UNVEILING THE MAGNETIC PROPERTIES OF A PROTOSTELLAR CORE WITH SOFIA

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THE CONTEXT: STAR FORMATION

An interplay among several forces, among which:

- B-fields
- Turbulence

Planck@353GHz

E. Redaelli, MPE
HOW TO OBSERVE B-FIELDS IN THE ISM

Key concept:

Dust alignment via radiative torque (RAT)

Lazarian & Hoang (2007)

External radiation

B-field
HOW TO OBSERVE B-FIELDS IN THE ISM

Key concept:

Dust alignment via radiative torque (RAT)
HOW TO OBSERVE B-FIELDS IN THE ISM

Polarisation both in absorption and emission

Optical/NIR
HOW TO OBSERVE B-FIELDS IN THE ISM

Polarisation both in absorption and emission

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B-FIELDS IN PROTOSTARS: THEORY

Mouschovias+(1991), Shu+(1994), Basu+(2009),…
B-FIELDS IN PROTOSTARS: OBSERVATIONS

IRAS 4A in NGC1333 (Girart+2006)

L1157-mm1 (Stephens+2013)
THE SOURCE: LUPUS I

- The less evolved cloud of the Lupus complex
- A nearby (d~150 pc) and young star forming regions
THE SOURCE: LUPUS I

IRAS 100μm map with overlaying optical polarization (R-band) vectors (Franco&Alves, 2015)

Very ordered B-field
THE SOURCE: IRAS15398

- A young class 0 object
- Driving a bipolar outflow

We want to investigate the magnetic field properties in early stages of star formation
OBSERVATIONS

• We used the HAWC+ instrument in band E (214 μm)

• The nominal FoV corresponds to 0.22x0.28 pc

• We ask for 5σ detection of 5% polarization (rms~0.5 mJy/pix)

• The final integration time is ~2.5 h
A FIRST LOOK TO THE DATA

rms~2-3mJy/pix
\( \chi^2 \) ANALYSIS OF THE DATA

Credit: Dr. Fabio Santos

- Used to test the reproducibility of the dataset and the consistency of the uncertainties

- The available files are divided according to individual dither sets (~4 files per bin)

- Observations in each bin are merged separately

- The file containing all the observations merged together is the reference for the \( \chi^2 \)

- \( \chi^2 \) maps are produced for each Stokes parameter
$\chi^2$ ANALYSIS: RESULTS

- Calculated median $\chi^2 = 1.08$
- Expected median $\chi^2 = 0.79$
- Excess noise $\sqrt{\frac{\chi^2}{\chi^2_{\text{exp}}}} = 1.16$

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- Calculated median $\chi^2 = 0.74$
- Expected median $\chi^2 = 0.79$
- Excess noise $\sqrt{\frac{\chi^2}{\chi^2_{\text{exp}}}} = 0.97$
χ² ANALYSIS: RESIDUALS

Bin 1

Median = 0.09 +/- 0.02

Median = 0.04 +/- 0.02

Median = -0.04 +/- 0.02
THE STOKES PARAMETERS

We smoothed to 42” of resolution

\[ P_{\text{pol}} = \frac{\sqrt{Q^2 + U^2}}{I} \]

\[ PA = \frac{1}{2} \arctan \left( \frac{U}{Q} \right) \]
MAGNETIC FIELD DIRECTION

- Black: SOFIA vectors, Green: optical vectors
- We show only vectors with $P(\%) < 0.50$, SNR $> 3.0$

B-field vectors are aligned with the optical ones
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MAGNETIC FIELD DIRECTION

- Outflows PA=35°
  (Bjerkei + 2016)

B-field is aligned with the outflow direction
THE HOURGLASS SHAPE
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THE $\text{H}_2$ COLUMN DENSITY

- Gould Belt Survey data (André+2010)
**THE P% VS AV CORRELATION**

Possible explanations:
- Geometric smearing
- Grain-growth
- Radiation field attenuation

\[ A_V = \frac{N(\text{H}_2)}{9.4 \times 10^{20}}, \text{Bohlin+}(1978) \]
THE P% VS $A_V$ CORRELATION

Optical vs FIR data

We are looking at two different regimes

$P_{pol}/A_V \propto A_V^{-0.57}$

$P_{pol} \propto A_V^{-1.21}$
ADF ANALYSIS

Autocorrelation function of the position angles

\[
\langle \Delta \Phi^2(l) \rangle = 2 \sqrt{2\pi} \left( \frac{B_t}{B_0} \right)^2 \frac{\delta^3}{(\delta^2 + 2W^2) \Delta^2} \left[ 1 - \exp \left( -\frac{l^2}{2(\delta^2 + 2W^2)} \right) \right] + m^2 l^2
\]

Key parameter!

Distance

Turbulence coherent length

Effective thickness

Beam size

Hildebrand+(2009), Houde+(2009)
ADF ANALYSIS

Data divided in 9 distance bins

$$\langle \Delta \Phi^2(l) \rangle = 2\sqrt{2\pi} \left( \frac{B_t}{B_0} \right)^2 \frac{\delta^3}{(\delta^2 + 2W^2)} \Delta' \left[ 1 - \exp \left( -\frac{l^2}{2(\delta^2 + 2W^2)} \right) \right] + m^2 l^2$$

Assumptions:

$$\delta = 20\text{mpc}$$

$$\Delta' = 0.1\text{pc}$$

e.g. Houde+(2009), Frau+(2014), Coudé+(2019)
ADF ANALYSIS: RESULTS

\[ \frac{B_t}{B_0} = 0.267 \pm 0.007 \]

Ordered component prevails
THE FIELD STRENGTH

Modified Chandrasekhar-Fermi analysis

\[ B_{\text{pos}} = \sqrt{\frac{4\pi \mu m_H n_{\text{H}_2}}{\delta \phi}} \frac{\sigma_V}{B_t/B_0} \]

- \[ B_{\text{pos}} = 78 \mu G \]
- \[ 2.6 \times 10^4 \text{ cm}^{-3} \]
- \[ 0.17 \text{ km s}^{-1} \]

Benedettini+ (2012)

Crutcher+ (2004)
MASS-TO-FLUX PARAMETER

It indicates the dynamical state of the core

\[ \lambda = \frac{(M/\Phi)_{\text{obs}}}{(M/\Phi)_{\text{crit}}} = 7.6 \times 10^{-21} \frac{N(\text{H}_2)}{B_{\text{pos}}} = 0.95 \]

The core is transcritical

Crutcher+ (2004)
CONCLUSIONS

• A possible first detection of the hourglass shape from SOFIA/HAWC+ in the low-mass regime

• An ordered magnetic field, stronger than the turbulent component

• The core is in a transcritical state (consistent with presence of protostar)
ON-GOING WORK

APEX proposal on lines: C^{18}O and DCO^+ 

Goal: relation between kinematics and B fields
APEX DATA

DCO$^+$ data
FUTURE PROJECTS

• ALMA proposal to trace the envelope-scale magnetic field

• Possible new SOFIA proposal at different wavelength
THANKS FOR THE ATTENTION!

…Questions??