The Science Case for SPICA Far-Infrared Polarimetry

Draft: 2007 July 5
By C. Darren Dowell¹, Paul Goldsmith¹, William Langer¹, Michael Werner¹, Harold Yorke¹

¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, U.S.A.

Comments are very welcome. I hope we can build an even stronger case for polarimetry with feedback from scientists in the US, Japan, Europe, and elsewhere.

Abstract

Magnetic fields are predicted to be one of the dominant forces driving and guiding the flow of material in galaxies and galactic nuclei. Indeed, magnetic fields may be the determining factor in the structure of the interstellar medium and govern the rate and distribution of stellar mass formation. In comparison with gravity, pressure, and kinematics, the effects of magnetic fields in the interstellar medium are relatively difficult to measure. One of the very few available techniques – far-infrared/(sub)millimeter polarimetry of dust emission – has been applied to the study of magnetic fields in molecular cloud cores using suborbital telescopes. Combining this approach with the sensitivity of large, cold far-infrared space telescope such as SPICA would revolutionize our understanding of magnetic fields in the interstellar medium of the Galaxy and nearby spiral galaxies. Among the questions that a SPICA far-infrared polarimeter could address are:

• Do giant molecular clouds form in spiral arms from the swing amplifier effect, magneto-rotational instability, (magneto-)Jeans instability, or shocks?
• Are magnetic fields responsible for some elements of the rich structure in the ISM?
• How does the magnetic support of molecular clouds evolve during the star formation process?
• How do magnetic fields direct the flow of gas in the Galactic center?
• What is the structure of the magnetic field at high Galactic latitude?
• How does environment affect the magnetic alignment of dust grains?

Table of Contents

2. Worldwide Capabilities in Far-IR/(Sub)mm Polarimetry in the SPICA Era
3. Polarimetry with SPICA
   3a. Assumptions for a SPICA Polarimeter
   3b. The Magnetic Field Structure of Spiral Galaxies
   3c. Star Formation, Cloud Structure, Magnetic Support, and Turbulence

1
3d. Galactic Center
3e. Dust Grain Physics, High-Latitude Magnetic Fields, and Cosmological Foregrounds
3f. Far-Infrared Polarimetry Technique Relevant to SPICA

4. References


Predictions that the aligned dust grains that produce polarized starlight through absorption would also produce polarized emission in the far infrared (Stein 1966) were confirmed through pioneering observations of the Orion core (Cudlip et al 1982; Hildebrand, Dragovan, & Novak 1984). Continued effort with larger and more sensitive detectors has shown that polarization at the few percent level is widespread within molecular cloud cores across the far-infrared through millimeter (\(\lambda = 60-1300 \mu m\)) spectrum (e.g., Hildebrand et al. 1999; Siringo et al. 2004; Matthews et al. 2005). With near certainty, the polarization in most of these measurements is caused by the alignment of dust grains with respect to the local magnetic field (Hildebrand 1998; Martin 1971). It is the potential to map magnetic field structures in the interstellar medium which motivates much of this experimental and observational work.

Interferometric techniques have been applied to polarimetry at \(\lambda \geq 850 \mu m\) (Akeson et al. 1996; Girart, Rao, & Marrone 2006). As for unpolarized continuum imaging, interferometric polarimetry excels at high angular resolution studies of, for example, protostellar envelopes and disks. “Radio” techniques have also detected polarized molecular line emission arising from the Goldreich-Kylafis (1981, 1982) effect – also a probe of magnetic field direction – but mapping results have so far been less extensive than for dust continuum (e.g., Girart et al. 2004; compare Schleuning 1998).

Polarimetry in the mid-infrared (\(\lambda = 5-30 \mu m\)) typically studies a minority population of dust but offers high angular resolution (e.g., Aitken 1991) and sensitivity to spectral features of, for example, silicates (Smith et al. 2000).

While emission from polarized dust provides exciting opportunities to measure the magnetic fields in interstellar clouds, it also hinders our measurements of the Cosmic Microwave Background (CMB). In the deepening investigation of the properties of the CMB, cosmologists are now faced with understanding the polarized foreground dust emission from the Galaxy. Due to the arcminute- and degree-sized beams of CMB experiments, there is the potential to map magnetic fields over large areas of the Galaxy (Benoit et al. 2004; Ponthieu et al. 2005; Dowell 2007).

To illustrate the potential of polarization measurements to understand the dynamics of a wide variety of processes in the interstellar medium, we highlight some selected results from far-IR/(sub)mm polarimetry in the list and figures below. Since two conventions are used for displaying polarization vectors in the literature (“E vectors”, which are parallel to the grain long axes and perpendicular to the local magnetic field; and “B
vectors”, which are parallel to the local magnetic field), we have noted which convention was used in the caption of each figure. Highlights include:

- Observations of “magnetic pinches” indicative of cloud core collapse models, but sometimes seen on larger angular scales (Figure 1)
- Magnetic fields lying in the plane of two T Tauri star disks, apparently wound up from rotation (Figure 2)
- An example of a field apparently wound up by a much larger disk – the 3 pc ring at the Galactic center (Hildebrand et al. 1993)
- A possible transition from toroidal magnetic fields in the densest material to poloidal fields observed in most of the Galactic center volume (Figure 3).
- The first, and to date only, detection of polarized far-IR/(sub)mm dust emission from another galaxy (M82, Greaves et al. 2000)
- Estimates of the magnetic field strength in prestellar cores via submillimeter polarimetry (Kirk, Ward-Thompson, & Crutcher 2006)
- Magnetic field patterns revealing the evolutionary history of clouds (e.g., Dotson 1996)
- Evidence for multiple populations of far-IR-emitting grains from the spectral dependence of polarization (Figure 4)

Figure 1 [B vectors]: “Pinched” magnetic fields in regions of star formation. In the protostellar envelope of NGC 1333 IRAS 4A (left; Girart et al. 2006), the scale of the pinch is ~1000 AU, roughly the size scale of “pseudodisks” in the star formation models of F. Shu and collaborators (Galli & Shu 2003). The size scale of the apparent pinch in the high-mass star formation site DR21 is 100 times larger (right; Dowell et al. 2003).
Figure 2 [E vectors]: First detections of polarized dust emission from circumstellar “T Tauri” disks (Tamura et al. 1999). In both cases, the beam-averaged magnetic field is in the plane of the disk (as measured with interferometry), consistent with polarization from a magnetic field wound up by the rotating disk.

Figure 3 [B vectors]: Magnetic field vectors measured in dense neutral clouds in the Galactic center (left, Chuss et al. 2003). In the densest clouds, the field is toroidal – parallel to Galactic plane. However, there is evidence that in the lower density material, the field is poloidal, as in the ionized Radio Arc and as in the accretion model of Uchida, Shibata, & Sofue (1985).
Figure 4: Continuum polarization spectrum of several molecular clouds undergoing high-mass star formation, normalized at 350 µm (Vaillancourt 2002). The predicted spectrum from a single grain component is nearly wavelength-independent in the far infrared, so multiple grain components with different polarizing efficiencies are required to explain the measurements.

The observations have encouraged theoretical modeling of the details of dust grain alignment (Lazarian 2003) as well as simulated polarization maps for distinguishing various models of turbulence and grain alignment (Ostriker et al. 2001; Padoan et al. 2001; Heitsch et al. 2001; Pelkonen et al. 2007). It is now an observational challenge to produce polarization maps with the extent and dynamic range of the simulations (Figure 5).

Figure 5: Predicted polarization emergent from a simulated magnetized medium with supersonic and super-Alfvenic turbulence which has resulted in the formation of cores (Padoan et al. 2001). Current far-IR/(sub)mm polarimetry capabilities permit study of only the cores, and a large, cold space telescope is necessary to investigate the surrounding medium.

2. Worldwide Capabilities in Far-IR/(Sub)mm Polarimetry in the SPICA Era

Before SPICA is in orbit, Planck will have made the first all-sky map of polarized dust emission. Planck will have the best sensitivity to polarized dust at 850 µm. Planck is
likely to detect polarization along lines of sight with visual optical $A_V$ as low as 1 mag. and to achieve 0.3% polarization uncertainties where $A_V > 5$ mag. (Sensitivity estimated from Planck: The Scientific Programme, astroph/0604069, p. 10.) Unfortunately, Planck’s beam size is 5’, which will average over a lot of cloud structure even within our Galaxy. However, with Planck observations, we will have, for the first-time, the “magnetic context” for any subsequent measurement.

Polarimetry will continue with ground-based telescopes. Two particularly powerful instruments will come on-line by the beginning of the next decade: SCUBA2 and its polarimeter, and ALMA, both working at $\lambda \geq 450$ µm, and both having the potential to make magnetic field maps with thousands of vectors. However, due to the severe limitations imposed by the atmosphere, there is little sensitivity to dust components of different temperature, and magnetic field measurements on the largest scales and at the lowest surface brightnesses are likely to be filtered from the maps.

SOFIA is likely to have a polarimeter during its projected twenty-year lifetime, and it provides the most direct competition to a SPICA polarimeter for certain science topics because it has a similar aperture and access to the far-infrared range. However, the instantaneous sensitivity of a SOFIA polarimeter (Dowell et al. 2003) is ~1000 times worse than a SPICA polarimeter, and SOFIA’s capability is limited by the relatively small observing time available, typically 900 hours per year divided among at least five facility instruments and several PI instruments. Thus, one can expect, at most, 50 hours per year devoted to mapping magnetic fields in galaxies with SOFIA.

Despite the importance of the magnetic fields to galactic dynamics and star formation, and the exciting capabilities offered by current technology, there is no far-IR/(sub)mm polarization mission foreseen in the next decade which matches a SPICA polarimeter in terms of sensitivity to diffuse dust emission combined with high angular resolution. Herschel in particular has no polarization capability worthy of mention in this regard.

3. Polarimetry with SPICA

Despite years of concerted effort observing interstellar gas in a variety of tracers and wavelengths, it is still difficult to quantify the relative importance of turbulence and magnetic fields in governing the evolution of molecular clouds (e.g., Crutcher 2007). Furthermore, even if turbulence is the dominant factor in interstellar evolution, it is likely that much of it is in the form of magnetohydrodynamic waves. More observations which allow a statistical measure of the contribution of fields are necessary to establish general rules of thumb, and only comprehensive measurements including the magnetic field have any hope of telling the full story for any particular interstellar cloud.

SPICA offers the best opportunity to make a breakthrough in our understanding of interstellar magnetic fields within the next decade. Undoubtedly our own Galaxy would be the focus of much of the investigation; however, polarimetry of nearby spiral galaxies – made possible for the first time with SPICA – will provide critical information about
galactic dynamics. Of utmost importance is to understand the role of magnetic fields in
galactic nuclei, including our own, where magnetic fields likely guide and/or drive the
flow of material into and out of the galaxy.

3a. Assumptions for a SPICA Polarimeter

The integrated dust spectrum of a typical spiral galaxy peaks at $\lambda \sim 100$ $\mu$m (e.g., Dale et al. 2005). Since the emission from the SPICA telescope is negligible at this wavelength, it has an enormous sensitivity advantage over contemporaneous facilities for dust in the
20 – 100 K range. Much of the SPICA magnetic field science can be performed with a
polarimeter operating only at 100 $\mu$m, but see Section 3e for arguments for extended
wavelength coverage.

The sensitivity expected for a SPICA far-infrared camera is discussed by Onaka et al.
(2005). The quoted sensitivity (after 1 hour integration) is dominated by confusion noise
from distant galaxies, so the noise does not integrate down as $1/\sqrt{t}$. Therefore,
to estimate the sensitivity of a SPICA 100 $\mu$m polarimeter observing with a shorter
integration time per beam, we performed a “first-principles” calculation. Since
polarimetry requires high signal-to-noise, the priority targets are likely to be brighter than
$\sim 10$ MJy/sr, so the photon noise from the target itself is an important contributor. Here,
we consider observations of targets as faint as 40 MJy/sr, which is estimated to
correspond to regions with visual optical depth $A_V = 1$ mag. The photon noise from this
intensity is of order $60$ kJy/sr $s^{1/2}$, or $0.06$ mJy $s^{1/2}$ in one SPICA beam. Achieving
background-limited performance is especially difficult in the far infrared, so in the table
below we consider a baseline instrument with 5× worse sensitivity and only a modest
detector array.

<table>
<thead>
<tr>
<th>telescope diameter</th>
<th>3.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelength</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>angular resolution</td>
<td>7”</td>
</tr>
<tr>
<td>point-source sensitivity</td>
<td>0.3 MJy/sr $s^{1/2}$</td>
</tr>
<tr>
<td>extended-source sensitivity</td>
<td>0.3 MJy/sr $s^{1/2}$</td>
</tr>
<tr>
<td>visual optical depth sensitivity</td>
<td>0.01 $A_V s^{1/2}$</td>
</tr>
<tr>
<td>polarization uncertainty $\sigma(P)$ for $A_V = 1$</td>
<td>1% / $\sqrt{t}$, t in seconds</td>
</tr>
<tr>
<td>number of detectors</td>
<td>100</td>
</tr>
</tbody>
</table>
| time to survey 1 square degree with $A_V \geq 1$
to $\sigma(P) \leq 0.3\%$ | 20 hours |
| number of beams in 1 square degree | 300,000 |
| integration time per beam | 25 sec |

Table: Baseline 100 $\mu$m polarimeter sensitivity

Even with a modest SPICA polarimeter, one may be able to produce polarization maps
with 1,000,000 magnetic field vectors in them.

3b. The Magnetic Field Structure of Spiral Galaxies
A particularly exciting prospect for SPICA polarimetry is the study of molecular cloud formation and evolution in nearby spiral galaxies. Only space polarimeters have the sensitivity to measure widespread polarized emission from normal spiral galaxies, and only a far-infrared telescope as large as SPICA has the angular resolution required to resolve individual Giant Molecular Clouds (GMCs) in the most nearby systems at their $\lambda \approx 100 \mu$m spectral peak.

A number of authors have modeled the formation of GMCs within spiral arms. Several processes could trigger cloud formation, including: the swing amplifier effect (Goldreich & Lynden-Bell 1965; Julian & Toomre 1966), the magnetorotational instability (Kim, Ostriker, & Stone 2003), the magneto-Jeans instability (Kim & Ostriker 2006), or large-scale shocks. Magnetic fields in the diffuse medium are typically along spiral arms (Beck 2007), so that can be considered the initial condition of GMC formation. The swing amplifier operates in the absence of magnetic fields and would twist up weak fields, so the observational test for that model is a random orientation of GMC fields relative to the spiral arms. The mechanisms involving magnetic fields have been simulated (e.g., Figure 6), and the detailed patterns of the field can be compared to measurements of spiral galaxies such as M31.

Figure 6: Time evolution of GMC formation within a rotationally sheared spiral galaxy (Kim & Ostriker 2006). The grayscale shows density, and the lines show the magnetic field. In this model, a density wave shock has caused the gas to become magneto-Jeans unstable.

A survey of M31 would ideally detect polarization toward column densities as low as $A_V = 0.5$ and therefore sample all of the shielded, neutral gas. Where the column density is at least that large, polarization uncertainties $\leq 0.3\%$ can be achieved over the $3^\circ \times 1^\circ$ extent of the galaxy in 10 days.
3c. Star Formation, Cloud Structure, Magnetic Support, and Turbulence

Crutcher (2007) summarized how polarimetry may be used to test star formation theory. He considered two cases: a magnetically-supported cloud, and a turbulence-dominated cloud. The essential measurements to distinguish these cases are the magnetic field strength and morphology.

The magnetic field strength can be estimated from far-infrared polarimetry using the Chandrasekhar-Fermi (1953) method, which has been updated to account for the effects of beam smoothing and large angle dispersion (Ostriker et al. 2001; Padoan et al. 2001; Heitsch et al. 2001). A large or small dispersion in polarization position angle indicates an energetically weak or strong field, respectively, and ancillary observations of density and velocity can be used to convert to absolute field strength. Radio observations of the Zeeman effect, although challenging, provide an alternative measure of magnetic field strength (e.g., Levin et al. 2001). The sensitive Zeeman measurements possible with ALMA, EVLA, and SKA are highly complementary to the SPICA science. Line widths of neutral and ionized species provide an additional method for quantifying the line-of-sight component of the magnetic field (e.g., Lai, Velusamy, & Langer 2003).

Far-IR/(sub)mm polarimetry is the best technique for measuring magnetic field morphology within molecular clouds, since the effect is measurable with high angular resolution over a large area. Magnetically-supported clouds have predictable shapes of the fields and correlations with structure, for example “hourglass” or “pinched” fields (Figure 1) and fields perpendicular to collapsed “pancake” clouds. In turbulence-dominated clouds, the correlation between field direction and cloud structure will be weaker, and compressive waves may tend to create flattened structures with in-plane fields. Attempts to measure morphological correlations have reached inconclusive results so far (Kane et al. 2003; Vallee & Bastein 2000), so more work, with attention to observational bias, is critical to advance our understanding of cloud formation and evolution.
Statistical approaches will provide strong constraints on star formation theory. In general, clouds which are in a magnetically-supported phase are evolving much more slowly than ones dominated by turbulence, so the degree of magnetic support sets the star formation time scale. Two interesting “axes” to explore with a SPICA polarimeter are density and evolutionary state. Since magnetic fields are frozen into the material on short time scales and leak out on longer time scales, the scaling of magnetic field strength with density indicates the typical manner of cloud evolution (Crutcher 2007). Cloud evolution is not independent of the stars that form within, so a good sample should include prestellar cores (magnetically-supported?), clouds with embedded protostars (transitioning from magnetically subcritical to supercritical?), and HII complexes (turbulence dominated?).

The interpretation of the data should be rooted in statistical measures referenced to MHD simulations, especially since “in between” cases with partial magnetic field and turbulent support may be important. Maps of density and velocity should be incorporated as much as possible. Histograms, correlations, and power spectra are the statistical techniques likely to be useful.

Galactic star formation and cloud evolution is an easy target for a SPICA polarimeter, since polarization can be mapped in degree-sized areas with $A_V > 1$ mag. in 20 hours or less (Section 3a). While Planck will map large angular scales, SPICA will specialize in high resolution maps, which are critical for studying galactic nuclei.

![Figure 8: Predicted density + polarization maps from a MHD simulation by Ostriker et al. (2001). The left panel is for a strong magnetic field (left), and the right panel is for a weak field. These two cases can be easily distinguished by SPICA observations of polarization and, to a lesser extent, column density. (In this figure, the vectors show polarized intensity: polarization fraction × total intensity.)](image)

3d. Galactic Center

The lifecycle of the interstellar medium in the central ~100 pc of galaxies is altered by the effects of increased density, rotation frequency, and tidal forces. The relative proximity of our own Galactic nucleus allows us to study the effects of the central
environment in detail, including environmental influences on the evolution of black hole/accretion disk systems.

Radio studies of the Galactic center (e.g., LaRosa et al. 2000) show striking evidence for magnetic fields permeating the ionized medium that are vertical in the Galactic reference frame. Limited submillimeter polarization vectors sampling the molecular material imply the magnetic field is largely horizontal (Novak et al. 2003; Chuss et al. 2003; Figure 3), suggesting a globally azimuthal geometry for this component. This interaction between vertical and azimuthal fields may influence the spectrum and/or the evolution of galactic nuclei (Serabyn & Morris 1994; Chuss et al. 2003). If so, then much of the non-thermal radio luminosity of the central 100 pc of the Galaxy comes from an “environmental” effect, rather than the activity associated with the black hole.

A SPICA polarization survey of the Galactic center will seek the twisted vertical fields proposed to explain the ejection of gas out of the plane (Uchida, Shibata, & Sofue 1985; Novak et al. 2003). Magnetic phenomena in the central ~100 pc represent an extreme case, but through their study we may learn lessons relevant to our understanding of the overall morphology of the Galactic field.

3e. Dust Grain Physics, High-Latitude Magnetic Fields, and Cosmological Foregrounds

The surprising wavelength dependence of far-infrared/submillimeter polarization (Vaillancourt 2002; Figure 4) and the absence of a complete model for it indicate that there is more to learn about the alignment of interstellar grains. Effects unrelated to alignment may be important for the Wien portion of the far-infrared spectrum (Onaka 1995), but multiple grain components with different degrees of alignment are needed to explain the remainder of the spectrum.

Recent studies of grain alignment theory point to the importance of exposure to radiation in aligning the grains (e.g., Cho & Lazarian 2005). The theory can be tested by observing clouds with varying degrees of exposure to stellar radiation. Polarimetry at multiple wavelengths – selecting the warmer and colder grains – is needed to test models. SPICA provides, for the first time, the ability to detect far-infrared polarization from very low column densities where all grains are exposed to radiation.

An especially interesting cloud type to study is the infrared cirrus. The cirrus clouds are typically found at high Galactic latitudes where confusion is minimal, have no embedded star formation, and are optically transparent. In addition, they are the dominant foreground in deep CMB experiments at \( \nu > 100 \) GHz, and a multiwavelength study of their polarization is key in recovering weak CMB signals. The relationship of magnetic fields to the cirrus is unknown. Planck will likely detect cirrus polarization in its all-sky survey, but SPICA will add short-wavelength, high-resolution data, and the pointed observatory mode allows observing strategies that would maximize the science return.

3f. Far-Infrared Polarimetry Technique Relevant to SPICA
Semiconducting bolometers have been shown to have the sensitivity, dynamic range, and bandwidth necessary for far-IR/(sub)mm polarimetry with suborbital telescopes (Platt et al. 1991; Dowell 1997; Schleuning et al. 1997; Dowell et al. 1998; Greaves et al. 2003; Siringo et al. 2004; Masi et al. 2006; Jones et al. 2006; QUaD Collaboration 2007). By the end of the decade, Planck will map polarization using background-limited semiconducting bolometers (Planck: The Scientific Programme, astroph/0604069).

Polarimeters using the next generation superconducting bolometers are on the verge of entering the field (e.g., Holland et al. 2006). In some cases, the bolometers have intrinsic polarization response, while in other cases, separate polarizers are used.

Since the fractional polarization is typically small (<10%), the polarized signal must be modulated in some way to distinguish it from the unpolarized signal. Attractive solutions for SPICA include a continuously rotating half-wave plate (Siringo et al. 2004; Bastien et al. 2005) or raster scanning (Masi et al. 2006; Jones et al. 2006; QUaD Collaboration 2007).

The polarimetry mode of the Infrared Space Observatory (ISO) far-infrared photometer used photoconductors and three polarizers in a filter wheel. Observing time and results were limited (Laureijs & Siebenmorgen 1999) because polarimetry with ISO was not a high priority at the time of instrument development.

To meet the requirements of a SPICA broadband far-infrared polarimeter, bolometers operating at 0.1 K can achieve background-limited sensitivity with sufficient dynamic range and bandwidth. Polarization could be detected with either a rotating half-wave plate or raster scanning.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

4. References


Hildebrand, R. H. 1988, QJRAS, 29, 327 – “Magnetic Fields and Stardust”


Martin, P. G. 1971, 153, 279 – “On Interstellar Grain Alignment by a Magnetic Field”


