Magnetic fields in the cores of Taurus/B213 from JCMT BISTRO survey
(preliminary results)

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Collaborators
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and
BISTRO team
LDN1495/B213 in Taurus

→ L1495/B213 is one of the most prominent filaments in nearby clouds in Gould belt.

→ well-studied
→ Length ~ 10 pc
→ Mass > 700 $M_{\text{sun}}$
→ ~40 YSOs,
→ ~20 dense cores

(Hacar & Tafalla 2011, Hacar+ 2013)

→ Agents governing the connection between low density ISM, filaments, cores, and star formation in them?

Distribution of regions and their cores. $C^{18}\text{O}$ (black contour: 0.5 K km/s) and $N_2H^+$ (red contour: N2H+). Solid & open stars: Class I/Flat & Class II/III (Rebull+ 2010). Distance ~130 pc (Dzib+ 2019)
B-fields at larger scales based on optical and NIR polarimetry

At ~ pc to ~several pc scales B-fields are organized; either perpendicular to the dense filaments or aligned parallel to the low density striations. SCUBA-POL2 FOV: 16’ diameter. Column density map is from Gould belt Survey (Palmeirim+ 2013; http://gouldbelt-herschel.cea.fr/archives)
B213 NW filament and its hierarchically fragmented chain of cores

- Dust continuum map at 1.15 mm with NIKA camera of IRAM-30 m telescope

(Bracco+ 2017)

3 prestellar and 3 protostellar

<table>
<thead>
<tr>
<th>Object</th>
<th>Evolutionary stage</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>Abbreviation in text and figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGBS-J041937.7+271526\textsuperscript{a,e}</td>
<td>Prestellar</td>
<td>04\textsuperscript{h}19\textsuperscript{m}37.7\textsuperscript{s}</td>
<td>+27°15’20.0’’</td>
<td>Miz-2</td>
</tr>
<tr>
<td>HGBS-J041923.9+271453\textsuperscript{e}</td>
<td>Prestellar</td>
<td>04\textsuperscript{h}19\textsuperscript{m}23.9\textsuperscript{s}</td>
<td>+27°14’53.0’’</td>
<td>HGBS-1</td>
</tr>
<tr>
<td>Miz-8\textsuperscript{b,a,c}</td>
<td>Prestellar</td>
<td>04\textsuperscript{h}19\textsuperscript{m}51.0\textsuperscript{s}</td>
<td>+27°11’42.2’’</td>
<td>Miz-8b</td>
</tr>
<tr>
<td>K04166\textsuperscript{b}</td>
<td>Class 0/I</td>
<td>04\textsuperscript{h}19\textsuperscript{m}42.9\textsuperscript{s}</td>
<td>+27°13’38.8’’</td>
<td>K04166</td>
</tr>
<tr>
<td>K04169\textsuperscript{b}</td>
<td>Class 0/I</td>
<td>04\textsuperscript{h}19\textsuperscript{m}58.9\textsuperscript{s}</td>
<td>+27°10’00.5’’</td>
<td>K04169</td>
</tr>
<tr>
<td>J04194148+2716070\textsuperscript{d}</td>
<td>T Tauri</td>
<td>04\textsuperscript{h}19\textsuperscript{m}41.5\textsuperscript{s}</td>
<td>+27°16’07.0’’</td>
<td>T Tauri</td>
</tr>
</tbody>
</table>
Log of observations

Log of observations: date, number of sets acquired, sequence number, and atmospheric opacity.

<table>
<thead>
<tr>
<th>Date of observation</th>
<th>No. of sets</th>
<th>Sequence number</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018 Nov 23</td>
<td>3</td>
<td>40,41,45</td>
<td>0.04,0.04,0.04</td>
</tr>
<tr>
<td>2018 Nov 25</td>
<td>3</td>
<td>51,53,58</td>
<td>0.05,0.06,0.06</td>
</tr>
<tr>
<td>2018 Dec 03</td>
<td>2</td>
<td>32,39</td>
<td>0.05,0.05</td>
</tr>
<tr>
<td>2018 Dec 06</td>
<td>4</td>
<td>18,22,28,44</td>
<td>0.04,0.03,0.05,0.05</td>
</tr>
<tr>
<td>2018 Dec 11</td>
<td>2</td>
<td>45,48</td>
<td>0.02,0.2</td>
</tr>
<tr>
<td>2018 Dec 21</td>
<td>1</td>
<td>48</td>
<td>0.03</td>
</tr>
<tr>
<td>2018 Dec 23</td>
<td>1</td>
<td>44</td>
<td>0.05</td>
</tr>
<tr>
<td>2019 Jan 03</td>
<td>1</td>
<td>18</td>
<td>0.05</td>
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<tr>
<td>2019 Jan 04</td>
<td>2</td>
<td>10,14</td>
<td>0.04,0.04</td>
</tr>
<tr>
<td>2019 Jan 08</td>
<td>1</td>
<td>11</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Total 20 sets were acquired with a total observing time of ~14.1 hrs

Recent (04 April 2019) pol2map is used

POL2MAP: options in steps 1, 2, and 3: NNNY, YYNY, YYNY
(skyloop, mapvar, normalise, obsweight)

Two sets (#40 and #41) acquired on 2018 Nov 23 are given lowest weight and are excluded by pol2map; therefore 18 sets used to produce final results

Tau < 0.07
Band 1 & 2 weather
B-field geometry in the cores of B213 based on JCMT/SCUBAPOL2

Rms noise: 5 mJy/beam, pixel size =4", vector map binned over 12 arcsec
Data selection: P/DP > 2, I/DI > 10, P < 30%
Background image: POL2 Stokes I map, black contour at 25 mJy/beam
Absence of coherency between Optical/NIR/Planck and JCMT/SCUBAPOL2 B-fields. However, B-fields in HGBS-1, K01466, k04169 are coherent with large scales B-fields, while in Miz-2, Miz-8b, and T-Tauri they are perpendicular.
B-fields at cores scales are either parallel or perpendicular to the filament long axis (and also to the larger scale B-fields)

Major axes of the cores are either parallel or perpendicular to their mean B-field geometries

==> Bimodal distribution at larger and smaller scales
Correlation between the morphologies of B-fields and cores (other studies)

B-fields at pc and sub-pc scales are either parallel and/or perpendicular to the core geometries in massive star forming cores indicating the importance of B-fields.

B-fields vs core geometries in 14 different massive clumps, bimodal distribution, (based on SMA data, Zhang+ 2014)

B-fields at pc and sub-pc scales are either parallel and/or perpendicular to the core geometries in massive star forming cores indicating the importance of B-fields.
Magnetically dominated star formation in K04166?

Mean B-fields at various scales

Optical $29 \pm 14$ deg
NIR $37 \pm 17$ deg
Planck $29 \pm 17$ deg

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JCMT-POL2 $26 \pm 20$ deg
Outflow PA $30$ deg

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Magnetically regulated low-mass star formation via ambipolar diffusion?

Hour-glass B-fields?

B-field strength using DCF relation, magnetic criticality parameter

<table>
<thead>
<tr>
<th>sno</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Column density N(H$_2$) ($10^{21}$ cm$^{-2}$)</td>
<td>$22 \pm 6$</td>
</tr>
<tr>
<td>2</td>
<td>Effective radius ($R_{eff}$; arcsec)</td>
<td>$10.96 \pm 0.08$</td>
</tr>
<tr>
<td>3</td>
<td>Number density n(H$_2$) ($\times 10^9$) (cm$^{-3}$)</td>
<td>$8.27 \pm 0.17$</td>
</tr>
<tr>
<td>4</td>
<td>Mass ($M_\odot$)</td>
<td>$0.08$</td>
</tr>
<tr>
<td>5</td>
<td>Gas velocity dispersion ($\sigma_{V_{LSR}}$, km/s, from N$_2$H$^+$)</td>
<td>$0.119 \pm 0.024$</td>
</tr>
<tr>
<td>6</td>
<td>Kinetic temperature ($T_{kin}$, K, from NH$_3$)</td>
<td>$10.39 \pm 0.52$</td>
</tr>
<tr>
<td>7</td>
<td>Thermal velocity dispersion $\sigma_T$ (km/s)</td>
<td>$0.055 \pm 0.012$</td>
</tr>
<tr>
<td>8</td>
<td>Non-thermal velocity dispersion $\sigma_{NT}$ (km/s)</td>
<td>$0.106 \pm 0.027$</td>
</tr>
<tr>
<td>9</td>
<td>Angular dispersion in $\theta_B$ (degree; Gaussian fit)</td>
<td>$20 \pm 2$</td>
</tr>
</tbody>
</table>

From Davis-Chandrasekhar-Fermi (DCF) method

<table>
<thead>
<tr>
<th>sno</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B-field strength ($\mu$G)</td>
<td>$106 \pm 29$</td>
</tr>
<tr>
<td>2</td>
<td>$P_B$ ($\times 10^{-10}$) (dyn cm$^{-2}$)</td>
<td>$4.5 \pm 2.4$</td>
</tr>
<tr>
<td>3</td>
<td>$P_{turb}$ ($\times 10^{-10}$) (dyn cm$^{-2}$)</td>
<td>$4.3 \pm 2.2$</td>
</tr>
<tr>
<td>4</td>
<td>$P_B/P_{turb}$</td>
<td>$1.0 \pm 0.8$</td>
</tr>
<tr>
<td>5</td>
<td>Magnetic criticality ($\mu$)</td>
<td>$1.5 \pm 0.6$</td>
</tr>
</tbody>
</table>
B-field strength: 100-180 μG
Magnetic criticality ≥ 1 and $P_B / P_{\text{Turb}} ≥ 1$
K04166 => supercritical

Structure Function and Auto-correlation Function analyses

<table>
<thead>
<tr>
<th>From Structure function (SF) analysis</th>
<th>From Auto-correlation function (ACF) analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Angular dispersion ($\sigma_\theta$; degree)</td>
<td>1 Angular dispersion ($\sigma_\theta$)</td>
</tr>
<tr>
<td>2 $\langle \delta B^2 \rangle^{1/2} / \langle B_0 \rangle$</td>
<td>2 $\langle \delta B^2 \rangle / \langle B_0^2 \rangle$</td>
</tr>
<tr>
<td>3 B-field strength (modified DCF) (μG)</td>
<td>3 $(\langle \delta B^2 \rangle / \langle B_0^2 \rangle)^{1/2}$</td>
</tr>
<tr>
<td>4 $P_B \times 10^{-10}$ (dyn cm$^{-2}$)</td>
<td>4 Turbulent correlation length ($\delta$ in arcsec)</td>
</tr>
<tr>
<td>5 $P_B / P_{\text{Turb}}$</td>
<td>5 Coefficient ($a'_2$) $\times 10^{-6}$ (arcsec$^2$)</td>
</tr>
<tr>
<td>6 Magnetic criticality (μ)</td>
<td>6 B-field strength (modified DCF) (μG)</td>
</tr>
<tr>
<td>7 $P_B \times 10^{-10}$ (dyn cm$^{-2}$)</td>
<td>7 $P_B / P_{\text{Turb}}$</td>
</tr>
<tr>
<td>8 Magnetic criticality (μ)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>
Summary

- Traced B-fields in the pre/protostellar cores of B213
- Coherent and ordered B-fields at larger scales > 1 pc
- At cores scales bimodal distribution (parallel and perpendicular)
- Morphological correlation b/n B-fields, filament, and cores

**Detailed analyses for K04166**

- Magnetically regulated star formation?
- B-fields coherent with those of larger scales
- Outflows aligned with B-fields
- B-field strength 100-180 μG using DCF, SF, ACF analyses
- Magnetic criticality > 1; supercritical, core collapse
- B-field and turbulence pressures, comparable to eachother
- Future observing proposals: SMA and ALMA

Observed complex B-fields – due to interaction between the supersonic converging flows, fibers, or bundles?

Future observations with SOFIA and SPICA-POL (B-BOP)

Eswaraiah, Li, +BISTRO team (in preparation)
Mass accretion in B213/B211

(Left) 12CO and 13CO gas towards B211/B213. (Right) Schema of velocity structure.

- Red: 12CO, 6.6 – 7.4 km/s
- Blue: 12CO, 4.2 – 5.5 km/s
- Green: 13CO, 5.6 – 6.4 km/s

(Palmeirim+ 2013, Shimijari+ 2019)

Fray and fragmentation scenario of core formation. (Left) Two colliding supersonic gas flows forming the filament. (Middle) Formation of fibers due to residual turbulence and gravity. (Right) Gravitational fragmentation to form chain of cores (Tafalla & Hacar 2015).

B-field guiding the material flows on to the filament, based on optical/NIR polarimetry (Palmeirim+ 2013, Chapman+ 2011)
B-fields at cores scales could more complex than those ordered B-fields at larger scales due to the interaction between fibers and gravitational compression, etc.

B-fields perpendicular to the filament axis, and the axial component got amplified due to gravitational or turbulence compression (see Andre+ 2019, and references therein) or reorientation of oblique shocks in magnetized colliding flows (Fogerty+ 2017)
Composed of 35 network of overlapping filaments – known as fibers

- Complex kinematics
- Overlapping
- Typical length \( \sim 0.5 \) pc
- \( M/L \sim 15 \) Msun/pc
- Subsonic/transonic

Cores in B213 NW part are formed in the filament number ‘20’ – which is not overlapping and interacting with adjacent fibers.

(Hacar & Tafalla 2011, Hacar+ 2013)
Figure 1. Mechanisms for generating filaments normal to magnetic field lines. Top panel: magneto-gravitational collapse. Jeans unstable gas will initially collapse along field lines (1–2). Once enough mass accumulates in the resultant filament, mass can flow along the filament and drag magnetic field lines inwards (3-4). Bottom panel: reorientation of magnetized oblique shocks. Uppercase letters denote wave modes, and lowercase letters give regions (see the text). Flow direction is given by the black arrows, and a representative magnetic field line is shown in red. The left-hand and right-hand panels give the initial and reoriented structures, respectively. The top and bottom rows give the moderate ($\beta = 1$) and weak field ($\beta = 10$) cases of this paper. The grey shaded region represents the growing filament.
B-fields at pc scales

Red vectors: Optical  
Cyan vectors: NIR  
Yellow vectors: Planck/870um (for I > 0.008 K_{CMB}); Resolution=5 arcmin  
Background image: column density

Consistency between Optical/NIR and Planck/870um B-fields
B-fields at core scales (from JCMTPOL2) have mainly two components: 0 and 110 deg.

Optical, NIR, and sub-mm (*Planck*) yielded mean B-fields orientations are at ~30 deg (4th column; Table below).

B-fields at larger scales are perpendicular to the filament (5th column; Table below).

At smaller (< 0.1 pc) scales, B-fields follow bimodal distribution: parallel and perpendicular to the filament axis.

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**Table 2.** Mean B-field orientations based on Optical, NIR, and sub-mm (*Planck/870 μm*) polarization observations.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>diameter (arcmin)</th>
<th>No of stars/vectors</th>
<th>Gaussian Mean±σ (°)</th>
<th>Offset PA± (°) (relative to filament PA of 135 deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>60</td>
<td>15</td>
<td>29±14</td>
<td>106</td>
</tr>
<tr>
<td>NIR</td>
<td>60</td>
<td>42</td>
<td>37±17</td>
<td>98</td>
</tr>
<tr>
<td>Sub-mm (<em>Planck</em>)</td>
<td>60</td>
<td>445</td>
<td>29±17</td>
<td>106</td>
</tr>
<tr>
<td>Sub-mm (<em>Planck</em>)</td>
<td>16</td>
<td>51</td>
<td>32±10</td>
<td>103</td>
</tr>
</tbody>
</table>
Dominance of other kinematics (rotation, collapse, accretion) in K04169?

Velocity gradients (based on N2H+; Punanova+ 2018) are seem to be complex nearly following the B-field orientations. Outflows are also seem to be not consistent with the large scale B-fields.
B-field orientation at different scales ranging from several pc to 100’s of AU with AREPO simulations with different Alfvén Mac numbers (Hull+ 2017a)
B-fields in intercloud medium (ICM) vs cloud orientation at several pc to 10's of pc scales.

Li+ (2013)

Strong B-fields guide the gravitational contract and channel sub-alfvénic turbulence to produce filaments aligned perpendicular and parallel to the B-fields.

B-field strength remain constant during the cloud accumulation process in the ICM.
Correlation between B-fields and core structure in hub-filament system of IC5146

Schematic to demonstrate the observed B-fields (Wang+ 2019, towards IC5146, based on JCMTPOL2)
Observational evidences for strong and weak B-field regulated star formation in low-mass cores

Hourglass shaped B-fields around the Class 0 protostars of L1157 (Hull+ 2014, Stephens+ 203) and NGC1333 IRAS4A (Girart+ 2006, Hull+ 2014)

Ordered B-fields at larger scales and chaotic at smaller scales of Class 0 protostar Ser-emb 8 (Matthews+ 1994, Hull+ 2014, Hull+ 2017a)

(Also see Hull+ 2019)
Large scale velocity gradients (red; from C18O data) in Miz2, K04166 and K04169 seem to be aligned with the B-fields. However, local velocity gradients (black) seems complex, in K04169 both larger and local gradients match with each other and also with B-field orientations.
VG orientations seem to be different at different tracers without a preferred orientation

Larger scale gradients (C18O) are in all the cores are not consistent with those of local gradients (N2H+, N2D+, DCO+, H13CO+)

**K04169**

B-fields at K04169 as well as VGs are complicated

SMA observations: envelope and disk rotations are opposite to each other

Overall Vlsr vs length ==> wave-like pattern – signifying anything?

(All figures are from Punanova+ 2018)
Fig. 4.12. $V_{\text{LSR}}$ along the filament direction (from core 19 in the south-east to core 8 in the north-west). The transitions are shown with colours: $\text{N}_{2}^{+}\text{D}^\text{2}(2-1)$ – red circles; $\text{N}_{2}^{+}\text{H}^\text{1}(1-0)$ – blue squares. The vertical bars show the $\text{N}_{2}^{+}\text{H}^\text{1}(1-0)$ emission peaks. Stars show the positions of YSOs from Rebull et al. (2010); black stars indicate flat and Class I objects, white stars indicate Class II and III objects.

Fig. 5. $V_{\text{LSR}}$ along the filament direction (from core 19 in the south-east to core 8 in the north-west). The transitions are shown with colours: $\text{N}_{2}^{+}\text{D}^\text{2}(2-1)$ – red circles; $\text{N}_{2}^{+}\text{H}^\text{1}(1-0)$ – blue squares; $\text{DCO}^\text{+}(2-1)$ – orange filled triangles; $\text{H}_{2}^{13}\text{CO}^\text{+}(1-0)$ – green triangles; and $\text{C}^{18}\text{O}(1-0)$ – black circles. The vertical bars show the $\text{N}_{2}^{+}\text{H}^\text{1}(1-0)$ emission peaks. Stars show the positions of YSOs from Rebull et al. (2010); black stars indicate flat and Class I objects, white stars indicate Class II and III objects.
Fig. 9. Schematic picture of the relation between the B211/B213 cloud and Per OB2 association. The black arrows indicate the line of sight. The horizontal line indicates the sky plane. Red and blue arrows indicate the direction of the gas accretion in the northeastern and southwestern sheet components, respectively. Green arrows indicate the direction of the compression by Per OB2 association. $\theta_N$ and $\theta_S$ are the inclination angles of the northeastern and southwestern sheet components to the line of sight. Red and blue arrows of length scaling quantitatively with the magnitude velocity field indicate the direction of the acceleration flow of ambient cloud material.

Fig. 10. Distributions of the H$\alpha$ (color; Finkbeiner 2003) and 857 GHz dust (gray; Planck Collaboration I 2014) emission. The units of the H$\alpha$ and 857 GHz maps are R (Rayleigh, $4\pi \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$) and MJy sr$^{-1}$, respectively. The magenta dashed circle indicates a HI supershell (Lim et al. 2013). The diameter of the HI supershell might be $>200$ pc since the distances to the Taurus and Perseus clouds are 140 and 340 pc, respectively. The distribution of HI emission is shown in Figs. A.4 and A.5. See also Fig. A.6.
3D view of the model filament system similar to Taurus B211/B213 with B-fields (blue), a cylindrical filament (red lines), and sheet-like background (light green)

B-fields nearly perpendicular to the filament axis, and the axial component got amplified due to gravitational or turbulence compression


Synthetic B-field map expected at the resolution of ~20” of SPICA-POL/B-BOP at 200 micron according to the model.

Synthetic B-field map expected at the 5’ resolution with Planck as per the model.

Our results from JCMT-POL2: B-fields in more evolved protostellar cores follow those at larger scales, while in the prestellar cores they are in parallel configuration.
Distribution of B-fields

26$\pm$20°

Outflow PA = 30.4°

Filament PA = 135°

K04166
Miz-2, T-Tauri, Miz8-b, K04169 have the B-fields components parallel to the filament.

HGBS-1, K04166, K04169 have B-fields coherent with large scale B-fields (perpendicular to the filament).

Core orientations are either parallel or perpendicular to the mean B-field geometries.

Table 3. Weighted mean orientation of B-fields of the seven cores of B213 based on JCMT/SCUBA-POL2.

<table>
<thead>
<tr>
<th>Name of the core</th>
<th>No. of vectors</th>
<th>Weighted mean±error (°)</th>
<th>standard deviation (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGBS-1</td>
<td>3</td>
<td>23 ± 6</td>
<td>23</td>
</tr>
<tr>
<td>Miz-2</td>
<td>4</td>
<td>119 ± 5</td>
<td>41</td>
</tr>
<tr>
<td>TTauri</td>
<td>2</td>
<td>128 ± 6</td>
<td>16</td>
</tr>
<tr>
<td>K04166*</td>
<td>26</td>
<td>30 ± 1</td>
<td>22</td>
</tr>
<tr>
<td>Miz-8b</td>
<td>9</td>
<td>122 ± 3</td>
<td>29</td>
</tr>
<tr>
<td>K04169*</td>
<td>8</td>
<td>77 ± 4</td>
<td>22</td>
</tr>
<tr>
<td>K04169b</td>
<td>5</td>
<td>167 ± 4</td>
<td>16</td>
</tr>
</tbody>
</table>
Absence of coherency between Optical/NIR/Planck and JCMT/SCUBAPOL2 B-fields. However, B-fields in HGBS-1, K01466, k04169 are coherent with large scales B-fields, while in Miz-2, Miz-8b, and T-Tauri they are perpendicular.