THE MILKY WAY MAGNETIC FIELD MAPPING MISSION: M4

D. Clemens

Institute for Astrophysical Research, Boston University, USA.

ABSTRACT

M4 is a Small Explorer (SMEX) concept for a dedicated space-borne far-infrared imaging polarimeter satellite, which was proposed to NASA in 1997 and which will be proposed again in the upcoming SMEX competition planned for the end of this year. When flown, M4 will be the first mission to conduct large-area surveys of the magnetic field directions and structures in the dense interstellar medium of the Milky Way, nearby star-forming and quiescent dark molecular clouds, and the infrared cirrus. M4 consists of a superfluid helium cooled 20 cm telescope, polarization light analysis optics, and two 32 $\times$ 32 Ge:Ga array detectors operating broadband at 95 μm wavelength. With no moving parts, M4 achieves high photometric and polarimetric sensitivity (S/N=150-600:1) via a novel mix of stepped spacecraft roll maneuvers and frequent recalibration using an internal light source. In its 4 to 6 month lifetime, M4 will map the magnetic field directions of over 1200 square degrees of the Milky Way with 0.8 - 2 arcmin resolution. The M4 flight plan also calls for a strong Guest Investigator Program of magnetic field mapping of nearby galaxies and Galactic targets.

Key words: Infrared astronomy; polarimetry; magnetic fields.

1. INTRODUCTION

Are magnetic fields in space important? Over Galactic-scale distances magnetic fields are known to accelerate cosmic rays and may mediate cloud collisions, shock conditions, and provide connection or communication between clouds or cloud complexes. Over cloud and cloud complex size distances, magnetic fields and magnetic turbulence may support clouds and cores against gravitational collapse. Ambipolar diffusion of fields in cloud cores may determine the rate of star formation. In protostellar environments, embedded magnetic fields may regulate anisotropic gravitational collapse and the formation of disks and eventually planets.

Yet the quantity of information available for the study of magnetic fields in the dense, star-forming interstellar medium is exceedingly small. In order to make substantial progress toward understanding the roles played by magnetic fields in the star formation process, a dramatic improvement in data quantity, in the form of large-scale surveys, is needed. Ground-based observations of the Zeeman effect are useful for directly measuring the line-of-sight magnetic field strengths in dark clouds, but have limited angular resolution, sensitivity, and telescope access. Progress in this area would require construction of the equivalent of 1000 - 10,000 observatories of Arecibo-class.

An alternate approach is to directly sense the embedded magnetic fields in the cool dust via measurement of far-infrared linear polarization, as has been performed on the Kuiper Airborne Observatory (e.g. Novak et al. 1997) and recently in space using *ISO* (Clemens, Kraemer, & Ciardi 1999 - this volume). However, *ISO* performed only limited area far-infrared polarimetric mapping, and did not survey large areas. The KAO, and its successor SOFIA, are limited to probing polarimetrically only the few brightest regions of the few brightest sources, and will be unable to provide large-scale context maps of the magnetic field in the dense ISM.

Instead, a new approach aimed at boosting the numbers of sky positions measured polarimetrically by factors of 1000 - 10,000 through the execution of large-area mapping surveys with high sensitivity is necessary. A team of us has designed a small, near-earth orbit cryogenic satellite observatory, called M4, which will be capable of conducting these surveys. The mission goal is to discover answers to three fundamental science questions:

- What is the magnetic field structure in the interstellar medium of the Milky Way Galaxy?
- What role to magnetic fields play in the star-formation process?
- What magnetic field structures exist in the infrared cirrus clouds?

Each of these science questions arise from subsets of related questions which may be directly answered using the data to be obtained by M4. For example, answering the first question above will directly relate to the answers developed for these questions: Is there a Galaxy-wide magnetic field in the dense ISM of the Milky Way disk? Does it trace out a spiral pattern? What is the field pattern inside and outside of the 5 kpc molecular ring?

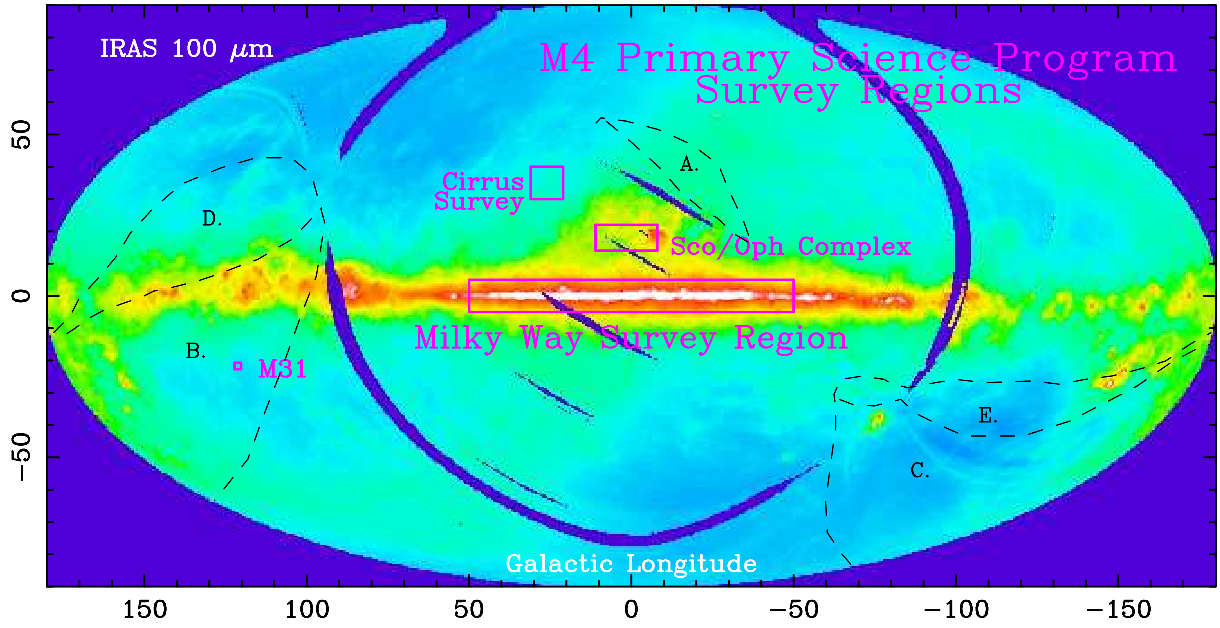

Figure 1. IRAS 100 μm image, showing M4 Primary Science Program surveys and viewing limits. The M4 Primary Science Program consists of an inner Milky Way survey, a Sco/Oph survey, an infrared Cirrus survey, and Guest Investigator surveys. The regions delineated with dashed black lines identify regions unviewable from M4.

In the following sections, details of the M4 concept and the SMEX constraints are described. The surveys comprising the M4 Prime Science Program are described and estimates of sensitivity and data quality are presented.

2. SMEX FEATURES AND CONSTRAINTS

NASA Small Explorers are intended to feature rapid execution, "off-the-shelf" technology, low costs, and to be launched at a rate of about one per year. The rapid execution feature translates to short durations for the design and development project phases, with proposal through launch time scales of 2 - 4 years. This places limits on the technology which can be flown. New detector and other technology development is essentially precluded – however SMEX platforms are ideal for proving flight-ready subsystems. Total mission costs are in the range 70 - 75M$, and must include all aspects of the mission, including launch costs and mission operations/data analysis (MODA). This "life-cycle" costing is rapidly becoming the standard for many NASA programs and missions.

For far-infrared cryogenic missions, cost constraints limit the options for launch vehicles. This in turn limits such missions to low Earth orbits (LEO; 250 - 600 km), modest payload masses (250 - 400 kg), and limited payload volumes. The need to carry on-board cryogen limits the payload volume available for the telescope and strongly limits the duration of the science mission. The need to reduce mission risk from single point failures is a common theme in SMEX concepts – these small missions do not have the multiple, redundant systems common to larger missions and manned missions. For polarimetry, a rotating half-wave plate increases mission risk.

3. M4 SCIENCE

The Primary Science Program for M4, as articulated in the 1997 M4 SMEX proposal, consists of four components. These are a Milky Way disk survey, a survey of the Sco/Oph region of dark molecular clouds, a survey of a representative patch of infrared cirrus, and the Guest Investigator surveys. The survey regions are shown on Figure 1, the *IRAS* 100 μm all sky map, rendered into Galactic coordinates.

The Milky Way disk survey samples 1000 square degrees of the inner disk, from -50°to +50° of Galactic longitude and -5° to +5°of latitude. This wide angle survey samples most of the inner disk, including the 5 kpc star forming ring, the Galactic Center, an enormous number of star-forming clouds and complexes, as well as thousands of protostellar regions and embedded young clusters. The angular resolution requirement is 2 arcmin, with a goal to reach 48 arcsec (the pixel sampling size) through super-resolution techniques. Throughout the entire disk survey region, the photometric S/N requirement of 150:1 will permit detection and mapping of the stronger polarized regions. The S/N goal of 600:1 will permit obtaining polarization position angle uncertainties under 6° throughout the survey region.

The Sco/Oph survey will sample a smaller area, but with more sensitivity in order to probe fainter star forming and quiescent regions in this nearby (120 - 160 pc) complex of dark molecular clouds. The entire complex spans some 150 square degrees, but with a low filling factor (∼15%). M4 will survey the dark clouds covering about 22 square degrees, including ρ Oph's core and streamers. By conducting this more sensitive survey, magnetic field patterns in quiescent streamers may be traced all the way into protostellar environments. M4 will be the only mission capable of providing this important contextual information.

The magnetic field properties of the infrared cirrus can only be tested using a space-based instrument capable of polarimetric mapping like M4. The cirrus is too faint to be observed polarimetrically from either SOFIA or from balloons. The M4 cirrus survey will measure several tens of square degrees at the limiting sensitivity of the instrument toward the North Polar Spur (NPS). These observations will be able to determine the role of magnetic fields in the creation and maintenance of the cirrus and its structure.

Finally, the M4 Primary Science Program contains a strong guest investigator (GI) program, comprising 25% of the observing time. M4 will have the requisite sensitivity and angular resolution to polarimetrically survey nearby galaxies as well as specific Galactic star formation regions. For example, a complete survey of M31 would require only one day of M4 time.

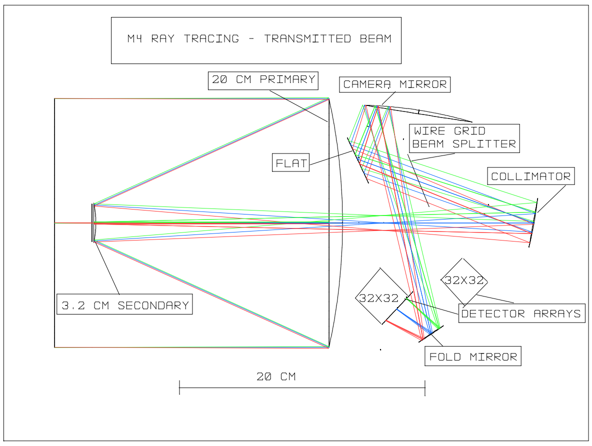

Figure 2. ZEMAX partial ray tracing of the M4 telescope, optics, and array detector systems. This tracing follows the beam transmitted by the fixed wire grid. The reflected beam goes to its own camera mirror and fold mirror to arrive at the second detector array, shown to the right of the transmitted beam's array.

4. M4 INSTRUMENT CONCEPT

The instrument designed to perform the surveys described consists of a small, 20 cm cooled telescope, light analysis optics comprising a no-moving-parts imaging polarimeter, and twin 32×32 pixel unstressed Ge:Ga array detectors, developed for the SIRTF mission (see Figure 2). This pixel count is 256 times the number of ISOPHT C200 camera pixels used for the first space-based far-infrared polarimetry. The cryostat needed to contain this instrument also holds 75 liters of superfluid liquid helium and keeps the optics temperatures under 6 K and the detectors at 2 K for the duration of the 4 - 5 month mission.

The cold telescope and optics are necessary to obtain background-limited sensitivities (NESB = 0.2 MJy/sr), where the background is the Zodiacal light except for some of the Galactic disk pointings where signal poisson noise dominates. The twin detectors view the two different polarizations of the light transmitted and reflected by a wire grid beamsplitter from the same piece of sky. In this design, M4 carries no rotating half-wave plate and modulates the polarization signal by conducting spacecraft rolls. The LEO altitude of 500 km is Sun-synchronous, permitting the solar panels to be fully illuminated throughout the short mission.

The M4 spacecraft bus is a short, 3-axis stabilized high-performance system consisting of flight computer and memory, attitude control system, reaction wheels, magnetic torque rods, power management circuitry, star tracker, and communications and telemetry. Because the M4 detector arrays generate fairly low data rates, M4 can operate unattended for days at a time, executing multiple mapping plans and storing/compressing data for later download to ground. A cut-away diagram of M4 is shown in Figure 3.

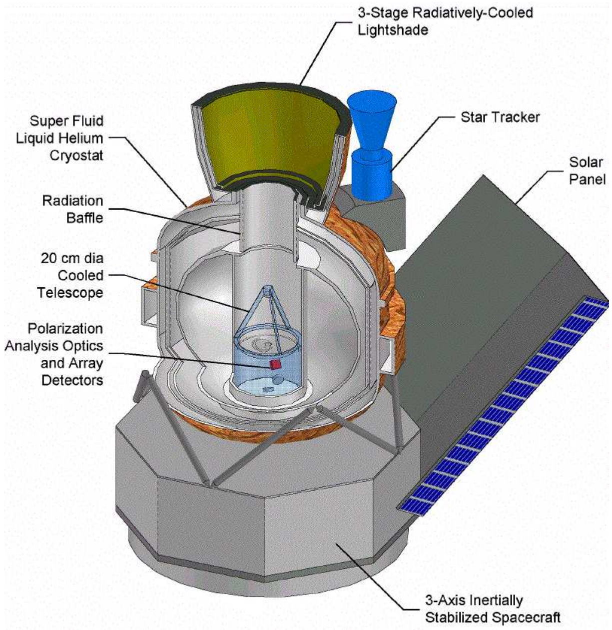

Figure 3. Three dimensional rendered drawing of M4 in its deployed configuration, after ejection of the aperture cover. The cutaway view of the instrument and cryostat shows the simple arrangement of the optics and detector arrays attached to the small spacecraft. The forward light shield rejects Sun and Earth light. The star tracker is sighted along the same axis as the far-infrared telescope. The stepped roll of M4 in its LEO always presents the same face to the Earth, and the solar panel is always illuminated by the Sun (and acts as a shade of the "topside" of the M4 shell including the star tracker).

5. M4 OPERATION

M4 is able to perform precision far-infrared imaging polarimetry without any moving parts through the combination of the dual-channel detection system and regular rolls of the spacecraft about the optical

Table 1. M4 AOT Summary.

	AOT-1	AOT-2	AOT-3
$T_{Integrat.}$ per read [s]	0.15	1.5	14
Reads per map point	33	6	6
Time between Calibrations [s]	20	6.5	16
Map Format [NX × NY]	5×5	4×4	2×2
Area Mapped per 4 segments [sq. deg.]	1.13	0.73	0.18
Effective Stokes $T_{Integrat.}$ per 4 seg. [s]	40	72	672
Downlinked Data Volume/AOT [MBytes]	6.1	1.7	0.8
Survey Application	Galactic Center, Plane GIs	Galactic Plane Sco/Oph GIs	Cirrus, GIs M31

axis. Borrowing from *ISO*, M4 is designed to execute polarimetric mapping using only three Astronomical Observation Templates (AOTs), distinguished by the brightness of the scene being imaged (Table 1).

Each M4 orbit of about 90 minutes is broken down into ten orbital "segments" during which the spacecraft orientation is fixed in space. In advancing from one segment to the next, the spacecraft rolls 45° about its optical axis. During any one segment, the twin array detectors will measure one Stokes parameter (e.g., U) for each sky position seen. During the next segment, the other Stokes parameter (e.g., Q) is developed because of the 45° roll. Two more such segments effectively switch the polarization senses seen by each detector on the sky to reduce systematic effects (e.g., U^* & Q^*). During each segment small, pointed raster maps are obtained. Together, each four-segment AOT executed by M4 will measure all linear polarization Stokes parameters for small, overlapping rasters on the sky.

During each pointing in each orbital segment, the detector arrays will measure sky brightness in a fashion similar to that used by the C100 and C200 cameras of ISOPHT, with integration ramps whose slopes with time are related to the source fluxes. In order to maintain high precision, a far-infrared emitter, similar in function to the ISOPHT FCS, will flash frequently (as often as every 6-7 seconds).

As shown in Table 2, meeting the Prime Science Program survey data requirements involves mapping substantial portions of the sky using the three M4 AOTs. What is not shown here is the complex relationships between Earth limb avoidance, orbital sequences, AOTs, and sky availability of the survey zones (Galactic plane, Sco/Oph, NPS cirrus zone). The sky availability was ascertained using a dynamic mission modeling tool which "flew" the M4 mission, including mapping the Galactic plane with realistic AOTs while avoiding the Earth limb and other constraints. Use of this model showed that the Guest Investigator program could utilize up to about 25% of each orbit without compromising the other elements of the Science Program.

Table 2. M4 Flight Time Allocation Plan.

Mission Element	AOT Mode	Time Req'd. [days]	Survey Area [°²]	Data Volume [Gbyt.]
Checkout/Verif.	All	15	...	0.75
MW Disk Survey	AOT-1	3	120	0.65
	AOT-2	32	880	2.05
Sco/Oph Survey	AOT-2	15	22	0.90
Cirrus Survey	AOT-3	15	100	0.50
Guest Invest.	All	21	100	1.25
Calibration	All	15	...	0.85
Reserve (15%)	...	17	...	0.75
Total	...	133	1222	7.7

6. SUMMARY

There is a great deal we do not know about the nature and importance of magnetic fields within the star-forming molecular interstellar medium of the Milky Way. *ISO* observations have recently shown that space-based far-infrared imaging linear polarimetry is capable of measuring magnetic field structures in both star-forming and quiescent material in nearby dark clouds. KAO, and in the future SOFIA, observations have probed the magnetic field structures of the brightest nearby regions of massive star formation. However, these observations are unguided by any large-scale contextual maps of the magnetic field in these settings. Such large-scale surveys of the magnetic field can only be performed by a dedicated space-based mission.

The three most important surveys which need to be carried out are a survey of the inner Milky Way, a survey of a nearby region of star formation, and a survey of a representative piece of infrared cirrus. These three surveys comprise the Primary Science Program of M4.

The M4 satellite concept consists of a cooled 20 cm telescope, simple polarization analyzing optics with no moving parts, and twin 32×32 pixel Ge:Ga detector arrays, operating at far-infrared wavelength spanning 95 μm. The combination of stepped spacecraft roll by 45° about the optical axis between orbital segments of fixed roll angle permits obtaining all linear polarization Stokes parameters. High photometric and polarimetric precision is maintained through frequent recalibration. Super-resolution is supported using pixel sampling finer than the diffraction limit of the telescope.

During its 4-6 month lifetime, M4 will generate survey data sets with 1000 to 10,000 times more far-infrared polarimetric measurements than all previous studies combined. This vast increase in data will provide the context necessary to understand existing magnetic field observations, the targets for follow-up magnetic field observations with SOFIA, and a comprehensive view of an important constituent of the star-forming ISM which has remained invisible until now.

ACKNOWLEDGEMENTS

The 1997 M4 SMEX proposal team developed and refined the M4 concept presented here. The members of this team include Terry Jones (Deputy PI; Univ. of Minnesota), Benton Ellis (Ball Aerospace), Alyssa Goodman (Harvard), Steve Lord (IPAC), George Rieke (Univ. of Arizona), Erick Young (Univ. of Arizona), Bruce Draine (Princeton), George Field (CfA), Carl Heiles (Berkeley), Roger Hildebrand (Univ. of Chicago), Chris McKee (Berkeley), Phil Myers (CfA), and Ellen Zweibel (Univ. of Colorado). Students working on the concept at Boston University included Jason Wright and Paul Ilardi. Ball Aerospace was our industrial Co-Investigator and their assistance through the M4, and its predecessor PIREX, efforts is greatly appreciated.

REFERENCES

Novak, G., Dotson, J. L., Dowell, C. D., Goldsmith, P. F., Hildebrand, R. H., Platt, S. R., & Schleuning, D. A. 1997, ApJ, 487, 320