Filamentary Molecular Clouds, Star Formation, and Pristine B-Fields, as seen by SOFIA/HAWC+, Gaia DR2, and Mimir Near-IR Polarimetry

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Dan Clemens, A. El-Batal, J. Montgomery, C. Cerny, S. Kressy, G. Schroeder, & T. Pillai

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Filamentary Molecular Clouds, Star Formation, and Pristine B-Fields seen by SOFIA/HAWC+, Gaia DR2, and Mimir Near-IR Polarimetry

Dan Clemens¹, A. El-Batal¹, J. Montgomery¹, C. Cerny¹, S. Kressy¹, G. Schroeder², & T. Pillai¹

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Overall Question: Is the Magnetic Field (B-field) an important player in cloud, dense core, and star formation and evolution?

Specific Questions: Are B-field properties similar in cloud peripheries, dense core envelopes, and star formation regions? Is there a common B-field or is the B-field disrupted?

Laboratory: GF9 Filamentary Dark Cloud, GF9-2 YSO (d~200-440 pc)

B-field Probes: (1) Near-IR background starlight polarimetry (BSP) w/ Mimir; (2) SOFIA HAWC+ E-Band Polarimetry; (3) I-band BSP (Poidevin & Bastien ’06); (4) Planck (XIX ’15)

Photometric Probes: (1) WISE (Wright+ ’10); (2) Spitzer/IRAC; (3) IRAS; (4) ISO/ISOPHT

Distances: Gaia (DR2 ‘18)
Boston University Team

• From left:
  – Catherine Cerny
    • Joined in 2018 Summer – Gaia expert
  – Genevieve Schroeder (U. Rochester)
    • Summer 2017 REU intern
    • Flying on SOFIA tomorrow night and Friday night for HAWC+ observations
  – Jordan Montgomery, now Dr. J.M.
    • At MIT Lincoln Labs, along with Sadia Hoq, John Vaillancourt, Mike Pavel…
    • Flew on SOFIA 2016 December
  – Sofia Kressy
    • BU Senior Undergrad – lead on Mimir Orion project
  – Adham El-Batal
    • 3rd year grad student
    • Just back from GAIA workshop in Heidelberg
    • Flew on SOFIA 2016 December
  – Dr. Thushara Pillai
    • BU Senior Research Scientist
Filamentary Dark Clouds before they were all the rage... and their B-fields

- **L204** – McCutcheon+’86
  - Optical Palomar Sky Survey Plates
  - Optical starlight polarimetry
    - B-field in plane-of-sky
    - B-field orientation parallel to polarization position angle (PA) of intensity maximum (E-field direction)
    - One star at a time...
  - B-field position angle (BPA) generally perpendicular to filamentary cloud long axis (4°)
• Strong correlation of cloud location and gas kinematics
  – R.A. and RV (CO)
  – Gas dynamics matter
  – MHD turbulence likely present and bending BPAs on all size scales
• Support for Davis / Chandrasekhar-Fermi method of obtaining B-field strengths from BPA dispersions, gas dispersions, and gas mass densities
Globular Filaments, IRAS, and ISO

- Catalog of filamentary dark clouds (from POSS) exhibiting “globules” along their lengths (Schneider & Elmegreen ’79; GF#s)
  - Likely sites of current or future star formation
  - Prescient study!

- We selected one, Northern, isolated GF (#9) for CO mapping, *Infrared Astronomical Satellite* (IRAS), *Infrared Space Observatory* (ISO, an ESA mission):
  - FIR photometric mapping [red rectangles]
  - FIR polarimetry (160 μm) [blue squares]
• ISOPHT FIR “array” was 2x2 pixels
• Three, fixed-angle wire grids in a filter wheel
  – 0, 60, 120 deg
  – Integrate in one, move to next, repeat
• No chopping or nodding; only slow pointing changes
• Cycled among the 4 zones, putting each pixel of the array on the center of each zone, so 4 cycles
  – Yields four 3x3 pixel maps
• Pre-Planck, so difficult calibration
• Differenced intensities against position with weakest signal (“C-OFF”)
• Corrected using best estimates of instrumental polarization for each pixel
• Shortly after GF9 observations, ISO ran out of helium coolant, mission ended…

Clemens+’99
Two Decades Pass...

• Tried to move toward more access to FIR polarimetry
  – Proposed SMEX mission(s): PIREX, M4
  – Proposed SOFIA 2nd Generation Instrument: IMPP
• Instead...
  – Built ground-based NIR imaging polarimeter
    • Mimir (Clemens+’07)
    • Use it to survey Galactic plane and other friends
      (like L204, GF9)
• Others:
  – Optical polarimetry of the GF9 region (Poidevin & Bastien ‘06)
  – Limited NIR polarimetry of ISO-mapped GF9 Core and Filament regions (Jones ’03)
  – NIR BPAs don’t agree with the ISO FIR pol. ones

Portion of L204 ("Cloud 3") as seen by Wise (RGB) and Mimir H-band polar. (white vectors)
Cashman & Clemens ‘14
GF9 does have active star formation

- Four IRAS Point sources
- One at the Core zone
- IRAS 20503+6006 (aka GF 9-2, L1082 C, or LM 351)
  - Class 0 YSO (quite young, though MIR/FIR visible)
  - \( L_{\text{YSO}} \sim 0.3-0.5 \, \text{L}_\odot \)
  - Outflow sought since ’96 (Bontemps+), found in ’14 (Furuya+)
Low-Mass, Young, YSO – maybe B-field not (yet) disrupted?

- Most B-field studies look at the most luminous objects
  - Fastest, most likely to generate findings
  - But, biased toward super-bright, massive cloud cores with cluster-mode, high-mass star formation
  - Poor little B-fields likely shredded, stomped on, or tangled, if not already super-strong

- Wimpy little GF9-2 could be an ideal place to sniff for what the B-fields look like before all the damage takes place

GF9-2 as seen by \textit{WISE} B3 (12\,\mu m – red), \textit{Spitzer} IRAC B4 (8\,\mu m – green) and \textit{Spitzer} IRAC B2 (4.6\,\mu m blue)
• Used Mimir NIR imaging polarimeter (Clemens+’07) on 1.8m Perkins telescope of Lowell Observatory.
• FOV = 10x10 arcmin at 1024x1024 pixels at 0.6”/pixel.
• H (1.6μm) and K (2.2μm) stellar polarimetry.
• Background Image = deep K-band (2.2µm)
• Blue vectors = H-band (1.6µm) polarization
  – 1% references at bottom right
• Purple vectors = K-band polarization
• Lots of stars, wide range of fractional polarizations
• Stars avoid the IR-dark, optical-dark region
• Can’t do NIR polarimetry beyond about A_v ~20-30 mag
• PAs (B-Field) look quite uniform
• Jones ‘03 NIR polarization PAs deviant; Poidevin & Bastien ‘06 optical PAs consistent with new NIR
• What about FIR, though?
Mimir Polarimetry in H, K bands: 860 stars, but which ones are useful?

- Selecting stars for B-field mapping using Polarization Signal-to-Noise (PSNR)
- High PSNR for bright stars
- Merges into PSNR~1 due to Rice distribution
- Study of ‘False positives’ (Clemens & Montgomery ’18, in prep.)
- Select H-stars down to 15.1 mag
Oh, my, Gaia! DR2... Wow! Virtually every NIR pol. star has a distance!

Image = Mimir K (2.2 μm) band
Contours = SOFIA/HAWC+ 214μm
Circles = Gaia stars [R: <0.5kpc , G: 0.5-1.0 kpc, B: > 1kpc]
Seeking step-up of $P_H$ at distance of GF9 cloud
- Insufficient stars closer than ~300 pc to see step
- Polarization stars are nearly all behind cloud
- No rise in $P_H$ with distance -> single dust layer
- Ideal for Background Starlight Pol B-field mapping

Seeking step-up of (H-M) reddening
- Few stars closer than 250 pc
- Extinction seen for stars as close as 250-300pc
- No rise in extinction with distance, also implies single dust layer

NIR H-Band Polarization Fraction (left) and (H-M) color (right) versus Gaia DR2 Parallaxes
Cheat, look in the “back of the book”

- Need to determine distance to GF9
  - Distances range 150 – 440 pc
  - Impacts all astrophysical conclusions
- But, Gaia DR2 distances didn’t reveal much jump in P or (H-M)
- What about the **uniform PA**, though?
  - Is there a step into that uniform PA at some distance?
  - PA vs distance plot
- Bayesian Markov Chain Monte Carlo
  - Fit for: $\text{PA}_{\text{BEFORE}}, \text{PA}_{\text{AFTER}},$ transition parallax
  - Clean corner plot
  - $d = 270 \pm 10 \text{ pc}$
Need FIR polarimetry to probe opaque cloud cores like GF9-2

Two Big Questions:

1. Is there PA rotation with wavelength?
   - If so, we are all in deep trouble
   - Signify changes in dust properties and B-field properties with depth into cloud core

2. What is the nature of the B-field where low-mass stars might form in isolation?
   - Must probe into higher $A_v$s than NIR can probe
   - Very faint FIR emission, though...

- SOFIA /HAWC+ Cycle 4 Observing
- December 2016 –portions of 2 flights

SOFIA/HAWC+ and post-processing

- Our initial “data products” were cell phone pix...
- Soooooo much happier to see rapid turn-around of HAWC+ data through the commissioned pipeline!
- For GF9-2, the total intensity (“Stokes I”) image and SNR are fine and reveal dust columns identical to those seen by WISE & Spitzer
- But, Stokes U and Q images have very low SNR
  - No Polarization detection at the detector pixel native resolution
  - Must “post-process” to trade angular resolution for SNR
  - Convolve with gaussian, using inverse variance weighting of the pixel-based U and Q values
  - Recover better U and Q, for selected “pointings” of “synthetic beams” (Clemens+’14 for SCUPOL)

Cell phone pic of GF9-2 total intensity (black & white image) with overlaid polarization vectors (2) obtained surreptitiously in flight...
Follow the Flux…

- Select synthetic beam **placements** that:
  1. Are centered on the brightest Stokes I emission (thin contours in the figure)
  2. Are offset from each other so as to be independent samples (the circles don’t cross)

- Select synthetic beam **sizes** so that:
  1. Maximize the number of synthetic beams with good PSNR
  2. Don’t give away too much angular resolution

- Tried a range of gaussian sizes, found best at **4 HAWC+ pixels FWHM**
  - 6 beams with PSNR > 1.6 ($\sigma_{\text{PA}} < 18^\circ$); 11 not detected
Zoom – *WISE, Spitzer, Mimir, HAWC+

- 5 of 6 SOFIA/HAWC+ synthetic beam BPAs agree closely with NIR H-band BPAs
  - Like, really closely...
  - The NE beam shows a BPA that is perpendicular to the others
- None of the beams along the East or West arm yielded FIR pol detections
- Q1: How does BPA vary with offset from YSO?
- Q2: How does BPA vary with $\lambda$?
Combining all B-field probes – Plane of Sky Magnetic Field Orientation vs Offset from YSO

- B-field orientation is unchanged from ~3pc to ~6000 AU; No B-field disruption near the YSO
- No strong evidence of B-field orientation change with $\lambda$
No BPA change with $\lambda$ – deep averages

- Inverse variance weighted averages of full data sets by waveband
  - Optical (P&B ‘06)
  - Mimir H
  - Mimir K
  - SOFIA/HAWC+ 214$\mu$m
  - Planck 850$\mu$m
- Linear and power-law fits
- Very little change with wavelength
- SOFIA/HAWC+ point includes all 6 synthetic beams with detections – if the one deviant beam is rejected, the orange triangle moves down 10 deg
P(FIR) vs Offset; P/A_V vs A_V

• Tough to tease out of the GF9-2 laboratory
  • FIR emission is faint, few points available for testing

• Synthetic Beam Values
  • YSO position – P’(E-band) = 1.9 ± 1.1%
    • P’ = (P_{RAW}^2 - \sigma_p^2)^{0.5} = “debiased” estimator
  • Mean of 8 beams offset from YSO P’ = 3.2 ± 0.9%
    • Mean of 5 detection beams P’ = 3.8 ± 1.1%
  • Polarization “hole”? -> meh...
    • \Delta P’ = 1.9 ± 1.6%

• Higher Angular Resolution with HAWC+ Bands C, A?
  • GF9-2 is too faint for polarimetry in these bands

• P/A_V vs A_V & grain alignment – TBD
  • But, strong agreement of FIR with NIR/Optical/Planck suggests all sampling common B-field, so alignment can’t be horrible
Comparisons with Models

- Hull+’17
  - Simulations with synthetic observations
  - Multi-scale
- GF9-2 observations are most consistent with strong B-field case
  - BPA uniform from 3pc to 6000AU
  - Last column, top two rows
- Seems GF9-2 YSO formed in a fairly strong B-field region
Next Steps, Other Cases

- **GF9-2**
  - Recently obtained ARO CO, $^{13}$CO, CS data to augment older FCRAO data (Ciardi+’00) and fully cover the 10x10 arcmin Mimir FOV
  - Estimate gas dispersion, density
  - B-field strength map
  - Too few HAWC+ points to help much, though

- **L1544** – low-mass, pre-stellar dense core
  - Deep Mimir polarimetry (Clemens+’14)
  - Some HAWC+ obs, more on current flight series

- **L1448** – multiple, low-mass YSOs with advanced outflows
  - HAWC+ obs tomorrow night and Friday night
  - Former REU student Genevieve Schroeder will be on-board SOFIA for these observations.
Old dogs
new tricks...

• **Gaia DR2**
  – Wowzer!
  – Nearly all GF9 Mimir stars have distances now!

• **Bayesian MCMC**
  – Better distances to clouds, cores, YSOs
  – P, PA steps at cloud locations
  – Wait until you see our U, Q versions! (different project...)

• **HAWC**
  – Wowzer!
  – Seeing where NIR can’t
  – Faint, quiescent as well as the usual, bright suspects...

• **Synthetic Beam “Re-Obs”**
  – Trade resolution for SNR to pull out faint polarization signals
  – Pick placements wisely...
Summary

Big Question – Are B-fields important in clouds->cores->star formation?

Tested here – Are B-fields strongly modified at/for some length scales?

Tools: (1) Near-IR polarimetry in H, K bands w/ Mimir
(2) SOFIA/HAWC+ E-band (214 μm) polarimetry

Laboratory: GF9-2, a very young, low-mass, Class 0 protostar with only a weak outflow

Findings: (1) B-field orientations preserved from largest scales (> 3pc) to smallest probed (~6000 AU).
(2) No evidence for B-field orientation change with wavelength.
(3) Distance to GF9 cloud/core/YSO is 270 ± 10pc (thanks Gaia DR2!)
(4) Mimir NIR + SOFIA HAWC+ FIR polarimetry = powerful combination for elucidating B-field properties in core, star formation
References Cited

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Arizona Radio Observatory radio spectral lines observed in 2017 toward the GF9-2 YSO position. Note self-absorptions and asymmetries

H to K polarization position angle differences vs mH (upper) and (H-K) lower – no significant trends
The three SOFIA HAWC+ polarization detections SW of the YSO sit on the larger cloud core first revealed by ISO at 70μm.