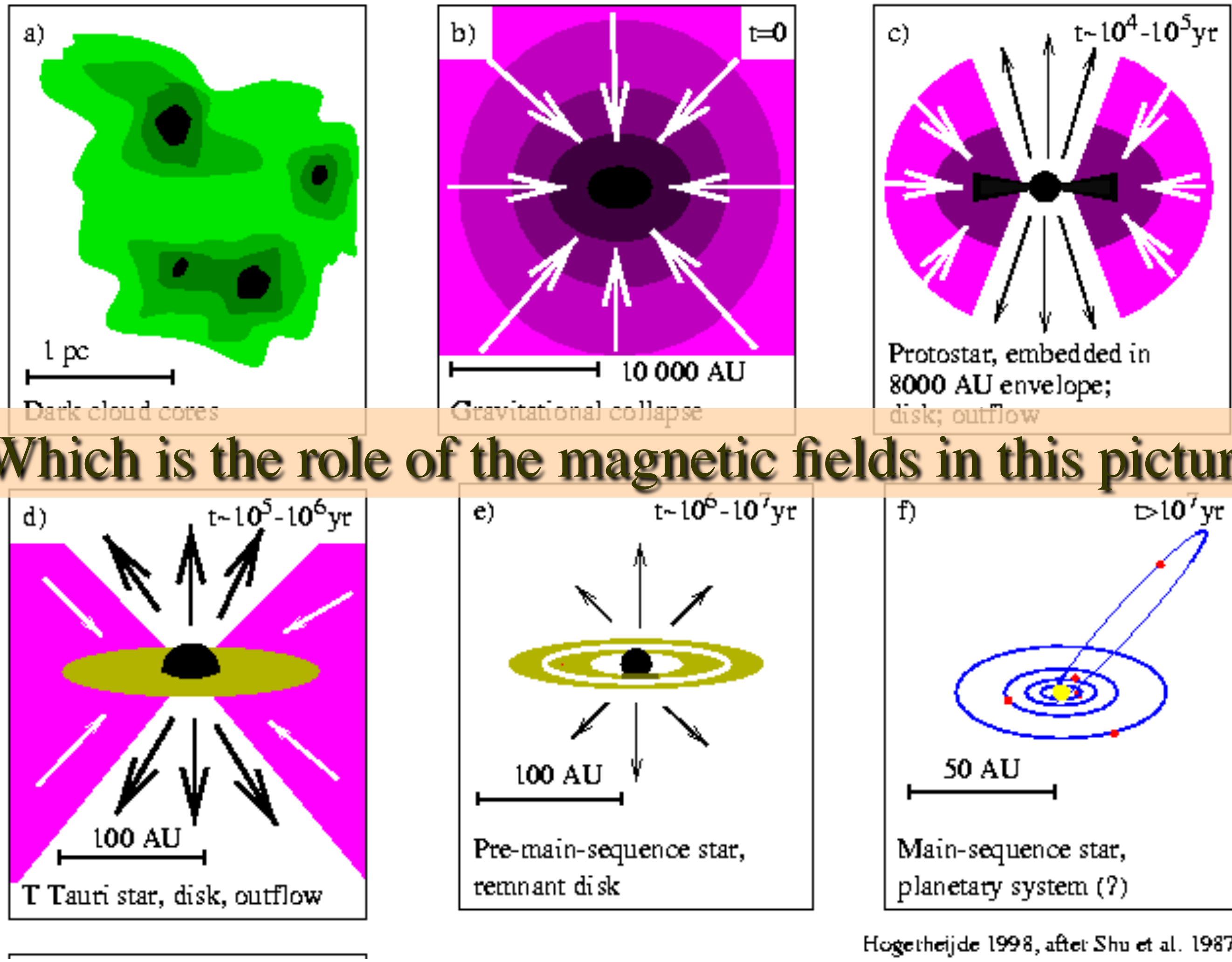
The Star Formation Sequence for Low Mass Stars

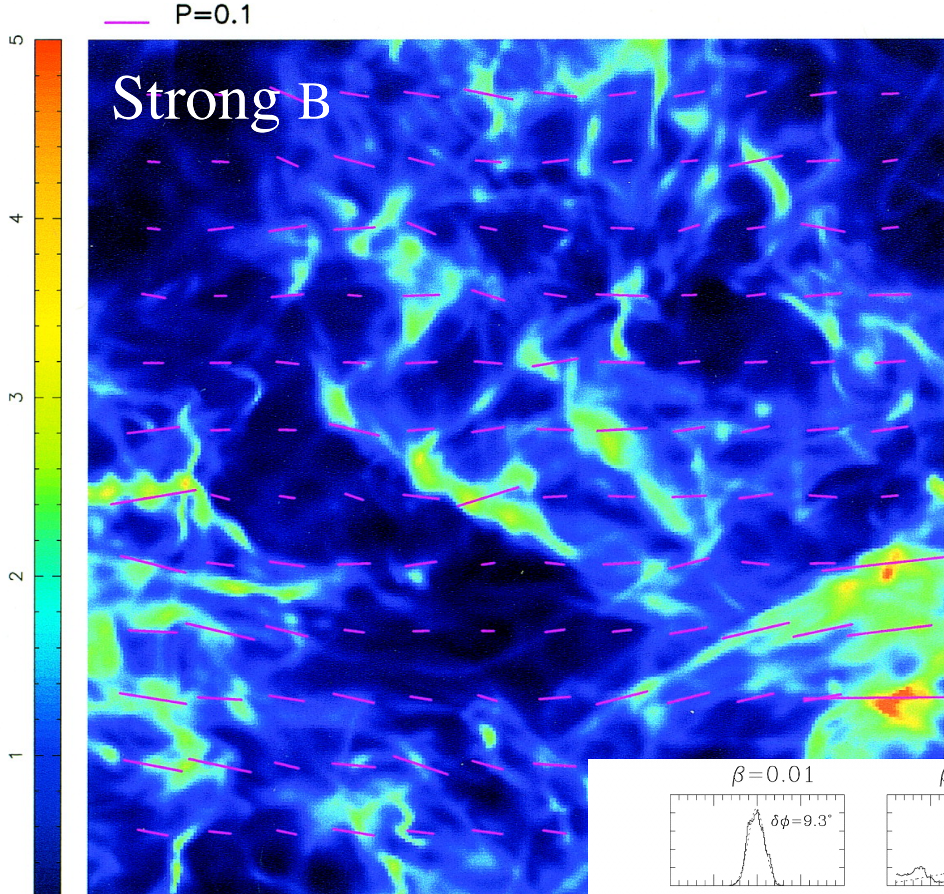
- Simultaneous process of infall and outflow

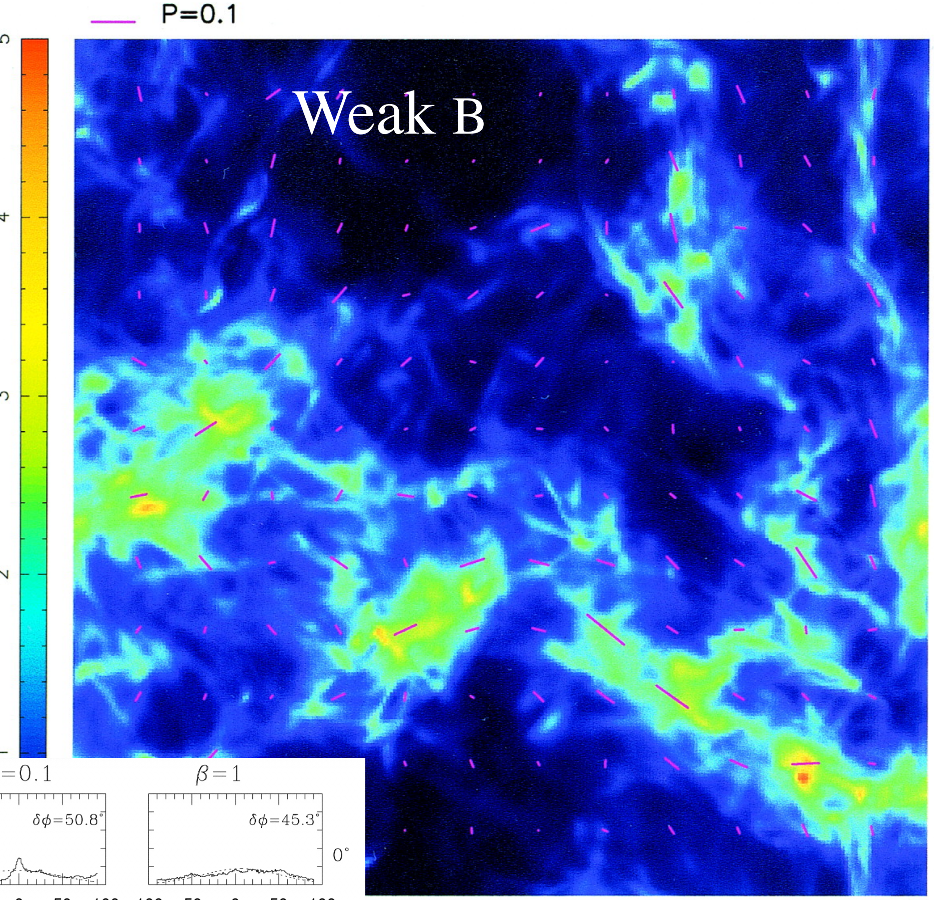


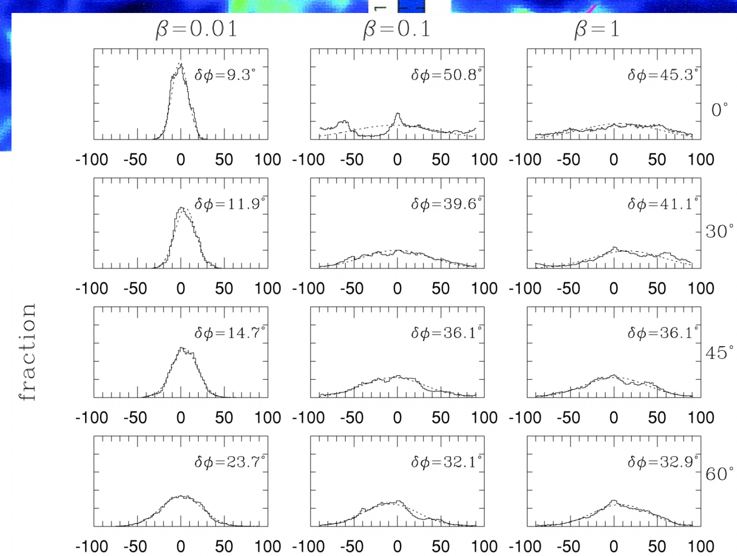
Which is the role of the magnetic fields in this picture?

Hogerheijde 1998, after Shu et al. 1987

Star formation: Magnetic fields & Turbulence







Ostriker et al. 2001

Polarization properties of the ISM can help to check how strong is the B field

Star formation: Magnetic fields & Angular momentum

Rapid rotating envelope, weak B field

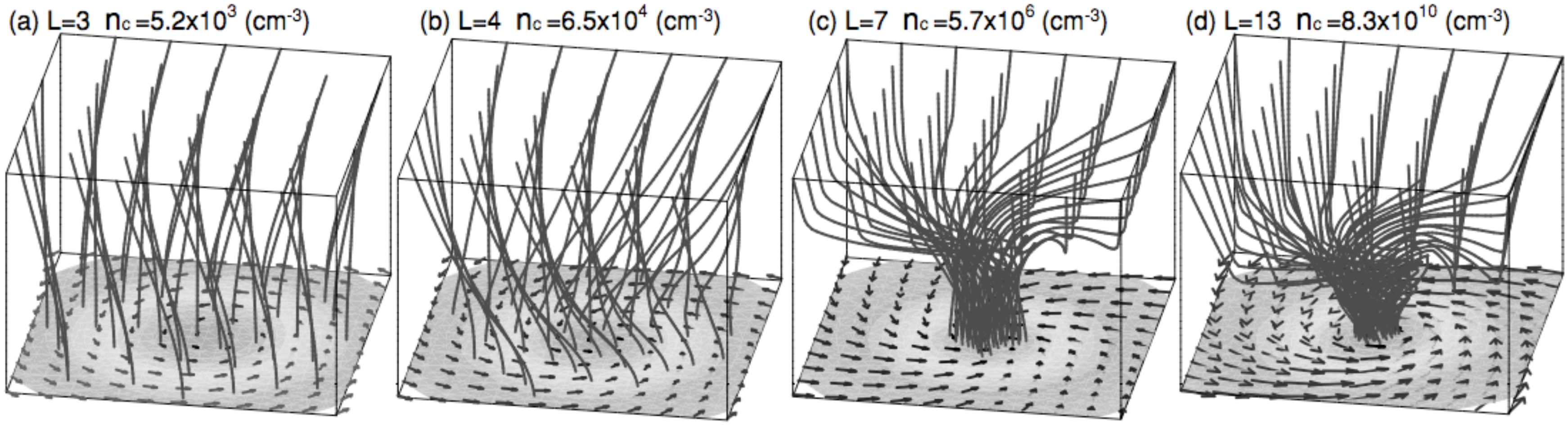
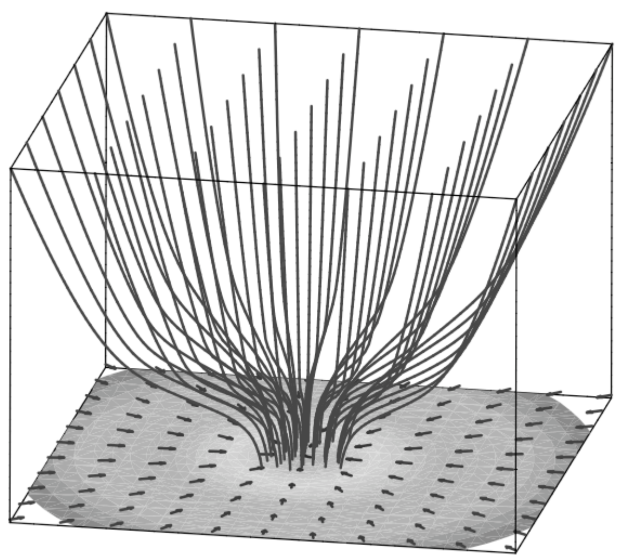


Figure 9. The magnetic field lines at the same epoch as Fig. 8. Each frame denotes a cube with side-lengths (a) 1.7×10^5 au, (b) 8.4×10^4 au, (c) 1.1×10^4 au, and (d) 1.6×10^2 au, respectively. The grey-scale and arrows have the same meaning as in Fig. 5.

Slow rotating envelope, strong B field

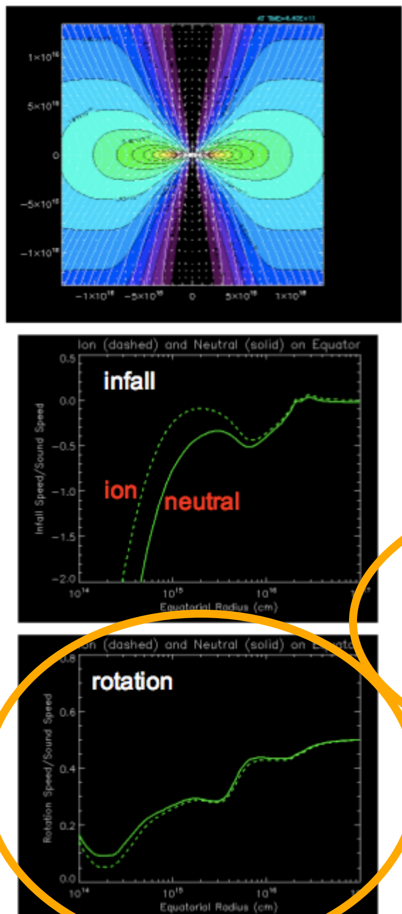


Machida et al. 2005, 2006

Magnetic fields & Angular momentum: magnetic braking

Slide from Zhi-Yun Li & Richard Mellon (Univ. of Virginia):

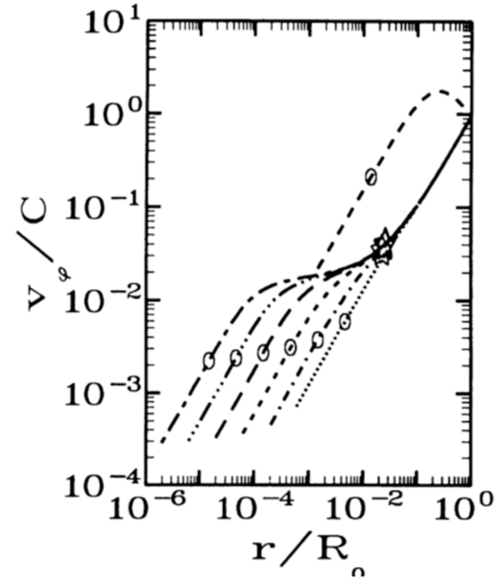
Possible Observational Signatures



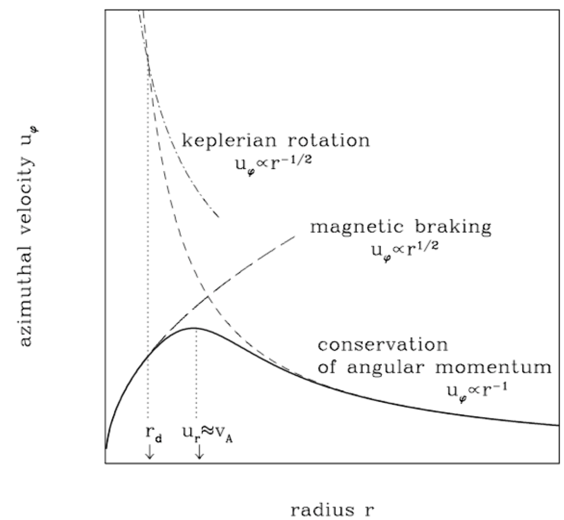
- Dynamically important magnetic field
  - Zeeman measurements (lack of suitable molecules?)
  - polarization of dust emission (e.g., Girart et al. 06)
  - flattened mass distribution - pseudodisk
    - (e.g., Galli & Shu 93, Looney et al. 07, Kwon's poster)
- Ambipolar diffusion
  - difference in ion and neutral infall speeds, a fraction of c_s (ALMA?)
  - pause in infall - evidence for accumulation of magnetic flux
    - associated with central (stellar) mass?
- Magnetic braking
  - spin-down of infalling gas (spatially resolved spectra, ALMA? Molecules?)
  - where does the extracted angular momentum go?
    - expelled in a low speed wind if B is strong
    - stored in puffed up circumstellar structure supported by toroidal
      - magnetic field and rotation

detection complicated by protostellar outflows

Mellon & Li 2008



Basu & Mouschovias 1994



Galli et al. 2006

Why care about polarization?

Polarization is the characteristic signature of magnetic fields

Dust polarization: Emission & Absorption

Caused by elongated dust grains
Polarize emission/absorption is perpendicular/parallel to $\mathbf{B}_{pos}$
No direct information of B strength

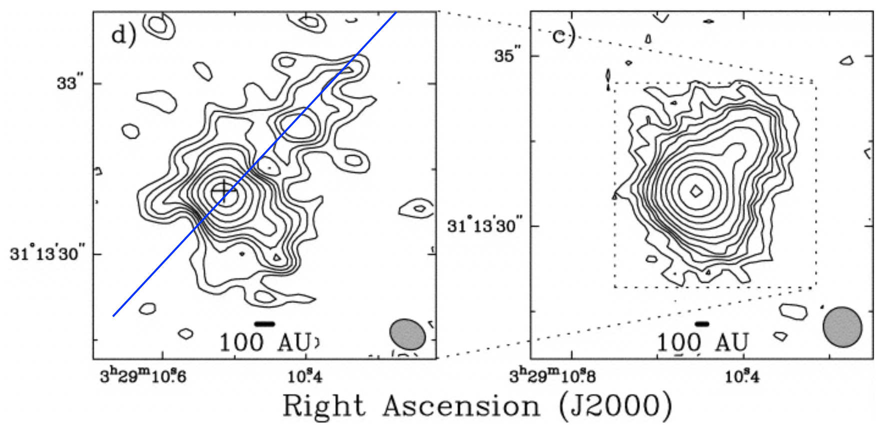
Zeeman Effect

Observable in those species with an unpaired outer e^-
Direct measure of |**B**| in the l.o.s.
Few species available: CN, CH, CCS, SO

Polarized Molecular Line Emission (Goldreich-Kylafis Effect)

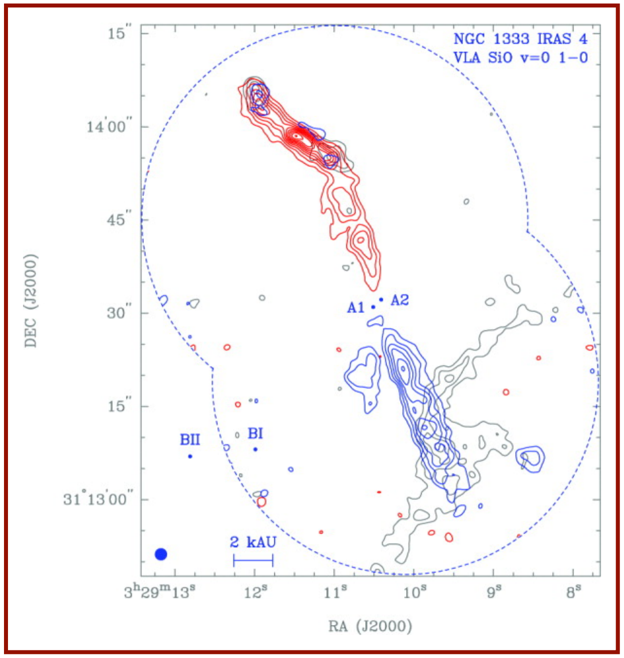
Measure magnetic field direction in the plane of the sky
Polarization either parallel or perpendicular to $\mathbf{B}_{pos}$
Degree of polarization depends on:
optical depth,
degree of anisotropy,
ratio of collisional excitation to radiative rates
PA_{pol} depend on the angles between the l.o.s, **B** and the axis of symmetry of the velocity fields
So many constrains makes detection very difficult

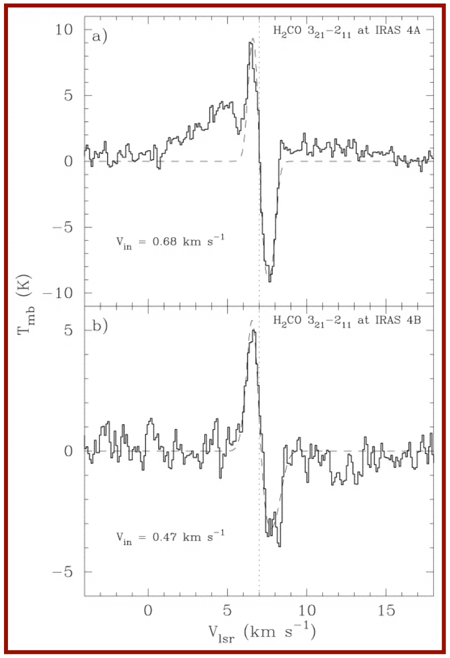
NGC 1333 IRAS 4A: A Class 0 Low Mass YSO



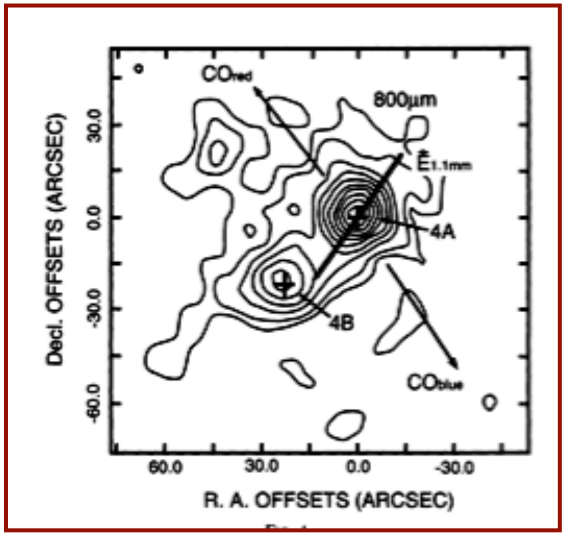
- Located in Perseus (300 pc)
- Resolved into binary components (Lay et al. 1995; Looney et al. 1997)
- Components 4A1 and 4A2 at a separation of 2" with total mass ~ 1 $M_\odot$

- Large scale well collimated molecular outflow (Blake et al. 1995; Choi 2005)
- Kinematics signatures of: infall, outflow, rotation and turbulence (diFrancesco et al. 2001)
- Age of 10^4 yrs from accretion rate



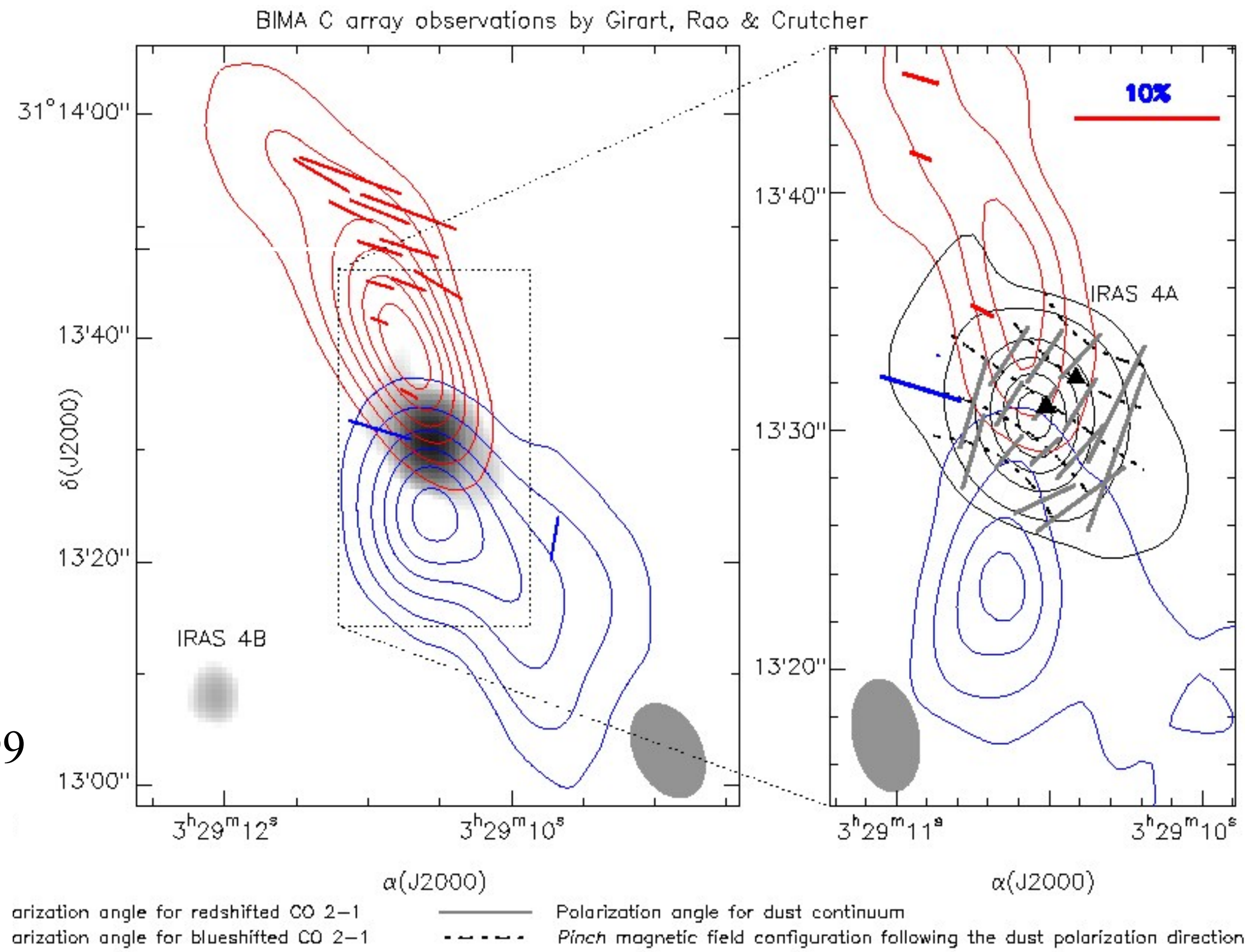


CO polarization from a molecular outflow



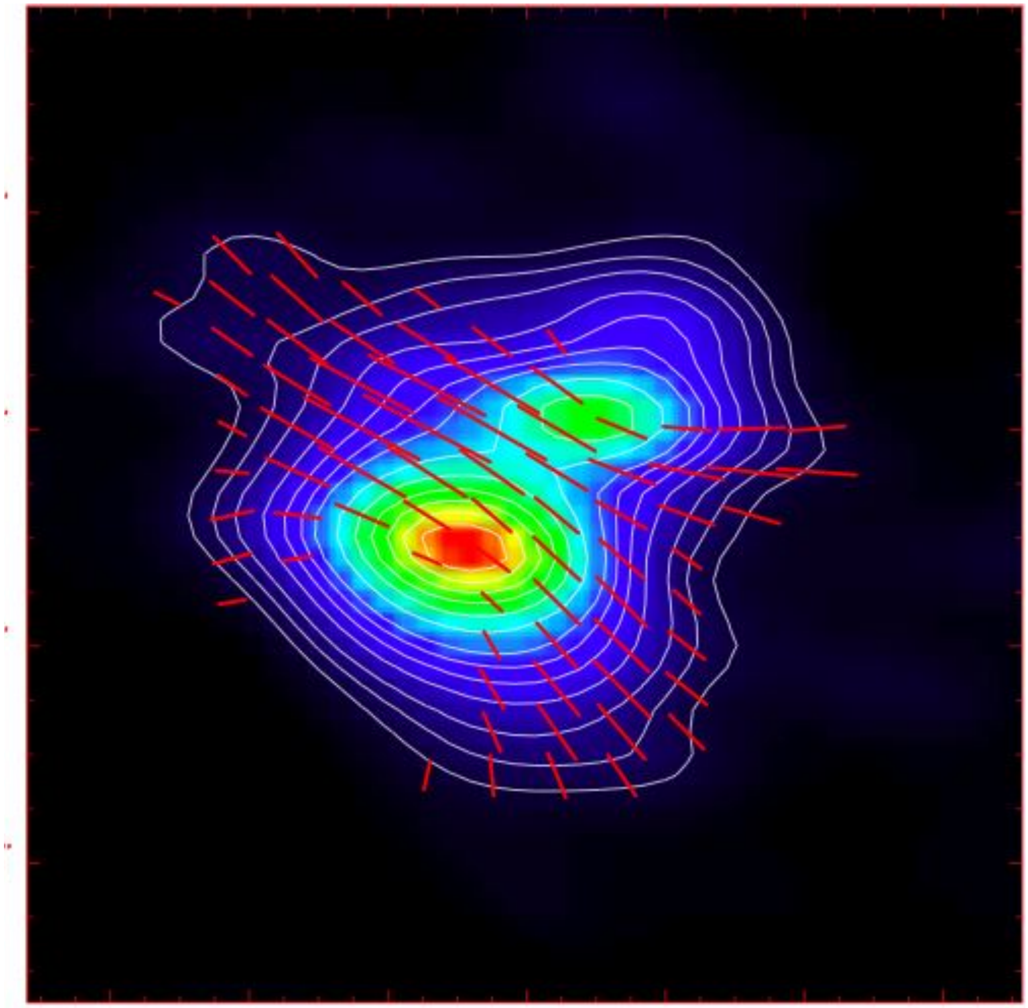
Hayashi et al. 1995

Girart, Crutcher & Rao 1999



- Simultaneous detection of polarization in CO and dust
- Magnetic field inferred form the two type of pol are in agreement

NGC 1333 IRAS4A - B vectors



- Hour glass shape of the magnetic field structure in the circumbinary envelope
- The field axis seems well aligned with the minor axis

Girart, Rao & Marrone 2006, Science

More about B in NGC 1333 IRAS4A

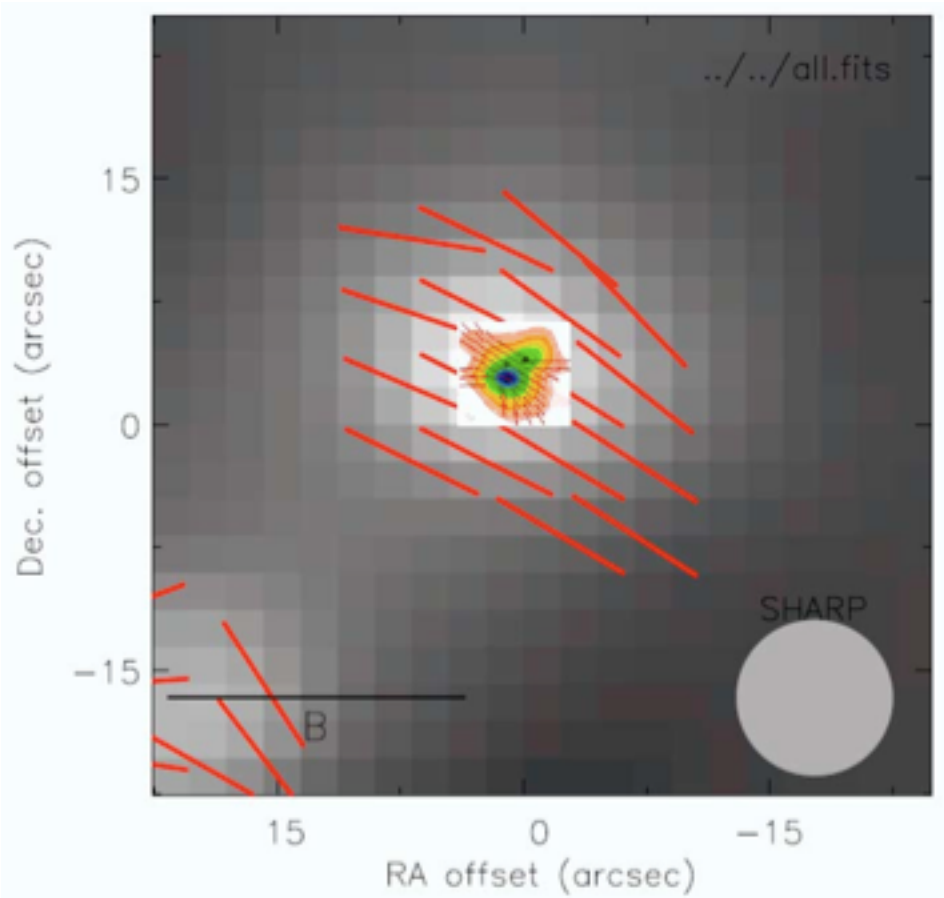


Figure from Attard et al. (2009)
Large scale B vectors from CSO SHARP Polarimeter

$$B_{\rm p} = Q\sqrt{4\pi\rho}\,\frac{\delta v_{los}}{\delta\theta_{int}}$$

$$\frac{f_{\rm tension}}{f_{\rm gravity}} = 5\left[\frac{B}{\rm mG}\right]^2\left[\frac{R}{0.1{\rm pc}}\right]^{-1}\left[\frac{M}{1\,{\rm M}_\odot}\right]^{-1}\left[\frac{n}{10^7\,{\rm cm}^{-3}}\right]^{-1}\left[\frac{D}{0.1\,{\rm pc}}\right]^2$$

$$MtB = \frac{M}{\Phi_B} = 1.0\left[\frac{N({\rm H_2})}{10^{20}\,{\rm cm}^{-2}}\right]\left[\frac{B}{\mu{\rm G}}\right]^{-1}$$

$$\beta_{turb} = \frac{\sigma^2}{V_A^2}$$

(Chandrasekhar & Fermi 1953; Mouschovias 1991; Scheuling 1998; Crutcher 1999; Lai et al. 2002)

Input parameters:

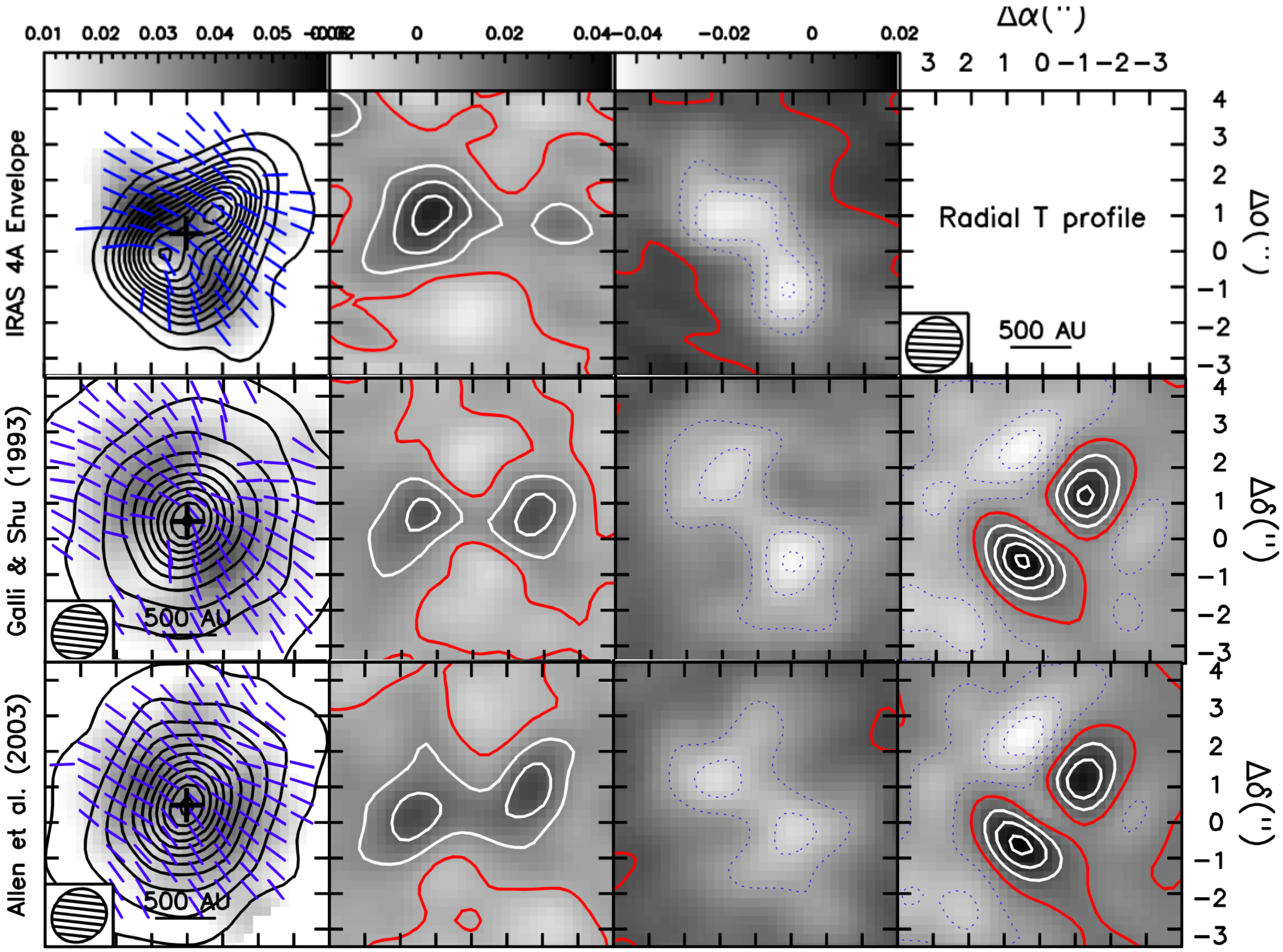
- $n(H_2) \approx 4\times10^7$ cm^{-3}
- $M \approx 1.2\ M_\odot$
- $N(H_2) \approx 8\times10^{23}$ cm^{-2}
- $\delta\theta_{int} \approx 5^o$
- $\Delta v_{turb} \approx 0.5$ km s^{-1}

Output parameters:

- $B_{pos} \approx 5$ mG
- $\beta_{turb} \approx 0.1$
- $MtB \approx 2$
- $f_{tension}/f_{gravity} \approx 0.2$

Girart, Rao & Marrone 2006

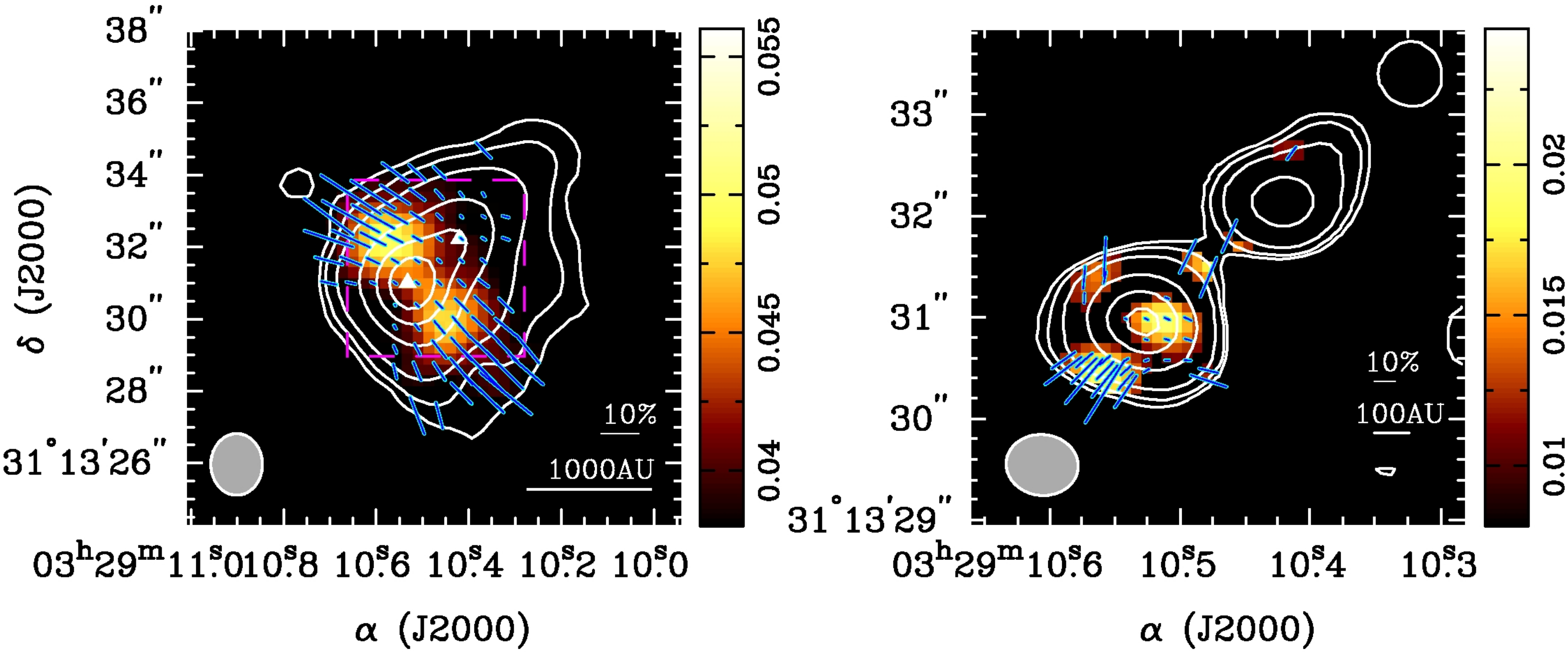
IRAS 4A: Modelling the B field.



- Galli Shu 1993. **Collapse of a singular isothermal sphere threaded by an initially uniform magnetic field**.
- Allen al 2003. Similar to Galli & Shu 1993 but numerical, taking into account rotation. Initially core already flattened
- $\boldsymbol{B_0}$ = 0.4-0.9 mG
- $\boldsymbol{t}$ = 10^4 yr

Gonçalves, Galli & Girart 2008, A&A; Frau, Galli, Girart 2011, in preparation

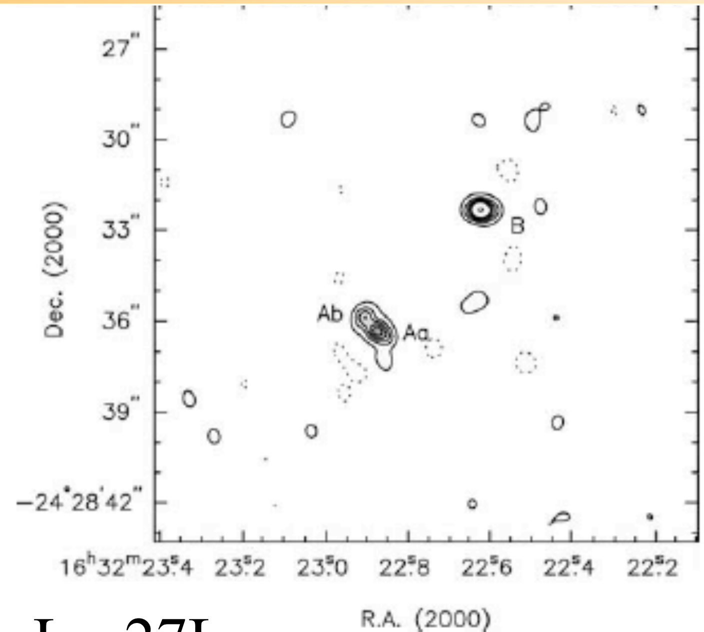
IRAS 4A: Polarized emission from the disk?



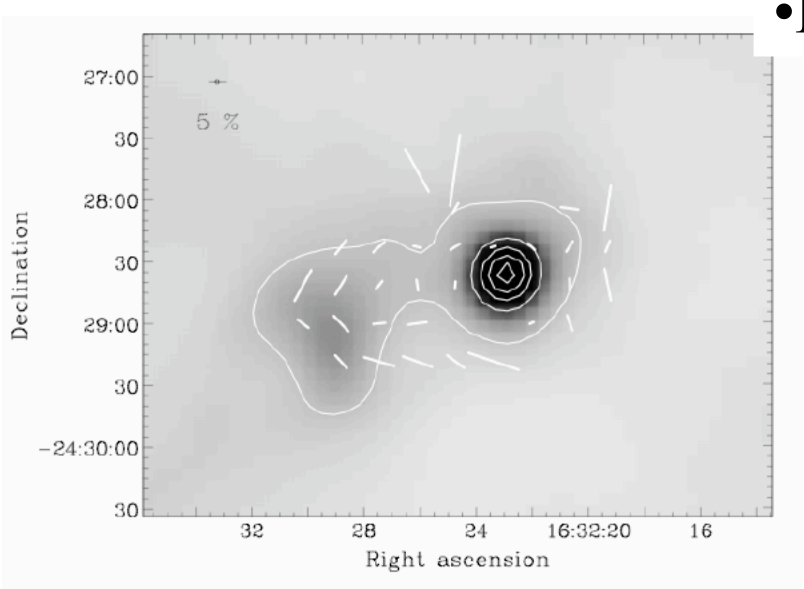
Lai et al. , in preparation

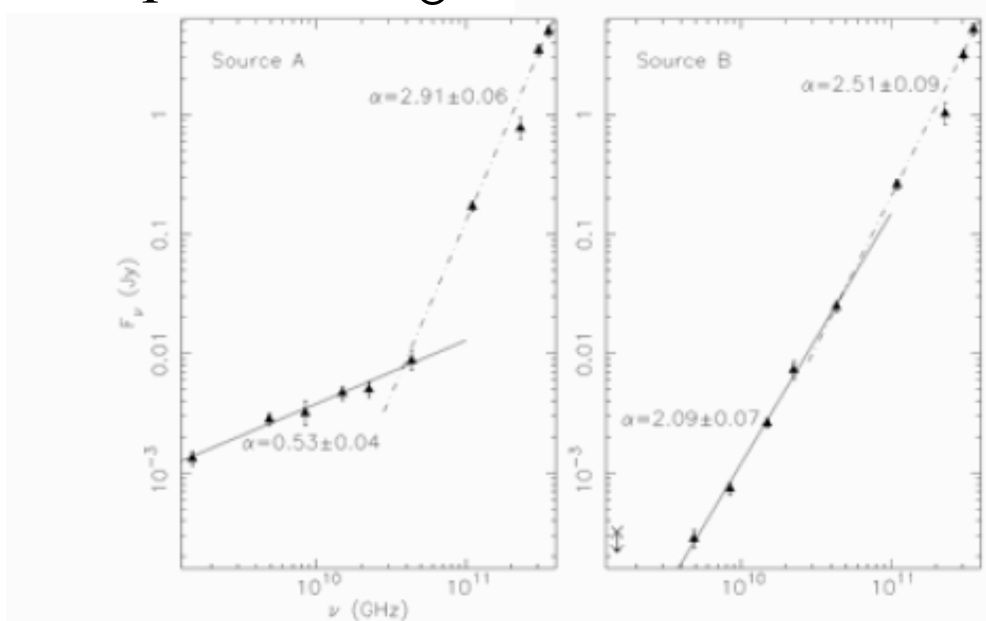
Another Class 0: IRAS 16293-2422

- Source A shows multiplicity
- A and B have different spectral indices
- Molecular outflows seem to be associated with Source A
- A and B thus appear to be at different evolutionary stages



•D= 140 pc L= 27$L_\odot$

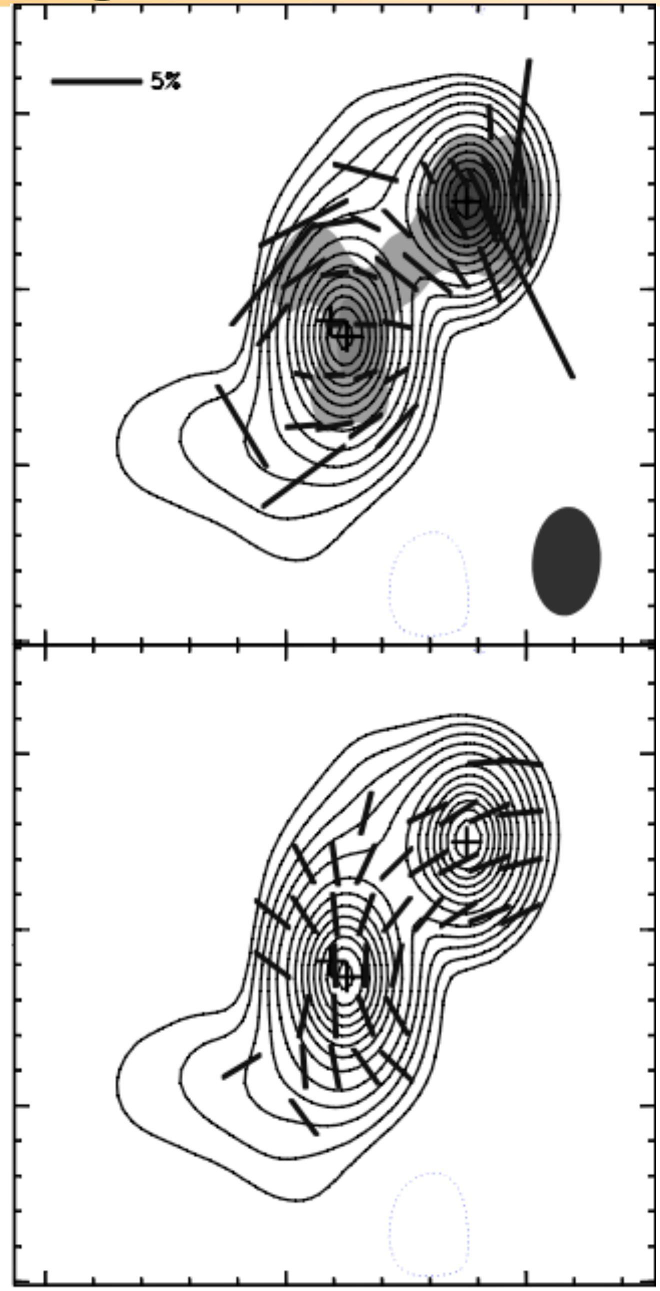




IRAS 16293: A complex magnetic field

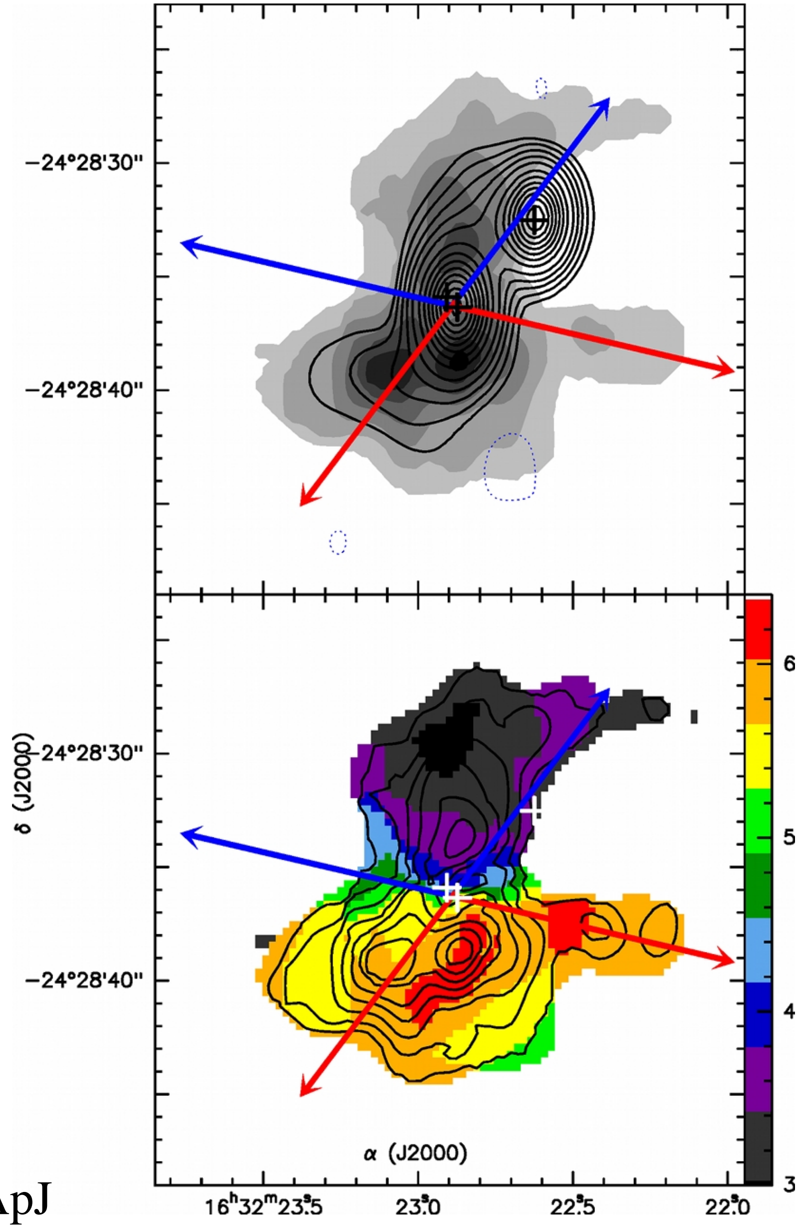
- Magnetic field from SMA observations
- The dust emission is well resolved in two cores separated by 5"
- The magnetic field information shows that A is pinched, whereas source B appears to be uniform
- A fit with a set of parabolic functions restricted to source A fits also B!
- $n(H_2) \approx 5\times10^7$ cm^{-3}
- $M \approx 0.3\ M_\odot$
- $B_{pos} \approx 4$ mG
- Supercritical cores

Rao, Girart et al. 2009, The Astrophysical Journal



IRAS 16293: rotation around Source A

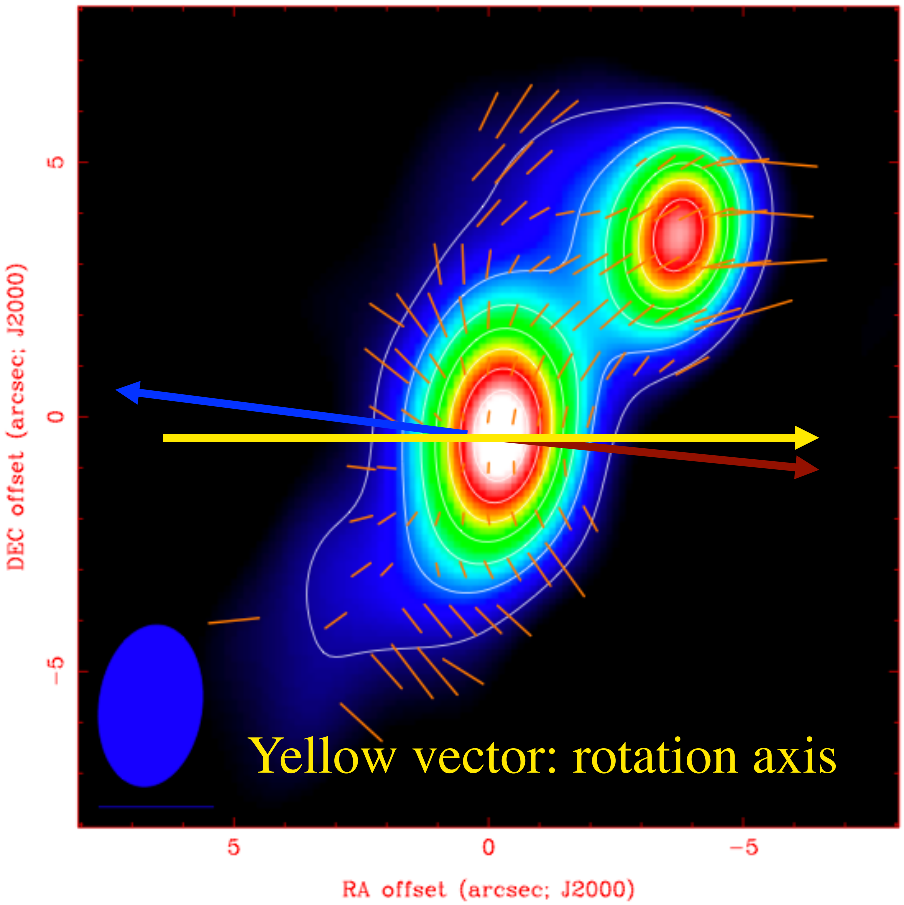
- $H^{13}CO^+$ 4-3 is extended N-S over ~2500 × 1500 AU and centered around source A
- Source B appears to be devoid of the $H^{13}CO^+$ emission
- Velocity gradient along N-S of 0.31 km/s or $4.5 \times 10^{-12}\ s^{-1}$
- Magnetic energy is comparable with centrifugal energy
- Rotation axis aligned with the outflow axis but perpendicular to the B field direction ????



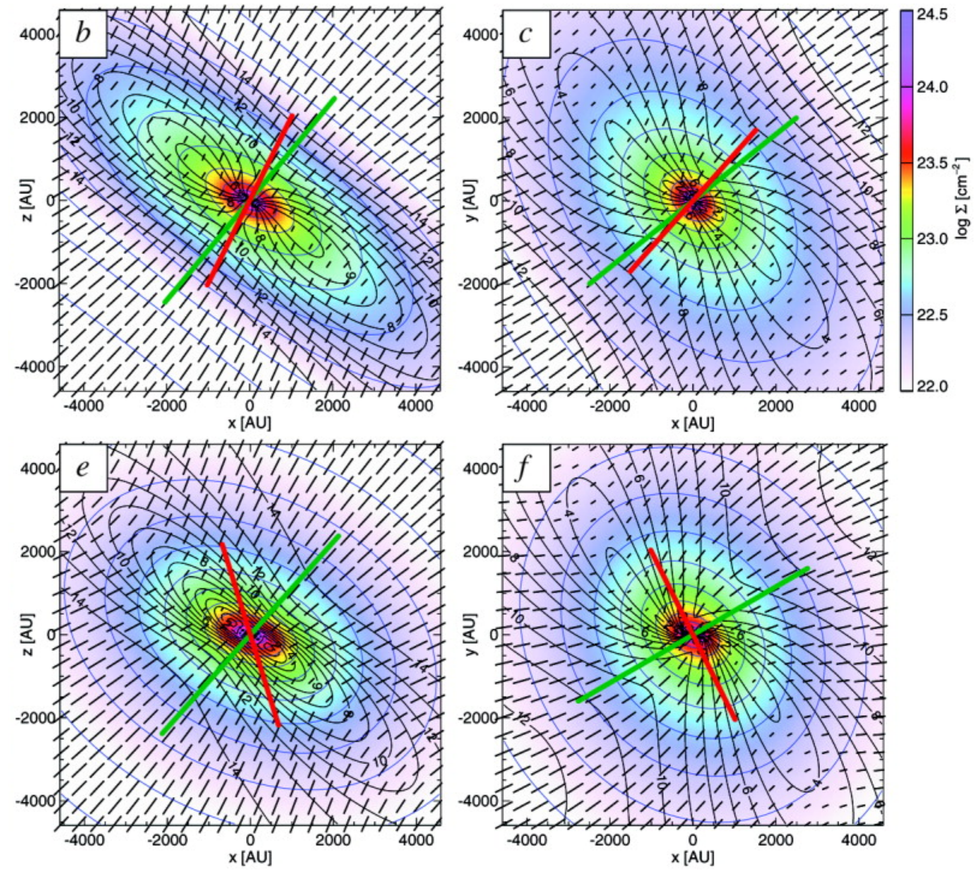
Rao et al. 2009, ApJ

IRAS 16293: a puzzling source??

Blue red: main outflow direction



Red vectors: outflow direction

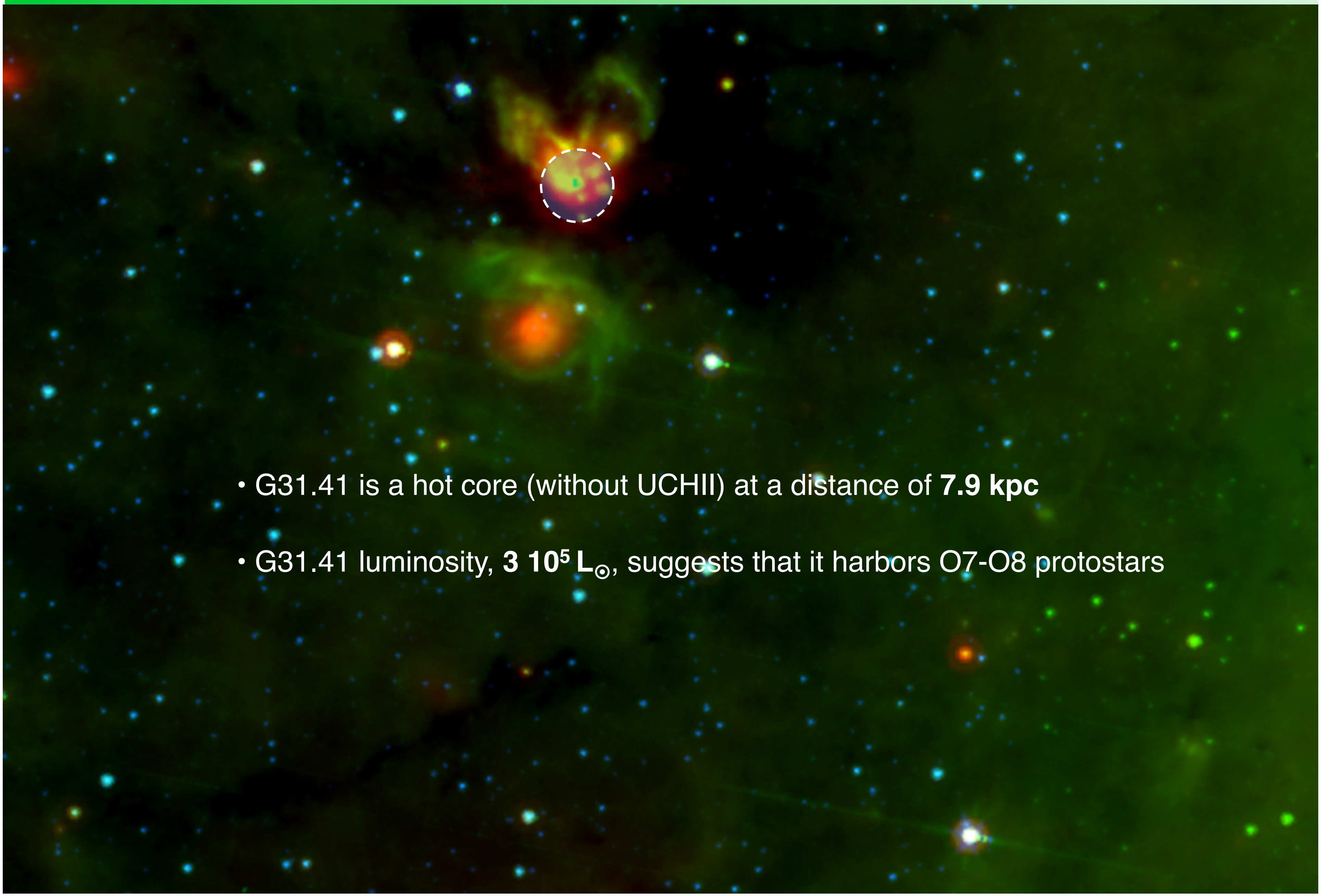


Predictions for misaligned B and rotation axes for the case of strong centrifugal forces wrt B

(Matsumoto 2006)

Rao et al. 2009, ApJ

Magnetic fields, rotation & infall towards G31.41+0.31

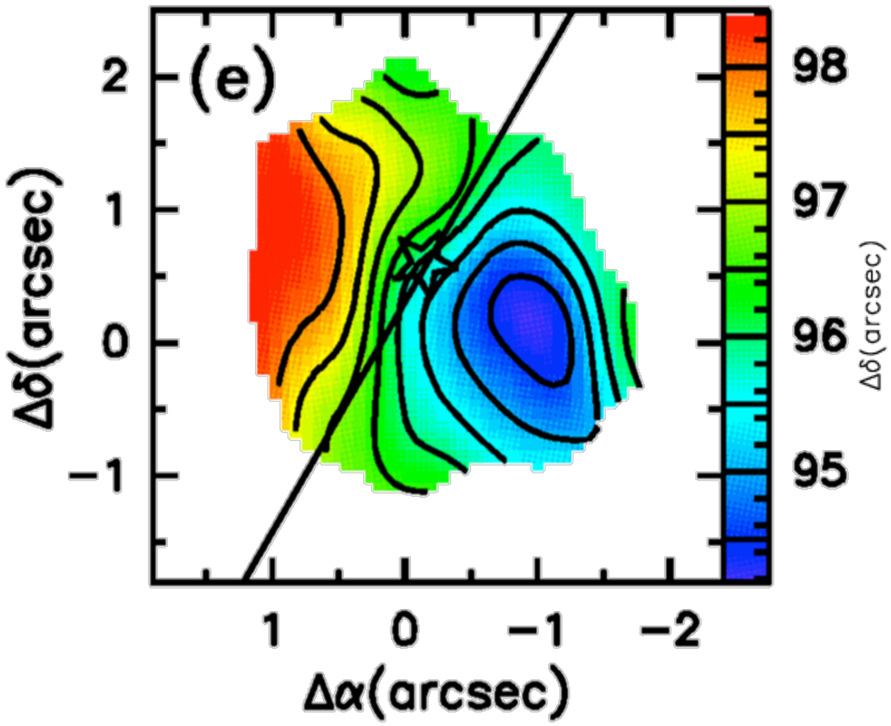


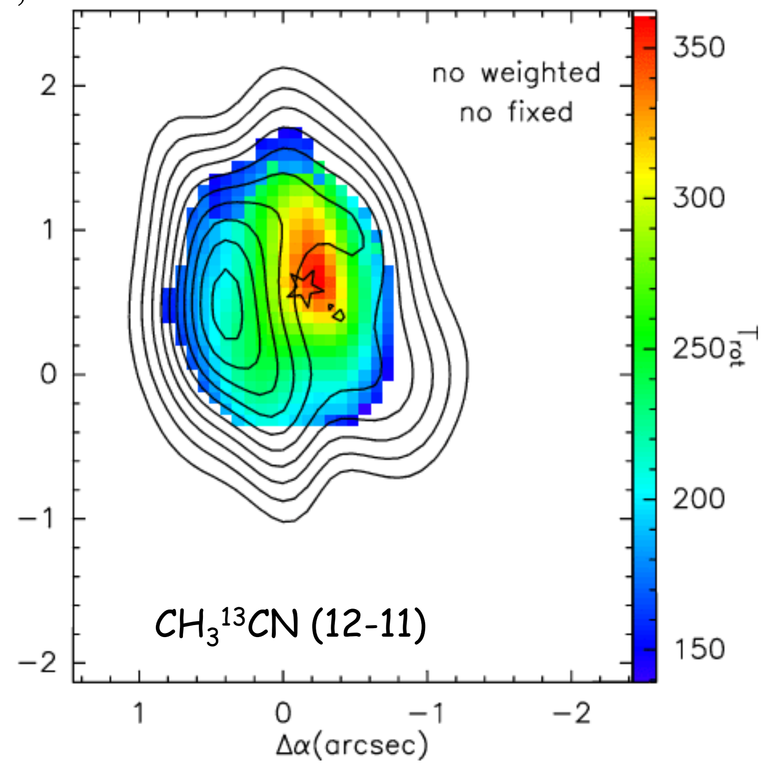
• G31.41 is a hot core (without UCHII) at a distance of **7.9 kpc**

• G31.41 luminosity, **3 10^5 $L_{\odot}$**, suggests that it harbors O7-O8 protostars

The hot molecular core (HMC) in G31.41+0.31

Beltran et al. 2004, 2005

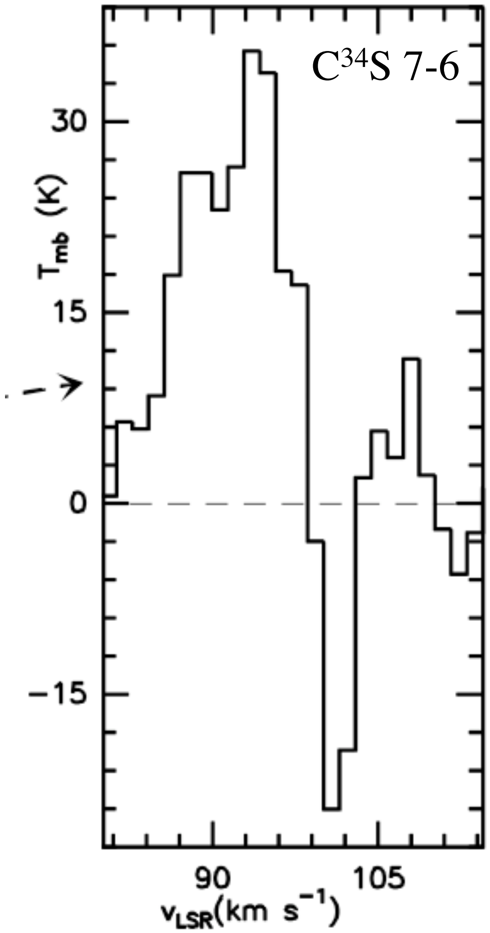


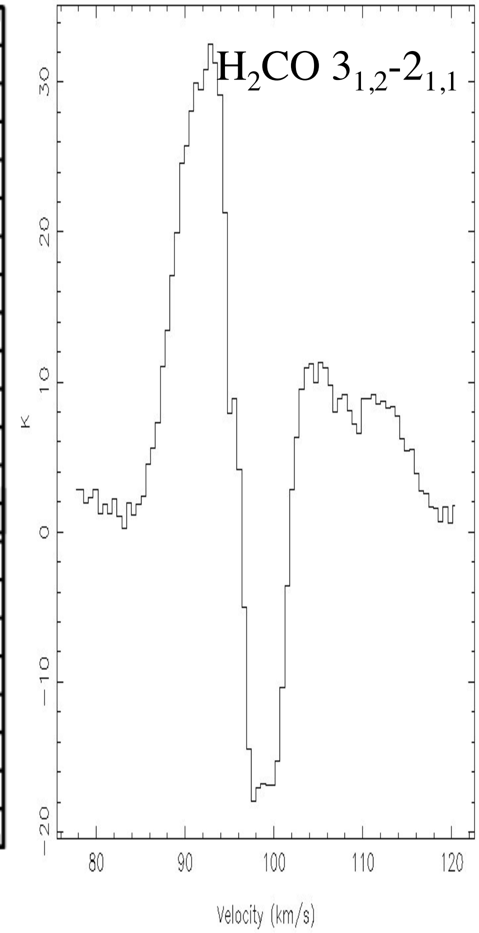


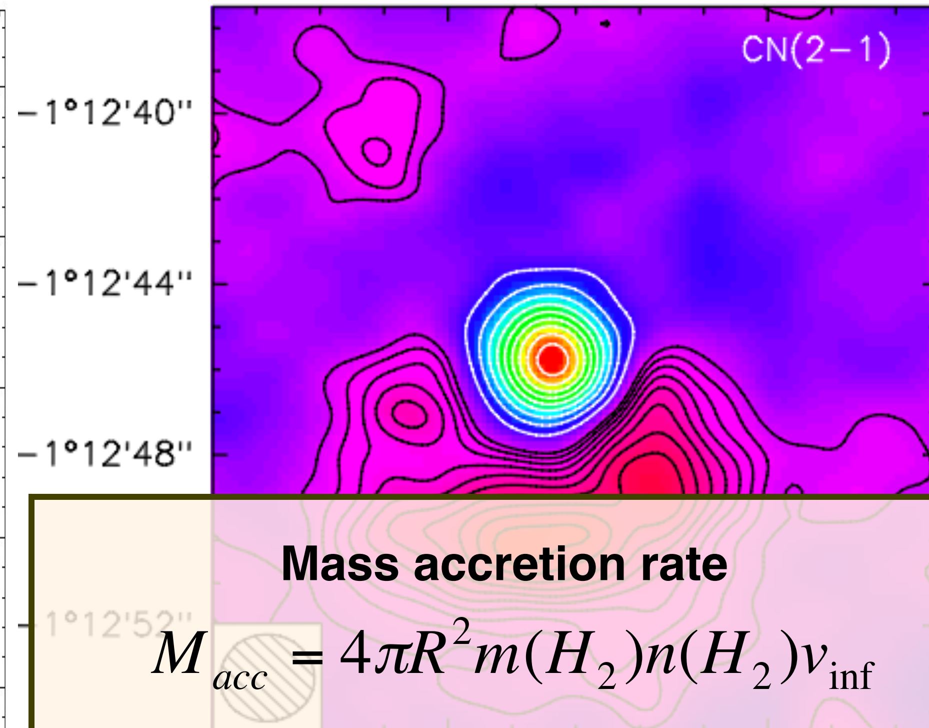
• Beltrán et al. 2004 detected a massive, dense and hot rotating “toroid”

• The mass of the toroid, 490 $M_{\odot}$, is much larger than the dynamical mass needed for equilibrium, 44 $M_{\odot}$: the hot core is unstable and undergoing gravitational collapse.

Infall towards the G31.41+0.31 HMC







Mass accretion rate

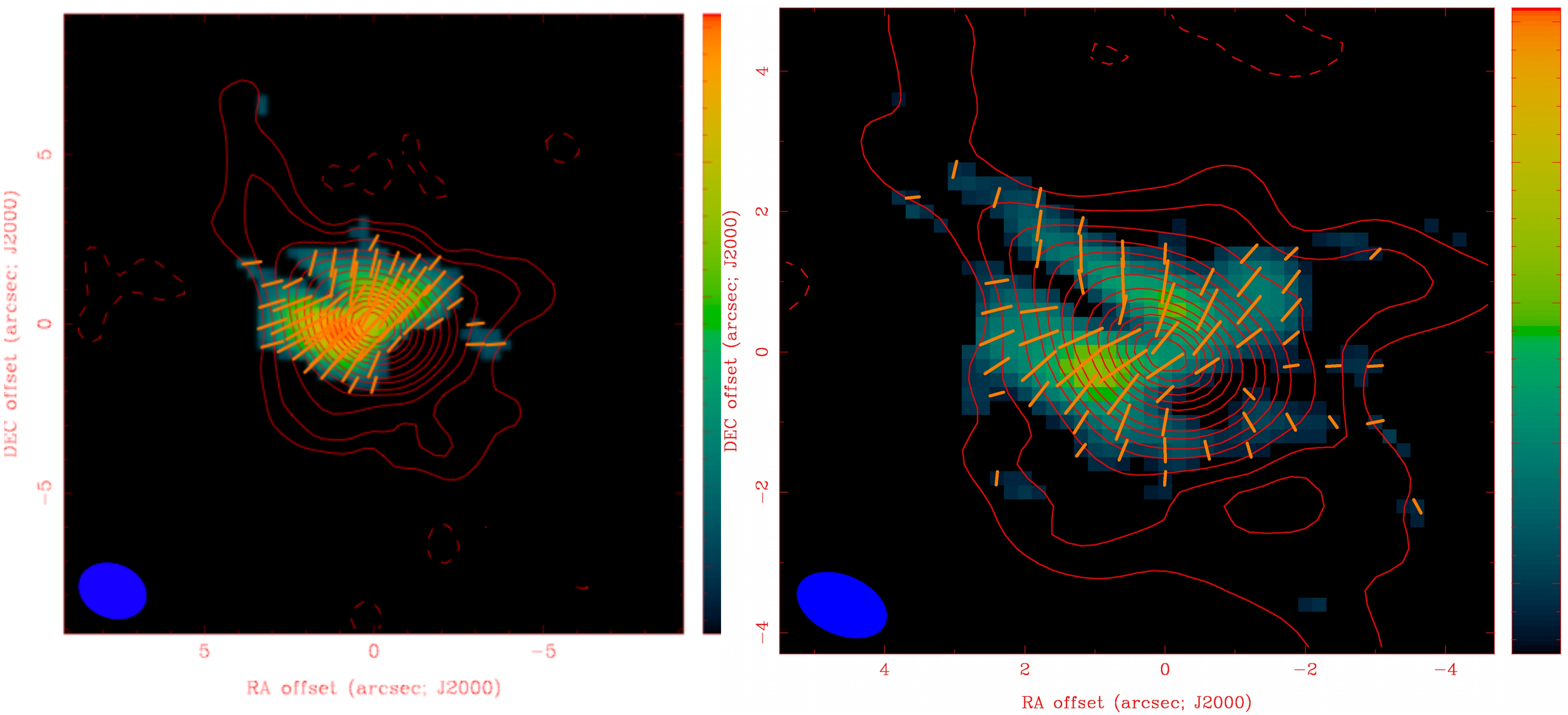
$$M_{acc} = 4\pi R^2 m(H_2) n(H_2) v_{\rm inf}$$

M_{acc} = Ω /(4π) **[3×10^{-3}—3×10^{-2}] M$_\odot$ yr^{-1}:** in agreement with the Osorio et al. 2009 estimate

• The signature is well seen in low energy transitions (<100K) and is probably due to a very hot compact dust component around the massive (proto)stars.

• There is a clear inverse P-Cygni in $C^{34}S$ 7-6, H_2CO $3_{1,2}$-$2_{1,1}$ and CN 2-1 profile that suggests infalling gas.

Magnetic fields threading the G31.41+0.31 HMC



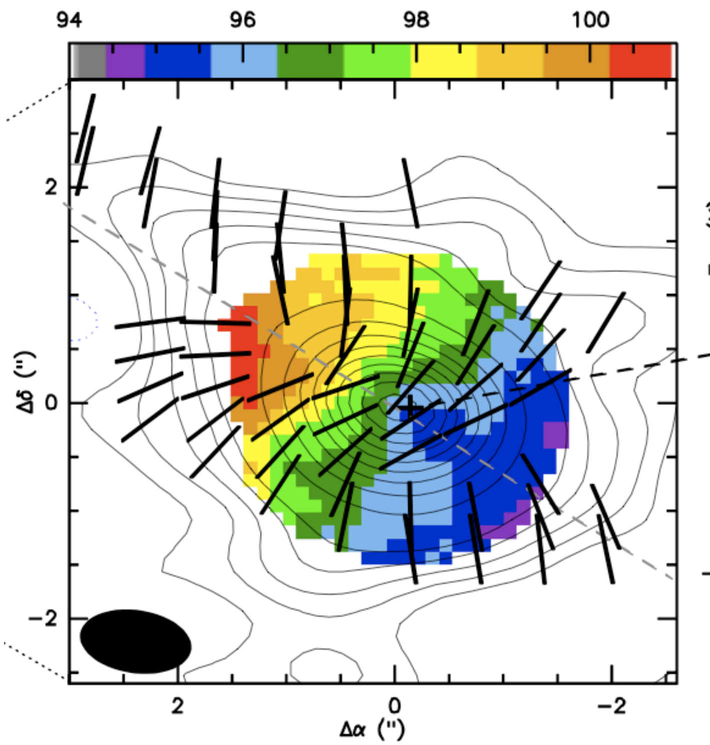
• Hot Core elongated in the NE-SW direction **$M_{core} \approx 577 M_\odot$** n(H2) $\approx 3 \times 10^6$ cm^{-3}

• The dust polarization pattern yields an **hourglass shape morphology**, similar to the one found in IRAS4A but the scale and mass involved are much larger

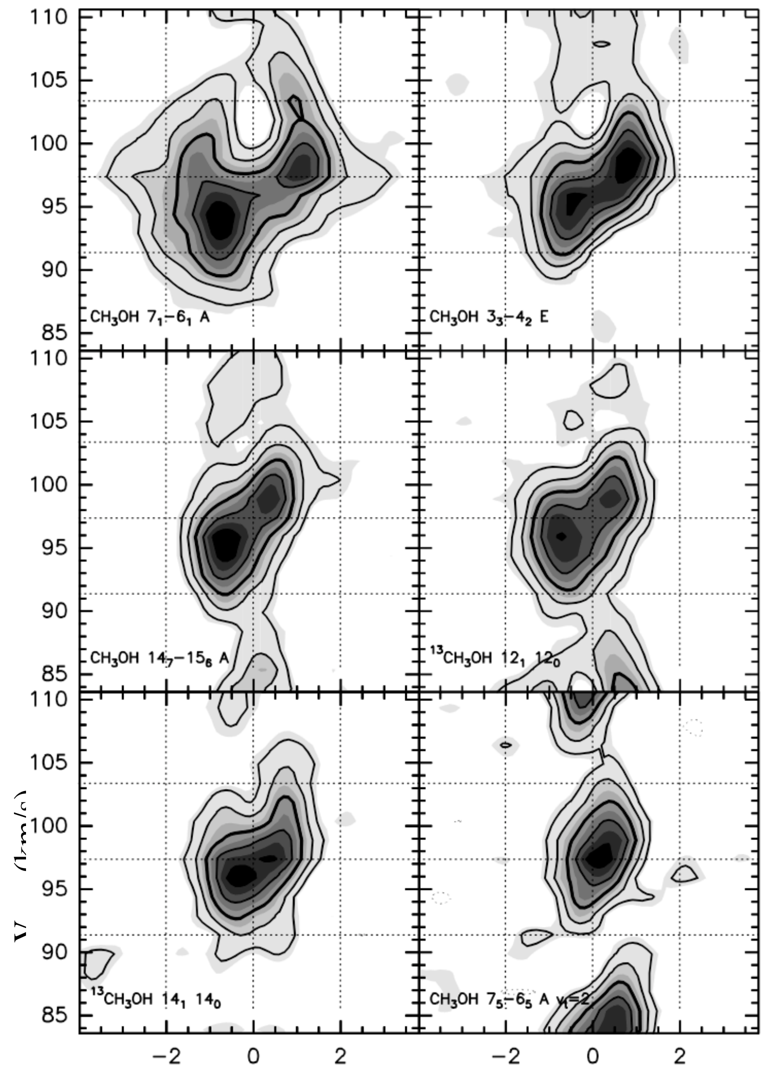
• B lines perpendicular to the major axis of the hot core

Girart et al. 2009

Rotation towards G31.41+0.31



• The velocity gradient (due to **rotation**) in the hot core is along the major axis, where the pinched magnetic field lines are observed



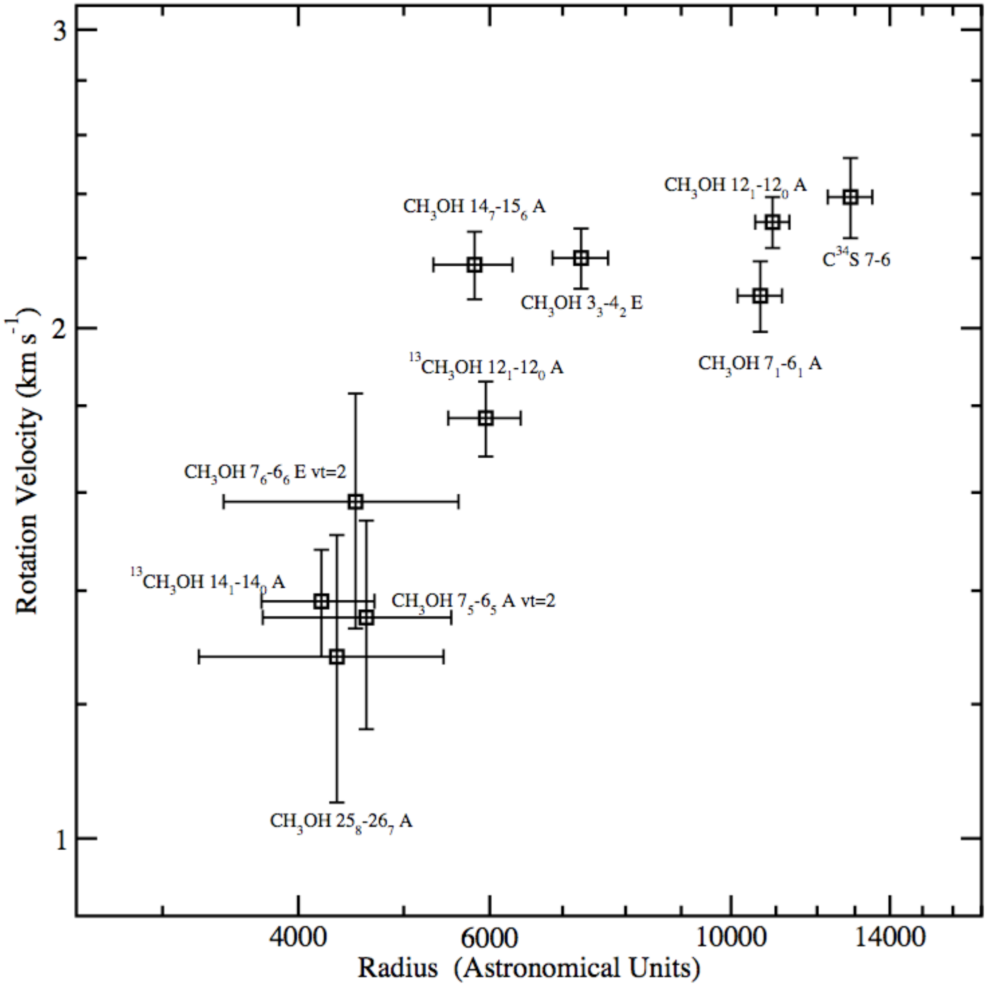
• Compact lines trace typically higher excitation energy transitions

• Methanol transitions are likely optically thick, so each line traces a shell with a specific radius

• The more compact transitions show a shorter velocity range, that is a smaller rotation velocity

Girart et al. 2009

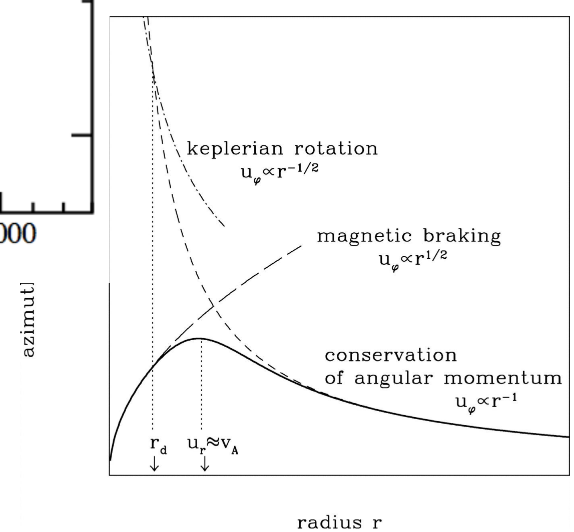
Magnetic Braking towards G31.41+0.31 ?!



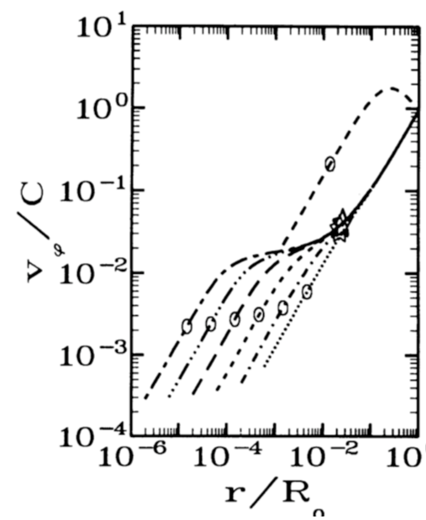
Girart et al. 2009

- Rotation and radius has been measured from the Half Maximum contour of different methanol transitions in the zero and first order maps of the integrated emission.
- The measured spin velocity of the hot core decreases with decreasing radius
- Therefore the angular momentum is not conserved: **Magnetic braking**

Galli et al. 2006



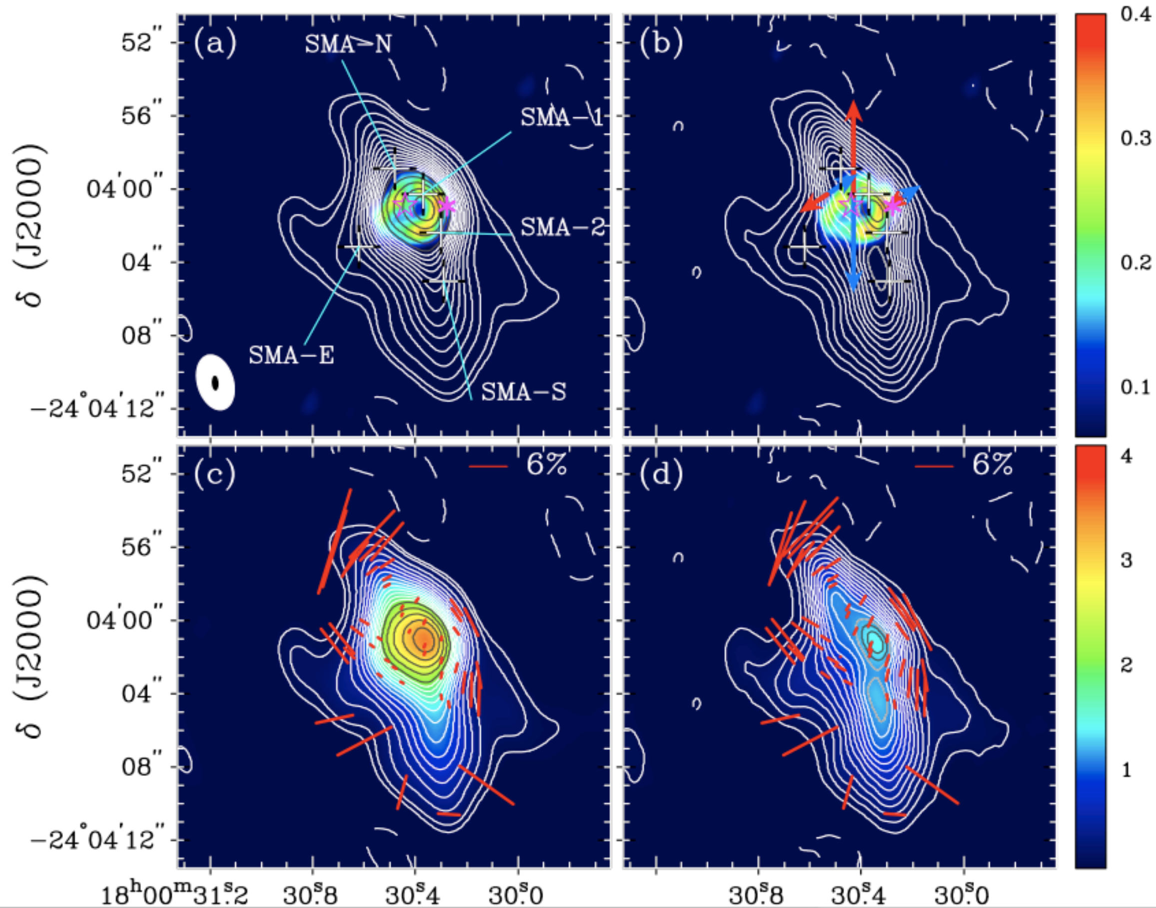
Basu & Mouschovias 1994



High-mass star forming core: UCHII G5.89-0.39

• G5.89 is a shell-like **ultracompact HII** region at a distance of **2 kpc** (eg. Acord et al. 1998)

• G5.89 contains an **O5 V** star (Feldt et al. 2003).



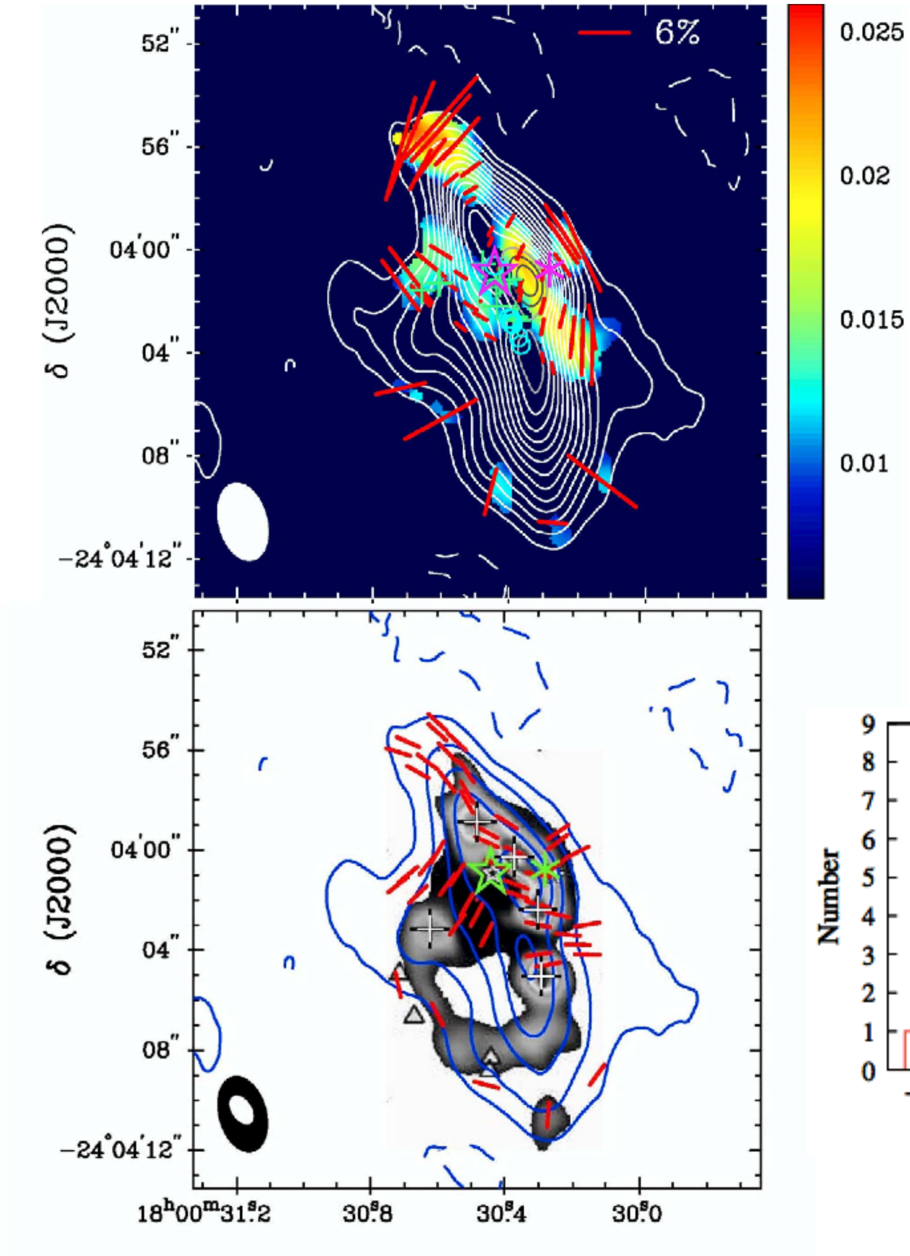
Tang, Ho, Girart et al. 2009, ApJ

• H_2O and OH masers indicate that further star formation activities are on going.

• The gas mass associated with the dust core is $\mathbf{M_{core} \approx 280 M_{\odot}}$, and the volume density n(H2) $\approx 2 \times 10^7$ cm^{-3}

• The polarization pattern shows an apparently not very well organized pattern

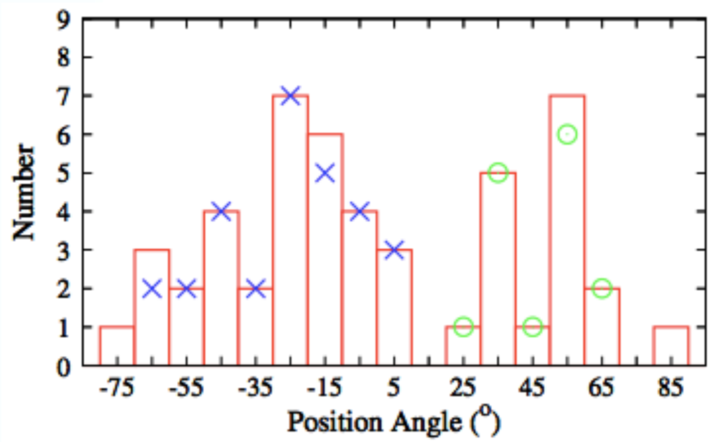
G5.89-0.39



• Significant depolarization over a wide region of the dense molecular envelope

• Most of the polarized emission arises around the UC HII

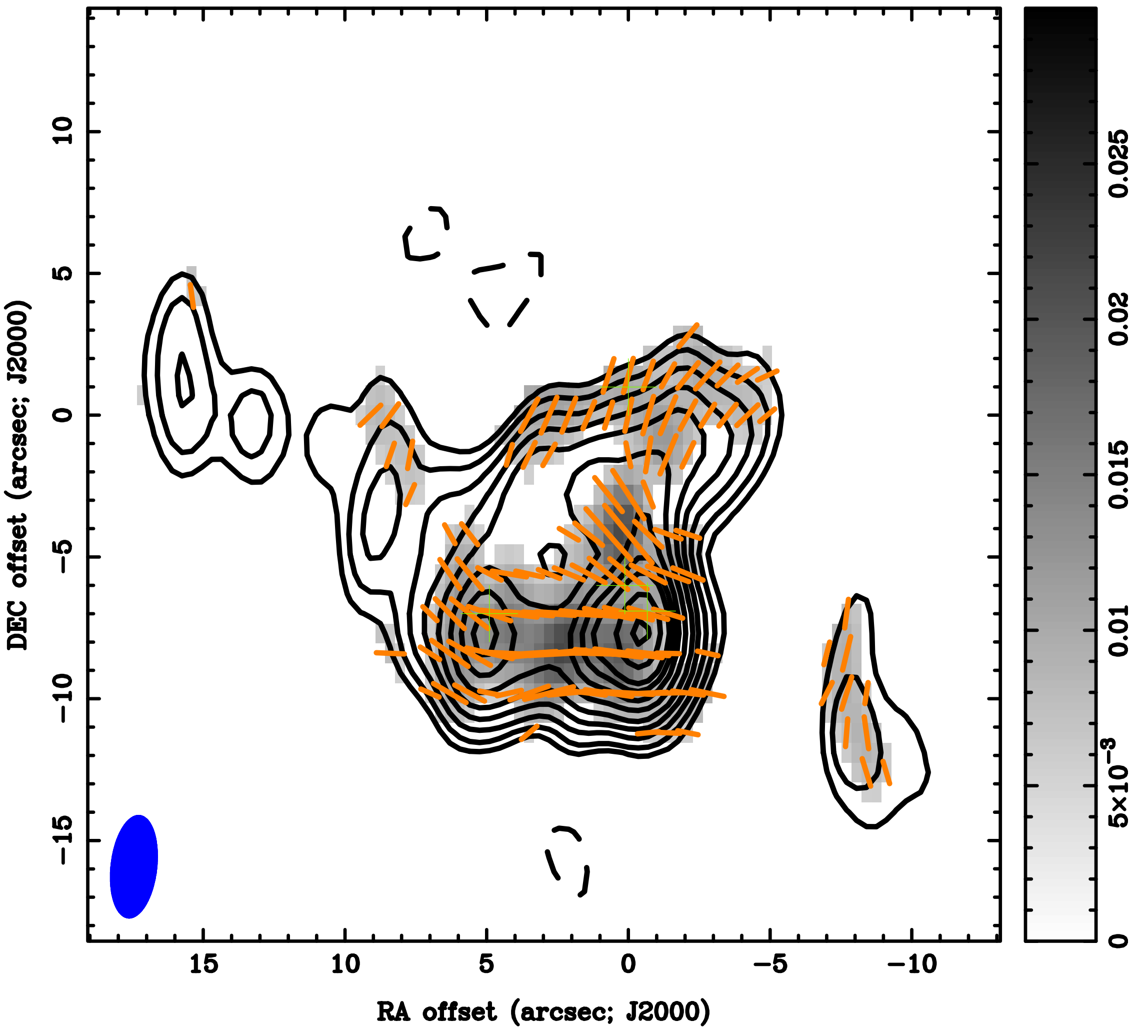
• B field structures are already overwhelmed and dominated by the radiation, outflows, and turbulence from the newly formed massive stars.



Tang, Ho, Girart et al. 2009, ApJ

SMA Legacy project: Filaments, Star Formation and Magnetic Fields

The goal is to make significant progress in understanding the role of magnetic fields in the formation of filaments, dense cores and massive stars.

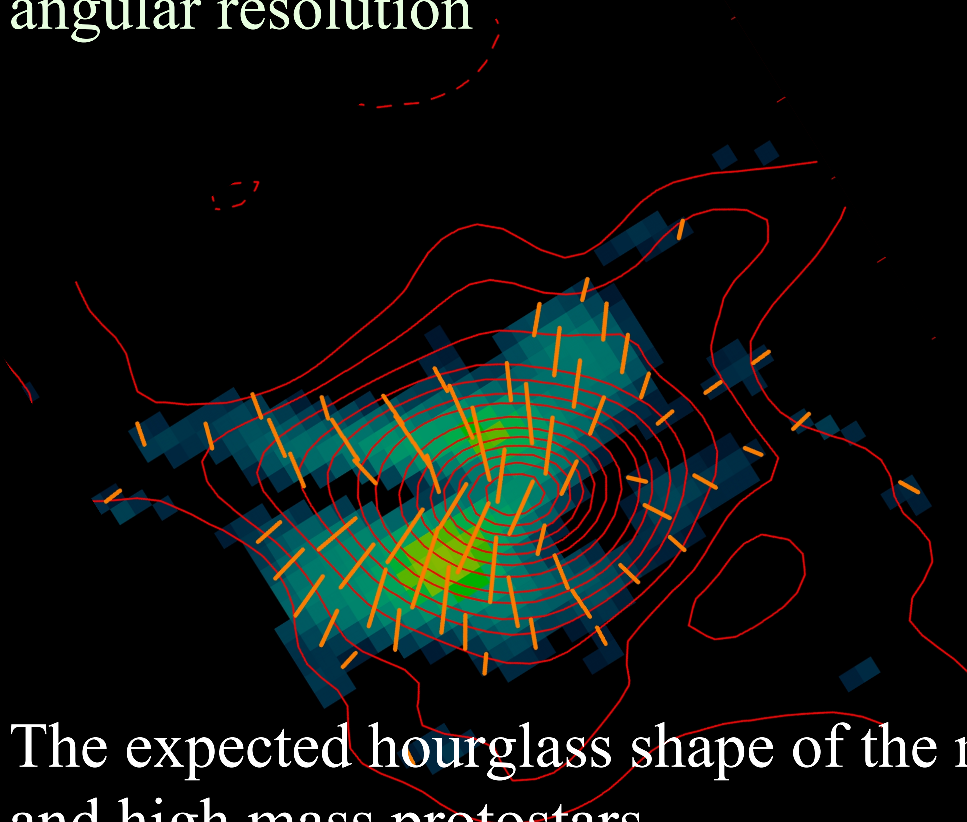


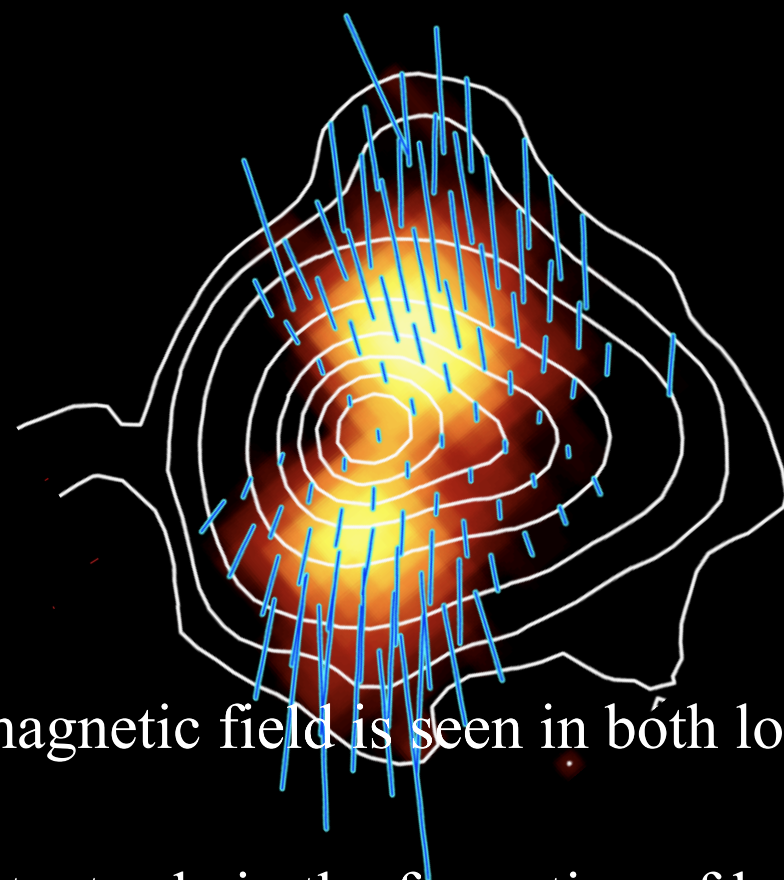
PI: Q. Zhang (CfA)

Ongoing observations: some tracks already obtained in compact and subcompact configurations

NGC 6634 v

- **SMA** has already provided very important information of the role of magnetic fields in star forming region at 1"
- SMA is an **unique** instrument to do submm polarization at high angular resolution





- The expected hourglass shape of the magnetic field is seen in both low and high mass protostars
- Magnetic fields seem to play an important role in the formation of low mass and high mass stars