FIELDMAPS
Filaments Extremely Long and Dark: a Magnetic Polarization Survey: A SOFIA Legacy Program

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Image Credit: Spitzer GLIMPSE+MIPGSAL
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Stars Form in Filaments

Spitzer Observations (GLIMPSE+MIPSGAL)
Star-forming region seen in extinction
(light from background is blocked)

Star-forming region seen in emission
(far-infrared light directly from star-forming sites)

Spitzer/GLIMPSE/MIPSGAL, Herschel/HiGal, Ke Wang (ESO)
Herschel Observations of Orion

Credit: ESA/Herschel/PACS, SPIRE/N. Schneider, Ph. André, V. Könyves (CEA Saclay, France) for the 'Gould Belt survey' Key Programme
Large extinction filaments tracing spiral arms

Credit: NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA)
The Snake

Features also found in Milky Way

“The Snake”

Spitzer/GLIMPSE/MIPSGAL, Herschel/HiGal, Ke Wang (ESO)
“Nessie” Jackson et al. (2010)
(e.g., Goodman et al. 2014; Zucker et al. 2015, 2018)
• “Bones of the Milky Way”
• Bones well observed
  ➢ Dust continuum (Herschel, ground-based)
  ➢ Molecular Lines
• Most parameters well constrained:
  ➢ lengths, widths, aspect ratios, velocity information, masses, column densities, dust temperatures, Galactic altitudes, kinematic separation from arms in l − v space, and distances (e.g., Zucker et al. 2018)
  ➢ notably not the magnetic field
    o star formation rate, flow direction, shape
    o collapse time-scale, fragmentation
• Original expectation: Fields will be perpendicular to the bones!
• Planck XXXV (didn’t resolve filaments!)

Gray: Observations
Blue: Weak Fields
Green: Equipartion with Turbulence (Alfvenic)
Red: Strong Fields

Planck Collaboration XXXV (2016)
• Original expectation: Fields will be perpendicular to the bones!
• Gravitational accretion flow of bones perpendicular to bones

Gomez et al. (2018)
• Nevertheless, since we are resolving bones, we may see something else!
• Flows through the bones

Chen & Ostriker et al. (2014)
Spheroidal grains align with short axis perpendicular to B-field.

\[ \mathbf{E} \perp \mathbf{B} \]

Lazarian (2007)
Spitzer/GLIMPSE/MIPSGAL, Herschel/HiGal, Ke Wang, European Southern Observatory
First Try!
First Try

• Quite perpendicular
• Is this a ubiquitous feature?

• We teach our Astronomy 101 students that most stars form due to the compression in the spiral potential. Fields likely play a role.

• It would be beneficial to survey the entirety of many bones
Major Goals:

- **Role of magnetic fields in Bones**
  - Critical for collapse?

- **Whether magnetic fields vary for bones in the arm vs interarm regions**
  - Compression in spiral potential vs sheared and stretched

- **Overall morphology**
  - (e.g., perpendicular fields vs fields guiding flow through the bones)

- **Setup a Legacy data product** that can used for studying how star-forming gas collects in the magnetized spiral potential
Above shows NMC. OTF actual
FIELDMAPS

Novel:
Magnetic fields of bones have not been significantly studied, but are the largest, dense filamentary structures in the Galaxy.

The bones are potentially the best way to study how star-forming gas collapses in the magnetized Spiral potential for all galaxies. The key missing component of the bone analysis it the magnetic field.

This is a pioneering phase.

We expected all perpendicular
Filament 4

The image shows a map of the Filament 4 region in Galactic coordinates. The map uses different color intensities to represent variations in the measured parameter, with a color bar indicating the scale from 0.8 to 2.0 (likely in units of cm$^{-2}$). The map is focused on a specific area in Galactic longitude and latitude.
First Try

• Quite perpendicular
• Is this a ubiquitous feature?
  ➢ Additional tries say “Nope!”
  ➢ But maybe at the highest densities
Line Interval Convolutions (LICs)

Credit: Leah Zuckerman
Line Interval Convolutions (LICs)

Credit: Leah Zuckerman
- G47 in ApJL
- Stephens et al. (2022)

- **Green** and **Blue** circles: Locations of Young Stellar Objects (Zhang et al. 2019)
Moving Box Analysis

- Slide a moving box down the spine of G47 (can change angle)
- Use the DCF technique to estimate B-field and mass-to-magnetic flux ratio in each box

Stephens et al. (2022)
Moving Box Analysis

• Critical Ratio

\[ \lambda = \frac{(M/\Phi)_{\text{observed}}}{(M/\Phi)_{\text{crit}}} \]

(Crutcher et al. 2004)

• \( \lambda < 1 \): Magnetic fields can support against gravitational collapse
• \( \lambda > 1 \): Magnetic fields cannot support against collapse
Moving Box Analysis

Fields strong enough to support against collapse along a lot of the bone. However, not necessarily toward areas with recent star formation.
- Higher densities are more likely to collapse
- Correlated with locations of known YSOs
Spherical Flux Freezing (SFF) model

Four reasonable assumptions:
• Background density
• Background B-field
• Collapse to a Plummer spheroid
• Flux-freezing

Straightforward to calculate the magnetic field throughout entire spheroid
Myers et al. (2018, 2020)

Also can do forward-modeling

Example of sphere above. Can be applied to any spheroid (including inclined) as well as multiple combined
Spherical Flux Freezing (SFF) model

Also can do forward-modeling

• Fit the spheroids column density maps with Plummer spheroids to determine field morphology
• Use DCF technique to calculate the field strength in area

• This gives you the magnetic field strength everywhere

Myers et al. (2020)
• G47 in ApJL
• Stephens et al. (2022)
Spherical Flux Freezing (SFF) model

Applied to G47 using two spheroids

Peak field strength: 108 µG
Average field strength: 56 µG

Mass-to-magnetic flux parameter: 1.7 (critical for collapse)

Stephens et al. (2022)
Quick summary of G47 Results

• Magnetic fields are structured but not ubiquitously perpendicular
• Field strengths of ~20 µG to 100 µG
• Fields are strong enough to support bone, except in locations of active star formation (highest column densities)
  • Potentially unstable to gravitational collapse at smaller scales
Spherical Flux Freezing (SFF) model

Proof of Concept: Filament 5

FIELDMAPS project: Filament 5 SOFIA polarization, $N$ column density, $B$ field lines

$N$ contours
$B$ pol segments

$SFF B$ lines on
$N$ contours, $B$ pol segments

$SFF B$ model lines

$LIC$ rendering
of $B$ pol on $N$ gray scale

PCM 19Oct21
Histograms of Relative Orientations (HROs)

Fields Parallel w/ Bone

Fields Perpendicular w/ Bone

Credit: Leah Zuckerman
Histories of Relative Orientations (HROs)

Fields Parallel w/ Bone

Fields Perpendicular w/ Bone

High columns: Perpendicular with Bones. Otherwise, more random

Credit:
Leah Zuckerman
Simulations by team members
Rowan Smith et al. (2014, 2020)

Observational comparisons
Zucker et al. (2019)

Initial simulations adding magnetic fields
Will compare using POLARIS code
Near-IR: Sugitani et al. (in prep)   HAWC+ 214 µm: Stephens et al.
Red and Yellow: SOFIA HAWC+
White: Near-IR
Sugitani et al. (in prep)
Perhaps the best map: Filament 8. Not yet observed
FIELDMAPS: Filaments Extremely Long and Dark: a MAgnetic Polarization Survey
FIELDMAPS’ Legacy

• Galaxy MHD Simulations have just reached the point where they achieve resolutions of SOFIA (e.g., Dobbs et al. 2016)

• Will be the best high-resolution data for understanding the role of magnetic fields in collecting star-forming gas in the spiral potential

• Ancillary data to be published with program:
  • Bone parameters from Zucker et al. (2015, 2018)
  • Near-IR polarization observations of all bones lead by Koji Sugitani
  • Molecular line data, e.g., NH$_3$ from the RAMPS survey (Hogge et al. 2018; in prep)
  • Spitzer and Herschel data (including column density and temperature maps)
  • YSO locations
Summary

• FIELDMAPS is probing how star-forming gas collapses into the magnetized spiral potential via observing the bones. We are look at the largest known filaments in the Galaxy. The key missing component is the B-field.

• Contrary to expectations, fields are not always perpendicular

• Fields appear to be significantly strong enough to provide support against collapse

• We have shown capability of measuring magnetic field strengths across the Bones and whether they are unstable to collapse

• We have upcoming simulations to compare with