First Clear Detection of CCS Zeeman Splitting of TMC-1

Fumitaka Nakamura (NAOJ)

Collaborators

Seiji Kameno (JAO/ALMA), Kazuhito Dobashi (Tokyo Gakugei Univ.), Tomomi Shimoikura (Tokyo Gakugei Univ.), Kotomi Taniguchi (NRO/NAOJ), Hideo Ogawa (Osaka Pref. Univ.) and Z45 team
Outline

- Introduction
  Importance of magnetic field in SF process
  previous Zeeman observations of star-forming regions
- Nobeyama Zeeman Project: Z45
  CCS Zeeman Measurements with Z45
- Latest results
  A prestellar core in Taurus: TMC-1
- Future Zeeman Project collaborating with Taiwan
- Summary
Role of Magnetic Fields in SF

- Support molecular clouds and cores against gravitational contraction.
  influence timescale of SF and rate of SF

- Remove angular momentum from central regions of cores
  initiate SF

Magnetic fields can control star formation process
Critical Mass below which magnetic field can support the cloud against gravity

\[ M < M_{cr} \]

magnetically subcritical

\[ \left( \frac{M}{\Phi} \right)_{\text{crit}} \approx \left( \frac{1}{8\pi G} \right)^{1/2} \]

\[ M_{cr} \sim 10M_\odot, R \sim 0.05 \text{ pc} \]
\[ \rightarrow B_{cr} \sim 170 \mu G \]

The evolution of dense cores is determined by the magnetic field.

magnetically supercritical

It is important to measure the field strengths of dense cores observationally to investigate the core evolution.
Observations of Magnetic Fields in Star Forming Regions

- **Linear polarization**
  background star light (optical and near IR)
  dust thermal emission
  field direction on the plane of the sky.
  difficult to measure field strength precisely

- **Zeeman observation**
  direct measurement of magnetic field strength
  line of sight component

example of linear polarization
Sugitani, FN, et al. (2011)
Zeeman Effect

\[ E_M = E_0 + \mu MB \]

\[ M = J, J - 1, J - 2, \ldots, -J + 1, -J \]

\[ \mu = \frac{eh}{4\pi m_e c} = 9.3 \times 10^{21} \text{ (erg/G)} \]

selection rule for transition

\[ \Delta m = -1, 0, +1 \]

molecular lines having large magnetic moments

<table>
<thead>
<tr>
<th>Molecule</th>
<th>freq (GHz)</th>
<th>Splitting freq. per 1 (\mu)G (Hz/(\mu)G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI</td>
<td>1.420</td>
<td>2.8</td>
</tr>
<tr>
<td>OH 1.665 GHz</td>
<td>1.665</td>
<td>3.27</td>
</tr>
<tr>
<td>OH 1.667 GHz</td>
<td>1.667</td>
<td>1.96</td>
</tr>
<tr>
<td>CCS (43-32)</td>
<td>45.379</td>
<td>0.63</td>
</tr>
<tr>
<td>CN</td>
<td>113.5</td>
<td>2.18</td>
</tr>
</tbody>
</table>

Majumdar (2000)
Interstellar magnetic fields tend to be weak. Therefore, the splitting frequency is small, often obscured by the Doppler broadening. Spectral lines having large magnetic dipole moments have been used for previous Zeeman measurements. However, they trace B fields in low density parts such as cloud envelopes.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>freq (GHz)</th>
<th>Splitting freq. per 1 μG (Hz/μG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI</td>
<td>1.420</td>
<td>2.8</td>
</tr>
<tr>
<td>OH 1.665 GHz</td>
<td>1.665</td>
<td>3.27</td>
</tr>
<tr>
<td>OH 1.667 GHz</td>
<td>1.667</td>
<td>1.96</td>
</tr>
<tr>
<td>CCS (43-32)</td>
<td>45.379</td>
<td>0.63</td>
</tr>
<tr>
<td>CN</td>
<td>113.5</td>
<td>2.18</td>
</tr>
</tbody>
</table>

The low frequency lines such as HI and OH have been used for the previous Zeeman measurements. However, they trace B fields in low density parts such as cloud envelopes.
HI and OH have low critical densities, and trace only low-density regions. CN tends to be strong at regions where stars already formed.

Our goal is to measure the field strength of prestellar cores at the densities of $10^4\text{cm}^{-3}$ using Zeeman observations.
To measure the strengths of magnetic fields in prestellar cores, we chose CCS ($J_N=4_{3}-3_{2}$) as a target line for the Zeeman observation.

CCS has a large magnetic dipole moment and abundant in the early phase of core evolution.

NRO45m CCS ($J_N=4_{3}-3_{2}$) Shinnaga et al. (1999)

CCS ($J_N=3_{2}-2_{1}$) DSN Levin et al. (2001)
C4H GBT Turner & Heiles (2001)
SO ($J_N= 1_{2}-1_{1}$) Effelsberg Uchida et al. (2001)

no clear detection of the CCS Zeeman splitting
Nobeyama Zeeman Project: Z45

- A new dual-linear polarization receiver system
  (Nakamura et al. 2015; Mizuno et al. 2015)
  (in previous CCS Zeeman, circular polarization receivers are used)
  Taking cross correlation of two linearly polarized components to derive stokes V spectra. → minimize the artificial polarization

- Apply the Smoothed Bandpass Calibration (SBC) to reduce the total observation time

- Carefully selecting targets (TMC-1, L1495B, ...)
  strong CCS emission + steep edges of line profiles
  stokes V ∝ dl/dv
The system overview

Z45
Nakamura et al. (2015)

Dual-pol receiver Z45 w/ cal device
NEW

VLBI backend
Reference

Polarization Spectrometer
Full-stokes spectra, Total power

Trx ~50 K
Observations

Taurus molecular cloud d~140 pc
Beam ~ 38”@45 GHz = 0.024 pc

Nanten C$^{18}$O map (T. Onishi)
Observations

- **Target:** TMC-1
  - 2\textsuperscript{nd} strongest CCS (peak $T_A^* \sim 2.5$ K)
  - largest $\frac{\text{d}I}{\text{d}v}$
  - Stokes $V \propto \frac{\text{d}I}{\text{d}v}$

- **Calibration**
  - Crab nebula & planets (Venus, Jupiter, Moon)
  - NRO 45-m + Z45 + PolariS
  - 2014.4-2016.3
  - Total obs. time $\sim 30$-40 hours

- **Obervation mode**
  - Smoothed Bandpass Calibration
    (SBC; Yamaki, Kameno, Beppu 2012)

- **Verification**
  - observe CCS and HC\textsubscript{3}N *simultaneously*.

\[ I_{\text{HC}_3\text{N}} \gtrsim I_{\text{CCS}} \]
Results: Detection of CCS Zeeman Splitting

- Fit the Stokes I to derive $dI/dv$
- Fit the Stokes V profile with $V = a_0 + a_1 I + a_2 \frac{dI}{dv}$

Zeeman Shift = 134.6 ± 15.0 Hz

$134.6/15 = 9\sigma$

$134.6 / 64 = 210 \, \mu G$
**HC$_3$N Stokes I and V Spectra**

- Fit the Stokes I to derive $dI/dv$
- Fit the Stokes V profile with  
  $$V = a_0 + a_1 I + a_2 \frac{dI}{dv}$$

Zeeman Shift = $-9.9 \pm 14.2$ Hz

No Stokes V splitting
CCS line at TMC-1

- CCS has 4 components along line of sight.
  \[ I = I_1 + I_2 + I_3 + I_4 \]
- Assuming that all 4 components have the same field strengths,
- Stokes \( V = a \left( \frac{dI_1}{d\nu} + \frac{dI_2}{d\nu} + \frac{dI_3}{d\nu} + \frac{dI_4}{d\nu} \right) \)
- \( = adI/d\nu \)
We conduct the same observations on 2014 and 2015, and detected the same Zeeman shift of CCS.

Using the same system, we detected Zeeman shift of CH$_3$OH maser toward OMC-2, but not for other sources (S235, S255, NGC2264).

We observed CCS and HC$_3$N (HC$_5$N) lines simultaneously, and we did not detect the Zeeman splitting of HC$_3$N and HC$_5$N.

L1495B (tentative result): no detection of CCS shift (< 71\mu G)
We have detected CCS Zeeman splitting toward TMC-1. TMC-1 appears to be magnetically supported.
Physical Properties of TMC-1

- Density traced by CCS (Suzuki et al. 1992)
  Applying LVG with CCS $J_N=2_1-1_0$ and $4_3-3_2$, $n_{H_2} \sim 3 \times 10^4 \text{ cm}^{-3}$

- From our Zeeman observations, $B_{\text{obs}} = 210 \mu \text{G}$

- Assuming $T=10$ K,
  $$\beta \equiv \frac{B^2}{8\pi c_s^2 \rho} \approx 0.01$$

- Critical magnetic field strength
  $$B_{cr} = 2\pi G^{1/2} \Sigma \approx 240 \mu \text{G} \quad \Sigma \sim 3 \times 10^{22} \text{ cm}^{-2} \text{ from Herschel data}$$

- Normalized mass-to-flux ratio
  $$\frac{B_{cr}}{B_{\text{obs}}} = \frac{240}{210} = 1.14$$

- TMC-1 is strongly magnetized.
ALMA band-1

- 33-50 GHz
  CCS \((J_N=3_2-2_1\ 43\ GHz)\),  CCS \((J_N=4_3-3_2\ 45\ GHz)\)
- CCS Zeeman measurements towards prestellar cores
- Observe non-Zeeman lines such as HC\(_3\)N simultaneously to verify the detection.
- Applying LVG to two CCS lines to derive the physical parameters.
(near) Future Development

- We should prepare for ALMA band-1.

- Building a new receiver (with band-1 technology) for 45-m (frontend: Chau Ching Chon (ASIAA) backend: PolariN (NAOJ))

Trx ~ 50 K $\rightarrow$ 20K
A few hour observations
30 hours $\rightarrow$ 5 hours

- Cover 30 to 50 GHz
  Targets: SO (30 GHz), CCS (43, 45 GHz)
  SO: 1.74 Hz $\mu$G$^{-1}$ 3 times larger than those of CCS
We conducted CCS Zeeman observations toward TMC-1.

We detected CCS Zeeman splitting.

Similar observations can be done with ALMA band-1.

We plan to build a new 40GHz-band receiver for the Nobeyama 45-m telescope.
The system overview

Nakamura et al. (2015)

Mizuno et al. (2015)

Dual-pol receiver Z45 w/ cal device

VLBI backend

Polarization Spectrometer

NEW

Frequency Standard

Trx ~50 K

Q and U depend on parallel-correlations
... Need precise gain calibrations
R/L Beam Squint to Produce Fake Zeeman Shift

Model

\[ \theta_s = \pm \sin^{-1} \left( \frac{\lambda \sin \theta_0}{4\pi F} \right) \]

Measurements

OMC-2 CH\textsubscript{3}OH maser

dAz=-2.0", dEl = 0.24

dAz = -2.06 \pm 0.30, dEl = -0.24 \pm 0.30

For Z45:

\[ \frac{\theta_0 = 27^\circ.5}{\lambda/F = 0.037} \rightarrow \theta_s = \pm 0^\circ.077 \]

magnification = 16 \[ \theta_s = \pm 17''.4 \]

on the sky

\[ \theta_s = \pm 1''.03 \pm 0.15 \]

some compensation in the flat mirror
Velocity Gradient of TMC-1

integrated intensity (mom0)  velocity field (mom1)

**HC$_3$N**

velocity grad.

\[
\left( \frac{dv}{d\alpha}, \frac{dv}{d\delta} \right) = (3.68, 3.43) \text{ km/s/deg} \\
= (152, 115) \text{ Hz/arcsec}
\]

**CCS**

velocity grad.

\[
\left( \frac{dv}{d\alpha}, \frac{dv}{d\delta} \right) = (3.63, 2.74) \text{ km/s/deg} \\
= (152, 115) \text{ Hz/arcsec}
\]
TMC-1 HC3N: Stokes V vs. Parallactic Angle

PA-EL > 45°

-45° < PA-EL < 45°

PA-EL < -45°

After beam squint correction

Before

~5 hours

-523.9 ± 31.0 Hz

~15 hours

-428.4 ± 23 Hz

~15 hours

-869 ± 17.6 Hz

After beam squint correction

-103.7 ± 38.8 Hz

7.5 ± 25.3 Hz

4.2 ± 18.5 Hz
TMC-1 CCS : Stokes V vs. Parallactic Angle

PA-EL > 45°
-45° < PA-EL < 45°
PA-EL < -45°

Before

After beam squint correction

~5 hours
-14.1 ± 18.4 Hz
50.7 ± 31.1 Hz

~15 hours
-123.3 ± 25 Hz
112.1 ± 26.2 Hz

~15 hours
-183.0 ± 27.2 Hz
139 ± 19.5 Hz

04h41m42.47, +25°41′27″.1 (J2000)