Zeeman interferometric observations of CN(2-1) transitions with CARMA

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General Goals

Understanding role of B fields in formation of:

- Molecular clouds
- Molecular cores
- Protostars
- Protostellar outflows
- Protoplanetary disks
- Stars and planets
Theoretical Controversy

Do magnetic fields dominate cloud formation & evolution?

- **Strong B models**: ambipolar diffusion drives collapse into protostars.  
  (Mouschouvias 1991; Mouscouvias & Ciolek 1999)

- **Weak B models**: turbulent flows control cloud formation with cores either dissipating or collapsing if they become self-gravitating.  
  (Padoan & Nordlund 1999; MacLow & Kleesun 2004)

(Crutcher 2012)
Observational Techniques

Direct measurements:

Zeeman effect

Statistical measurements (Chandrasekhar-Fermi method):

Linearly polarized emission from grains aligned by magnetic fields

Goldreich-Kylafis effect (linear polarization on spectral lines)
Zeeman Effect

Only available technique for measuring directly magnetic field strengths in molecular clouds

\[ V \propto \frac{dI}{d\nu} \]

\[ V \propto \frac{\Delta \nu_z}{\delta \nu} \]

\[ \Delta \nu_z = \pm Z B_{LOS} \]

\[ Q, U \propto \left( \frac{\Delta \nu_z}{\delta \nu} \right)^2 B_{POS} \]
Testing Ambipolar Diffusion Model

For Strong B model, \( \frac{M}{\Phi} \) is expected to increase from envelope to cores

\[
M \propto N_{H2} \\
\Phi \propto |\vec{B}| \propto B_{LOS}/\cos(\theta)
\]

\[
\frac{[M/\Phi]_{\text{core}}}{[M/\Phi]_{\text{envelope}}} = \frac{[N_{H2}/B_{LOS}]_{\text{core}}}{[N_{H2}/B_{LOS}]_{\text{envelope}}}
\]
Massive Star-Forming Sites

CN has a large magnetic dipole, implying larger Zeeman splitting.

CN high density tracer mostly detected in high-mass star-forming regions (DR21 & W3OH).

Single-dish campaigns to detect Zeeman effect in dense clouds using CN.

Crutcher et al. (1996)
Crutcher et al. (1999)
Falgarone et al. (2008)
Maury et al. (2012)

CN Zeeman spectra on W3OH (Falgarone et al. 2008)
CARMA dataset: 1mm continuum emission

Polarization results similar to those found in Chen et al. 2012 (SMA observations)
CARMA CN(2-1) Observations

<table>
<thead>
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$V_i(\nu) = C_1 I_i(\nu) + C_2 \frac{dI_i(\nu)}{d\nu} + C_3 Z_i \frac{dI_i(\nu)}{d\nu}$

- C1: absorbs gain difference between left and right polarization and any linear polarized line signal.
- C2: absorbs instrumental polarization effects that produce pseudo-Zeeman splitting.
- C3: non-zero if there is circular polarization line splitting due to the CN Zeeman effect.
Fitting 9 CN(2-1) transitions simultaneously

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Zeeman effect detections

Low velocity gas

$|V| \sim [0.3, 4.5] \text{ km/s}$

High velocity gas

$|V| \sim [4.5, 10.0] \text{ km/s}$
- Selected positions with “easy” spectra.
- Zeeman effect detected through the analysis of the 9 spectral lines simultaneously.
Zeeman effect detections

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First detection of Zeeman effect with an interferometer!
CONCLUSIONS

Interferometric mapping of Blos at high density and high angular resolution is possible.

Blos maps can test the role of magnetic fields of different cloud/core formation theories.

Zeeman maps together with dust and spectral-line linear polarization maps can be modeled to test 3D morphologies and strengths of magnetic fields in regions of star formation.

Another set of CARMA observations have been obtained and combined with these dataset and we also got IRAM 30m data, which we're combining these days to recover the zero-spacing.

CARMA has been a fruitful pathfinder for ALMA, which should enable great progress in understanding magnetic fields.
CARMA telescope. Cedar Flat, Big Pine, CA.
Hints of G-K effect detection

Velocity INTEGRATED EMISSION maps

&&

Velocity AVERAGED linearly POLARIZED emission

- Hints of G-K effect (linearly polarized CN emission).
- We have to add the rest of the lines.
Hints of G-K effect detection

Velocity INTEGRATED EMISSION maps

&&

Velocity AVERAGED linearly POLARIZED emission
Hints of G-K effect detection