Far-infrared polarimetry:
an essential tool for investigating interstellar magnetic fields and dust

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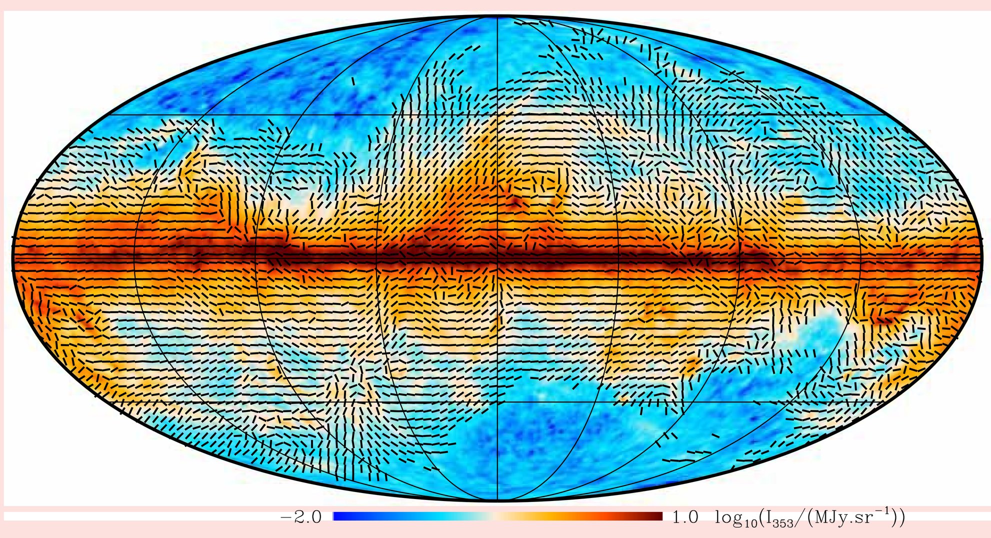
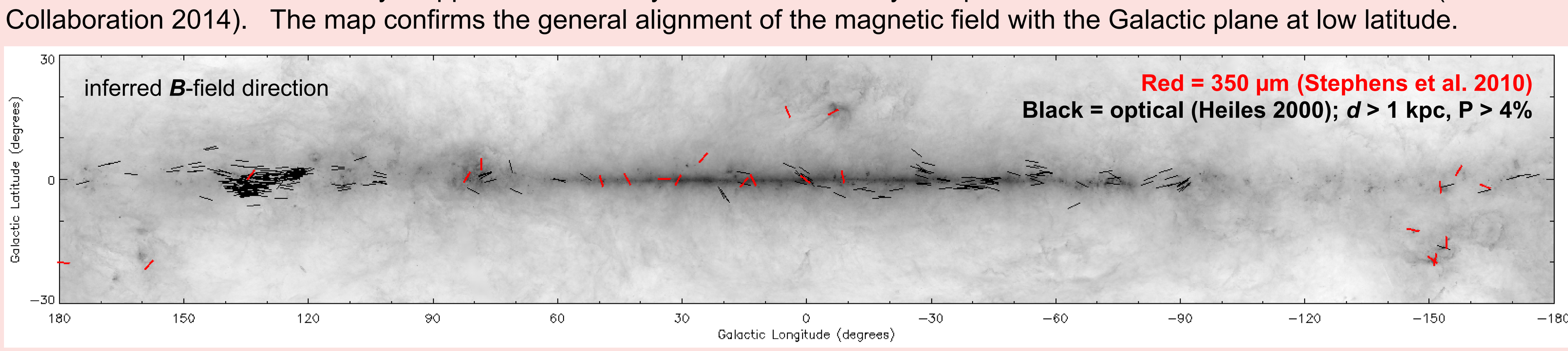
Abstract: Far-infrared (~30-500 micron) polarimetry of dust emission is a key observational tool for understanding interstellar magnetic fields, star formation, and the evolution of the interstellar medium. Ground-based, airborne, and balloon-borne instruments operating at multiple wavelength bands are able to make large, ~10-arcsecond-resolution maps of magnetic fields in Galactic molecular clouds, as well as to map high-latitude dust emission (cosmological foregrounds) at sub-degree scales. NASA balloons and SOFIA/HAWC+ will lead this work in the present decade. Recent theoretical and analytical advancements – particularly improved magneto-hydrodynamic models, the capability of extracting information from the statistics of polarization angle fluctuations, and radiative aligning torque (RAT) theory – provide an excellent foundation for maximizing the scientific output of these upcoming observations.The sensitivity available from space is required to make widespread, high-resolution magnetic field maps of diffuse gas, at scales where cloud fields connect to the larger Galactic field. We discuss sensitivity estimates and example astrophysical investigations for several conceptual observatories, and review status of enabling technologies for sensitive, wide-field far-infrared polarization mapping. With a modest enhancement to the capability of a space observatory, it will be possible to estimate the magnetic field strength in many of the interstellar features visible over the sky, as well as to make the first field maps in the neutral media of nearby Milky Way analogues. The nature of dust is of fundamental importance to far-infrared continuum observations. Multiwavelength observations are required to distinguish the microphysical state (size, composition, and temperature) from the macroscopic. The addition of polarimetry to such observations will provide additional insight, particularly into grain shape and environment.

Magnetic Fields at Large Scales

Magnetic fields affect gas dynamics on a large range of scales (kpc to fractions of an AU). Among the few methods to directly measure interstellar magnetic fields, far-infrared polarimetry provides key information about the neutral medium involved in star formation.



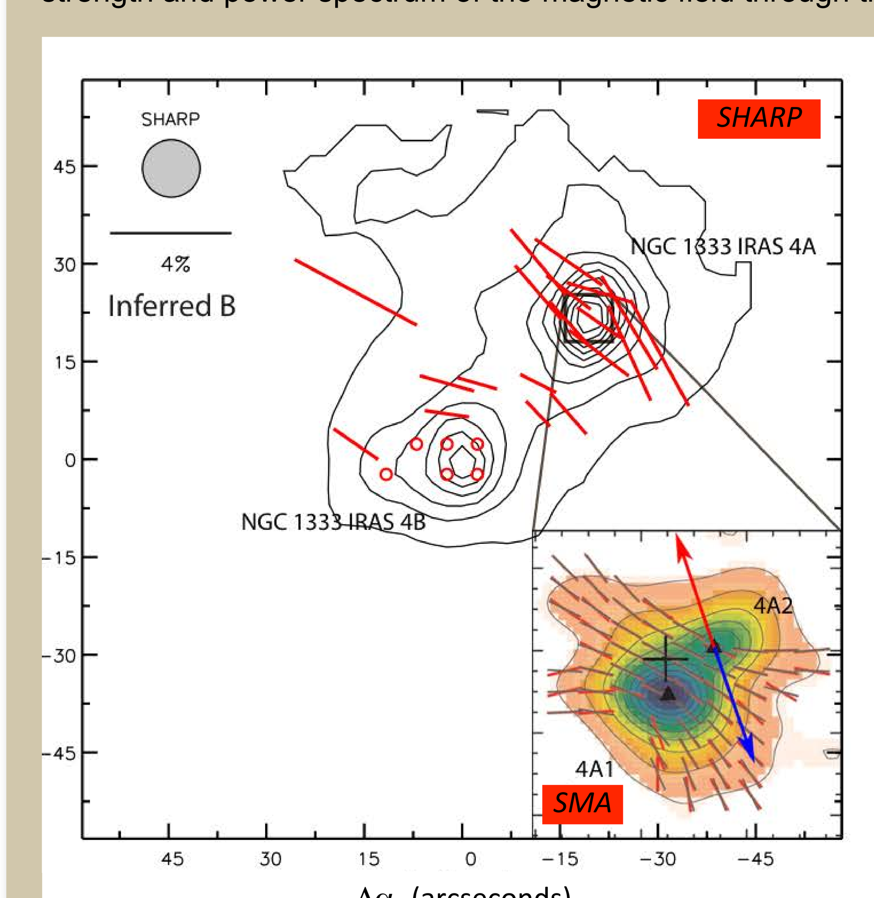
The Planck mission has recently mapped the entire sky in 850 mm intensity and polarization with 5 arcminute resolution (Planck Collaboration 2014). The map confirms the general alignment of the magnetic field with the Galactic plane at low latitude.



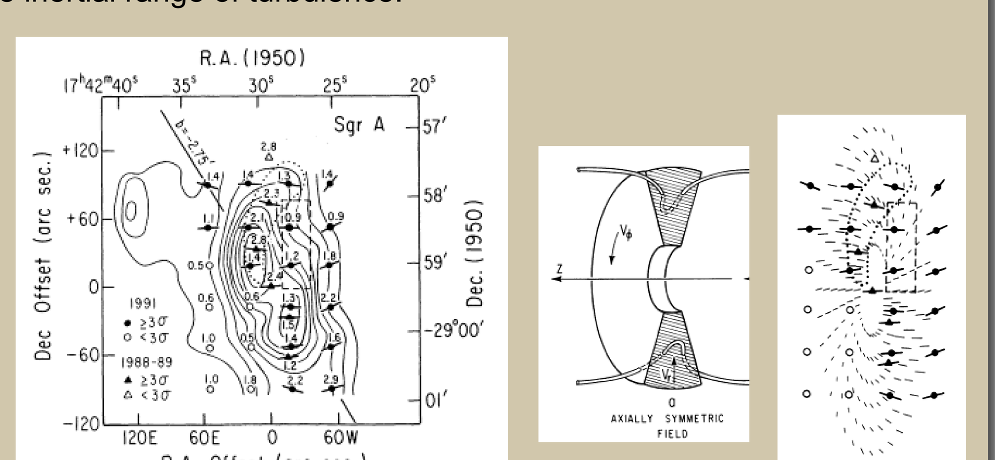
While the Galactic field shows order at large scales and in the lower density neutral medium (here shown with optical polarimetry, black vectors), the field in high density molecular clouds appears random with respect to the Galactic plane (red vectors). This disorder may be a result of cloud formation or feedback from star formation.

Magnetic Fields at Small Scales

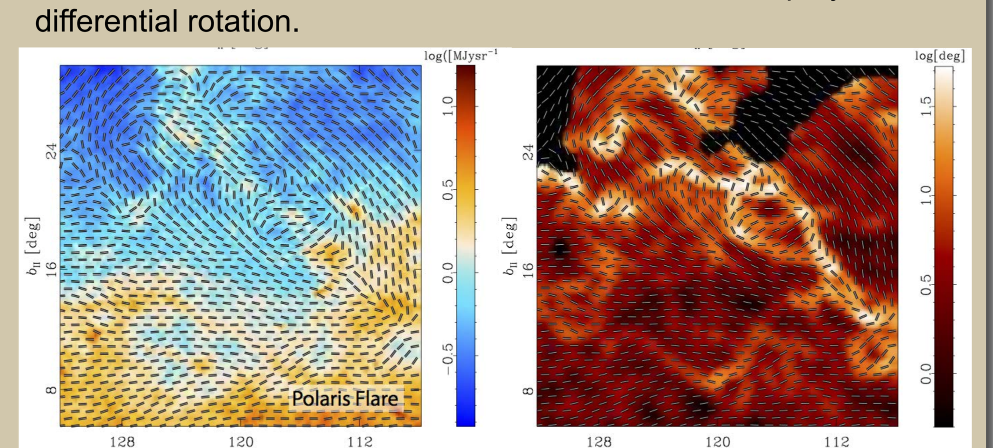
Polarization observations with arcminute through sub-arcsecond resolution are needed to probe the magnetic field in Galactic environments of cloud and star formation – to test models of field structure (whether expected or not) and to estimate the strength and power spectrum of the magnetic field through the inertial range of turbulence.



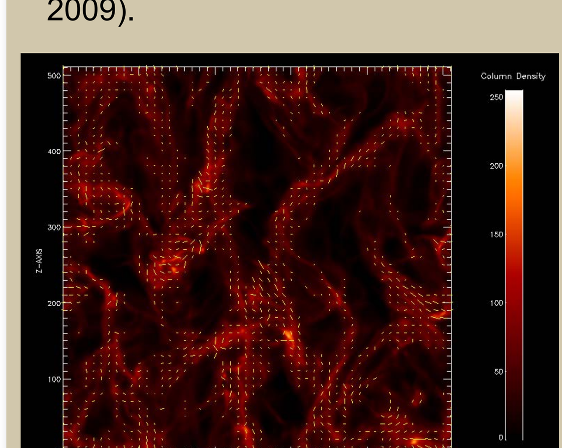
Submillimeter polarimetry of a multiple protostellar system in NGC 1333. The high-resolution SMA observations (lower right, Girart+ 2006) show an "hourglass" field line structure reminiscent of theoretical models of gravitationally-contracting protostellar cores. The SHARP observations show that the axis of the hourglass aligns fairly well the field in the envelope on larger scales (Attard+ 2009).

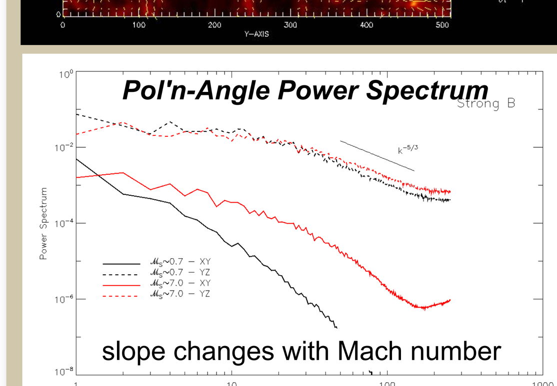


Galactic Center Circum-Nuclear Disk: 100 mm observations (E vectors), best-fit model, and comparison to data (Hildebrand+ 1993). The model has an initial vertical field which is wound up by differential rotation.

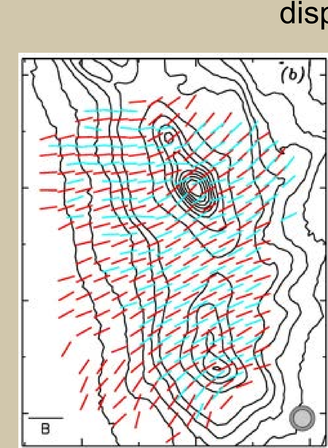


The Planck maps at mid Galactic latitudes have discovered filamentary regions of large field dispersion which do not correspond closely density features. (Planck Collaboration 2014). The left image shows density and field, and the right image shows dispersion and field.

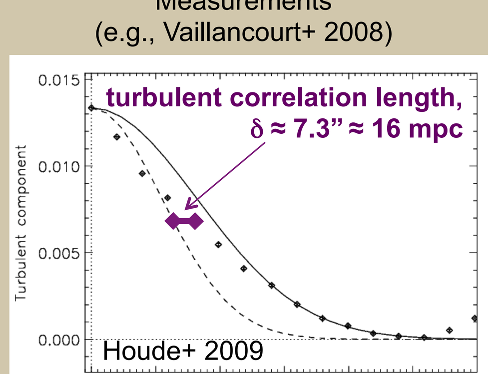




Numerical simulations with MHD and self-gravity (Falceta-Concalves, Lazarian+ 2008)



Measurements (e.g., Vaillancourt+ 2008)



Turbulent part of angular dispersion spectrum

B Strength and Turbulent Power Spectrum

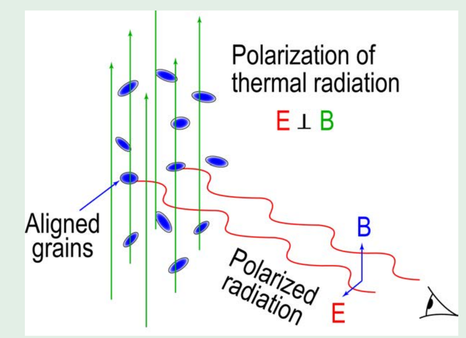
Chandresekhar and Fermi (1953) suggested a method for extracting the magnetic field strength from dispersion in magnetic field polarization angles:

$$\frac{B^2}{4\pi\rho\sigma^2(v)} \approx \frac{1}{\left(\Delta\phi\right)^2}$$

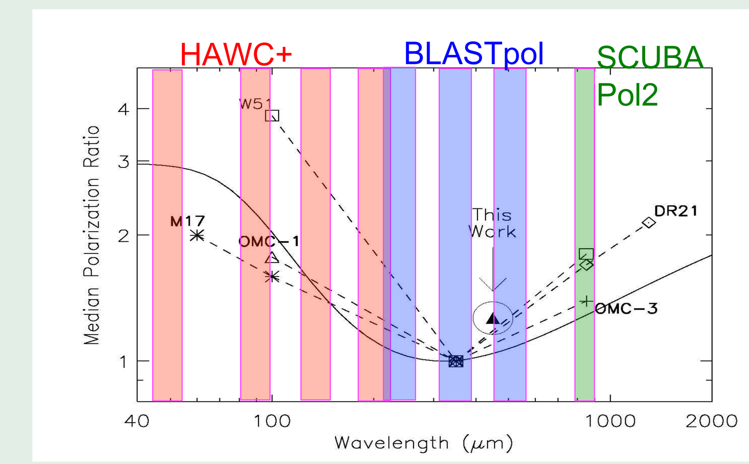
Since that time, several groups have studied the effects on that relation of averaging along the line of sight and within the measurement beam (e.g., Myers+ 1991; Ostriker+ 2001; Padoan+ 2001, Heitsch+ 2001, Pelkonen+ 2007, Falceta-Goncalves+ 2008; Houde+ 2009), which to first order results in a numerical pre-factor.

Besides the large-scale component of the field, measurements can also constrain the finer structure. The gap between measurements and simulations of the turbulent ISM is narrowing rapidly. High-resolution (3"=6 mpc) interferometric measurements can resolve the turbulent scale and test theory (Houde+ 2011). In the closest molecular clouds (*d* < 250 pc) this size scale can be resolved with a SOFIA polarimeter. Single dish observations will also add much-needed zero-baseline coverage not possible with interferometers.

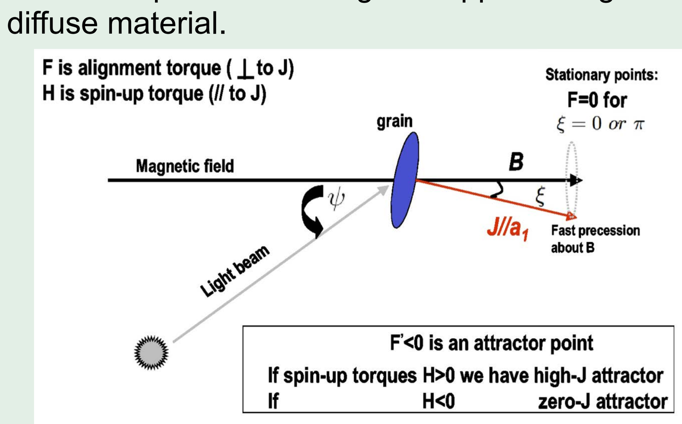
Far-Infrared Polarization and Dust



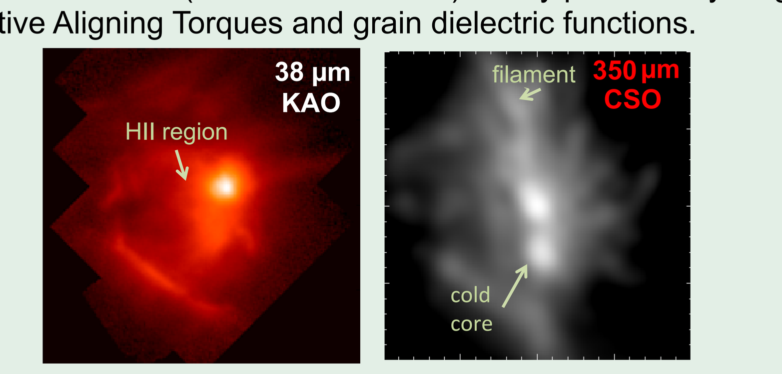
Far-infrared polarization is due to emission from elongated dust grains with spin axes along the magnetic field. (Figure concept: A. Goodman.) Planck has found polarization degrees approaching 20% in diffuse material.



The far-infrared polarization spectrum – already known to have reproducible features (Vaillancourt+ 2008) – may provide key diagnostics of Radiative Aligning Torques and grain dielectric functions.

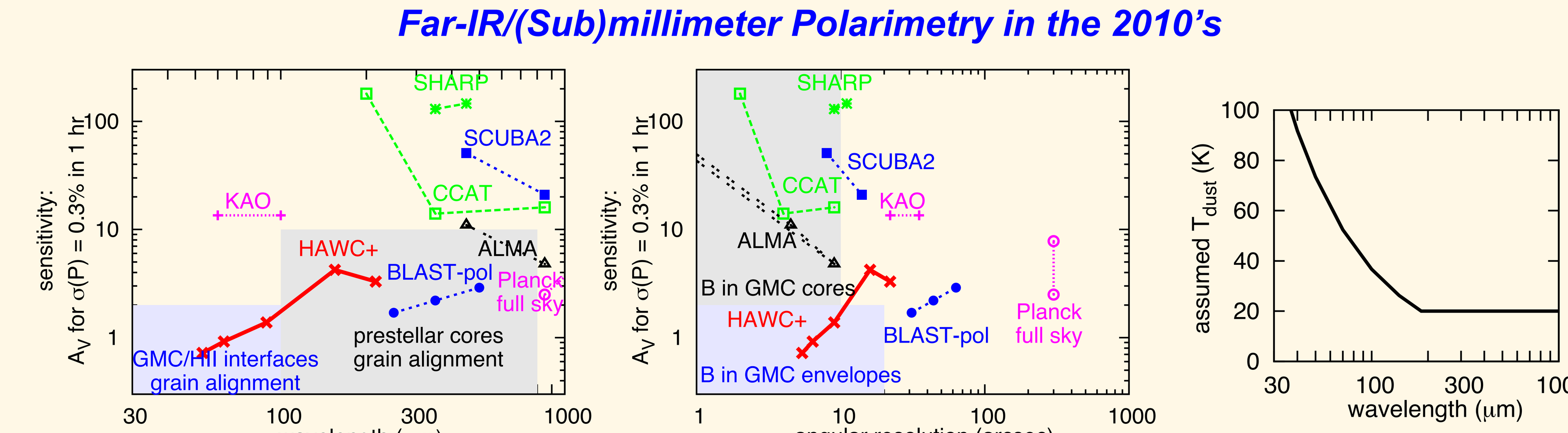


The current leading theory for grain alignment is Radiative Aligning Torques (e.g. Lazarian+ 2007)

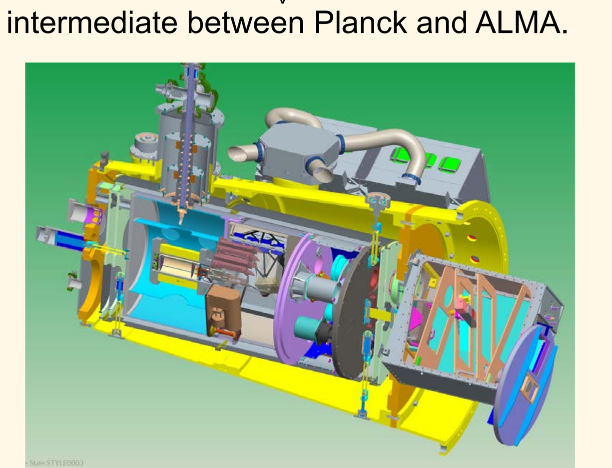


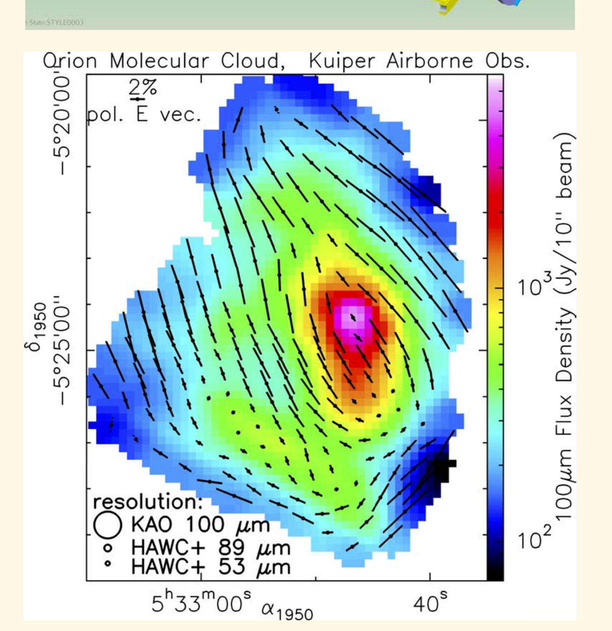
Besides the microphysics of grains, multi-wavelength polarimetry can also probe different physical components of clouds (Stacey+ 1995; Lis+ 1998).

Far-IR/(Sub)millimeter Polarimetry in the 2010's

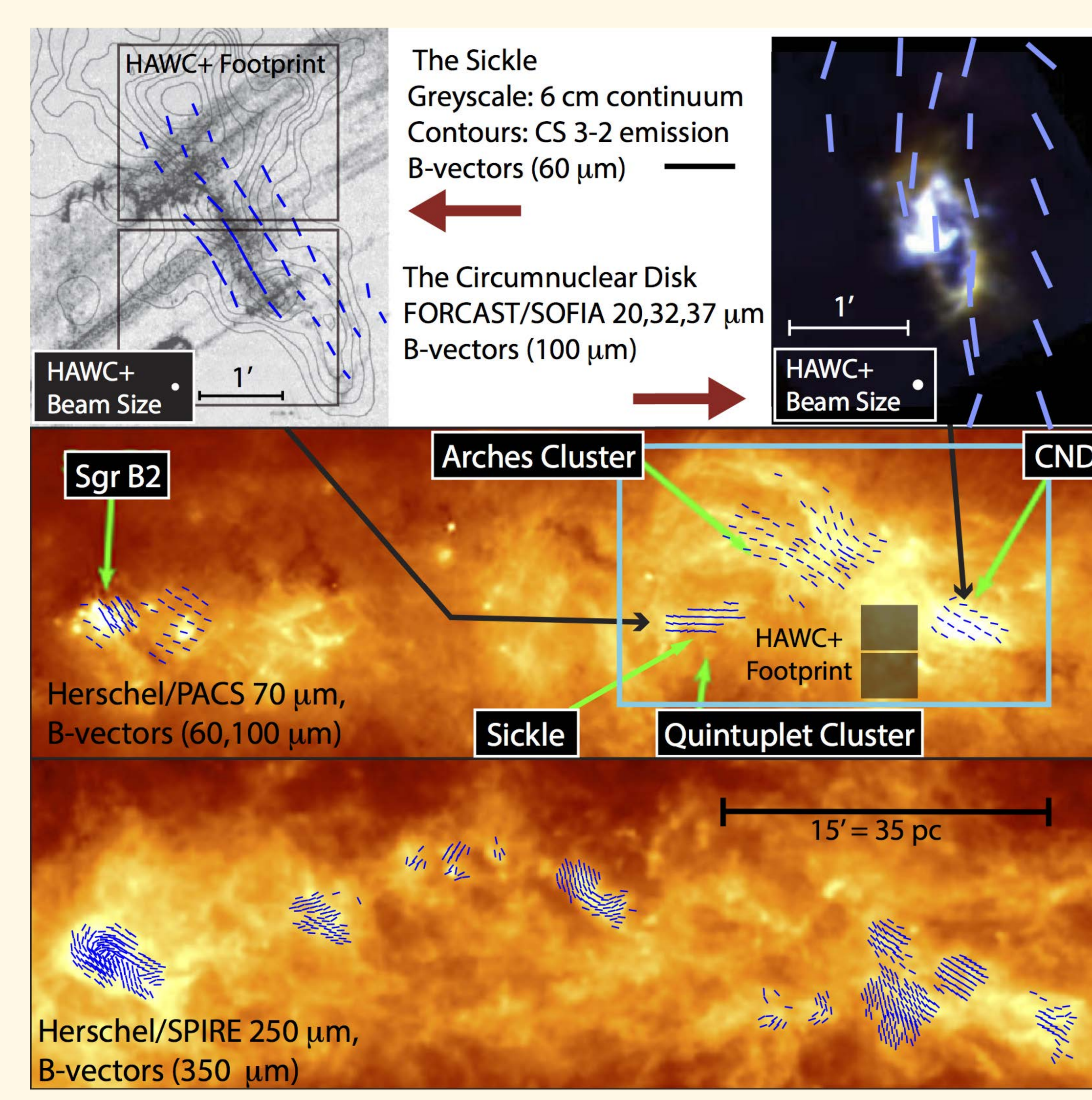


During the second half of the decade, the capabilities for far-infrared through millimeter polarimetry cover much of phase space for molecular clouds, A_V > 1. Airborne and balloon-borne telescopes provide key coverage in wavelength and of angular scales intermediate between Planck and ALMA.





We are upgrading the HAWC instrument, targeting wide-field multi-wavelength polarimetry with SOFIA by the end of 2015. The resolution and sensitivity of SOFIA/HAWC are a major leap from KAO/Stokes.



Priority Galactic Center targets for HAWC+. HAWC+ can survey the cyan box in 2 hours, achieving low polarization uncertainty for each beam of median flux density in that box.

Far-IR Polarimetry from Space

The polarization sensitivity of an imaging system with a polarization modulator added to the beam is approximately (Dowell+ 2010):

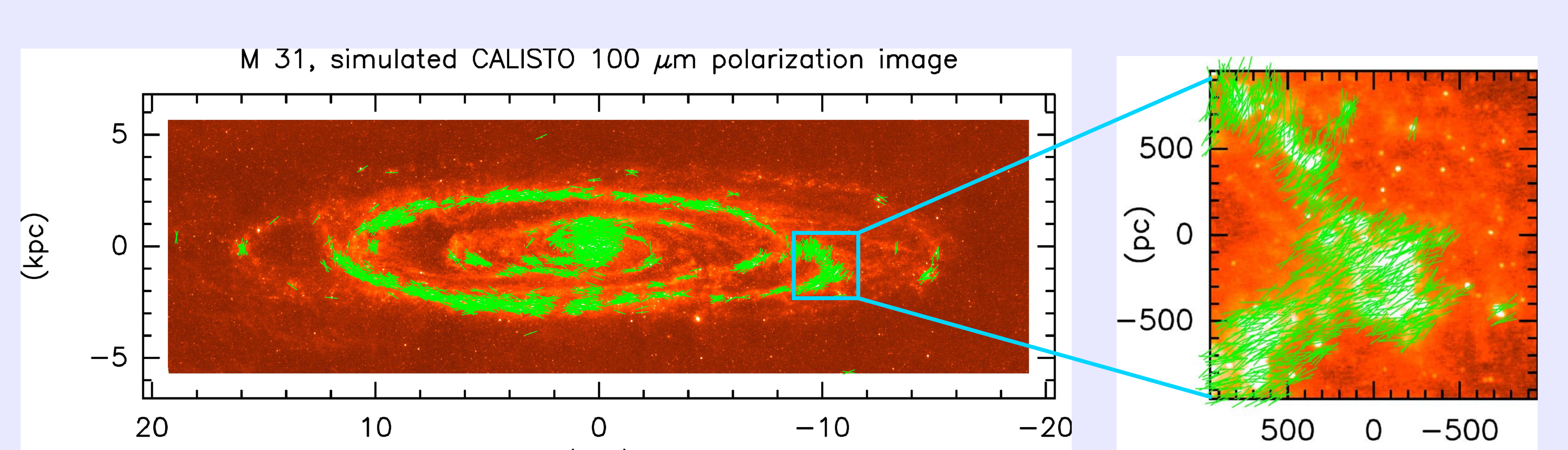
σ (P) ≈ 2.2 NEFD(imaging mode) / (F_n $t^{1/2}$)

The typical degree of polarization is 1 – 5%; targeting σ(P) = 0.3%, then the necessary equivalent imaging signal-to-noise is:

S/N (equivalent for imaging mode) ≈ 700

As an enhancement to a space continuum imaging mission, far-infrared polarimetry can address the following astrophysical themes:

1) Estimates of magnetic field strength for the well-resolved clouds over a significant fraction of the sky, e.g., the Galactic plane for a survey with few arcsecond resolution (CALISTO/SAFIR), or the entire sky for a survey with sub-arcminute resolution (EPIC/CMBPOL). Moderate resolution is needed to resolve the magnetic structure.
2) Magnetic field patterns of clouds within the spiral arms of nearby galaxies, providing a perspective not possible for the Milky Way.
3) Subarsecond-resolution magnetic field mapping of disks and other circumstellar material with a far-IR interferometer.
4) Far-IR spectropolarimetry for dust diagnostics, where space allows high accuracy and no restrictions on observation wavelengths.



Simulated polarization map, to illustrate signal-to-noise, for a 5 m cold telescope, 10000-element detector, and 5 hour integration.

Contact / References / Acknowledgments

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REFERENCES: M. Attard et al. (2009, ApJ, 702, 158); S. Chandrasekhar & E. Fermi (1953, ApJ, 118, 113); C. Dowell et al. (2010, SPIE, 7735, #6H); D. Falceta-Goncalves et al. (2008, ApJ, 679, 537); J. Girart et al. (2006, Science, 313, 812); F. Heitsch et al. (2001, ApJ, 695, 248), R. Hildebrand et al. (1993, ApJ, 417, 565); M. Houde et al. (2009, ApJ, 706, 1504); M. Houde et al. (2011, ApJ, 773, 109); A. Lazarian & T. Hoang (2007, MNRAS, 378, 910), D. Lis et al. (1998, ApJ, 509, 299); P. Myers & A. Goodman (1991, ApJ, 373, 509); E. Ostriker et al. (2001, ApJ, 546, 980); P. Padoan et al. (2001, ApJ, 559, 1005); V. Pelkonen et al. (2007, A&A, 461, 551); Planck Collaboration (2014, arXiv:1405.0871); G. Stacey et al. (1995); J. Vaillancourt+ (2008, ApJ, 679, L25)

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.