Introduction
Analyzing POL-2 data
POL-2 850 micron maps
POL-2 sensitivity

850 μm vs. 450 μm maps

Summary

... with my apology for totally incomplete references

Polarization imaging:
lessons learned and wishes for future instrumentation

Ray S. Furuya (U. Tokushima, Japan)
$B$-field and polarimetry: questions to be addressed

- $B$ fields are detected via polarimetry towards any astronomical objects.
- What is the origin of $B$ fields?

**Are there primordial $B$ fields or are they produced by astrophysical process?**
Center of gravity can be defined

<table>
<thead>
<tr>
<th>Primordial</th>
<th>Primordial</th>
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</thead>
<tbody>
<tr>
<td>Circumstellar $B$</td>
<td>Circumnuclear $B$</td>
</tr>
<tr>
<td>Interstellar $B$</td>
<td>Intergalactic $B$ field</td>
</tr>
</tbody>
</table>

Primordial?, astrophysical process? or both?

Center of gravity cannot be defined
**Figure 6.** The observed magnetic field direction (orange vectors) overlayed on a colour-scale map of Stokes $I$. The direction of the magnetic field is assumed to be perpendicular to the direction of the observed polarisation angle, and magnetic field vectors are shown for the data points with $I > 15$ mJy beam$^{-1}$ and $\pi/3$ (thin vectors) or $\pi/5$ (thick vectors). White vectors are the magnetic field vectors observed by the Planck satellite (Planck Collaboration et al. 2018), whose spatial resolution is set as $100$ in this analysis. Positions of main infrared sources indicated in the figure are cited from Sandell & Knee (2001).

**Figure 7.** Intensity and polarisation vectors of individual sources. Gray scale is total intensity in 850 $\mu$m band. Polarisation in 850 $\mu$m is shown as orange vectors for the data points with $I > 15$ mJy beam$^{-1}$. Length of the polarisation vectors is proportional to $p\pi$, and their direction is rotated by $90^\circ$ so that the vectors represent the direction of the magnetic field. Interferometric observations by TADPOL (Hull et al. 2014), whose spatial resolution is $200.5$, are shown for reference. Cyan vectors are polarisation vectors in 1.3 mm rotated by $90^\circ$. White contours are 1.3 mm continuum intensity, whose levels are 2, 3, 5, 7, 10, 14, 20, 28, 40, 56, 79, 111, 155, 217 $\times$ $I$, where $I$ is the rms noise level. Red and blue contours are red- and blue-shifted CO ($J = 2 \rightarrow 1$) emission, whose contour levels are 4, 8, 12, 16 and 20, 25, 30 $\times$ $SL$, where $SL$ is the rms noise level. Noise levels of both 1.3 mm continuum and the CO ($J = 2 \rightarrow 1$) emission are indicated in the captions of individual figures. A reference scale for 0.1 pc is shown, in which we assume the distance to the source as 235 pc (Hirota et al. 2008).
In most astrophysical process, $B$ fields are passive in dynamics, however, $B$ fields play significant roles in some stages.

At what evolutionary stage, over what spatial scale, or/and over what density range do $B$ field is playing key role?
What does polarimetry tell us?

- **Intrinsic polarization of the emitter**
  - Anisotropy of directions of charged-particles’ motions
    - e.g., thermal emission from aligned dust, synchrotron radiation
  - Absorption or emission in molecules and atoms,
    - e.g., Zeeman effect, maser, laser, Goldreich-Kylafis effect

- **Polarization caused in radiative transfer process**
  - Linear polarization by scattering and reflection
  - Circular polarization by multiple scattering
  - Linear polarization by selective absorption and/or scattering,
    - e.g., absorption and scattering by aligned dust
  - Faraday rotation
Analyzing POL-2 data
Data and data reduction

- Tried to reduce the accessible data taken between 2015 and 2019 April. 450 micron data are limited to those taken under $\tau_{225} < 0.04$

- Successfully reduced,
  - Twenty-eight 450-micron observations (including 21 BISTRO targets)
  - Forty-three 850 micron observations (including 23 BISTRO targets)

Data reduction

- Starlink 2019-02-05 version (not the faster PCA version)
- 12 Linux machines — CPU 3 GHz 16 cores, memory = 256 Gb at NAOJ
- Tried pixel sizes of 4 and 12 arcseconds

Data volume and required scratch area

- Rawdata = 5.5 Tb, Starlink scratch area = 4.1 Tb for BISTRO data
- Rawdata = 2.1 Tb, Starlink scratch area = 1.5 Tb for non-BISTRO data

I greatly appreciate ADC!!
Data reduction procedure

1. **Reduced 850 micron** data pol2map pipeline

2. **Reduced 450 micro** data using the 850 map as a reference map, yielding a common pixel gridding

3. Convolved 450 um data with a single-gaussian-beam so that the dual-band data have the same beam size

4. Produced
   - (a) Pol. intensity ($PI$), pol. fraction ($P$), pol. angle ($PA$) maps
   - (b) Vector catalogues
   - (c) House keeping, e.g., verification, various images statistics

5. Vector catalog matching between the 450 and 850 data

6. Image display
POL-2 maps
What are presented here?
- **Data**: 850 micron
- **Image**: Stokes $I$
- **Contour**: 90\% percentile of Stokes $I$
- **Vectors**: rotated 90$^\text{deg}$, shown w. identical length to see directions

How vectors are selected?
- A threshold of $I/\Delta I > 10$ only, so as not to miss intrinsically-weak polarization

Because of,
the Eq. below,
we do not see polarization structure of
the inter-core gas, i.e.,
*B*-field structure inside filaments.

With the new camera, we would detect them toward the nearest low-mass star-forming region(s).

\[
\text{Largest detectable size [radian]} = \frac{\text{Scan velocity [radian Hz]}}{\text{Frequency cut [Hz]}}
\]
Because we already see "partially resolved-out" filaments towards a few SFRs with POL2, we may see their overall structure toward the nearby low-mass star-forming region(s).

With an enhanced sensitivity, striations may be detected in pol.

Because we already see "partially resolved-out" filament-and-hub structure toward a few SFRs, we may see their overall structure and associated filaments/striations toward the more distant star-forming region(s).

What we would see with 10-times higher scan speed?

Circumstellar B

0.089 pc

\( d \sim 460 \text{ pc} \)

What we would see with 10-times higher scan speed?

Because we already see "partially resolved-out" clump-core-filament system toward a few massive SFRs, we may see their overall structure of them toward the distant high-mass star-forming region(s) w. the new camera.

$0.33 \text{ pc}$

$d \sim 1700 \text{ pc}$

Arzoumanian, RSF et al. in prep.
POL-2 give us Stokes $Q$ and $U$ maps!

$\sim 78600$ pc

Circumnuclear $B$

Interstellar $B$?

$d \sim 78600$ pc

Stokes $Q$

Project code #M17AP074.
POL-2 give us Stokes $Q$ and $U$ maps!

$d \sim 78600 \text{ pc}$

Circumnuclear $B$

Interstellar $B$?

Stokes $U$

Project code #M17AP074.
Stokes $Q$ and $U$ yield polarized intensity, $PI$ map

Polarized intensity, $PI = \sqrt{Q^2 + U^2}$, always takes positive value.

PDF of $\Delta PI$: Rice distribution

Sorry that I forgot to bring the PI image of the G.C. in my laptop!!
POL-2 sensitivity
Each circle shows sensitivity of each 850 micron project.

Each project has $T \text{[min/obs]} \times n \text{[obs]}

e.g., BISTRO: 40 [min/obs] x 20 [obs].

- Adopted pixel size of 12"

- Note that some projects are still ongoing
How to get the sensitivity?

Stokes $I$

Stokes $I$ inside AST mask

Variance of $DI$ inside AST mask

Inside the AST mask
How to get the sensitivity?

Stokes $I$

Stokes $I$ inside AST mask

Variance of $DI$ inside AST mask

Due to e.g.,
- Time variation of atmospheric opacity?
- Uncertainty of instrumental polarization model?
  → Needs to monitor time variation during exposure
Sensitivity of POL-2 maps in Stokes $I$ vs. $PI$

- Green circles show sensitivity of each 850 micron project.
- Adopted pixel size of 12” for the dual bands
- Note that some projects are still ongoing
- Green and brown circles show sensitivity of each 850 and 450 micron project, respectively.
- Adopted pixel size of 12” for the dual bands
- 450 micron data were convolved so that they have 14” aperture
- Note that some projects are still ongoing
850 um sensitivity of POL-2 maps in Stokes I vs. P I

- Green circles show sensitivity of each 850 micron project.
- Adopted pixel size of 12” for the dual bands
- Note that some projects are still ongoing

A horizon of 850 um POL2 image may be ~3 mJy per 14” beam w. 12” pixel in I and P I.
Oph A 850 µm data inside AST mask: Stokes $I$ vs. $P_I$

- Each circle presents measurements w. 12-arcsec pixel inside the AST mask of a source.
- All data are plotted, i.e., no data clipping
- Color represents S/N ratio of polarized intensity, $P_I$.

Polarized Intensity [$\text{mJy beam}^{-1}$] vs. Stokes $I$, intensity [$\text{mJy beam}^{-1}$]

$P = \frac{P_I}{I}$

RSF+ in prep, see J. Kwon, ..., RSF et al. 2018
Oph A 850 μm data inside AST mask: $N_{\text{ISM}}$ vs. $P_I$

- Each circle presents measurements w. 12-arcsec pixel inside the AST mask of a source.
- All data are plotted, i.e., no data clipping.
- Color represents S/N ratio of polarized intensity, $P_I$.
- Horizontal axis is converted to $N_{\text{ISM}}$ with fiducial values of $\kappa$ and $\beta$. No temperature distribution was considered. So pls think the $N_{\text{ISM}}$ values as an approximation.

RSF et al. in prep, see Jungmi Kwon, RSF et al. 2018
Oph A 850 μm data inside AST mask: $N_{\text{ISM}}$ vs. $P_I$

Each circle presents measurements w. 12-arcsec pixel inside the AST mask of a source.

All data are plotted, i.e., no data clipping.

Color represents S/N ratio of polarized intensity, $P_I$.

Horizontal axis is converted to $N_{\text{ISM}}$.

**DIRECT** comparison w. NIR extinction polarimetry is *currently only* possible toward a few “lucky” positions.

RSF et al. in prep, see Jungmi Kwon, RSF et al. 2018
Do we really need 450 um?
Caught pol. structure even toward highest $N_{\text{ISM}}$ regions!

Image: 450 micron Stokes $I$
Contour: 90% percentile of $I$
Brown vectors: 450 micron
Green vectors: 850 micron

RSF et al., in prep
Caught pol. structure even toward highest $N_{\text{ISM}}$ regions!

**Image**: 450 micron Stokes $I$

**Contour**: 90% percentile of $I$

**Brown vectors**: 450 micron

**Green vectors**: 850 micron

0.25 pc

W. Kwon, ..., RSF et al., in prep
Caught pol. structure even toward highest $N_{\text{ISM}}$ regions!

**Image**: 450 micron Stokes $I$

**Contour**: 90% percentile of $I$

**Brown vectors**: 450 micron

**Green vectors**: 850 micron

0.48 pc

J. Hwang, ..., RSF et al., in prep
Caught pol. structure even toward highest $N_{\text{ISM}}$ regions!

**Image:** 450 micron Stokes $I$
**Contour:** 90% percentile of $I$
**Brown vectors:** 450 micron
**Green vectors:** 850 micron

0.61 pc

BISTRO Taiwan team, …, RSF et al., in prep
850 vs. 450 um maps: caught GK effect at 850 um?

Note that ranges of the color bars do not match at the dual bands.

Doi, …, RSF et al., in prep
The new camera is expected to link Interstellar $B$ with Circumstellar $B$.

The new camera should

- be **simple** design to get good IP correction
- be mappable **extended emission**
- be delivered to community in **timely manner**
- concentrate on **850 micron** only

**Summary**