Far-Infrared Polarimetry from SOFIA

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Abstract: **Polarimetry at far-infrared wavelengths (50–300 μm) is a key tool for studying physical processes on size scales ranging from interstellar dust grains to entire galaxies. In the next decade, SOFIA will be unique in the ability to provide access to this polarimetric phase space. A FIR polarimeter on SOFIA will allow multi-wavelength studies of thermal dust polarization in an effort constrain grains' physical properties and test grain alignment theory. High spatial resolution (5–20 arcsec) sensitive observations will allow studies of the influence of magnetic fields on infrared cirrus clouds, the envelopes and disks of YSOs, outflows from both low- and high-mass star forming regions, and the relative strength of magnetic, gravitational, and turbulent effects. Large-scale polarization maps will be made possible by SOFIA's large focal plane (≈8×8 square arcmin), finally making it feasible to perform statistical tests of key theories relating to grain alignment, gas dynamics, and star and galaxy formation. In this poster we highlight some of the key science objectives that can be pursued with a far-infrared polarimeter on SOFIA.**

Why do Polarimetry from SOFIA?

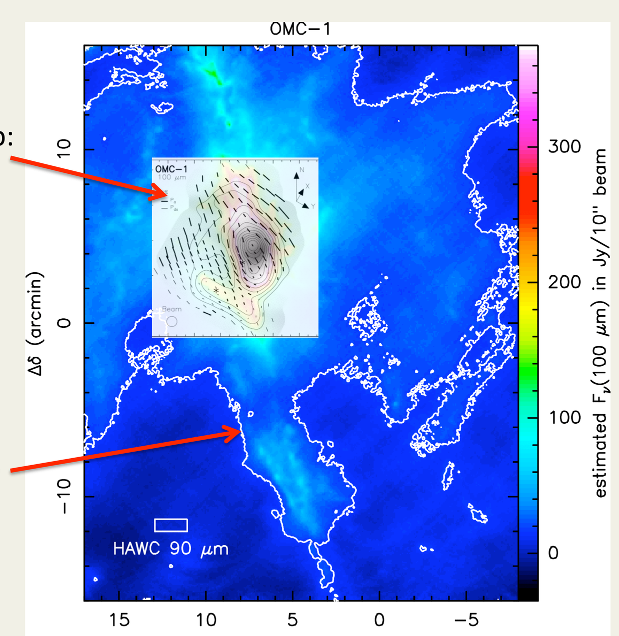
- **covers a unique niche**: No other observatory (orbital, sub-orbital, or ground) in active development will have FIR polarization capabilities
- **signal-to-noise**: observe *at peak of Galactic cloud spectrum*; e.g., SOFIA Design Reference Mission Case Study by Novak et al. (2005) estimates *100,000 vectors* in nine fields during 113 hours of observation
- **angular resolution**: 5 arcsec at 53 μm; *3 mpc at ρ Oph*
- **magnetic fields** are ubiquitous in astrophysics having an influence on cloud, star, and galaxy formation
- **polarization spectrum**: Grain alignment prescription is a key input for any cloud/core polarization model. Many experiments provide access to "submm rise", but only *SOFIA will provide the access to "far-IR drop"*

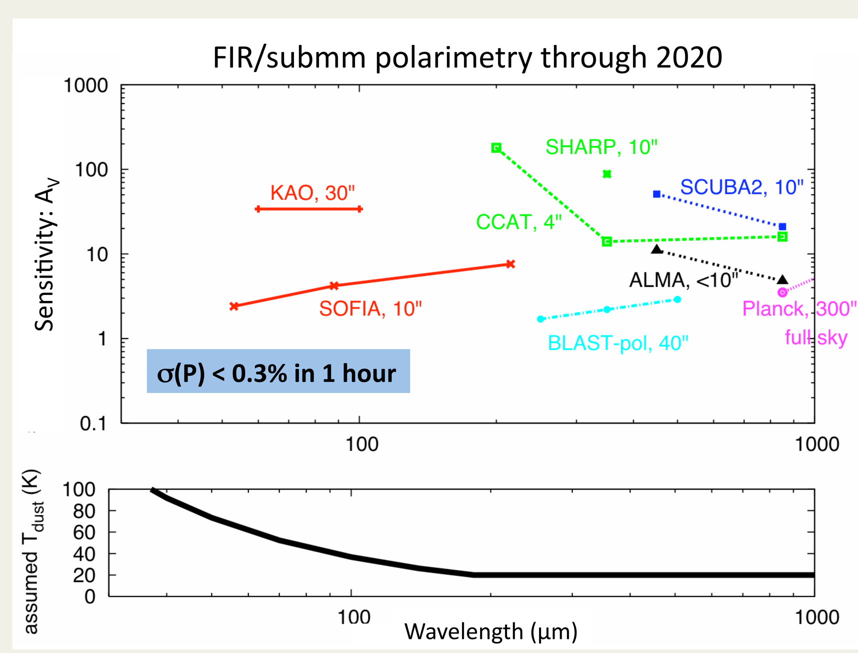
SOFIA Coverage & Sensitivity

With only modest integration times (≈ 1 hour) a background-limited SOFIA polarimeter will be able to measure polarizations with uncertainties as low as 0.3 % for source intensities of a few Jy/beam. (This is approximately a 3σ measurement of a 1% polarization, a value typical for ISM clouds at 100 μm.) This is comparable to the sensitivity of other instruments expected to come online in the next decade. A SOFIA polarimeter will provide important complementary short-wavelength coverage.

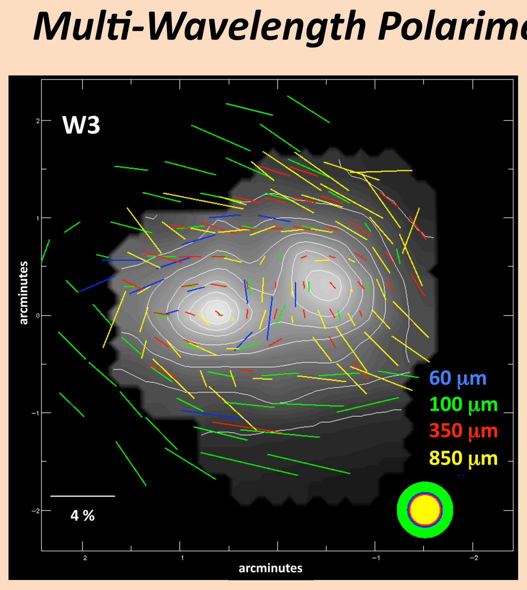
KAO polarization map: Schleuning (1998)

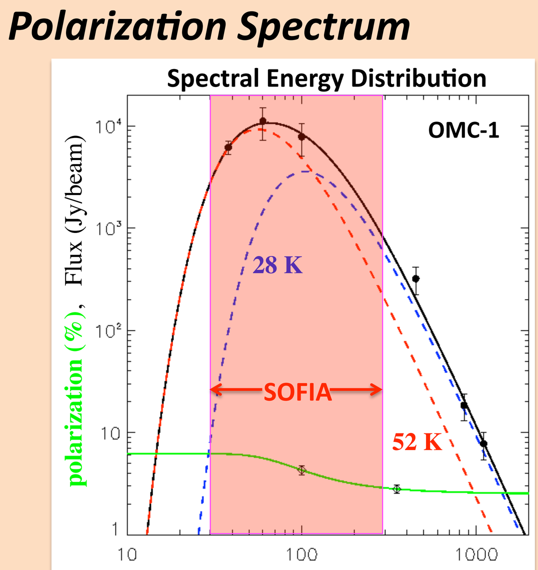
contour: pointings where σ(P) < 0.3% in 4 minutes with SOFIA
$A_V \sim 20-25$

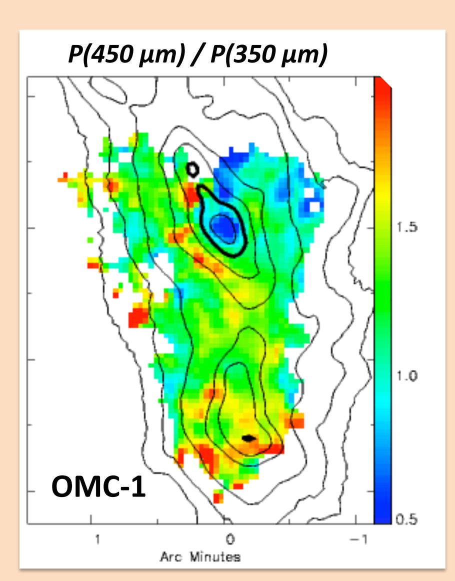




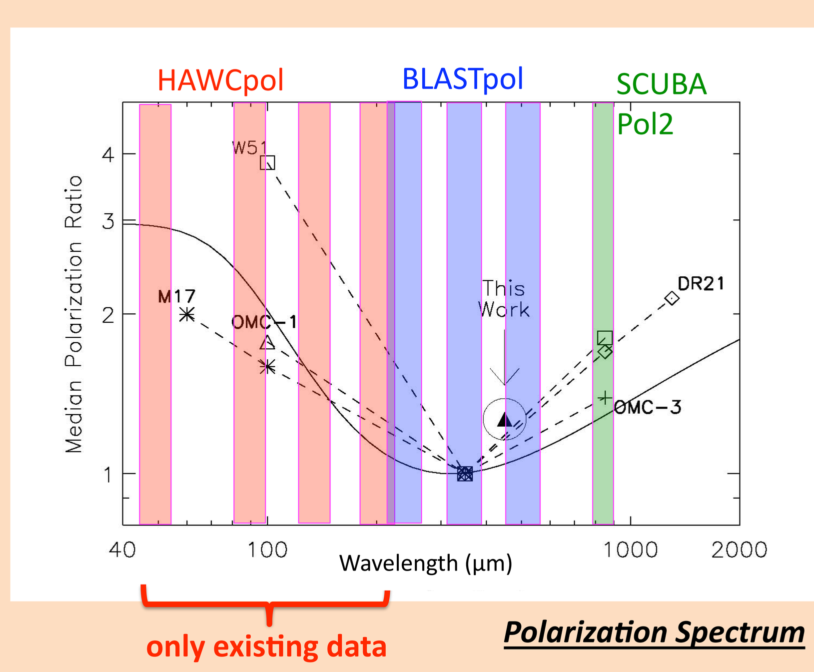
Multi-Wavelength Polarimetry and the Polarization Spectrum





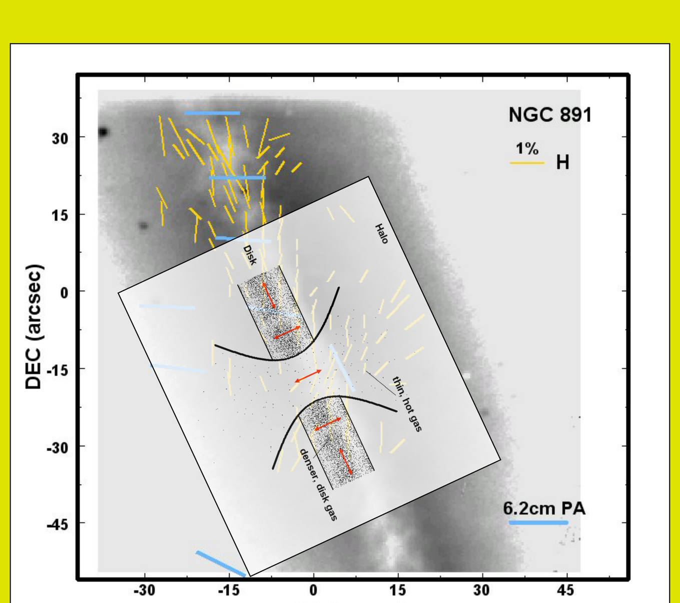


- Different wavelengths trace different grain temperature and emission components along the line of sight.
- Therefore, it also traces different magnetic field geometries at different cloud depths
- Components can be separated by careful measurements of both the total intensity spectra, and the polarization spectra over a wide range of wavelengths.
- Current polarization spectra of bright clouds exhibit 2 clear features:
  - The *"submm rise"* is fairly well explained (Bethell et al. 2007; Draine & Fraisse 2008), by grains in equilibrium with the interstellar radiation field. It can also be further tested with ground-based instruments.
  - The *"FIR drop"* may be due to the effect of radiation from embedded stars (e.g., Hildebrand et al. 1999), but clear tests require high-resolution FIR observations
- Grain alignment, grain temperature and emission properties depend on the radiation field, so mapping these values across a cloud tests theory in a diverse range of environments.
- SOFIA can extend current measurements to new frontiers including: the diffuse ISM, infrared cirrus clouds, starless environments, infrared dark clouds (IRDCs)



Polarization Spectrum

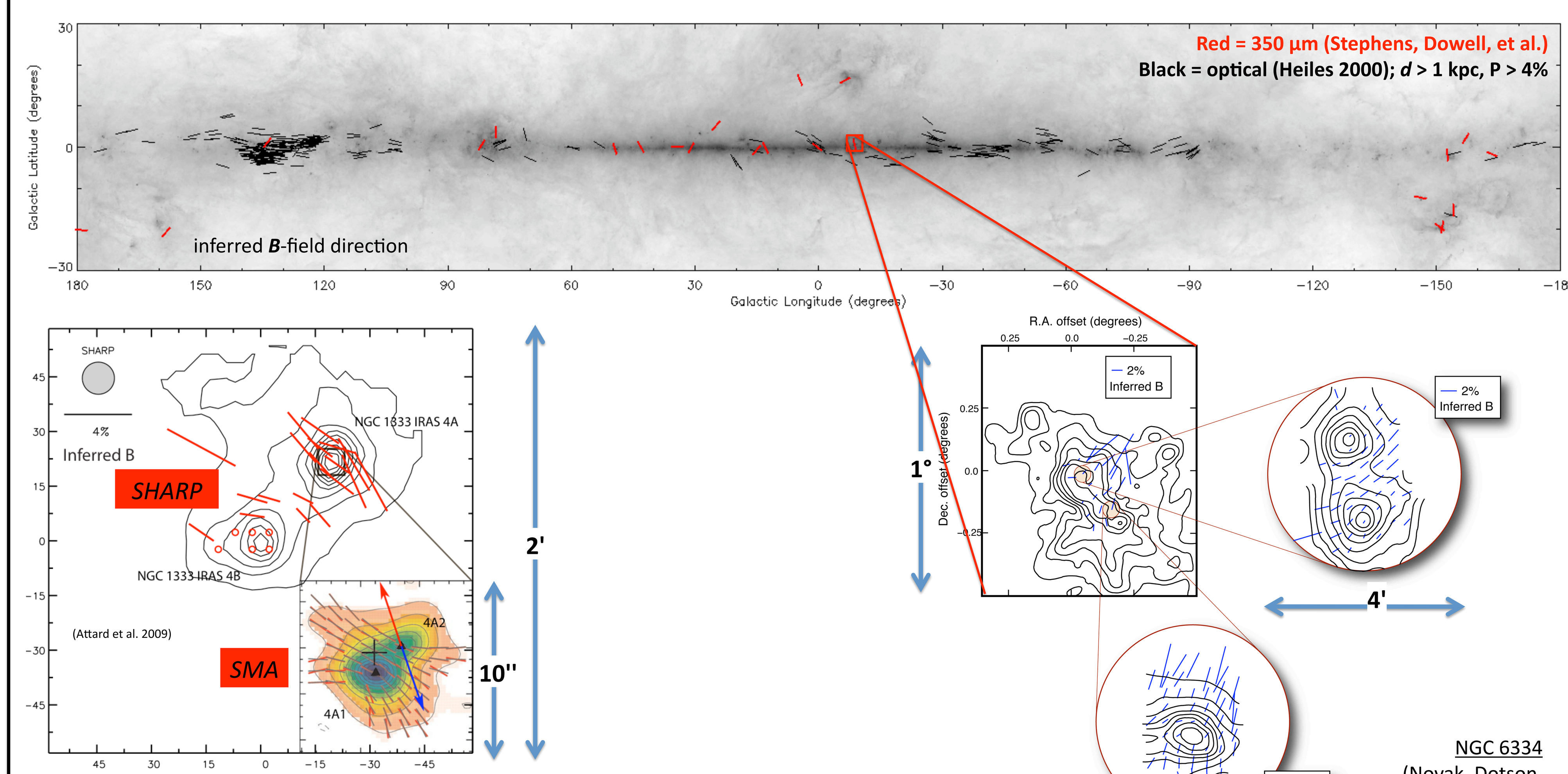
External Galaxies



There exist many outstanding questions about the global role of magnetic fields in galaxies. Addressing these questions requires multi-wavelength polarimetry. Some of the issues a SOFIA polarimeter may address include:

- **Nuclei of Starburst Galaxies**
  - Where does the vertical field transition to planar?
  - What is the strength of the magnetic field? The turbulent component?
- **IR Bright Galaxies**
  - Are there blowouts?
  - What is the strength of the magnetic field? The turbulent component?

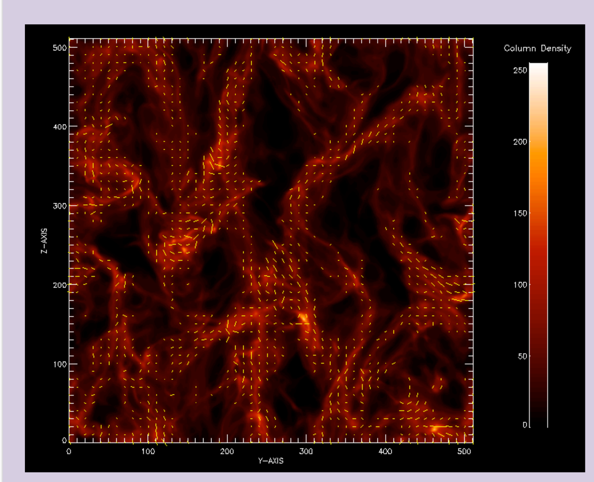
Magnetic fields from large to small spatial scales



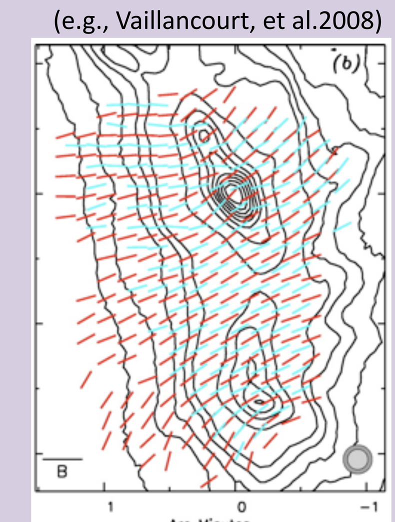
Magnetic-fields affect star/gas dynamics on a large range of scales (kpc to fractions of an AU). Theoretical tests need observations which follow these connections across size-scales. SOFIA/HAWC provides information on intermediate scales (few arcsec – few arcmin), in the gap between interferometers like SMA and ALMA (0.1's – few arcsec) and the largest scales (degrees) covered by CMB experiments like *Planck*.

Turbulent Power Spectrum

Numerical Simulations with MHD and self-gravity (Falceta-Gonçalves, Lazarian et al.)

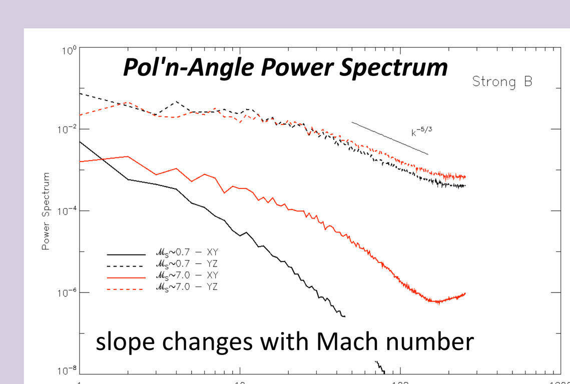


Measurements (e.g., Vaillancourt, et al.2008)

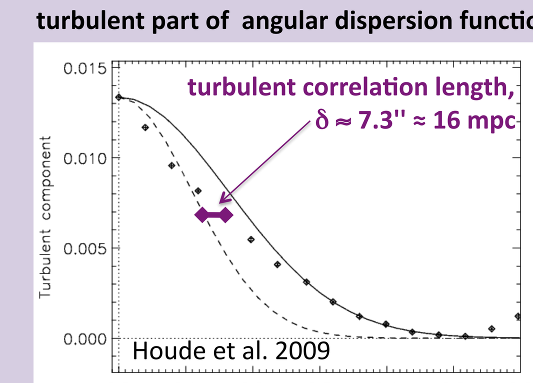


The gap between measurements and simulations of the turbulent ISM is narrowing rapidly. With the angular resolution of SOFIA, the effects of turbulence on the projected magnetic field direction may be disentangled from measurement uncertainties and large scale structure.

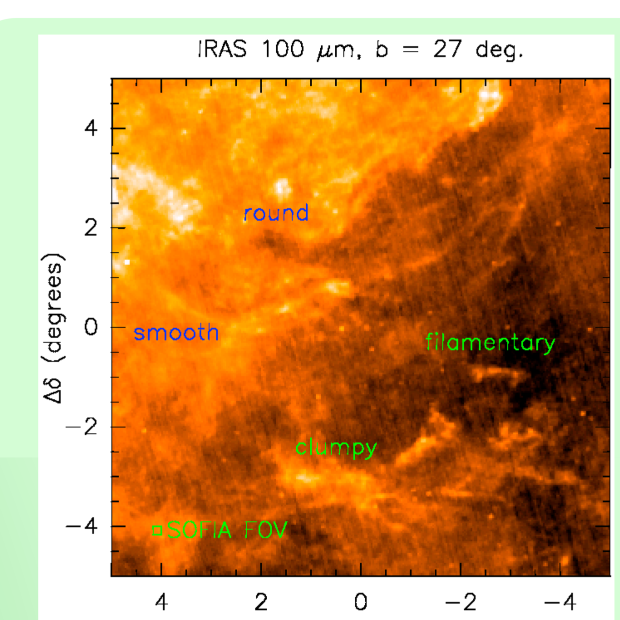
High-resolution (3''=6 mpc) interferometric measurements can resolve the turbulent scale and test theory. In the closest molecular clouds (*d* < 250 pc) this scale can be resolved with a SOFIA polarimeter. Single dish observations from SOFIA will also add much-needed zero-baseline coverage not possible with interferometers.



turbulent part of angular dispersion function



New Frontiers – Diffuse Clouds



Why:

- investigate role of magnetic fields in filamentary clouds
- measure polarization spectrum in diffuse regions to inform upcoming CMB polarization experiments
- compare with grain alignment theoretical predictions

Where:

≈ 50 filamentary structures identified by Jackson, Werner, & Gautier (2003) are observable with HAWC/pol

Wavelength (μm)	Beam size (arcsec)	Sensitivity (MJy/sr)	No. of FIR filaments
88	9	400	2
155	15	100	49
215	21	60	53

The Galactic Center

- Bright large-scale non-thermal filaments indicate magnetic fields perpendicular to the Galactic plane
- Large-scale submillimeter polarimetry implies a magnetic field parallel to the Galactic plane
- The small-scale field observed by submillimeter polarimetry is quite complex

Outstanding Questions

1. What is the geometry of the magnetic field?
2. What is the strength of the magnetic field?
3. How do the radio filaments form?

What can a SOFIA polarimeter do?

- Study the magnetic fields threading warm dust at high spatial resolution (5 – 20 arcseconds)
- Multi-frequency observations can sample different dust populations along the line of sight
- High sensitivity will probe the interaction sites between filaments and associated molecular clouds