Design Reference Mission Case Study
Stratospheric Observatory for Infrared Astronomy Science Steering Committee

Magnetic Fields, Turbulence, and Star Formation

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Scientific category:	STAR FORMATION
Instruments:	SUPERHAWC CAMERA/POLARIMETER
Hours of observation:	113

Abstract

We propose a major investigation of magnetic fields in star-forming regions based on multi-wavelength polarimetry. The observations will be made with SuperHAWC, an upgrade of the first-round photometer, HAWC, to provide over 5,000 pixels and the capability to do polarimetry in all of the initial HAWC passbands (53, 88, 155, and 215 microns). Our object list includes nearby Galactic clouds with a wide range of properties. For a large sample of Bok Globules, we will map magnetic field morphology in order to search for the predicted "magnetic pinches" and discover any correlations between field directions and disk or outflow axes. For giant molecular clouds, we will construct large scale polarization maps containing a total of $\sim 100,000$ polarization vectors, for comparison with synthetic polarization maps based on MHD turbulence simulations. Such comparisons will provide a new estimate for the mass-to-flux ratio, an important parameter of star formation theory. Other questions that we will address include the continuity of magnetic fields across different ISM phases, and the small scale cutoff for magnetic fluctuations.

Observing Summary:

Target	RA	Dec	F_{Jy}	Configuration/mode	Hours
RHO OPH PK (160)	16 21	-24 25	4	53/88/155/215	15
RHO OPH NE (160)	16 23	-24 15	1.5	88/155/215	20
ORION KL (500)	5 35	-5 20	45	53/88/155/215	2
ORION ISF N (500)	5 35	-5 00	10	88/155/215	5
ORION A CNTR (500)	5 40	-7 33	1.5	88/155/215	17
NGC 6334 (1700)	17 20	-35 58	10	88/155/215	5
M 17 (1700)	18 20	-16 11	10	88/155/215	5
W3 (2300)	2 27	61 52	10	88/155/215	5
DR 21 (2500)	20 39	42 20	10	88/155/215	5
CB 68 (160)	16 54	-16 05	see p. 13	53/88/155/215	2
B 335 (250)	19 35	7 27	"	53/88/155/215	2
L 723 (300)	19 16	19 07	"	53/88/155/215	2
L 1448C (220)	3 23	30 33	"	53/88/155/215	2
L1527 (140)	4 37	25 57	"	53/88/155/215	2
L 483 (200)	18 15	-4 41	"	53/88/155/215	2
L 1455 (220)	3 25	30 03	"	53/88/155/215	2
L 43 (125)	16 32	-15 41	"	53/88/155/215	2
SSV 13 (220)	3 26	31 05	"	53/88/155/215	2
L 1551-IRS5 (160)	4 29	18 02	"	53/88/155/215	2
NGC 1333 IRAS 4 (350)	3 29	31 13	"	53/88/155/215	2
NGC 1333 IRAS 2 (350)	3 28	31 14	"	53/88/155/215	2
SVS 13 (350)	3 29	31 15	"	53/88/155/215	2
L1448 IRS3 (320)	3 25	30 45	"	53/88/155/215	2
VLA 1623 (160)	16 26	-24 24	"	53/88/155/215	2
IRAS 16293-2422 (160)	16 32	-24 28	"	53/88/155/215	2
B 133 (200)	19 06	-06 53	"	215	1
L 1689B (125)	16 32	-24 32	"	215	1
				Grand total hours	113

Scientific Objectives

Introduction

The roles of magnetic fields and magnetohydrodynamic (MHD) turbulence in molecular cloud evolution and star formation are subjects of intense theoretical and observational interest (Stahler & Palla 2004; Elmegreen & Scalo 2004; Mac Low & Klessen 2004; Myers, Evans, & Ohashi 2000). Questions that will become accessible when SOFIA is equipped to do far-IR polarimetry include the following:

- Do magnetic fields control star formation and determine the initial mass function, or is star formation regulated by turbulence? Does the answer vary for low-mass vs. high-mass star formation?
- Is the smallest scale of magnetic fluctuations set by viscous damping?
- Are magnetic fields continuous between regions of different ISM phases and regions of different densities?
- Are cores and other structures in molecular clouds elongated (or flattened) along the direction of the magnetic field? Does the answer depend on density?
- How do magnetic fields in protostellar cores evolve? Are field directions correlated with the orientations of disks and outflows?

To date most of the relevant observations of turbulence are spectroscopic, and involve the gas kinematics. Magnetic fields are detected through the Zeeman effect, which gives the coherent line-of-sight component; through spectral line polarization at mm wavelengths; through optical/near-IR polarimetry of starlight; and through far-IR and submillimeter polarization mapping of the field in the plane of the sky. Far-IR polarization mapping allows comparison of the field and gas morphologies, while analysis of the fluctuations in polarization direction yields information on the strength of the field and the structure of the turbulence. But far-IR/submm mapping has been underutilized due to limitations in modeling cloud structure as well as limitations in the observations.

Our capabilities for modeling molecular cloud structure have improved dramatically in recent years due to the development of large-scale 3D simulations of compressible MHD turbulence including self-gravity. One successful application of the simulations is their ability to reproduce the observed size/line-width relations (Ostriker, Stone, & Gammie 2001). Even the slope of the initial mass function (IMF) has been derived from the properties of simulated turbulence in star forming clouds (Padoan et al. 2004), although alternative models are serious contenders (Shu, Li, & Allen 2004).

A key uncertainty in the turbulence simulations is the assumed ratio of mass to magnetic flux. The work by Padoan et al. (2004) mentioned above is based on the premise that this ratio is much higher than the so-called "critical" value, but this is highly uncertain, as we discuss below. The mass-to-flux ratio is a parameter that can be directly probed by far-IR/submm polarimetry via the comparison of measured fluctuations in polarization angle with theoretically predicted fluctuations derived from simulations (a technique based on the method of Chandrasekhar & Fermi 1953). However, it has not yet been possible to obtain definitive determinations of the mass-to-flux ratio, or other conclusive tests of laminar and turbulent models, due to limitations in precision and statistics for polarization mapping in real clouds.

The polarimeter, SuperHAWC, on SOFIA will overcome these limitations. Considering only the improvement in the number of pixels and the estimated NEFDs, SuperHAWC will have a data rate over 3,000 times that for Stokes, on the Kuiper Airborne Observatory (KAO), the only previous polarimeter in the far-infrared (see archive of Stokes results: Dotson et al. 2000). The problem of observing turbulent fields is hindered by averaging along the line of sight and across the beams, so that existing polarization maps often appear smooth, with no significant dispersion above the uncertainties associated with the 3σ measurements typical of previous work. The improved sensitivity of SuperHAWC/SOFIA will permit point-by-point observations with significance $P/\sigma_P \sim 10$ (or $\sigma(\Phi) \sim 3°$) for hundreds of thousands of measurements. A further advance over previous work is improved data analysis techniques (Kirby et al. 2005; Li et al. 2005) that greatly reduce the noise and bias introduced by atmospheric fluctuations when observing faint sources.

The angular resolution will be improved by more than the ratio of apertures of SOFIA to the KAO since Stokes was not diffraction-limited. The resolution of SuperHAWC (in arcseconds) will be $\sim \lambda(\mu m)/10$ or $\sim 5''$ at 50 μm, SuperHAWCs shortest passband. At that resolution, magnetic structure down to a few hundredths of a parsec, below which ions and neutrals are decoupled, can be easily resolved in clouds within a few kpc of the Sun. (Distances to all our targets are given in parsecs in the Observation Summary, just after the target name.) Observations at these scales, combined with Doppler probes of the velocity field, will make it possible to test the relationship between magnetic and velocity fluctuations below the decoupling scale (e.g. Zweibel & McKee 1995; Cho, Lazarian, & Vishniac 2003).

SuperHAWC's four passbands ($53\mu m$ - $215\mu m$) supplemented by additional passbands at $350\mu m$ an $450\mu m$ from SHARP (Novak et al. 2004) and $850\mu m$ from SCUBA-2 will allow tests of assumptions about grain properties including temperature and alignment, in turbulent clouds (e.g. Juvela & Padoan 2003; Bethell et al. 2004). Other statistics that can be computed from polarization maps include two-point correlation functions for both polarization angle and degree, and correlations with column density. Comparison of statistics derived from real vs. simulated clouds will test turbulence models and constrain the mass-to-flux ratio.

Simulations of MHD turbulence have not yet reached the small scales and high densities associated with the formation of protostars in dense cores, but various theoretical models treat the role of magnetic fields in protostellar collapse and formation of disks and outflows (e.g. Allen, Li, & Shu 2003; Allen, Shu & Li 2003; Shu, Li, & Allen 2004). For nearby YSOs (100-200 pc), SuperHAWC will permit observations of magnetic fields within ~500-1000 AU of a protostar - an almost entirely unexplored area. Submillimeter polarimetry toward deeply embedded protostars has been limited by angular resolution and sensitivity, but the thermal emission from protostellar cores peaks dramatically in the far-IR, making these sources readily accessible to SuperHAWC/SOFIA. Unlike ground-based polarimetry in the submm, SuperHAWC observations of warm dust in protostellar cores will be uncontaminated by emission from cooler foreground and background dust, especially for the shorter-wavelength bands. It will become feasible to survey the field morphology for a large sample of isolated star-forming clouds (i.e., Bok Globules) as well as clouds forming binaries and clusters, and to thus discover any correlations between the direction of the field and the orientations of disks and outflows. Especially for clouds forming clusters, where the measurable polarized flux will be extended over a region large compared to our $\sim 5''$ beam (50 μm band), it will be possible to estimate mass-to-flux ratios, and to discover any magnetic pinches (Galli & Shu 1993a,b). Finally, we wil be able to study the dependence of these magnetic field properties on the evolutionary stage of the embedded protostar.

Related observations with SuperHAWC, to be presented in other Case Studies, include field mapping of IR cirrus, the Galactic Center, and external galaxies.

Observational Study of MHD Turbulence

We propose to study MHD turbulence in six Giant Molecular Clouds (GMCs), all lying within a few kpc of the Sun. In total, we will obtain $\sim$ 100,000 polarization measurements that will be used for detailed statistical comparison with synthetic far-IR polarization maps to be derived from MHD turbulence simulations (e.g. see Heitsch et al. 2001, and Padoan et al. 2001). A key goal is to determine the mass-to-flux ratio and compare it with the critical value, $0.13G^{-0.5}$. We will learn whether clouds are subcritical, marginally critical, or supercritical. This is a key factor for star formation theories: Subcritical clouds will contract only slowly via ambipolar diffusion, but supercritical clouds collapse rapidly, unimpeded by magnetic effects, with a transition in rates at criticality (Shu, Adams & Lizano 1987; Zweibel 1998; Indebetouw & Zweibel 2000). The critical mass-to-flux ratio in fact depends on cloud geometry, but the actual mass-to-flux ratio is always a crucial parameter for turbulence models.

Initial work by Crutcher et al. (2004) suggests that mass-to-flux ratios are near critical. This result is uncertain because it is based on polarization angle dispersion values obtained using small data sets (several tens of polarization vectors), but we can conclude from this preliminary work that clouds are neither extremely subcritical nor extremely supercritical (see also Bourke et al. 2000, Crutcher 2004). Thus, an observational resolution of the problem will require large data sets such as the one we are proposing here.

Because the measured dispersion in polarization direction depends on the inclination of the large-scale field to the line-of-sight, we have chosen six clouds that are separated from each other by at least 500 pc, and widely dispersed in Galactic longitude. In this way, we expect that the distribution of field inclination angles will be approximately random, and our result for the mean mass-to-flux ratio for the sample will not be significantly affected by uncertainty in field inclination. For two of our target clouds (Orion and Ophiuchus) we have

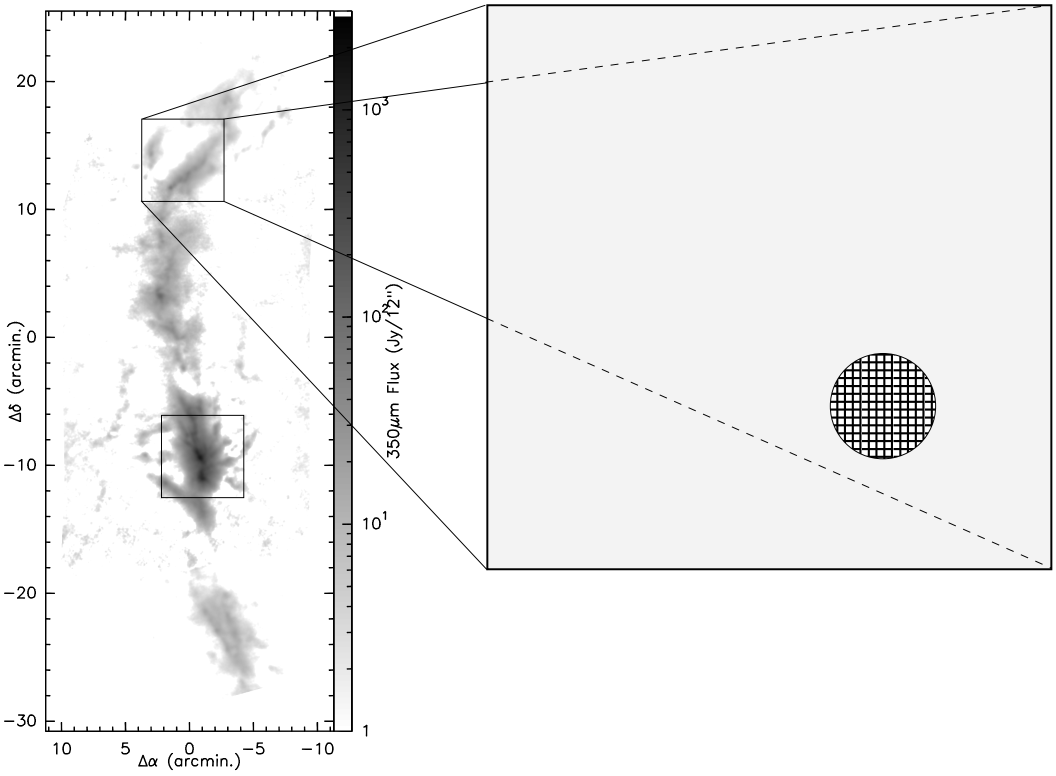

Figure 1: Map at left shows 350 μm emission from the Integral Shaped Filament (ISF) in Orion, made using SHARC-II/CSO with 10″ resolution. Boxes indicate two of the three fields in Orion that we propose to observe as part of our study of MHD turbulence ("KL" and "ISF N"). The size of the box corresponds to the array footprint for the 155 μm band, and a circular region within the expanded array footprint at right shows a few of the 5,184 pixels. We will obtain a total of $\sim$ 100,000 polarization measurements in nine fields distributed within six GMCs.

chosen multiple observing positions, with widely varying column density, for the purpose of exploring how polarization statistics and mass-to-flux ratios depend on column density and on mode of star formation (high mass vs. low mass).

The physical mechanism for magnetic alignment of grains in molecular clouds is not well understood, but we do know that there are significant variations in grain alignment efficiency within molecular clouds (Arce et al. 1998; Cho & Lazarian 2005). For full utilization of far-IR/submm polarimetry maps we need to know which physical conditions favor grain alignment. For example, if grains alignment is less efficient in denser regions, then our measurements along a given sight-line will preferentially sample regions of relatively lower density. Meaningful comparisons of observed polarization maps with simulations will require grain alignment prescriptions.

Based on their consideration of multi-wavelength polarization observations, including both stellar (polarization by extinction) and thermal emission measurements, Cho & Lazarian (2005) conclude that interstellar grains lying deep inside molecular clouds have a degree of alignment that depends strongly on grain size. Specifically, the larger grains are better aligned. They perform calculations based on the assumption that grains are brought into alignment with magnetic fields via the radiative torque mechanism (Dolginov 1972; Draine & Weingartner 1997), rather than the paramagnetic relaxation mechanism, and find that they can explain this preferential alignment of large grains inside molecular clouds in this way. (Grain size effects will influence the polarization spectrum because at long wavelengths, the large grains radiate more efficiently than the small grains.)

Co-investigators A. Lazarian and E. Zweibel will develop models for polarization maps in turbulent, magnetized molecular clouds incorporating the latest grain alignment prescriptions. By comparing our SuperHAWC GMC data with their models, we will simultaneously test turbulence models and grain alignment prescriptions. Spectropolarimetry with SuperHAWC/SOFIA, in combination with ground-based polarimetry at $350\mu m$, $450\mu m$, and $800\mu m$, will provide constraints for grain alignment theories. If the larger grains are preferentially aligned, as predicted by Cho & Lazarian (2005), then we might expect a far-IR polarization spectrum that rises with wavelength because larger grains are predicted to be cooler (Bethell et al. 2004) and in this case will dominate the long-wavelength emission. Available spectropolarimetric data sets (Hildebrand et al. 1999; Vaillancourt 2002; Hildebrand & Kirby 2003) show both rising and falling polarization curves, but SuperHAWC will produce vastly larger data sets that will in turn stimulate improved models of dust temperature.

Far-IR spectropolarimetry will also allow us to separately probe turbulence statistics within warm and cool regions along the same line-of-sight. This is a unique capability of SOFIA, because ground-based measurements almost always sample the Rayleigh-Jeans side of the thermal emission spectrum, regardless of temperature.

We have concentrated on the role of turbulent fields in star formation. But other questions about the nature of the fields will become accessible. For the Ophiuchus cloud, just 160 pc from the Sun, SuperHAWC's shortest wave band resolution will correspond to 0.004 pc, almost an order of magnitude below the minimum wavelength for propagation of Alfven waves. We can therefore test theories about the cutoff in the spectrum of magnetic fluctuations. By comparing our maps with those from large scale observations (e.g. PLANCK) and maps of starlight polarization, we will also be able to trace fields between regions of different densities and phases. Finally, a goal to be discussed in the next section, is to investigate protostellar cores.

Observations of Cloud Cores and Protostars

Bok Globules provide ideal test environments for low-mass star formation theories; they are simple environments with simple geometries and isolated conditions. Results obtained using JCMT/SCUBA-POL (Vallee, Bastien, & Greaves 2000; Henning et al. 2001; Wolf, Launhardt, & Henning 2003) show that Globules have measurable polarization at $850\mu m$. The level of polarization is high, ranging from a few to 14%. In addition, the number of detected polarization vectors within each Globule ranges from 1 to 50, with an average of 15 vectors.

The studies listed above show that indeed Bok Globules are very promising sites to test magnetic field aspects of star formation theory: (a) Do magnetic fields influence the structure of a starless Globule? (b) Do magnetic fields alter the collapse process within a Globule forming a protostar and disk? (c) Does the structure of the fields change over time (i.e., are the magnetic fields different for Globules with no embedded protostar, with a Class 0 protostar, with a Class 1 protostar, etc.)? (d) How do magnetic field and protostellar outflow directions correlate?

These questions, in particular question (a), are being addressed by the JCMT observers (e.g., Wolf, Launhardt, & Henning 2003). Preliminary results for six Globules indicate that the primordial magnetic fields within a Globule are preferentially parallel to the Globule's symmetry axis, but that the magnetic field structure may evolve with protostar age. In general, outflows do not align with the primordial magnetic field, but higher spatial resolution work is required to see how or whether the magnetic fields in the center of a Globule align with the outflows.

We have selected a sample of twelve nearby Globules at various stages of evolution for study with SuperHAWC. In addition, comparing isolated sources such as those in Globules to low-mass protostars forming in small groups or associations is an important step toward better understanding star formation. Is there a difference in the magnetic field morphology or its correlation with cloud shape and/or outflow axes in isolated systems compared to systems with multiple protostars? How important is the magnetic field in determining multiplicity in these cores? We have chosen six well-studied, nearby Class 0 and Class I protostars forming in associations, for study with SuperHAWC. To date, far-IR/submm polarimetry of these systems is sparse, mostly due to lack of resolution and sensitivity.

Our SuperHAWC observations will complement the work of SCUBA-POL; SuperHAWC will have better angular resolution ($5''$ and $9''$ vs. $14''$) than SCUBA-POL and will measure the far-IR fluxes from these sources. Far-IR wavelengths are more useful for probing the inner envelope infall regions surrounding YSOs. At 850 and 450 μm, deep images of Class 0 and Class I YSOs (Huard, Sandell, & Weintraub 1999) have revealed compact sources that are barely resolved, having $\sim 10''$ diameters. These correspond to structures of size scale $\sim$ 2000 AU that may represent evidence of pseudo-disks in the innermost regions of the infall envelope (Allen, Li, & Shu 2003 ; Allen, Shu & Li 2003; Shu, Li, & Allen 2004). According to theory, the magnetic field direction in the pseudo-disk should be perpendicular to the major axis of this disk, and parallel to the outflows in these systems. SuperHAWC observations will best test this picture.

Extrapolating the 450 μm emission to shorter wavelengths, using probable dust temperatures, shows that the far-IR emission from these $10''$ structures probably dominates the total far-IR fluxes from the sources. Hence, on SOFIA at $88\mu m$ and $155\mu m$ (and to some degree at $215\mu m$), the emission from these low-mass cores will be compact, and will highlight the magnetic field structure in the inner infall regions, which could be in the form of pseudo-disks due to magnetic fields. At $53\mu m$, many of the YSOs in our sample exhibit excesses above the extrapolation from 450 μm (Shirley et al. 2000). Thus, where possible, 53 μm measurements will give the best information on the magnetic field in the warmer regions of the pseudo-disk. It is these regions, highlighted in the far-IR, that will be most relevant to star formation and outflows; hence more relevant to addressing questions (b), (c) and (d) above. It is also within this region ($20''$ at 200 pc) that magnetic "pinches" should be observed according to some theories (Galli & Shu 1993a,b).

SCUBA-POL observations show that the inner regions of Globules are not as polarized as the outer regions. The outer region polarization fraction is typically on the order of 5 to 10%, vs. 1 - 2% for the inner region. This could be due to increased collisional misalignment, grain growth, or complex magnetic field structure within the cores. The latter could contribute significantly, especially since millimeter interferometric observations of a few of these sources (e.g. NGC 1333 IRAS 4 and L1448 IRS3; Girart et al. 1999; Kwon et al. 2006) have shown that the high-resolution observations, which are more sensitive to the compact, warmer material surrounding the YSOs, actually measure a higher degree of polarization than that obtained by submillimeter single-dish observations. Thus, the degree of polarization we will measure with SuperHAWC in compact warm material near the YSOs will probably be higher as well. In comparison with submillimeter/millimeter interferometers, SuperHAWC will have better sensitivity to the majority of the dust emission coming from within $\sim$ 500 AU of the protostar. The combination of SuperHAWC with complementary longer wavelength single dish and interferometric data will provide an unprecedented view into the role of magnetic fields in star formation at multiple spatial scales.

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SOFIA Uniqueness/Relationship to Other Facilities

Polarimetry using single-dish submillimeter and millimeter telescopes on the ground and in space will address important issues regarding magnetic structure of clouds. For example, at $4'$ scales the South Pole experiment QUAD will provide high sensitivity at $800\mu m$ and longward. PLANCK will be similar to QUAD in wavelength coverage and angular resolution and will have vastly better sensitivity. The proposed polarimeter for the balloon-borne BLAST experiment will achieve $1'$ resolution at 250-$500\mu m$. None of these experiments will achieve the combination of temperature selectivity and resolution of SuperHAWC/SOFIA. These advantages are crucial for the investigations we have described, that require the ability to separate grains with differing temperatures while at the same time probing the smallest scales of magnetic turbulence and the detailed structure of magnetic fields within the infall region surrounding a protostar.

For our study of cloud cores and protostars, SuperHAWC/SOFIA will uniquely sample the warm inner regions of the infall envelope, which may correspond to the outer regions of pseudo-disks surrounding the embedded protostars. SOFIA observations will therefore uniquely complement the observations to be made of Globules and cloud cores by: JCMT (SCUBA-2), which will provide unbiased mapping of the primordial magnetic fields in the Globules and clouds and the disturbance of these by outflows; SMA, CARMA and ALMA, which will map the magnetic fields within the accretion disks of the embedded protostars on spatial scales of arcseconds; and SHARP on the CSO, which will map polarization vectors of these sources at 350 μm (with $9''$ resolution), a wavelength that bridges the more global measurements at 850 μm and those of the compact emission surrounding the YSOs in the far-IR on SOFIA.

Observing Strategy

For our study of MHD turbulence, three "observation fields" are located in the Orion A molecular cloud that contains young and forming stars of all masses up to and including type O. One of the Orion observation fields lies near the center of the cloud and contains only low mass stars, another corresponds to the Kleinmann-Low nebula that is the birthplace of very high mass stars, and between these extremes lies the observation field ORION ISF N on the "integral shaped filament". The closest molecular cloud in this study is Rho Ophiuchus, where a bound stellar cluster is in the process of forming. The remaining clouds are GMCs within a few kpc of the Sun and are sites of formation of massive stars.

For Orion and Ophiuchus, we derived flux estimates as follows: We used IRAS data for the two shorter-wavelength bands ($53\mu m$ and $88\mu m$). For Band 3 ($155\mu m$) we used the dust extinction maps of Schlegel, Finkbeiner, & Davis (1998) together with the $I_\nu(170\mu m)/A_V$ conversion given by Toth et al. (2000) for cold dust. For Band 4 ($215\mu m$), we used a simple power law extrapolation. For the remaining four clouds, we adopted the flux estimate for Orion ISF. This is probably somewhat pessimistic. More realistic flux estimates are certainly possible for all nine fields, but will not greatly alter the total estimated observing time. In the above Observing Summary we give estimated Band 3 fluxes in Jy per resolution element.

We expect to benefit from the observed tendency for degrees of polarization to increase toward lower column densities (Matthews & Wilson 2000), because most positions we will observe correspond to lower column densities than have been observed in the past. Based on the values of polarization found by Matthews & Wilson (2000) for the lower column density regions in Orion ($\sim 8\%$), and on the observed polarization spectrum (Vaillancourt 2002), we expect a typical far-IR polarization magnitude of $\sim 8\%$. We have assumed polarimetric accuracy (1σ error) to be 1% in all cases (1σ error), giving high signal-to-noise.

For the purposes of observing time estimates, we assumed uniform brightness across each field, but observations (Fig. 1) show this is far from true. As a result, it is likely that our listed observing times will be too short to achieve detections of polarization for every pixel, but on the other hand the concentration of flux into filaments will make the brighter portions of each observing field easier to measure. Far-IR photometric maps to be made in advance of the polarimetric observations will be used to refine the observing strategy. Depending on the results, the sky area corresponding to each observation field might be expanded significantly. Regardless of the degree of non-uniformity, we expect to detect thousands of vectors per wavelength in each of the nine fields to be observed.

For our study of Bok Globules, target selection has been carried out with several restrictions in mind. The cut-off distance is 400 pc, corresponding to the maximum distance at which magnetic "pinches" should be observable at 53 μm with SOFIA. It is important to sample Globules at a variety of evolutionary stages, so we include some that contain Class 0 and Class I YSOs, as well as two starless Globules (that will be observed only at $215 \mu m$). In order to access more sources, we assume Southern Hemisphere deployments by SOFIA. This is an additional advantage of SOFIA over ground-based observatories.

The fluxes into a SuperHAWC beam are very uncertain for these sources. Time estimates are based on deep $450 \mu m$ & $850 \mu m$ observations of CB 68 and B 335, which show compact ($\sim 10''$) structures surrounding the YSOs. The emission from these structures, when extrapolated to far-IR wavelengths, dominates the far-IR emission from these clouds. We have assumed that such compact structures are common, and in this case much of the far-IR fluxes measured by IRAS, KAO, and ISO should be concentrated into such structures. The protostellar cores (cores with embedded sources) listed in the "Observing Summary" have far-IR fluxes that are similar to or greater than those of CB 68 and B 335. We have conservatively assumed that integration times for these sources will be similar to our time estimates for CB 68 and B 335. We assumed a required polarimetric accuracy (1σ error) of 0.3% for protostellar cores and 1.0% for starless cores (last two rows).

Special Requirements

The investigations described here will require an instrument that we are calling "Super-HAWC". This would be an upgrade of the first round instrument, HAWC, that would use the same cryostat, foreoptics, passbands, and pixel size, but would replace HAWC's 12 × 32 array of semiconductors with two 72 × 72 arrays of transition-edge sensors of the type developed by NIST for SCUBA-2. The increase in the number of pixels would enhance the photometric capabilities over those of the original HAWC instrument in addition to providing polarimetric capability. The photometric signals would be provided by adding the signals from the two arrays as is routinely done during polarimetry. Specifications are given in the table below.

Specifications for SuperHAWC

Parameter	Band 1	Band 2	Band 3	Band 4
Central wavelength (μm)*	53	88	155	215
Central frequency (THz)*	5.7	3.4	1.9	1.4
Band width, fwhm ($\Delta\lambda/\lambda$)*	0.10	0.10	0.14	0.20
Pixel size (arcsec)*	2.25	3.5	6	8
Pixel solid angle (10^{-9} sr)*	0.12	0.29	0.85	1.5
Resolution, 1.2 λ/D (arcsec)*	5.2	8.6	15.2	21
Field of view, 72×72 array (arcmin)	2.7	4.2	7.2	9.6
NEFD ($Jy/\sqrt{Hz}$)	2.0	1.3	1.2	0.7
$\sigma(P)$, 1 hr. 30 Jy source (%)	0.21	0.14	0.13	0.083
$\sigma(P)$, 10 hr. 1 Jy source (%)	2.1	1.4	1.3	0.8
Systematic error, ΔP (%)	<0.2	<0.2	<0.2	<0.2
$\sigma(\theta)$, 1 hr, 30 Jy source, $P = 3\%$	2°	1°	1°	1°
$\sigma(\theta)$, 10 hr, 1 Jy source, $P = 3\%$	20°	14°	13°	7°

*Same as current values for HAWC

Precursor/Supporting Observations

With respect to our study of MHD turbulence, we have noted above that far-IR photometric maps to be made with HAWC/SOFIA will be used to refine the size of each "observation field" in our study, and we have also noted that the CSO/SHARP and JCMT/SCUBA-2 polarimeters will help complete the polarization spectrum of GMCs. Another very important precursor to our proposed observations will be an extensive survey by HAWC of the far-IR emission of Globules and low-mass cloud cores. The current far-IR fluxes for these sources were all obtained using instruments that had poor spatial resolution. Are the structures barely seen at 450 μm real, and are they the source of much of the far-IR emission? Do pseudo-disks exist in large numbers? Our time estimates for detecting polarization vectors in our sources containing Class 0 and I YSOs depend critically on how the total far-IR fluxes are distributed about the YSOs. In the "Observing Summary" we have assumed that these sources are compact in the far-IR.

To complement our study of cores and protostars, supporting observations will be made with JCMT/SCUBA-2, CSO/SHARP, SMA, CARMA and ALMA. SuperHAWC on SOFIA will provide the best data for determining the inner envelope magnetic field structure and its alignment with YSO outflows. However, measurements from the observatories listed above will contribute crucial information by revealing the magnetic fields in parent clouds and in the accretion disks that surround the embedded YSOs.