SMA observations of magnetic fields around a low mass protostellar system: NGC1333 IRAS4A

Josep Miquel Girart
Institut de Ciències de l’Espai, CSIC
Institut d’Estudis Espacials de Catalunya

Ramprasad Rao
SMA - ASIAA

Daniel P. Marrone
Harvard Smithsonian Center for Astrophysics

ALMA 2006
Why care about polarization?

- Polarization is the characteristic signature of magnetic fields

- Detect magnetic fields via
  1. Zeeman effect
  2. Linear polarization of molecular emission (Goldreich-Kylafis effect)
  3. Linear polarization of aligned dust grains:
     - Emission is strong at submm/far-IR
     - Direction of $B_{\text{pos}}$
     - Field strength can be estimated indirectly

See Crutcher talk this afternoon

Rao et al. (1998)
Ambipolar-diffusion controlled versus Turbulence mediated star formation

- Struggle between gravity and magnetic forces. **Ambipolar diffusion** (AD) allows gravity overcome B.
- Interplay is measured by mass-to-magnetic flux ratio & the initial degree of ionization **observational parameters**.
- **Quasistatic formation** of magnetically supercritical cores, followed by **dynamic contraction**: **Hourglass morphology**. Envelope: remains magnetically supported.
- Timescales of **AD can be as short as 1 Myr and as long as >10 Myr**

*Mouschovias & Ciolek 1993; Mouschovias et al. 2006*

- **Interplay between gravity and supersonic turbulence**
  - Broad spectral lines indicate the presence of supersonic random motions (carrying enough energy to counterbalance gravity on global scales)
  - **Turbulence decays** on comparable to the free-fall time: it needs to be constantly replenished:
  - Turbulent velocity differences at scales > 0.05 pc are supersonic. Turbulence can generate density enhancement at these scales (observed cores, clumps)
  - Quiescent cores can be formed in a turbulent medium (random ram-pressure compression of large scales flows: when compression is at maximum, velocity dispersion is at minimum)

*Mac Low & Klessen (2004), Ballesteros-Paredes (2006)*
Low mass Class 0 protostar in Perseus (300 pc)

Strong dust continuum emission

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☉

Position angle of binary ~134°
• Large scale well collimated molecular outflow (Blake et al. 1995; Choi 2005)

• Kinematics studies reveal signatures of: infall, outflow, rotation and turbulence (diFrancesco et al. 2001)

• Age of $10^4$ yrs from accretion rate

• Star formation induced by outflows (Belloche et al. 2006)
Polarization observations: NGC 1333 IRAS 4A

Hayashi et al. 1995

Girart, Crutcher & Rao 1999

- Dust shows hints of hourglass magnetic field
- First detection of thermal polarization molecular line in a star forming region

NGC 1333 IRAS 4A is an ideal target for the SMA
• Contours & Pixel - I
• Beam size 1.6"x1.0"
• Resolve into 4A1 and 4A2
• Peak intensity: 1.9 Jy/bm
• Flux density: ~ 6 Jy
• RMS = 3 mJy/bm
• Dust tracing scales of ~300-1000 AU
SMA: NGC 1333 IRAS4A - E vectors

- Averaged pol = 4.7% @ 145°
- Peak pol = 9 % (45mJy/beam), & PA 153°
- At the peak of Stokes I - pol = 1%
- Polarization peak is offset
- Polarization hole

Contours - I, Pixel - polarized flux density $\sqrt{Q^2 + U^2}$
• Hour glass shape of the magnetic field structure in the circumbinary envelope

• The detected field axis is well aligned with the large scale field

• We will need some higher angular resolution observations to map the structure of the field between the two cores

• The field axis seems well aligned with the minor axis
NGC 1333 IRAS4A: Fit of the hourglass morphology

- Magnetic morphology fitted by a parabolic set of functions:
  - $PA = 61^\circ \pm 6^\circ$
  - Center of symmetry of $B$: between two dusty sources
  - Residual fit: $\delta\theta_{\text{obs}} \approx 8^\circ$
  - $B$ and dust axis are not exactly perpendicular

$$\delta\theta_{\text{obs}}^2 = \delta\theta_{\text{rms}}^2 + \delta\theta_{\text{int}}^2$$
$$\delta\theta_{\text{rms}} \approx 6^\circ$$

$$\delta\theta_{\text{int}} \approx 5^\circ$$
NGC 1333 IRAS4A: Estimating importance of magnetic fields

\[ B_p = Q \sqrt{4\pi\rho} \frac{\delta v_{\text{los}}}{\delta \theta_{\text{int}}} \]

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

\[ M_{tB} = \frac{M}{\Phi_B} = 1.0 \left[ \frac{N(\text{H}_2)}{10^{20} \text{cm}^{-2}} \right] \left[ \frac{B}{\mu\text{G}} \right]^{-1} \]

\[ \beta_{\text{turb}} = \frac{\sigma^2}{V_A^2} \]

**Input parameters:**

- \( n(\text{H}_2) \approx 4 \times 10^7 \text{ cm}^{-3} \)
- \( N(\text{H}_2) \approx 8 \times 10^{23} \text{ cm}^{-2} \)
- \( M \approx 1.2 \text{ M}_\odot \)
- \( \Delta v_{\text{turb}} \approx 0.5 \text{ km s}^{-1} \)
- \( \delta \theta_{\text{int}} \approx 5^\circ \)

**Output parameters:**

- \( B_{\text{pos}} \approx 5 \text{ mG} \)
- \( f_{\text{tension}}^{\text{gravity}} \approx 0.2 \)
- \( M_{tB} \approx 1.7 \)
- \( \beta_{\text{turb}} \approx 0.02 \)

(Chandrasekhar & Fermi 1953; Mouschovias 1991; Scheuling 1998; Crutcher 1999; Lai et al. 2002)
• Axis do not coincide:
  → $PA_B \approx 61^\circ$
  → $PA_{m.a.} \approx 44^\circ$
  → $PA_{outflow} \approx 19^\circ$

• … and fragmentation: a consequence that initially rotation and magnetic field axis do not coincide?

(see Machida et al. 2005, 2006)
SMA Observations

- **Dates:** December 4th and 5th, 2004
- **Array Configuration:** compact (5/6 antennas)
- **Weather:** Excellent; $\tau \sim 0.05$
- **Frequency:** 345.8 GHz (including CO 3-2)
- **Continuum Bandwidth:** 2 GHz in each sideband
- **Instrumental polarization:** 1% in USB; 3% in LSB.
- The feed-horns are intrinsically linearly polarized
- Circular polarization is produced by inserting a QWP made of a dielectric material (response is frequency dependent)
- Fast Walsh function switching in order to simulate simultaneous dual polarization
Conclusions/Future Work

- Successful mapping of B field structure at 1" (~300 AU)
- We can clearly see the expected hour glass shape of the magnetic field structure
- The magnetic field strength is ~5 mG
- Magnetic energy dominates over turbulence
- Supercritical core

→ Predicted scenario by magnetized core models

Future:
- Higher resolution/freq. SMA
- … and of course! ALMA