Department of Astronomy
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M4: The Milky Way Magnetic Field Mapping Mission

A Small Explorer Proposal to the
National Aeronautics and Space Administration
Explorer Program

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D. SCIENCE

The magnetic field, *one of the three major forces of gas dynamics* (gas pressure, gravity, magnetic fields) is generally treated by ignoring it in virtually all astrophysical settings. This is a serious omission – the field, which is typically equal in importance to the other two forces in the dense interstellar medium (ISM)[1,2], cannot be treated as a minor perturbation. This is akin to physicists omitting the electromagnetic force from elementary particle theory.

Knowledge of the role of the magnetic field in the Galaxy and other galaxies is needed to to meet a central goal in the "HST and Beyond" Report, namely to discover when and where the first heavy elements formed in the universe (because the star formation process is related to magnetic fields embedded in the gas).

The best way to rectify this situation is to bring the magnetic field's role in interstellar gas dynamics into sharp focus, via execution of a specialized space-based mission. The best laboratories for uncovering the roles played by the magnetic field are to be found in the disk, star forming complexes, and diffuse material contained in the Milky Way Galaxy.

In the following, we outline our proposed approach to advancing this field by executing a mission capable of collecting some 10,000 times more magnetic field structure data than has been obtained to date. This level of advance will come only by going into space, yet no other space mission, either past or currently envisioned, possessed or will possess the requisite instrumentation. M4, *The Milky Way Magnetic Field Mapping Mission*, will be the most capable small satellite for magnetic field surveys ever to be flown. M4 will map the polarization of the thermal emission from magnetically-aligned dust in the ISM, over a large fraction of the Galactic plane, with background-limited sensitivity. It will provide a revolutionary increase in our understanding of the interstellar magnetic field, just as the *IRAS* satellite provided a revolutionary increase in our understanding of the distribution and properties of interstellar dust.

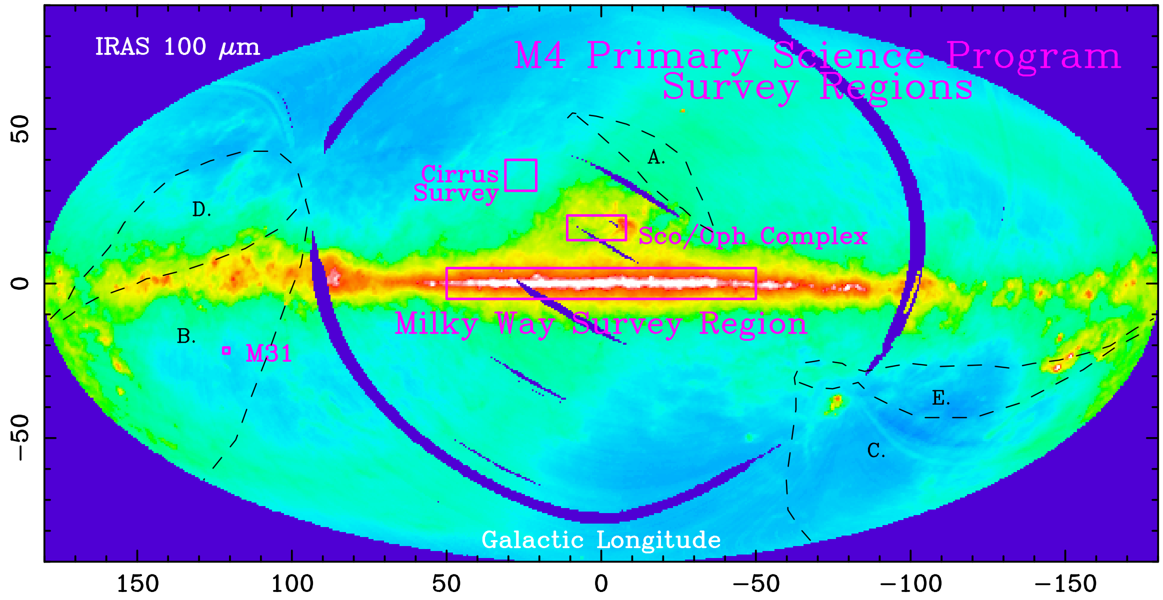


Figure 1: IRAS 100μm sky image, showing M4 Primary Science Program surveys and viewing limits. The M4 Primary Science Program consists of an inner Milky Way survey, a Sco/Oph survey, and a Cirrus survey. The regions delineated with dashed black lines identify directions unviewable from M4. "A," "B," and "C" can be viewed during the Extended Mission only; regions "D" and "E" cannot be viewed by M4 for a nominal 1 March 2001 launch.

The key elements of M4 are: far-infrared focal plane array detectors *already* developed for the *SIRTF* mission; an optics design optimized for low-level linear imaging polarimetry; and, a cold telescope design, whose critical technology of superfluid liquid helium management in orbit has been repeatedly demonstrated by our Co-Investigator Ball Aerospace.

D.1. Scientific Goals and Objectives

The M4 satellite concept has been developed to answer three fundamental questions:

1. What is the magnetic field structure in the ISM of the Milky Way?
2. What role do magnetic fields play in the star formation process?
3. What magnetic field structures exist in the infrared cirrus clouds?

The central goal of the M4 mission is to measure magnetic field directions in the ISM of the Milky Way Galaxy.

This goal will be met by conducting a Primary Science Program of three focussed surveys: an inner Milky Way disk survey of some 1000 square degrees; a deeper survey of some 22 square degrees of the nearby Scorpius/Ophiuchus cloud complex; and a survey of a 100 square degree region of faint infrared cirrus. Additionally, the M4 satellite will provide a unique platform for Guest Investigator (GI) magnetic field surveys of extragalactic and Galactic targets. We have planned strong support of our GI program: reserving 25% of the Prime mission for GI observations, and reserving M4 MO&DA funds for GI data analysis.

The M4 surveys will be conducted using imaging linear polarimetry with a 20cm cooled telescope at a central wavelength of 95μm ($\lambda/\Delta\lambda \sim 3$). The optics are diffraction limited with a beamsize of $2'$, sampled with a pixel size of $48''$, slightly smaller than Nyquist sampling. Figure 1 shows the IRAS 100μm sky image, the three Primary Science Program survey zones, and the outlines of the large M4 viewing zone.

D.1.a. *Magnetic Fields in the Dense ISM*

Galactic scale magnetic fields play roles in accelerating cosmic rays[3] and mediate shock conditions[4]. Within cloud complexes, the fields act to control the star formation rate via ambipolar diffusion of fields[5,6] and field turbulence[7,8]. In protostellar environments, embedded magnetic fields may regulate anisotropic cloud core collapse and promote the formation of disks and eventually planets. Finally, because most of the ISM mass is in dense clouds, these may play an important role in generating the overall Galactic magnetic field.

However at present, we have no large-scale observationally-based view of the magnetic field in the Milky Way's dense, neutral, interstellar medium.

Much of what we do know about the structure of interstellar magnetic fields pertains to low-density gas. For example, the polarization of background starlight[9] and of synchrotron radiation[10] reveals an overall spiral pattern in the magnetic field of external disk galaxies; and optical polarimetry shows that the local field in our own Galaxy lies predominantly in the Galactic plane, departing from the plane only to follow the "bubbles" evident in HI maps[11]. Yet, in the dense ISM, only far-infrared and sub-mm polarimetry of thermal dust emission can reveal the field structure, and very few such measurements exist, due to atmospheric limitations[12]. This imbalance of information severely restricts our physical understanding of the interactions between magnetic fields, density, and velocity structure in the ISM.

Existing observations have shown that fields play important roles in many physical processes taking place in the Galaxy. Yet, even the most basic questions about the structural nature of the field remain unanswered, including the very origin of the Galactic magnetic field. How much of a role do magnetic fields play in the evolution of H II regions, supernova remnants, and supershells? How do fields thread star-forming regions? Are outflows from young stars controlled or re-oriented by the field? Are the orientations of disks around young stars influenced by interstellar fields?

D.1.b. *Optimum Sensing Technique and Wavelength: FIR Imaging Polarimetry*

Magnetic fields are quite difficult to sense. Determining field strengths along the line of sight in dense neutral regions requires measurement of the Zeeman effect. For astrophysically important dense ISM fields in the μG range, this can require enormous quantities (e.g., days) of telescope time *per point* in a map[2]. Merely sensing the direction of the magnetic field along the line of sight still requires Zeeman observations, again with an enormous telescope appetite.

However, in the plane of the sky, the magnetic field direction can be sensed by linear polarimetry, whether via anisotropic absorption of background starlight or via anisotropic thermal emission, *both* produced by spinning, magnetically-aligned dust grains[13]. Although linear polarimetry cannot *directly* reveal field strength, it does provide a wealth of information about field geometry. Indirect arguments are used to infer field strength from the observed (ordered) geometry and turbulent velocities obtained from spectral line studies.

Advancing our naive understanding of the role of magnetic fields in the ISM requires new observations. Producing a large leap in Zeeman effect sensitivity is exceedingly unlikely, as it requires large, dedicated ground-based telescopes and instrumentation.

Nearly half a century ago, Hall and Hiltner discovered that the light from many stars appears linearly polarized[14,15]. They concluded that this was due to aligned dust grains in the diffuse ISM. In 1970, Mathewson & Ford published a map of the polarization of 1800 stars[11]. These stars are viewed through interstellar material which is all rather nearby – most of the stars are closer than 500pc. Their map (Figure 2 is a modern version) shows the local magnetic field is primarily confined to the Galactic plane, except in regions where supernova explosions have created the "supershells" found in H I maps.

Yet the interiors of the most active star forming regions in the ISM, the molecular clouds, are hidden from view by huge quantities of dust. Hence, the magnetic field cannot be traced from the diffuse into the dense ISM because of the lack of visible background stars.

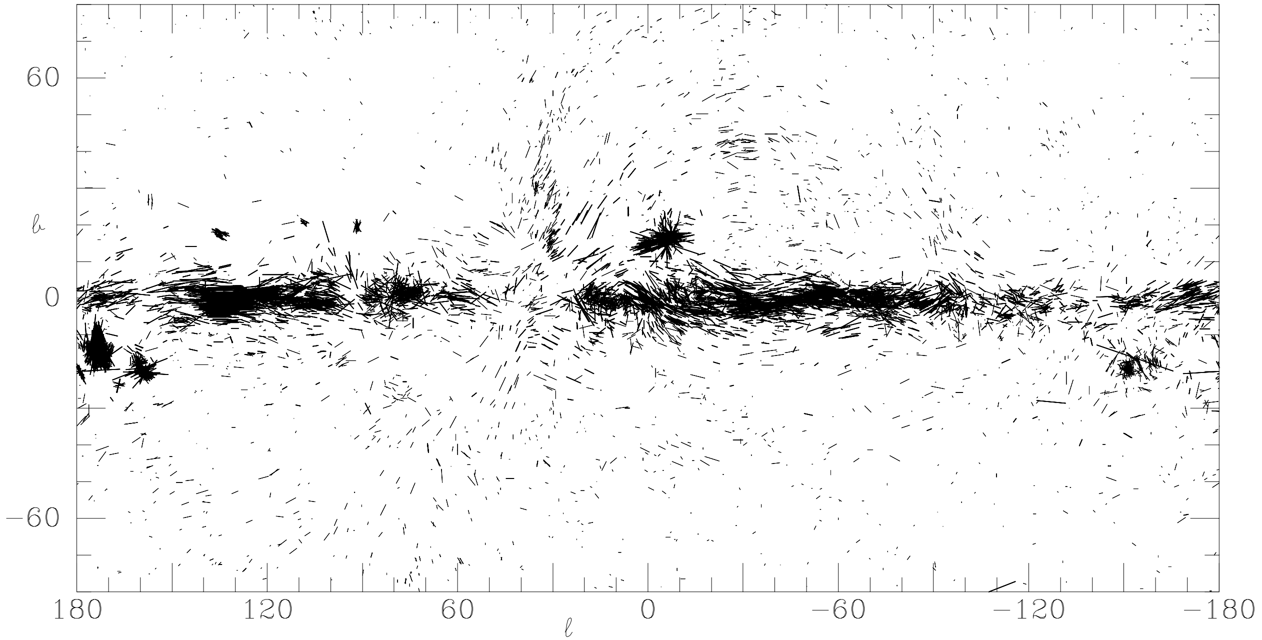


Figure 2: Magnetic field directions as traced by more than 4000 optical stellar polarization measurements. The length of each line is proportional to the degree of linear polarization, and the orientation reflects the polarization position angle. From the Mathewson & Ford compilation plus recent surveys of nearby dark clouds by Klare & Neckel[16] *and others.*

Despite this, virtually all modern theories of grain alignment predict that the short axis of a spinning dust grain will tend to align with the direction of the ambient magnetic field[17], except perhaps in cold, dense, quiescent regions. This produces polarization of the thermal emission from the dust grains along the long axis of the grain, and perpendicular to the projected magnetic field direction.

Fifteen years ago, Cudlip et al. made the first successful measurements of linearly polarized thermal emission from dust in the far-infrared using a balloon-borne polarimeter[18]. Since then, Hildebrand and collaborators have flown several far-infrared polarimeters on the Kuiper Airborne Observatory (KAO)[19]. To enhance polarization mapping, a 32-bolometer-array polarimeter, called STOKES, was constructed and flown on the KAO to map the polarization of thermal dust emission in eleven of the "brightest" molecular clouds including M17, Orion, W3, the arched filaments and dust ring associated with the Galactic Center (Figure 3), S106, W51, NGC 2024, SgrB2, DR21, and NGC 7538[20,21,22,23,24].

All of the airborne observations have been limited by the bright background presented by the partially transmitting atmosphere. Only the brightest small central portions of a few of the brightest sources have been detected. The polarimetric observations have shown the utility of the approach, while coming nowhere near fundamental sensitivity limits. The total number of independent sky positions measured for far-infrared polarimetry is only a few hundred, obtained at a rate of a few tens per KAO flight.

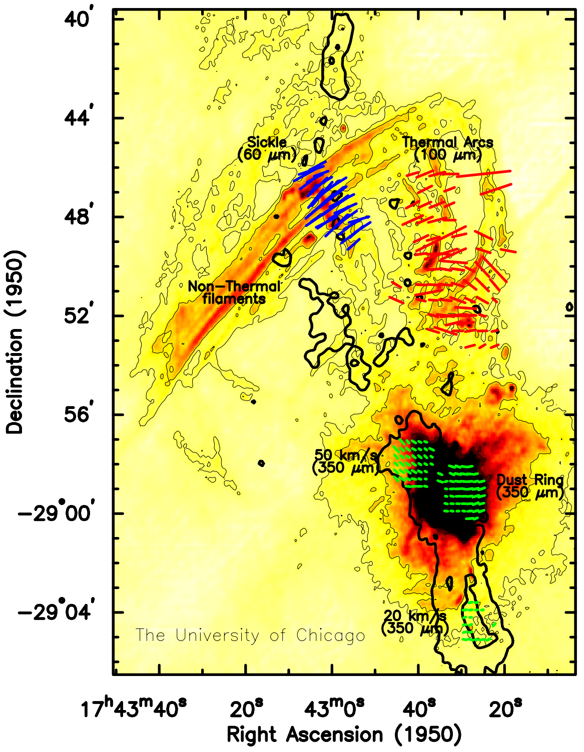


Figure 3: Comparison of far-infrared thermal dust polarization for five regions in the Galactic Center region with radio wavelength emission. The polarization data are from a combination of KAO (60 and 100μm) and CSO (350μm) observations by the Hildebrand group. Radio flux halftone image and thin contours are from Yusef-Zadeh (1986); thick contours are 800μm emission from Lis & Carlstrom (1994).

The KAO efforts have shown that the range of linear polarization values is between 0.5 – 10%, with a mean between 2 – 3%. In order to characterize magnetic field directions, uncertainty levels of the polarization position angles must be below 10°. This level of precision, coupled to the low polarization percentages, leads to challenging instrumental and observational requirements. For an average 2.5% polarized signal, reaching 10° uncertainty requires polarimetric uncertainty below 0.9%. This translates to photometric signal-to-noise (S/N) levels of 150:1.

Recent advances in SIRTF detector array technology allow reaching space-based background limited performance in the far-infrared. **A SMEX (M4) conducting polarimetry at the background limit would advance magnetic field observations by four orders of magnitude in quantity, area coverage, and sensitivity.**

COBE has shown the Galactic dust to have temperatures of 16-19K[25]. This dust emits strongly in the submm to far-infrared. While an M4 design wavelength closer to the emission peak would intercept stronger signals, no large format detectors comparable to the 32 × 32 MIPS arrays operate longward of 110μm. Similarly, the silicon BIB technology in *WIRE* has a long wavelength cutoff shortward of 50μm, too far off the emission peak to permit cool dust polarimetry. The best configuration for performing magnetic field mapping of the cool dust involves use of the *SIRTF* MIPS arrays near 100μm. These provide large pixel numbers, with good sensitivity to the cool dust. The selection of a wavelength just shortward of the emissivity peak also enhances the mapping angular resolution for a fixed telescope aperture.

D.1.c. The M4 Primary Science Program

Our solution to the problem of a general lack of knowledge concerning the role of magnetic fields in the Galaxy is to develop a short duration Small Explorer survey mission designed to make large- and small-scale maps of the magnetic field structure in the Milky Way using the technique of far-infrared imaging linear polarimetry. We have identified three surveys, which together with a robust Guest Investigator (GI) program comprise the Primary Science Program of the M4 mission. Additionally, the hardware design which meets the requirements of the 4 month Primary Science Program may allow up to a 2 month Extended Mission period.

D.1.c.1. Milky Way Magnetic Field Survey

The highest priority survey of the M4 mission is designed to answer several questions:

- Are the magnetic fields in dense clouds part of a Galaxy-wide spiral pattern?
- What is the magnetic field pattern inside and outside of the 5kpc radius molecular ring in the inner Galaxy?

- What is the magnetic field distribution in the Galactic Center? How does it relate to the distributions of gas and dust there?

The M4 Milky Way survey will cover 1000 square degrees of the Galactic disk, to $\pm 50^\circ$ of Galactic longitude (ℓ) and $\pm 5^\circ$ of latitude (b), requiring about five weeks of M4 observing time. The ℓ limits insure that the dense ISM in the inner Galaxy, especially in the region spanned by the 5kpc ring, is well-sampled. The b limits both completely cover the bright Galactic mid-plane and provide good latitude extent. With a $2'$ diffraction-limited beam and $48''$ pixel sampling, this survey will contain some 6 million pixels.

The magnetic field structure map developed will be used to examine connections between star forming regions, spiral arms, and shells, loops, chimneys, bubbles, and worms in the disk. The ambient field in the central 100pc of the Galaxy will be mapped in unprecedented detail, completely filling the entire region shown in Figure 3.

When combined with radio spectral line data, the 3-D structure of the Galactic field will be traced out using the thousands of bright cloud core regions already detected by *IRAS* (see Figure 4). This technique will help remove line-of-sight confusion for the optically thin far-infrared dust emission and permit testing detailed models of the structure of the Galactic magnetic field.

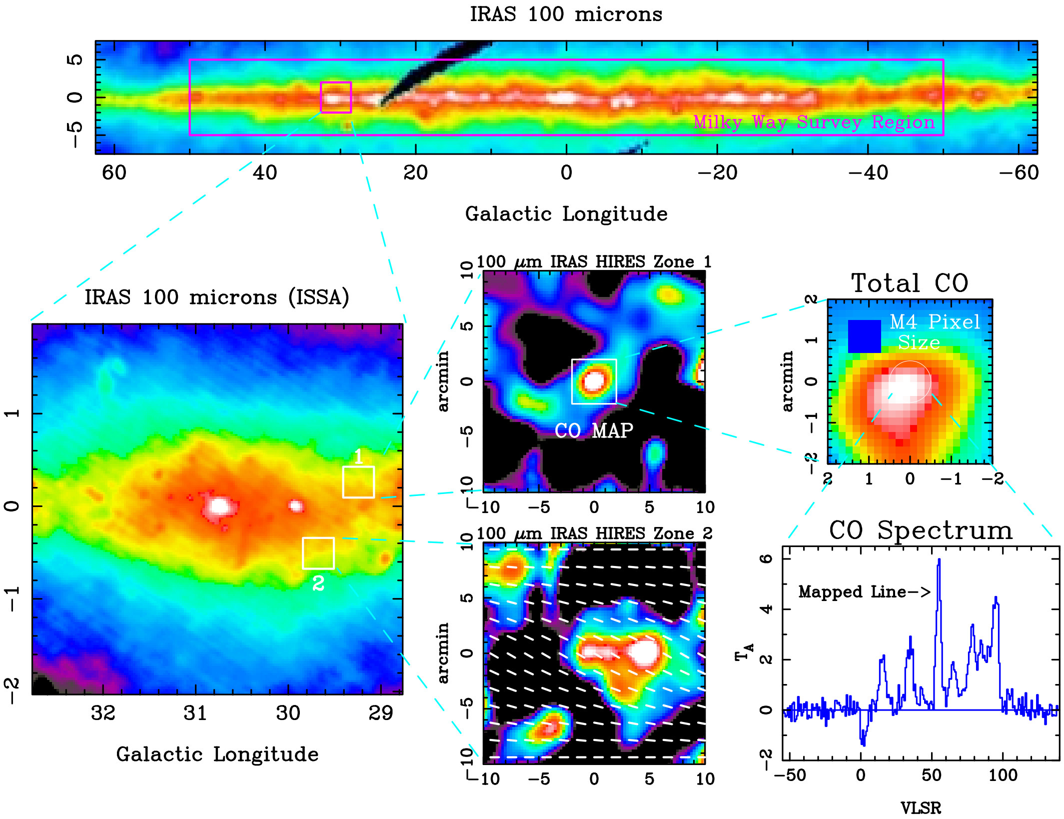


Figure 4: M4 Milky Way survey region and example zones shown with higher angular resolution to highlight the expected results of the survey and how region distances will be established. The top strip shows an enlargement of the IRAS 100μm map, with the 1000 square degree M4 survey region boxed. A portion near 30° longitude is expanded in the lower left (data taken from the IRAS ISSA data product). This is further expanded into two 20 arcmin zones, computed using the HIRES software at Boston University from the raw IRAS data. Each of these middle maps shows the presence of relatively bright point sources. In the lower middle panel, polarization vectors, as would be obtained using M4 are shown. In the upper middle panel, a small CO map was obtained at FCRAO near the point source. The central spectrum is shown in the lower right, and contains several emission lines indicating the presence of many clouds along this line of sight. However, only one of the lines yields an angular distribution similar to that of the infrared point source. That particular CO distribution is shown above the spectrum, and contains a block identifying the M4 pixel size on this scale. Construction of the Galactic magnetic field map will proceed via using the 1,000 - 2,000 bright infrared sources in the survey region as test particles whose polarization properties will be established using M4 and whose distances will be established via correlation with dense gas spectral line surveys.

D.1.c.2. Magnetic Fields in the Nearest Star-Forming Complex: Sco / Oph

The second priority in the Primary Science Program is to survey a nearby star forming cloud complex to address the following questions:

- What magnetic field patterns are found within dense clouds and large complexes?
- How do magnetic field patterns compare inside and outside of clouds?
- How does the relative mix of uniform and non-uniform magnetic field energies change in star forming clouds, especially in and around dense cores?

These questions can be answered directly via a deep survey of the Sco/Oph complex of dark clouds found at about 125pc distance[26,27]. This complex includes a wide range of dense ISM properties and settings, from intermediate-mass star-cluster formation in the ρOph cloud core[28], to the eastward-extending quiescent dust streamers, to the dark clouds affected by the ionizing radiation from the runaway O-star ζOph (e.g. L204), as well as many sites of single star formation.

The M4 Sco/Oph survey will provide a definitive test of the central hypothesis of molecular cloud support – the idea that clouds are supported against gravity primarily by their magnetic fields and associated waves and supersonic (but sub-Alfvénic) turbulence. By combining the M4 polarization position angle information with nonthermal line widths measured from existing data over the same region obtained in ^{13}CO, we will derive the relative contributions of the parallel and perpendicular magnetic field fluctuations, $\mathbf{b}_{\|}$ and $\mathbf{b}_{\perp}$, and thereby estimate the total field fluctuation amplitude $\mathbf{b}$, the static field strength $\mathbf{B}$, and the ratio $\mathbf{b}/\mathbf{B}$.

The M4 Sco/Oph survey will determine the spatial structure in at least two quite different environments in the Sco/Oph complex – the turbulent gas in the L1688 core, which contains a young embedded stellar cluster of more than 100 stars, and the quiescent gas in the dark "streamers," including L1709, L1720, L1712, and L1755. We will test whether the magnetic field structure is more turbulent in the cluster region than in the streamers, as expected from models of cluster formation via fragmentation.

The Sco/Oph complex covers about 150 square degrees on the sky, but with a fairly low filling factor (about 10-15%). Our M4 survey would completely map this dark material in a hybrid pointed-survey mode to cover approximately 22 square degrees during approximately two weeks of M4 observing time, and will yield small- to large-scale maps composed of about 100,000 polarization pixels.

D.1.c.3. Magnetic Properties of Infrared Cirrus

The third component of the Primary Science Program involves surveying a representative zone of faint infrared cirrus, a component of the Galaxy first discovered by IRAS, to answer:

- What is the structure of the magnetic fields in infrared cirrus clouds?
- How do cirrus magnetic fields relate to the global, Galactic field geometry?

These questions can be answered via analyses of a background-limited M4 survey of a region of cirrus emission. Because of the faintness of the cirrus, no ground-based or airborne instrument will ever measure the polarization produced by this material. Additionally, no space-based mission other than M4 will be able to map the magnetic field of the infrared cirrus.

Cirrus observations are needed to distinguish competing theories for the origin of the Galactic field (dynamo vs. primordial), and for obtaining a better understanding of the coupling between the disk and the halo[29]. Additionally, for M4 cirrus pixels overlapping directions with measured stellar polarizations, comparison of the polarization percentages for the far-infrared and optical, normalized by the optical extinction, provides a measure of the degree of grain alignment, which is useful for distinguishing between grain models.

Cirrus structure tends to be filamentary. In some regions, the magnetic field traced by starlight polarization lies parallel to cirrus filaments. Goals of the M4 Cirrus survey include testing whether this is a general characteristic, and whether the alignment persists to all substructures in the cirrus.

Magnetic fields greatly affect the thermal conductivity along field lines, linking the matter in flux tubes, and cooling as a unit to form the cold, dense filaments seen[30]. In these regions, the field should be parallel to the filament, and the magnetic field pressure should be comparable to the gas pressure. However, cirrus filaments also have substructure with departures of their orientations from the larger structures. To what degree are magnetic fields aligned with the substructures?

For the M4 Cirrus survey, we have chosen a region that lies in the North Polar Spur (NPS), a very large HI shell expanding at 20 km/s and exhibiting diffuse radio synchrotron emission in a famous loop structure[31] (see Fig 2). The NPS is well-sampled in stellar polarization, it is the only structure along the line of sight, and it has multiple small-scale structures within its filamentary cirrus clouds.

The M4 Cirrus survey will cover some 100 square degrees, with an effective angular resolution between $48''$ (the superresolution goal) and $24'$(using smoothing), depending on the surface brightness of each zone of the cirrus. This survey will require about two weeks of M4 observing time.

D.1.c.4. Guest Investigator Magnetic Field Surveys

M4 will be the unique platform for conducting surveys of magnetic field structure in the Milky Way and in galaxies. In constructing the Primary Science Program, we specifically focussed on the Galaxy. In doing so, we look to Guest Investigators (GIs) to use M4 to conduct surveys of other galaxies as well as of particular classes of objects within the Milky Way. With the specific exception of M31 (see next section), GIs will conduct M4 surveys of nearby galaxies, starburst galaxies, high latitude clouds, specific dark clouds, Bok globules, and other regions of interest to the community. **During the 4 month Primary Science Program of the M4 mission, 25% of the observing time (a minimum of 3 weeks) is reserved for GI magnetic field surveys.**

M4 will have the requisite angular resolution and sensitivity to map effectively nearby galaxies such as M33, M81, M82 and the Magellanic Clouds. For these galaxies, the relationship between the magnetic field geometry in regions of high far-infrared luminosity and the field geometry in the remainder of the galaxy can be investigated in detail. It will be possible, for example, to determine if the magnetic field threading through giant molecular cloud complexes in external galaxies is aligned with local spiral patterns.

D.1.c.5. Extended Mission Survey Priorities

Completion of the Primary Science Program, containing 16-18 weeks of surveys and checkout/calibration, requires that the instrument design lifetime be at least four months. Our current cryogen lifetime models indicate that a period of up to 2 months beyond the 4 month Primary Science Program may be likely. This Extended Mission will be allocated as 50% to GIs and 50% to Science Team secondary goals. These goals include a survey of magnetic field geometry in M31, observations of a second cirrus region, extending the b and/or ℓ coverages of the Milky Way survey, and surveying some of the dark clouds in Perseus, Taurus, and/or Orion should the mission lifetime permit viewing these regions.

D.1.d. Correlative Data Sets

The M4 Primary Science Program surveys will yield data sets which are capable of being used to address most of the questions listed above as well as supporting archival and correlative studies. However, the surveys, in particular the Milky Way survey, will be greatly enhanced by dense gase spectroscopic data sets to assign radial velocities and distances to the far-infrared polarimetric features detected. In order to produce a Galactic magnetic field direction map from the overlapped, optically thin emission which M4 will view, systematic spectral line surveys of dense gas in the plane of the Milky Way are needed.

A new program to obtain modern, high quality CS and ^{13}CO spectral line maps of the Northern 5kpc molecular ring of the Galaxy from the Five College Radio Astronomy Observatory will take place over the next three years, directed by Prof. Mark Heyer. FCRAO is about to commission a new, state-of-the-art receiver array (SEQUOIA) which will permit mapping the faint CS J=2-1 line with $25''$ sampling and superb signal to noise with a modest investment in telescope time.

The ASTRO submillimeter telescope, located at the South Pole, is expected to conduct a similar dense gas survey of the Southern inner Galaxy region. In the CO J=4-3 line, ASTRO has a $2'$ beam, identical to the M4 beamsize. This ASTRO survey would be directed by Profs. Thomas Bania and James Jackson, both of Boston University, in conjunction with the ASTRO PI, Dr. Tony Stark of the CfA.

The data from the new 5kpc ring surveys will permit matching dense gas properties with bright M4 polarimetric targets, to yield radial velocities (and distances) for those magnetic zones, without the need to obtain new observations of single objects. The data to be obtained for these surveys are expected to be collected and analyzed via non-NASA initiatives.

D.1.e. Other Missions and NASA OSS Themes

No other past or planned space-based mission has conducted or will conduct far-infrared polarimetry. *IRAS* and *MSX* did not fly with polarimeters. *SIRTF* will fly without any polarimetric capability. *SOFIA* is expected to have far-infrared polarimetric capability – but predominantly for high-angular resolution work on very bright sources. While the *ISO* satellite was launched with polarimetric capability for the PHT instrument, this capability has not yet been employed to conduct polarimetry of any thermal dust emission and appears unlikely to do so before cryogen exhaustion.

Nevertheless, the *photometric* imaging data sets from these missions, and from the ground-based 2MASS effort, are expected to be incorporated in correlative analyses of the M4 polarimetric surveys. For example, high angular resolution near-, mid-, and far-infrared imaging (2MASS, *MSX*, *ISO*, *WIRE*, *SIRTF*, and *SOFIA*) can be used to ascertain the detailed stellar contents of cloud cores unresolved to M4's polarimetric observations, thus providing key insight into tests of how star formation mode (single vs. cluster) is related to magnetic field properties.

WIRE observations at 12 and 25μm, to be conducted by Associate Investigators, are expected to probe the inner Galactic plane while the primary science program of extragalactic surveys is executed by the *WIRE* Science Team.

The M4 mission speaks directly to the central goal of the NASA OSS "Structure and Evolution of the Universe" theme, and provides important unique contributions to the "Origins" theme.

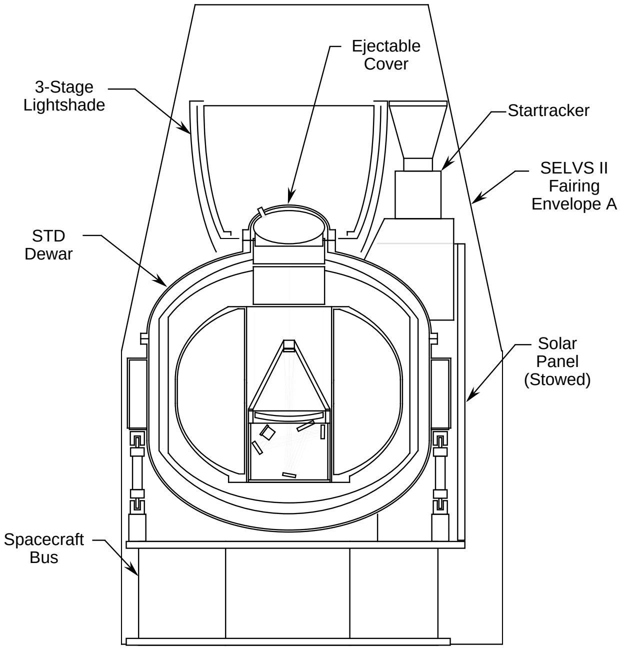
Magnetic fields are crucial to the removal of angular momentum and the development of disk and eventually planets around young stars. Without knowledge of the nature of magnetic fields in regions which are forming new stars, models of pre-planetary disks and planet formation will remain hampered. M4 does not quite have the requisite angular resolution to tackle these problems directly, hence its support of Origins research is indirect. M4, in conducting the deepest, broadest magnetic field surveys of the star forming dense gas to date, will show the way for future SOFIA and SIM observations. The magnetic field selected source lists and large-scale magnetic field structure maps provided by M4 will guide selected, higher angular resolution studies of the magnetic fields and planet-forming potential of star forming sites in the Milky Way.

On the other hand, **M4 will provide the most comprehensive, unique insight into the nature of the structure of the magnetic field in the ISM of the Milky Way and other galaxies.** No other mission, past or planned, will address questions of magnetic field structure to the degree possible with M4. Whether one is interested in knowning how galaxies formed and evolved, how interstellar gas is convinced into becoming new stars, or how the lifecycles of stars affect galaxy structure and evolution, **the magnetic field is a player in the drama**. Yet, until we fly M4, that player will remain silent.

D.2. Science Implementation

Executing the Primary Science Program requires design, development, and operation of a space-borne, background-limited far-infrared imaging polarimeter. To avoid potential single-point failures, the instrument has been designed to operate with *no moving parts*. To provide modulation of the far-infrared signal for polarimetry, the satellite will acquire and hold specific roll angles (relative to the observing line of sight) during short segments of each near earth orbit. By mapping the same area of sky during four such segments, each with a roll angle of 45° from the previous segment, M4 will obtain sensitive and highly precise magnetic field structure maps. Evolution of the sun-synchronous (dawn-dusk) orbit during the mission allows completion of the Primary Science Program surveys as well as many GI observations.

In the following, we offer summaries of the M4 instrument system, the spacecraft system, and the on-orbit operations and observations plans. Because the collection of scientific data by the M4 satellite involves an unusually close coupling of instrument, spacecraft, and orbit operations, we present estimated far-infrared polarimetric sensitivities and the derived mission lifetime requirements following the discussions of the other systems.



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Aerospace Systems Division

Figure 5: M4 Satellite concept, shown as a cutaway drawing within the SELVS II static envelope.

D.2.a. M4 Instrumentation: A No-Moving Parts Imaging Polarimeter

M4 (see Figure 5 and fold-out Figure 9) consists of a 20cm diameter telescope, operating below 6K, with fixed dual-channel polarization optics, feeding twin 32×32 pixel gallium doped germanium detector arrays. The 95μm central wavelength results in a $2'$ diffraction-limited beam size, for which the $48''$ pixel size gives an instrument field of view of almost $26'$. The high degree of PSF oversampling by the pixels supports our *goal* of attempting polarimetric superresolution image recovery. The twin arrays permit instantaneous measurement of one linear Stokes parameter with high precision (S/N at least to 150, with a goal of exceeding 600). Spacecraft roll of 45° for four nine-minute orbit segments, and overlap of dithered maps obtained within each segment will produce complete linear polarimetric data sets. Calibration will be developed from both frequent ($\sim$0.1 Hz) internal stimulator flashes and from observations of astronomical targets each orbit. The entire Primary Science Program, GI Program, and verification, checkout, and calibration observations can be completed within the four month design lifetime of the stored superfluid liquid Helium cryogen.

D.2.a.1. Science Requirements and Goals

The scientific goal of this investigation, to measure magnetic field directions in the ISM of the Milky Way, requires developing magnetic field directions with uncertainties below 10°. Further, in order to measure field structures and to them to physical structures, good angular resolution is required.

As stated earlier, an average polarization of 2.5% and the 10° directional certainty requires measuring linear polarizations to uncertainties below 0.9%. This leads to a *(differential) photometric requirement* of S/N ≥ 150. The *absolute photometric requirement* is of order ten times coarser (15:1) because all polarizations are under 10%, largely decoupling absolute photometric errors from polarimetric ones. Extending the directional uncertainty to polarizations near 0.6% establishes the *photometric goal* for S/N to exceed 600. The requirement, and goal, will be met if the intrinsic instrumental polarization is low (under 2%), stable, and correctable to $\leq 0.2\%$.

This intrinsic polarization requirement will be met by M4 via a dedicated polarimetric design, but will not be met by polarimeters on any larger, observatory class satellite, such as *ISO*. These observatories do not have the freedom to pursue low instrumental polarization designs, because of other optics constraints. **M4 will be the first satellite to be optimized for measurement of far-infrared linear polarization.**

The angular resolution of the magnetic field maps will be similar to the resolution of comparable maps of gas structure ($\sim$arcmin). To map the Primary Science Program regions quickly, the instrument field of view should be at least as large as $15'$. The detector formats should be sufficient to probe simultaneously many independent target positions to create detailed field maps and to measure the dispersions in the local field directions.

Polarimetric observations are naturally challenging of instrument precision, dynamic range, calibration, and stability. The M4 design provides sufficient capabilities and margins in these areas so as to fully meet the scientific data collection requirements and goals.

D.2.a.2. M4 Instrument Systems

There are three subsystems that together comprise the M4 instrument (see Figures 5, 6, 7, &9): the *optical system*; the *cryogenics system*; and the *control system*.

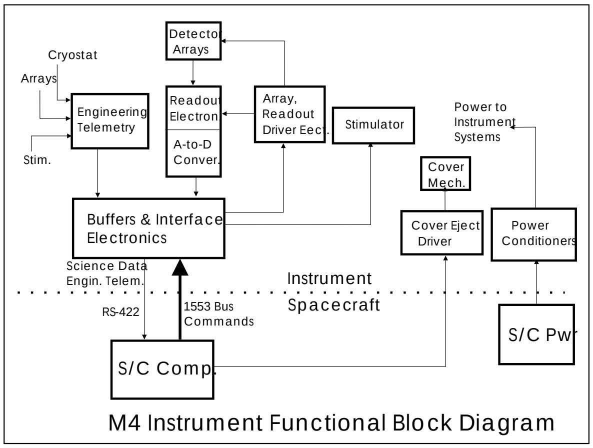

Figure 6: Functional Block Diagram of the M4 Instrument

D.2.a.2.a. Optical System

A partial ray tracing of the M4 optical system is shown in Figure 7. Light from the target passes through the cooled forward light shield (Figure 5), while all earthshine and sunshine are rejected to the angular limits of the shade (52° for the earth limb, 92° for the sun). Cold baffles prevent direct viewing of the inner light shield walls by the primary. Light from the astronomical target is reflected off the gold-flashed, light-weighted aluminum 20cm diameter $f/2.0$ primary and off the 3.2cm diameter secondary. The beam passes through focus to a tilted collimating mirror. The reflected collimated light travels to a fixed 45° wire grid beam splitter which transmits and reflects the two orthogonal polarization senses (the Figure 7 ray tracking follows only the transmitted beam path).

Each beam is reimaged by a combination of a camera mirror and a fold mirror to yield a $f/16$ focal plane on a detector array. Not shown are the cold pupil stop and baffles to control scattered light. This ray tracing was performed using the ZEMAX program (Focus Software, Tucson, AZ), and has been optimized for minimum image spot size, minimum image distortion, matched images on the two arrays, 1:1 scale factors in the two array dimensions, and minimum instrumental polarization. Instrumental polarization in M4 will be below 1%, and will be completely dominated by detector response effects. Because both the transmitted and reflected beams are detected by distinct detector arrays there is no light loss, and polarimetric efficiency is maximized.

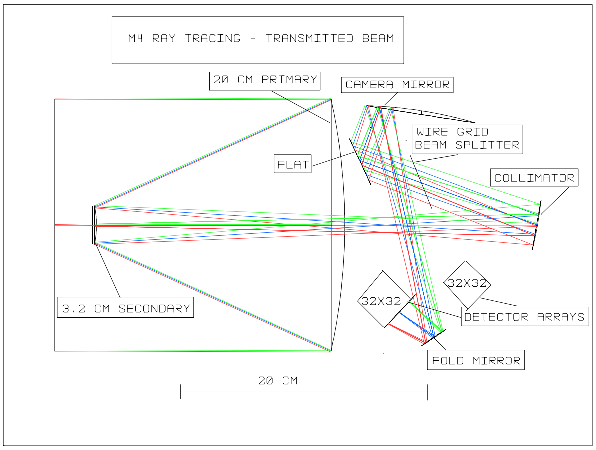

Figure 7: ZEMAX partial ray tracing of the telescope, optics, and detector systems. This tracing follows only the beam transmitted by the wire grid. The reflected beam goes to its own camera mirror and fold mirror to arrive at the second detector array, shown just to the right of the transmitted beam's array.

Once returned to the ground, the data from the two arrays will be registered, and the difference of the signals (pixel-by-pixel) will be divided by the sum of the signals. This will form an Instantaneous Simultaneous Stokes (ISS) parameter (ISS = Q or U, depending on satellite roll angle):

$$ISS_{i,j} = (I_{T_{i,j}} - I_{R_{i,j}})/(I_{T_{i,j}} + I_{R_{i,j}})$$

where $I_{T_{i,j}}$ represents the far-infrared intensity for one pixel in the T array, which sees the light *transmitted* by the beam splitter, and $I_{R_{i,j}}$ represents the intensity for the corresponding pixel in the R array, which sees the light *reflected* by the beam splitter.

After a 45° satellite roll about the optical axis and a second set of images are obtained, the Stokes variable designation of the ISS changes (e.g., $Q \rightarrow U$). Data from the two roll angle configurations will be combined to form the linear polarization quantities P and θ (and their uncertainties):

$$P_{i,j} = \sqrt{Q^2_{i,j} + U^2_{i,j}}\,;\ \theta_{i,j} = \frac{1}{2}\tan^{-1}(\frac{Q_{i,j}}{U_{i,j}}).$$

A second set of observations are obtained to allow removal of instrumental polarization. These second observations, executed at roll angles of 90° and 135° with respect to the original observations, have the effect of performing detector "swaps" (array $T \rightarrow R$) and transposition of the axes on the detector arrays. If the second observations are identified by primed quantities, then $U'_{i,j} = -U_{j,i}$. This will provide a critical cross-check for ensuring photometric and polarimetric accuracy, as well as a second set of observations for improving S/N.

For calibration, a far-infrared light source (the "stimulator") will be used to feed a stable photon signal to the detectors. The stimulator will provide immediate recalibration of all pixel relative responsivities every 6 - 20 seconds. This time scale is shorter than the time between charged particle hits for each pixel.

Because relative responsivity is directly related to polarimetric performance, stimulator stability is important. However, as the expected dust polarizations are all below 10%, a 1% stable stimulator will contribute no more than 0.1% polarization uncertainty to the total error budget. Stimulators with $\leq$ 1% stability have flown aboard *IRAS* and other missions. Absolute photometric calibration (less important than relative calibration) will be obtained via on-orbit observations of astronomical photometric and polarimetric standard sources (planets, asteroids, and *IRAS* sources).

The focal plane array detectors for M4 have already been developed for use in the MIPS instrument aboard *SIRTF* by Co-Is George Rieke and Erick Young (at the University of Arizona). Gallium doped germanium (Ge:Ga) was initially used in space on *IRAS*, for both Bands 3 (60μm) and 4 (100μm). It was employed on the Spacelab 2 Infrared Telescope, *COBE*, and is being used on *ISO*. As part of the development of focal planes for *SIRTF*, Ge:Ga photoconductors have been improved substantially, via use of optimized material with low energy ion implanted and metallized contacts provided by Eugene Haller (Lawrence Berkeley Laboratories). These detectors exhibit detective quantum efficiencies of 25%, dark currents of less than 150 e/sec, and good photometric behavior.

Co-Is Young and Rieke have demonstrated array concepts that meet the M4 requirements. The photoconductors are fabricated in 1×32 bars of pixels that are edge illuminated. The signals are taken to a 32-element integrating amplifier and readout multiplexer located behind the array. The Hughes CRC-696 readout has been designed specifically for this application and operates at the detector temperature ($\leq$ 2 K). The detector/readout assemblies are thin enough to permit stacking into high fill factor ($\sim$85%) two dimensional arrays, using optical concentrators to increase the effective pixel size to 750μm square. Laboratory prototype arrays of 4×32 format demonstrate 25 electrons read noise and pixel well depths of 2×10^5 electrons.

D.2.a.2.b. Cryogenic System

The M4 cryogenic system will cool the detectors to below 2 K and the optics to below 10 K for 4 months.

The cold-launch superfluid helium (SfHe) dewar configuration is shown in Figures 5 and 9. [Warm-launch (e.g. *SIRTF*-like) designs were considered, but yielded much shorter cold lifetimes for SMEX constraints.] The annular design is similar to the flight-proven *IRAS* and *COBE* designs, but has a more recent heritage in the SIRTF Technology Demonstration (STD) dewar constructed by Ball over the past year. The 110-liter central cryogen tank is surrounded by two vapor-cooled shields (VCSs) and multilayer insulation (MLI), and is supported by fiberglass tension straps. This flight-proven support system provides a high resonant frequency (32 Hz), while minimizing the parasitic heat to the SfHe. The focal plane arrays will be thermally connected to the 1.3K SfHe tank by thermal straps. The telescope optics will be cooled to 5.6K by a combination of direct contact with the inner cryostat walls and using effluent helium vapor from the first cooled shield.

Fill and vent lines and valving provide all the required fluid management operations. The two lines provide redundant capability for emergency venting through burst discs. Internal and external motor-operated valves provide all required operating modes. All components are flight qualified.

A deployable aperture cover includes a small LN2 cryostat and maintains the telescope in a contamination free, thermally controlled, light-tight environment through launch and into early operations phase. The cover is ejected from the dewar on orbit.

The cryogenic system thermal load analysis is derived from the *SIRTF* model, which is based on previous models validated by *IRAS*, *COBE*, and four other cryogenic dewars flown by Ball. The heat loads to the cryogen consists of 6mW generated by the focal plane (arrays, readouts, array heaters, and stimulator), 14mW of parasitic leak through the cryostat from the outer shell, and 8mW of radiation from the lower portion of the forward light shield. These total 28mW, which for a launch volume of 110L of SfLHe results in a cryogen lifetime of 4.4 months.

Because the focal plane heat load is small, the cryogen lifetime depends mostly on the exterior vacuum shell temperature. Detailed thermal modeling of the vacuum shell was performed for a wide range of realistic M4 earth illumination conditions, resulting in a mean shell temperature of 200 ± 6K.

The forward light shield was identified as the next most important heat load. The light rejecting action of the shield is necessary for allowing M4 to view directions out of the plane of the sun-synch orbit. For M4 to perform no-moving parts polarimetry, viewing angles of up to 60° away from the orbit plane are required. The light shield was designed to fully reject all earthshine more than 52° away from bore sight. Combined with the earth limb angle of 22-24° *below* the M4 local horizon (depending on orbit altitude), this light shield permits M4 to view the sky between angles of 2 - 60° away from the orbit plane.

This large light shield, however, presents a large view factor to the inner walls of the cryostat. To reduce the radiated heat load, the inner cone wall is highly polished, specularly reflective, and low emissivity. The shield is constructed of three layers of aluminum and MLI. Radiative surfaces at the bottom of the inner two cones and the top of the outermost shield passively cool the cones. Detailed thermal modeling, taking into account the outer shell heating by the earth, shows that the lower portion of the inner shield (with the largest view factor to the cryostat) will reach a temperature of about 109 ± 4K. This is low enough to maintain the radiated heat load below 1/3 of the total heat budget.

D.2.a.3 Control System

The relative simplicity of the M4 instrument allows the spacecraft (S/C) control computer to implement all instrument control functions (see Fig 6). The S/C computer communicates with the instrument via a 1553 bus and an RS-422 serial link. Typical operation of the S/C control computer involves polling the devices (terminals) connected to the S/C 1553 bus to obtain input data and writing commands or parameters to the devices via this same bus to effect control. A set of buffer and interface electronics will accept the commands from the S/C computer and direct these commands to the appropriate interfaces of the detector array readout and driver electronics. Digitized data collected by the array readout electronics will be stored in a buffer and transferred to the S/C computer when requested. This implementation allows the instrument to be a "software free zone." Such an approach reduces risk by minimizing software interfaces and focusing all software development within one subsystem.

Additional required instrument electronics include power conditioning and distribution and the ejectable cover driver.

D.2.b. Spacecraft Description

The M4 spacecraft concept is derived from the *SWAS* three-axis stabilized, pointed SMEX bus, incorporating recent advances in small spacecraft technology (e.g., SMEX-Lite components, Ball CT631 Star Tracker). At present, there are two competing M4 S/C bus options: SMEX-Lite (values obtained from the Web listing), and a new small Ball bus we identify as "Ball-Jr." Both meet the M4 requirements, but neither has yet been fully optimized for the M4 mission and we have elected to defer detailed selection until Phase A. Since a combination of the two options seems most likely, with components drawn from each, we list values for both S/C buses in Table 6 (see fold-out #2) and value ranges from the two S/C buses where appropriate below. A functional block diagram of the M4 spacecraft subsystems and their interconnections is shown in Figure 8.

The M4 spacecraft hosts 1.5 square meters of solar panels to produce 170W of continuous power (no eclipses in this short, sun-synch mission) and will have a 5-6 A-hr battery to carry the satellite through launch. Total S/C mass is between 110-129 kg, and when added to the 115 kg for the instrument yields a satellite mass of 225-244 kg. This gives between 11-18% of mass margin, for SELVS II performance based on the target 500km altitude, sun-synchronous orbit. Total S/C power consumption is between 79-95W, and when added to the 30W for the instrument leaves a 26-36% power margin.

D.2.b.1. Science Requirements and Goals

The required pointing, pointing jitter, and roll jitter performances levels of the M4 SMEX spacecraft are similar to those of *SWAS*. Blind pointing is required to be within 5° (2σ) to allow the Ball CT631 star tracker (20° FOV) to acquire target fields. Once acquired, pointing jitter will be under $24''$ (2σ) to allow subpixel registration of the far-infrared images. Roll jitter will be under $2^\circ(2\sigma)$ to prevent image smear and to enable polarimetric analyses.

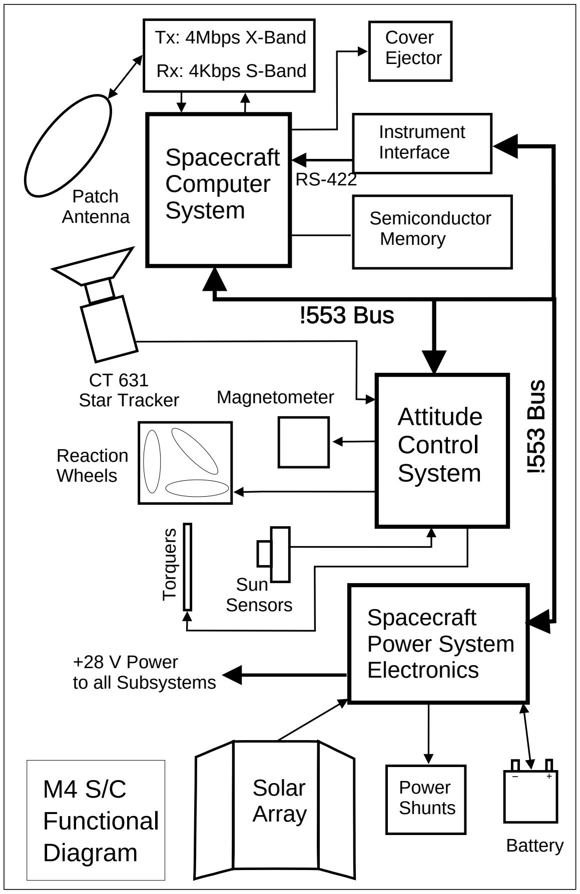

Figure 8: M4 spacecraft functional block diagram.

The spacecraft will move between a set of target positions to create a dithered map during the course of one 8 - 9 minute orbit segment. These small slews will normally be about $13'$ and will be executed, and the satellite stablized for data taking, in less than 12 seconds. Satellite roll maneuvers will take place at the end of each orbit segment. These rolls will be 45° and will take no longer than 90 seconds. Slews to new target fields from any previous pointing direction, including acquiring a new roll orientation, will not take longer than 3 minutes. These time requirements are necessary to ensure low total time overhead ($<25\%$).

D.2.b.2. M4 Spacecraft Systems

The M4 spacecraft bus (SMEX-Lite or Ball-Jr) will be built from high-heritage components. A single equipment plate houses bus avionics and a SELVS II Fairing A launch adapter. To facilitate integration, the M4 instrument mounts to thermally isolated hard points on the bus periphery. Power is generated by GaAs/Ge cells on a one-time-deploy, partial wrap-around solar array (see Figure 9 on fold-out #1). Energy is stored in a commercial NiCd battery pack, with a power control unit providing charge control. Command and data handling uses a RAD 6000 processor with 200 Mbytes of internal RAM for science data. A MIL-STD-1553B data bus and RS-422 serial line are used for signals between components. A hardware-in-loop software test bench ensures compatibility between hardware and derivative software. Attitude control uses reaction wheels for full 3-axis orientation, with magnetic torquers to dump momentum. The telecommunications system uses a NASA-standard transponder and standard patch antennas. Coarse pointing uses magnetometers and coarse sun sensors, while precise pointing uses the Ball CT-631 star tracker. The large FOV (20°) of this tracker permits gyroless operation for modest slew rates. A CT631 is currently in orbit as part of the *NEAR* mission.

D.2.c. Mission and Flight Operations

D.2.c.1. Orbit & Orbit Segments

M4 will be launched on 1 March 2001 (± 2 weeks) into a circular 500 km altitude, 98.2° inclination sun-synchronous orbit.

This orbit provides sufficient altitude margin to ensure an orbit lifetime of at least seven months. The sun-synchronous nature gives the highest observing efficiency with no earth eclipses during the 4-6 month mission. The launch date permits completing the Primary Science Program surveys in the shortest time.

Each roughly 90 minute M4 orbit consists of 10 almost equal "segments," during each of which the satellite will remain in a fixed inertial system, aligned to some angle with respect to celestial coordinates. M4 will execute programmed 45° roll motions at orbit segment boundaries to reorient the detector arrays to supporting polarimetric mapping.

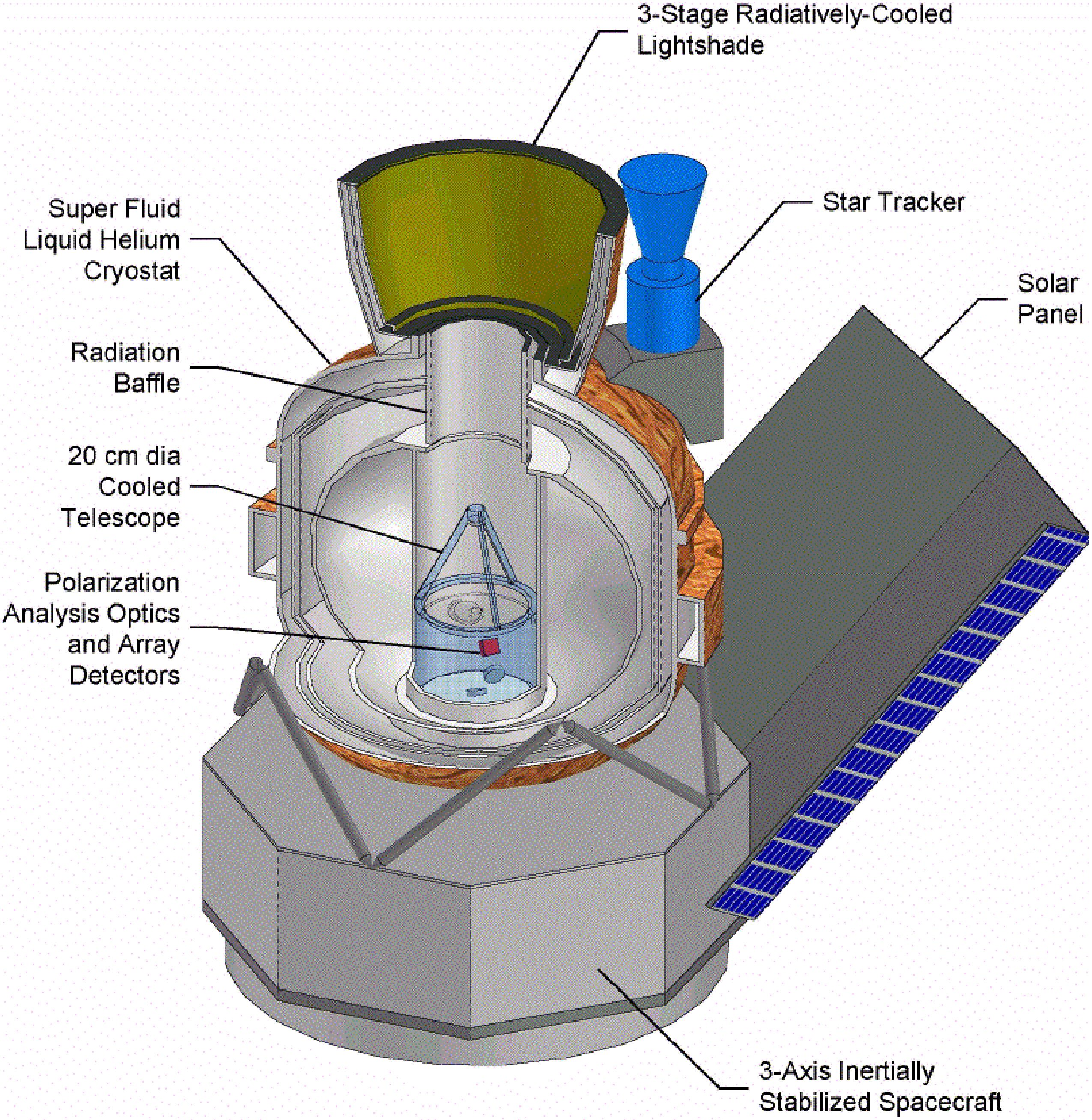

Figure 9: Three dimensional rendered drawing of M4 in its deployed configuration, after ejection of the aperture cover. The cutaway view of the instrument and cryostat shows the simple arrangement of the optics and detector arrays attached to the small spacecraft. The forward light shield rejects sun and earth light. The CT631 star tracker is sighted along the same axis as the far-infrared telescope. The stepped roll operation of M4 in its near-earth orbit 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).

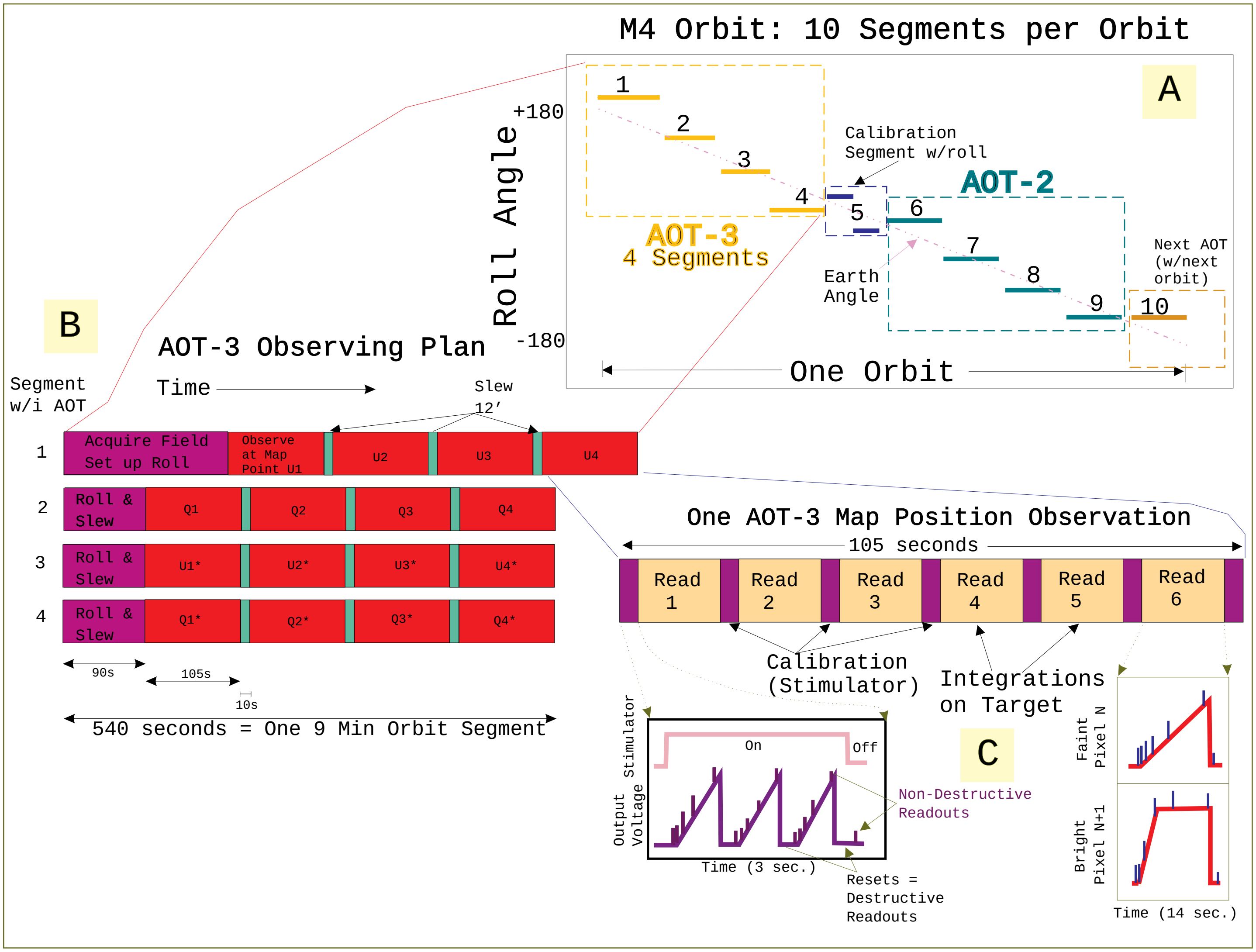

Figure 10: Summary of M4 data collection plan. (A) Roll Angle versus Orbit Phase, showing ten orbit "segments" during each of which the roll angle is fixed; (B) Detailed observing plan for AOT-3, showing all spacecraft motion periods and instrument integration periods for this 2×2 raster map; (C) Expanded view of instrument actions during one 105s observation in AOT-3, showing the interleaved calibration observations and the multiple array readouts (NDRs and DRs).

Choosing the stepped roll angle progression to match the average orbit aspect progression permits M4 to present virtually always the same side of the satellite to the warm earth emission (a moon-like presentation). This permits application of specific surface treatment combinations to enhance “underside” heat rejection from the earth and to enable excellent “topside” radiation of excess M4 heat into space. In this configuration, the solar array acts as a sun shade for the topside portion of the M4 shell.

D.2.c.2. Observing Modes (AOTs)

M4 will acquire data using only three fixed observing modes, known as Astronomical Observing Templates (AOTs), designed for fixed area polarimetric mapping of bright, average, and faint flux regions.

This AOT design permits uplink of the smallest number of parameters required to conduct several days of unattended robotic observing and allows accurate estimation of all data collection and data downlink parameters.

M4 will collect data using AOTs which generate an observation sequence comprising four consecutive orbit segments: a map in U, a segment boundary roll of 45°, a map in Q, a roll of 45°, a map in U'(detectors swapped relative to U), a roll of 45°, and a map in Q'.

TABLE 1: M4 AOT SUMMARY

	AOT-1	AOT-2	AOT-3
$T_{Int.}$ per read [s]	0.15	1.5	14
Reads per map point	33	6	6
Time between Cals [s]	20	6.5	16
Map Format [NX × NY]	5×5	4×4	2×2
Area Mapped per 4 seg. [sq. deg.]	1.13	0.73	0.18
Effective ISS $T_{Int.}$ per 4 seg. [s]	40	72	672
Downlinked Data Volume/AOT [Mbytes]	6.1	1.7	0.8
Survey Application	Galactic Center, Plane ($\lvert b \rvert < 1°$)	Galactic Plane ($\lvert b \rvert > 1°$) Sco/Oph GIs	Cirrus, GIs M31

Within each orbit segment, the observations consist of obtaining image data for a dithered grid of positions on the sky. For grid offsets of 1/2 of the detector array field of view, two dimensional dithering allows viewing of sky positions by four different array placements, leading to a four-fold increase in effective integration time (over some appropriate area).

The large range in surface brightness between the Galactic Center, the Galactic Plane, the Sco/Oph region, and the very faint Cirrus means that no single observation can capture all of the necessary data dynamic range. **However, with only *three* AOTs, all regions can be observed polarimetrically with M4 to meet the S/N goal of 600.** As outlined in Table 1, these AOTs differ in their basic integration times, their grid mapping format, and data volumes they return.

We constructed a software mission simulator to test the plan for mapping the Primary Science Program regions using the AOT scheme. This program follows the M4 sun-synch orbit, calculating the sky visibility for the four segments making up each AOT, and performs simulated mapping of the entire Milky Way survey region in AOT-2. The program takes into account the sun and earth avoidances and follows the orbit evolution throughout the mission. The output is rendered into movie form, and the latest Milky Way mapping portion of the M4 flight plan was shown at the Winston-Salem AAS meeting.

Table 2: M4 Flight Time Allocation Plan

Mission Phase	AOT Mode	Time Req'd. [days]	Survey Area [sq. deg.]	Data Volume [Gbytes]
PRIME MISSION				
Initial Checkout & Verification	All	15	...	0.75
Milky Way Survey:				
Center & Mid-Plane ($\lvert \ell \rvert \leq 30°$, $\lvert b \rvert \leq 1°$)	AOT-1	3	120	0.65
To $\lvert \ell \rvert = 50°$, $\lvert b \rvert = 5°$	AOT-2	32	880	2.05
Sco/Oph Survey	AOT-2	15	22	0.90
Cirrus Survey	AOT-3	15	100	0.50
Guest Investigators	All	21	10-100	1.25
Calibration	All	15	...	0.85
Contingency (15%)	...	17	...	0.75
SubTotal		133	~1200	7.7
EXTENDED MISSION				
Guest Investigators	All	25	10-100	1.25
Science Team	All	25	10-600	1.25
TOTAL		183	~1800	~10.2

This program was run to test various AOT schemes, as well as hardware options. The 52° opening angle of the forward light shade was established via simulation runs. The program was also used to examine launch date fidelity. Although two possible launch dates were found (spring and summer), the simulations showed the spring date possessed more flexible scheduling, executed the Primary Science Program surveys more efficiently, and avoided the autumn sun-synchronous earth eclipses.

D.2.c.3. Mission Flight Time Allocation

Using Table 1, the mission simulator, the descriptions of the Primary Science Program Surveys, and the M4 sensitivities (Table 3, below) the M4 mission time allocation plan was developed, as listed in Table 2. The Milky Way survey contains a mix of AOT-1 observations of the Galactic Center and Mid-Plane regions and AOT-2 observations of the remainder of the disk. The Sco/Oph region is best handled in AOT-2, as a series of 16 - 18 identical revisits to build up S/N. The Cirrus region will utilize the faint background AOT-3 polarimetric mode. Calibration will be distributed throughout the mission.

D.2.c.3.a. Guest Investigator Program

Guest Investigations are a required component of the M4 flight plan. The Primary Science Program has a Galactic focus, and reserves about 3/4 of the available orbit segments for viewing the three survey regions. The remaining 1/4 of the segments will be filled by Guest Investigator (GI) observations.

The two goals of the GI program are to involve more astronomers in the M4 mission and to provide a full mission target flight plan ahead of launch. We believe that an open competition, yielding target selections at least four months before flight, will enhance the M4 legacy of magnetic field science.

As part of our project planning, we have budgeted 1.2M$ of Phase E funds to permit about 15 GI groups to obtain, analyze, and publish M4 data. The GI selection method will be worked out with NASA during Phase A. In Table 2, the GI program is listed in two parts. During the Prime Mission, the GI program consists of an aggregate of 3 weeks of time, intermixed on an orbit segment basis with the surveys. In the Extended Mission, the GI program comprises half of the time.

D.2.e. Data Management

A comprehensive plan for integrated data management was developed to meet the challenging polarimetric and operations requirements of the M4 mission. This plan includes the details of data collection in the AOT scheme, taking into account the effects of charged particles, the full data flow path from detector arrays to scientist, and a discussion of the data products and delivery dates for M4 data migration to the astronomical community and to the public.

D.2.e.1. Data Collection Plan

The methodology for M4 data collection has been designed to maximize dynamic range, stability, linearity, immunity to charged particle effects, and to minimize overheads. Low-level polarimetric observations are inherently challenging of system dynamic range properties, especially in light of the S/N=150 requirement (and S/N=600 goal), and also in light of the very different target brightnesses expected (see Table 3). The fixed observing mode (AOT) implementation for M4 data collection relies on a combination of non-destructive and destructive readouts of the detectors, a mapping strategy which samples each sky position with multiple detector pixels in multiple roll orientations, and frequent recalibration with the stimulator.

D.2.e.1.a. Charged Particle Effects

Charged particle hits are a serious concern for doped germanium detectors, as they can produce crystal defects which act as donor sites, boosting detective efficiency. This leads to serious calibration errors. Two mitigations will be used in M4: occasional annealing of the detector arrays and frequent internal photometric recalibration. Annealing is the process whereby detectors are heated from 2K to 7K and back to 2K to release crystal stresses produced by the hits. This is a fairly quick process, but dumps heat into the cryogen. Based on ISO experience and $SIRTF$ plans for annealing the MIPS detectors, the M4 arrays will be annealed about twice per orbit, plus each time M4 passes through the South Atlantic Anomaly (SAA) and the polar horns.

The hit rate is expected to be in the range of once per array pixel every 20 – 60 seconds, after which the responsivity changes significantly. Responding to this high hit rate with frequent annealing would quickly vent all cryogen. Instead, note that although the pixel responsivity changes after a hit, if the responsivity is recalibrated, the net effect to the polarimetric data collection will be negligible. Our approach is to flash the stimulator to recalibrate responsivities on a duty cycle which is short compared to the hit rate.

D.2.e.1.b. M4 Data Collection Hierarchy

M4 data collection is structured at five distinct levels, as shown in Figure 10 (fold-out). At the highest level, completion of any one of the Primary Science Program surveys is accomplished via execution of many AOTs across a number of orbits (see Table 2).

At the second level, shown in the "A" region marked on Figure 10, each orbit is decomposed into ten orbit segments and allocated into individual AOTs. In the figure, the first four segments are assigned to become a single AOT-3 observation. The fifth segment might represent calibration observations toward an astronomical target (asteroid or late-type star) and could include an extra embedded satellite roll maneuver.

At the third level, the four segments of an AOT are each allocated to setup, observation, and satellite motion tasks. In AOT-3, shown as region "B" in the figure, the first segment starts with target pointing acquisition, roll aspect acquisition, and possibly detector array annealing and/or recalibration. These tasks can proceed to some degree in parallel and are allocated a total of 180s. AOT-3 is a 2×2 raster map (Table 1), so in each segment, four periods of observations are interleaved with 12s slews to the next map position. In the cases of AOT-2 and AOT-1, with 4×4 and 5×5 grids, there are 16 and 25 observations interleaved with 12s slews. At the beginning of each of the 2-4th AOT-3 segments, 90s are allocated to the 45° roll maneuvers. The four segments need not be of equal duration.

At the fourth level of data collection, each observation toward a sky position consists of a set of target integrations interspersed with calibration observations of the stimulator. The calibration frequency was set high enough to oversample the range of likely charged particle hit rates, and low enough to permit target observations with good efficiencies. As shown in region "C" of the figure, each 3s calibration consists of turning on the stimulator and collecting multiple samples of image data.

Observations of the target begin after the end of the calibration. For AOT-3, each 105s sky pointing breaks down as a set of 7 calibrations (C) of 3s duration and 6 target (T) observations of 14s duration. For AOT-2, the cycle is modified to CTTTCTTTC for each map position, where the target observations are of 1.5s duration. For AOT-1, the cycle is one C, followed by 33 Ts, each of 0.15s duration. The AOT integration times, target integration times per map point, map formats, and time between calibrations are summarized in Table 1. [Although the calibrations described are of fixed, intermediate duration this could introduce photometric errors due to the multiple time constants in these detectors. We will cross-calibrate these effects using some shorter and longer calibrations, executed during periods of satellite motion for target acquisition and roll maneuvering.]

At the fifth level of the data collection hierarchy, Figure 10, region "C," shows how the voltage ramp generated by the integrating amplifiers for each photoconductor pixel will be non-uniformly, multiply sampled. The slope of the ramp relates to the surface brightness of emission (background+source) seen by each pixel. The individual integration ramps must be sampled and the voltage values differenced to derive the illuminating surface brightness levels. This is performed by non-destructive readouts (NDR) of the ramp voltages at several time intervals and computing the slope (V/s) of the signal for each pixel. After the detector capacitors have discharged, further integration produces no change in signal voltages, requiring detector resets and destructive readouts (DR). In selecting observing with fixed AOTs, the NDR ramp sampling was chosen to produce at least two non-saturated values for all possible illumination levels. This is implemented as six NDRs, separated by logarithmically spaced time intervals, as shown on the ramps in Figure 10. This retains maximum dynamic range for faint and bright target regions seen by different pixels in the arrays (see the example stacked ramps in the lower right corner of the figure).

This five level data collection scheme will allow up to a ratio of 200:1 in brightness across the arrays to be observed in the same AOT. After combining this sampling scheme with the integration time ratio of 100 for AOT-1 compared to AOT-3 (Table 1) and the dithered mapping which repeats sky positions, **M4 will perform high S/N polarimetric observations across the surface brightness range of 1 to 60,000 MJ/sr.** The multiple non-destructive reads of the integrator ramps will also permit identification of particle hits.

D.2.e.1.c. Data Digitization/Dynamic Range

For detector/readout well depths of 2-4×10^5 electrons, and a conversion gain of 5 electrons per ADU, detector saturation will occur around 58,000 ADUs, requiring 16 bit analog to digital converters. These choices, and the sensitivities of M4, to be developed in the following section, imply a conversion gain of about 0.02MJy/sr per ADU unit. The average read noise of 100 electrons will generate about 2 ADU counts of digitization noise, smaller than the 11 ADUs produced by shot noise in AOT-3 observations of the Zodiacal light in the Cirrus survey region (Table 3).

In order to reach the high S/N levels needed to perform polarimetry, multiple exposures (DRs) and postprocessing averaging of the signals for each sky position are required. The number of DRs per map position and the number of map positions per orbit segment appearing in Table 1 were determined from the requirement to obtain an instantaneous S/N=150 per pixel at each map point. With 1/2 array size steps between map points, and the multiple exposures per sky position resulting from the U, Q, U', Q'observing scheme, the resulting S/N per pixel will exceed the goal of 600. Finally, because the pixels oversample the PSF of the telescope system, coadding of neighboring pixels (or, alternatively, fitting source function models to the observations) will result in even higher effective S/N for 2′ magnetic field maps.

TABLE 3: M4 SENSITIVITY & INTEGRATION TIME ESTIMATES [per 48″ pixel]

Survey Region Target Name	ℓ [deg.]	b [deg.]	Zodiacal Light Surf.Brite. [MJy/sr]	Galactic Dust Surf.Brite. [MJy/sr]	**NESB for M4** [MJy/sr]	Target Surface Brightness [MJy/sr]	Integration Time for S/N=600 [s]
Milky Way Survey:							
Gal.Ctr.	0	0	14	20000	12.0	20000	0.1
	3	0	15	2000	3.7	2000	1.2
	3	1.5	15	330	1.5	330	7.4
Gal.Plane	25	0	10	2400	4.1	2400	1.1
	25	1.5	10	330	1.5	330	7.4
	25	5.0	9	78	0.8	78	38.0
	48	5.0	6	35	0.5	35	73.0
Sco/Oph Survey:							
ρOph core			15	40	0.6	300–2400	0.02–1.4
envelope around core			15	40	0.6	50	52.0
dark filaments			15	40	0.6	5–80	20–5200
Infrared Cirrus Survey:							
Bright Cirrus Core	(48″ pixels)		4.6	0.2	0.2	8	225.0
Fainter filaments	(2′ pixels)		4.6	0.2	0.2	1–3	640–5800
GI, Extended Mission:							
M31 Core			6.4	3.7	0.3	40	20.0
M31 Spiral Arms	(Bright – 48″)		6.4	3.7	0.3	3–14	165–3600
M31 Spiral Arms	(Faint – 2′)		6.4	3.7	0.3	1–3	1400–13000

D.2.e.2. M4 Magnetic Field Imaging Sensitivities

Efficient conduct of the M4 mission requires accurate knowledge of the photometric and polarimetric sensitivities of the telescope, optics, and detector system. We have performed detailed modeling of the system sensitivity, verified these models against known performance levels, and used the M4 predicted sensitivity levels to develop the AOT approach to meeting the data collection requirements of the M4 Primary Science Program.

Performance of the M4 instrument was modeled using our instrument/background calculation software. This program has been verified against published *IRAS*, *ISO*, *SIRTF*, *KAO*, and *SOFIA* sensitivities. The program works by following the far-infrared photons from an astronomical source, adding the cosmic backgrounds (3K BB; Zodiacal; Galactic dust), the telescope optics, and instrument optics until detection by a pixel in one of the arrays. The program utilizes realistic detector characteristics and the full set of instrument and telescope optics, including the physical temperature of each optical element, the reflectivity or transmissivity of each element, and the emissivity of each element. Out of band emission is calculated for the bandpass filters preceding the arrays. Values of the astronomical backgrounds were obtained from *IRAS* and *COBE* data along directions toward our survey zones, using the IRSKY program (from IPAC), and are listed in Table 3.

The M4 telescope was characterized as two 97% reflective, 3% emissive 6K blackbody surfaces. The polarization analysis optics consist of a collimator mirror (R=97%, ϵ=3%, T=2K), a beamsplitter (Trans=48%, ϵ=3%, T= 2K), the camera mirror and folding mirror (same properties as for the collimator), 95μm center wavelength bandpass filter ($\lambda/\Delta\lambda \sim 3$; Trans=60%, ϵ=40%, T=2K in-band, and ϵ=100%, T=2K out of the filter band to the detector response limits at wavelengths of 35 and 115 μm). The Ge:Ga detectors were modeled as having detective quantum efficiencies (DQE) of 25%, responsivities of 6 A/W (resulting in photoconductive gains in the 37-50% range), dark currents of 150 e$^-$/s, read noise of 100e$^-$, and readout electron well depths of $2-4\times10^5$ e$^-$.

The resulting M4 polarimetry performances applied to the Primary Science Program surveys and possible Guest Investigations are listed in Table 3. The ultimate surface brightness sensitivity (NESB = Noise Equivalent Surface Brightness) for M4 polarimetry is about 0.2MJy/sr per root second away from the Galactic plane. Under these conditions, M4 is background limited by the Zodiacal light.

The S/N=150 *requirement* for each $48''$ pixel in each of the two arrays will yield a Stokes parameter, after one observation, with an uncertainty of 0.94%. After two such observations, the resulting percentage polarization uncertainty remains 0.94%. If the detected percentage polarization from the source corresponds to the mean value of 2.5%, the uncertainty in the polarization position angle on these measurements will be 10°, sufficient for making magnetic field structure maps. Note that pixel binning to one beamsize ($2'$) will reduce this angular uncertainty by a factor of 2.5, to 4°.

Reaching the S/N=600 *goal* will yield a polarization percentage uncertainty of 0.236% after observations of U and Q images. This, when combined with a polarization value of 0.6% will yield a position angle uncertainty of 10°. For 1% polarizations, the uncertainty is 6.4°.

Meeting the goals of the Primary Science Program requires angular resolution of about $2'$. However, by using smaller pixels ($48''$), we will conduct experiments aimed at recovering polarimetric information on this smaller angular scale. Such polarimetric superresolution has never before been demonstrated, and the M4 science goals do not require superresolution. Nevertheless, achieving better angular resolution is scientifically important, and we have based the time estimates in Table 3 on achieving the goal of 600:1 S/N in $48''$ pixels.

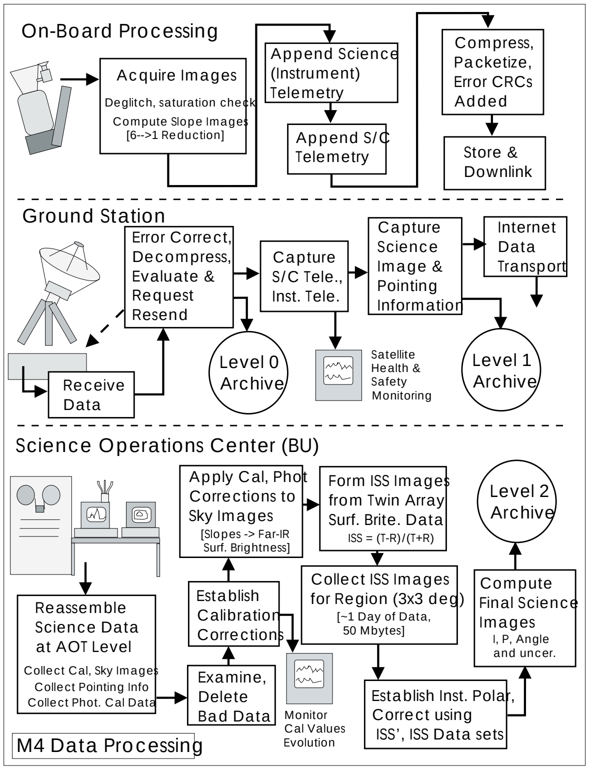

Figure 11: M4 data flow plan.

D.2.e.3. Data Flow and Processing Plan

The plan for data flow, from image acquisition through archiving is shown in Figure 11 for the three major components.

Aboard M4, the 6 NDRs per array DR are each examined for charged particle hits and ramp saturation. For each pixel, the best two NDRs are used to compute a scaled slope value for storage in the "slope image" (this represents a 6:1 data volume reduction). To each slope image, instrument and spacecraft engineering and science telemetry are appended before applying data compression (3:1 assumed), packetization, and error checking CRCs. These data "nuggets" (of size 1.7kbytes) are stored in the spacecraft semiconductor memory until downlink. Table 1 lists the compressed data volume generated for each AOT, including 25% for telemetry.

The maximum daily on-board data storage rate would occur for full utilization of all orbit segments in AOT-1 mode, which is highly unlikely. The resulting data rate is 16 orbits/day × 2.5 AOTs/orbit × 6.1Mbyte/AOT-1 = 244Mbyte per day. In reality, AOT-1 is needed only for 2% of the Prime Mission. All day AOT-2 operations are likely, though, and will generate about 70Mbyte per day. The spacecraft memory (200Mbytes) can hold almost 3 full days of continuous data collection.

Data will be downlinked once or twice per day, and retained on-board for one extra day to permit retransmit if required. At 4Mbps, the 70Mbytes generated in one day require only a little more than 2min of downlink, while M4 will be visible to most ground sites for a total of over 20min per day (aggregate over 16 orbits). Once downlinked, each data "nugget" (of value ~\$14 averaged over then entire mission cost) will be checked for errors, and resend requests generated for missing or corrupt packets to be sent on later downlinks. Error free nuggets will be decompressed and saved in the Level 0 archive. As shown in the middle of Figure 11, satellite health and safety will be derived from the telemetry stream in the Level 0 data and monitored (by GSFC), with corrective action recommendations made to the Boston University M4 Science Operations Center (BU/SOC).

The low data rates permit transfer of data from the ground station to the BU/SOC via either existing internet lines or phone lines and modems. Even with the internet operated during mid-day, moving 70Mbytes across the country takes no more than an hour. Phone modems can provide backup, with download times of under 7hrs for 70Mbytes at 28kbaud. These Level 1 science data, can be archived by GSFC and will be archived by the BU/SOC.

At the BU/SOC, the Level 1 science data will be reassembled into AOT-level observations. Pointing information will be reconstructed from spacecraft and instrument telemetry, star tracker output, and calibration on celestial targets. Residual charged particle glitches and other defects will be edited at this stage. Calibration values for each pixel will be obtained from each pair of target-bracketing calibrations. These calibration values will become part of an ongoing database used to monitor instrument performance trends and to spot anomalies.

D.2.e.3.a. Data Type, Rate, Format, Volume

The calibration values will be applied to correct the target observations. Next the data for the two arrays will be combined to form the Instantaneous Single Stokes image (ISS; U, Q, U', or Q', but also possibly arbitrarily rotated). These ISS and their corresponding ISS$'$ images will be combined across a region larger than a single AOT map, to establish instrumental polarizations and to obtain final Stokes U and Q images. A typical-sized region might represent one day of AOT-2 from the Milky Way survey, of size about $3.5 \times 3.5°$, yielding 50Mbytes of calibrated data.

These final, combined images will be used to produce the final science data and will be moved into the Level 2 archive. The form of the data will be FITS images, containing sky positions in the FITS headers, as well as a history of all calibrations applied and the AOT serial numbers used. For the average region presented in the previous paragraph, the image size is 256×256 four byte pixels. A total of ten of these images will be placed in the archive for this region. These will be images of the values and uncertainties for the following quantities: the total sky surface brightness (Stokes I); the polarization percentage (P); the polarization position angle (θ); the instrumental polarization (P_I); and the instrumental polarization position angle (θ_I). For an average daily Level 2 archive submission rate of 5.2Mbytes, the entire 4-6 month M4 mission will generate a final Level 2 data base of about 1 Gbyte. This can be mastered onto a 2 CD set for distribution, or served out over the internet from a fairly small computer and dedicated disk.

Construction, analysis, and publication of the Primary Science Program survey data sets from the Level 2 archive will be done by a mix of BU/SOC and Science Team members.

E. EDUCATION, OUTREACH, TECHNOLOGY, AND SMALL DISADVANTAGED BUSINESS PLAN

E.1. Education/Outreach Plan

We have instituted an advisory committee composed of local area, state-wide, and nationally recognized formal and informal science educators to work with NASA investigators at Boston University. The committee includes representatives from the Massachusetts Association of Science Teachers (MAST), the Christa Corrigan McAuliffe Challenger Center at Framingham State College, the Science Education team in our Boston University School of Education (including Prof. Douglas Zook, one of the authors of the National Science Education Standards), the Charles Hayden Planetarium of the Boston Museum of Science, as well as local elementary, middle, and high school science teachers and coordinators, and the Boston University Office of Public Relations. This review committee has helped us to identify five major guiding components of a successful SMEX E&PO program. These are:

E.1.a. Guiding Components

Management The M4 E&PO program will be run from Boston University, under the direct authority and with the full participation of the M4 PI, and supervised by a full-time Education/Outreach Manager (EOM). The M4 E&PO program will be reviewed regularly by an advisory committee of educators.

Process The M4 E&PO program must avoid needless duplication and reinvention through ignorance of exiting materials and standing programs. Our E&PO program will include a period for market assessment, preceding any phase of materials development. In addition to developing new materials, we will include components of teacher training (both pre-service and in-service), regular review and assessment of the effectiveness of the products and training we develop, and long-term support of our products and materials.

Teaming The maximum leverage of educational impact occurs when classroom materials are developed with the direction and assistance of teachers, are evaluated by teachers, are adopted by teachers, and are promoted by teachers. We will work toward improving our educational leverage through teaming in two ways. One is to include co-development of pre-service teacher training units (and research opportunities) with the Microcosmos program run within our Science Education division of the Boston University School of Education, under the direction of Professor Zook. Joining the forces of the existing, strong Microcosmos program with the excitement of the M4 active space flight mission will lead to a powerful attraction for teacher involvement in both programs. The second path involves working with the Massachusetts Association of Science Teachers (MAST) and the Christa Corrigan McAuliffe Challenger Center at Framingham State University to identify interested and energetic elementary, middle, and high school teachers eager to help co-develop, stage, and evaluate the new classroom units and programs developed within the M4 E&PO program.

We are also aware of NASA inroads via the Facilitator/Broker and Forum initiatives. We look forward to working with the selected units to boost our leverage, especially via appropriate distribution of our developed materials and approaches. We will not duplicate the functions of these NASA-sponsored programs.

Content We are interested in bringing the unique aspects of the M4 mission to the public and into the classroom. We are equally well-aware that arcane jargon and slick photographs can produce unintended negative consequences, and that working closely with educators is required to strike a balance that serves all. The M4 theme in the area of content is to “Bring the Galaxy Closer”. This Science Team and the Boston University Astronomy Department are expertly staffed with practitioners of Milky Way astrophysics. We are the best groups to help elementary students come to know and embrace the Milky Way, to show middle school students where and how new stars are born, and to help high school students come to understand why angular momentum conservation during protostellar collapse naturally leads to disk and planet formation.

Commitment Our advisory board specifically identified long-term commitment, including teacher support, as the most important aspect of any NASA-related program. The educators are wary of “here today, gone tomorrow” programs, and strongly urge us to design programs and processes for the long term. We see the SMEX time scale (7-8 years) as being very conducive to long-term support of significant E&PO programs, and an ideal vehicle for building long-term relationships with local, state, and national level educators and their students.

E.1.b. M4 E&PO Goals

After meeting with our advisory committee, we have identified three E&PO goals we can accomplish during the course of the M4 investigation.

The first goal of our E&PO plan is to develop and broaden our educational advisory forum into an ongoing meeting and review series. In this series, the needs of the educational community can be articulated to the M4 project and to the Boston University portion of the NASA-sponsored science community, and our planning and development of teacher and student materials can be reviewed and critiqued. We have budgeted sufficient resources in the B/C/D/E phases to sponsor frequent meetings of our forum, and to sponsor representation at yearly MAST and other regional meetings.

Our second goal is to help co-develop a set of classroom activities (lesson plans) which focus on the content theme of "Bringing the Galaxy Closer." We plan to allocate up to about 10% of project personnel time to helping to co-develop age-appropriate curricula and materials. We have also included summer support for pre-service teachers in our School of Education to join the M4 BU/SOC to assist with material development and evaluation and to gain experience in the conduct of research. M4 project personnel will visit classrooms to demonstrate these lesson plans and to try out video conferencing technology (and perform teacher training on these units, see below). In order to support more teacher exposure to the research process (i.e., more than mere exposure to research results), and to provide input to the lesson plan development process, we expect to pursue additional NASA add-on funding to allow inclusion of teachers in our summer research and education endeavors.

The final goal of our E&PO plan is to distribute and support the infusion of a modest amount of computer and internet technology to disadvantaged area schools. To this end, we have budgeted funds to purchase 25 PCs (at $2000 each), and 40 video conferencing units (at $400 each). These units attach to the new PCs (and existing PCs - hence the mismatch in the numbers of computers and video units) and allow live two-way interactive video conferencing across the internet.

We expect to use this video conferencing method to support an interactive "Live from the Galaxy" series of sessions for our client schools. In such a regular, two-way meeting, students can form significant relationships with our investigation team in the most efficient manner possible (for everyone!). Additionally, by placing these units in multiple schools, school-to-school video conferencing will be possible, effectively multiplying our impact several-fold. Because of the ubiquity of the internet, distance is not a critical factor, making school-to-school and program leveraging possible clear across the country. *[Note that we are not budgeting funds for* **establishing** *internet connections. We intend to rely on our skills and personal connections to find the most cost effective strategy for getting these PCs and video units access to the internet, either through existing direct internet lines or via additional phone lines and fast modems.]*

We also believe it is important to provide incentives for our researchers and project members to become involved and vested in E&PO activities, especially in light of the already heavy burdens on their time. Technology infusion and training can meet some of the needs of some area schools while also acting as incentives (i.e., "new toys") for our personnel to explore and master while working with teachers and their students.

E.1.c. Implementation

Our E&PO program beings at the outset of Phase B (March 1998) with the hiring of the full-time M4 Education/Outreach Manager (EOM), and some early, limited experiments in supporting local area school teachers via internet video conferencing. The E&PO program, and budget, grows through Phases C and D mostly in the areas of developing the educational forum meeting series, performing a market assessment for relevant or related classroom materials, and beginning to outline the elements of our lesson plan development program. Technology infusion will progress at a fairly constant rate of outfitting new schools and revising our video conferencing offerings, style, and contents. As M4 moves into the flight phase, completes it short mission, and leaves its rich legacy of unique data, the BU/SOC is expected to grow to support the larger data processing and analysis needs of the project. This growth is echoed by an even stronger growth of the E&PO program, to an annual budget of over $200,000 during the Phase E years (FY2001, 2, 3, and 4). During this final project period, two School of Education (SEd) pre-service teachers (Masters students) will be funded each of three summers to join in our efforts to develop materials, critique our lesson plans and implementations, become involved in the video conferencing activities, and learn first hand how space science investigations are performed. The overall non-launch costs budgeted for M4 E&PO activities total 1.27M$, or 2.4%, not counting the 10% of personnel time reserved for E&PO participation.

E.2. Technology Plan

As part of the SMEX program, the M4 mission is a response to the desire to have frequent, less expensive missions that address specific science topics. This approach requires innovative technology that can offer significant cost and/or performance advantages in order to meet these goals. At the same time, the technology used must be well developed in order to be able to accommodate the abbreviated schedule required to meet the SMEX program development times.

The M4 mission utilizes such innovative, well-developed technology in several areas - e.g., the cryostat, the detector arrays, and the spacecraft bus. The superfluid liquid helium cryostat for the M4 mission is based upon a recent Ball technology demonstration dewar that was funded internally to support the SIRTF Cryogenic Telescope Assembly program. The M4 mission uses a slightly modified version of this technology demonstration dewar, thereby realizing significant cost savings. In addition, the experience gained in designing and building the demonstration dewar will lower risks to cost and schedule.

The detector arrays also leverage the development effort for the SIRTF program. The M4 mission uses two Ge:Ga arrays that are identical to those being built for the SIRTF MIPS instrument. The M4 detectors will be constructed by the same personnel and using the same facilities as the SIRTF detectors. The schedule for the M4 arrays will dovetail well with the SIRTF detector schedule. Hence, M4 will benefit from cost and risk viewpoints.

The spacecraft bus is another area where M4 stands to benefit from the recent development of relatively low-cost, high performance buses that have the design heritage of earlier generations of spacecraft. A new generation of spacecraft (e.g., SMEX-Lite and similar Ball buses) are smaller, lighter, and more flexible in their capability to accommodate different mission requirements, yet offer the same or better performance than earlier spacecraft designs.

E.3. BATC Disadvantaged Business Plan

It is the policy of Ball Aerospace and Technologies Corporation (BATC) that Small Business Concerns, Small Disadvantaged Business Concerns, and Woman Owned Small Business Concerns, as well as Historically Black Colleges and Universities and Minority Institutions, shall have the maximum practicable opportunity to participate in the performance of Subcontracts, awarded by BATCs Procurement Department. This is reflected by the steadily increasing percentages reported on BATCs SF295s for NASA contracts below.

TABLE 4: BATC SDB PERFORMANCE

Year	SDB Actuals
1994	6.8%
1995	7.9%
1996	8.1%
1997	11.8%

During the M4 Concept Study, BATC will examine the participation of minority and woman owned small businesses as part of Ball's M4 procurement plans in order to meet NASA's goals. BATC will prepare a Subcontracting Plan for Small, Small Disadvantaged, and Woman Owned Small Business Concerns during the Concept Study phase of the M4 program effort.

BATCs Small Business Program and their Master Plan is approved by Defense Control Management Command (DCMC). BATC was awarded the Small Business Administration's "Award of Distinction" in 1992. BATCs Small Business Liaison Officer has served on the Board of Directors for the Small and Disadvantaged Business Outreach Committee for the past eight years, and is currently Vice-Chair.

F. MISSION IMPLEMENTATION

F.1. Mission Overview

The M4 mission begins with a 3.5 year design and development phase, culminating with launch on 1 March 2001. M4 flight operations span 4 to 6 months, ending when the 110L of cryogen are exhausted. The M4 mission ends after a 3 year phase of data analysis, delivery, and science findings publication.

F.2. Instrument: Requirements, Design, Mass, Power, Volume, and Lifetime

Operating at a wavelength of 95μm, the M4 instrument requires cryogenically cooled optics and detectors to reduce the background levels sufficiently to achieve the science goals. This one requirement drives the design of the instrument to the use of a superfluid liquid helium cryostat. To allow observation of the desired portion of the sky (the plane of the Milky Way within $\pm 50^\circ$ of longitude of the Galactic Center) and yet achieve sufficient helium lifetime (4 months minimum), a passively cooled light shield is required. The M4 instrument conceptual design, as shown in Figures 5 and 9, meets these requirements and fits within the SELVS II payload envelope. Total instrument mass, as detailed in Table 5, is 115 kg. Optimum instrument pointing is achieved by mounting the star tracker used for attitude control on the outside of the instrument cryostat and aligning it with the telescope axis. The instrument has no moving parts and instantaneously detects one linear Stokes parameter. AOT-driven spacecraft roll maneuvers will change the instrument field of view 45° around the line of sight to develop complete linear polarization data sets. The simplicity of the instrument keeps power consumption low - only 30 watts, as detailed in Table 5.

F.3. Spacecraft: Mass, Power, Volume, Data Handling / Storage, and Lifetime

Table 6 lists the major systems of the M4 spacecraft and the mass and power values for the Ball-Jr and SMEX-Lite spacecraft. Using the Web-posted values for SMEX-Lite, we also developed a partial sub-system breakdown within most of the major system categories, and these are listed in the table. For SMEX-Lite, we substituted the lighter CT631 star tracker which permits gyroless operation (a big mass savings). The two S/C are fairly similar in their mass distributions. Exceptions include the Power and Structure lines, where the solar panel back-up structure appears in the Structure line for the Ball S/C, but in the Power line for the SMEX-Lite S/C. The other main difference is in the CD&H line, where the lightweighted SMEX-Lite wiring produces a significant mass savings.

Both S/C use the same computer system, both have identical data storage (200 Mbytes) and communication resources. Both S/C have lifetimes limited only by earth eclipses, which will not occur during either the Prime Mission or the Extended Mission.

F.3.a. S/C Acquisition Options

Execution of the data collection portion of the M4 mission, and instrument accommodation do not produce strong constraints on spacecraft performance, except for S/C volume (especially height). Both the Ball-Jr and SMEX-Lite buses will meet all M4 performance requirements. During proposal development, we directed available attention to resolving instrument concerns, and deferred detailed S/C design and optimizations until Phase A.

The three S/C acquisition options are: select the Ball-Jr bus, in its current configuration; select the SMEX-Lite bus, in the configuration called out in Table 6, or; develop a hybrid S/C bus at Ball, incorporating the highest performance (or lowest mass) components from SMEX-Lite. The first option is easiest, but leads to higher S/C cost, relative to the aggressively developed SMEX-Lite bus. The second option is likely less expensive in direct acquisition costs, but will increase integration costs substantially. The final option, while requiring more Phase A effort, will result in lower overall costs (acquisition+integration, since integration will be performed at Ball, where the M4 instrument will be developed).

We received a cost estimate for the Ball-Jr S/C (Appendix) and applied a 15% reduction factor to develop the estimated costs in Table 7 for a hybrid Ball-GSFC S/C.

F.4. Spacecraft / Instrument Integration

The mechanical, thermal, and electrical interfaces between the instrument and spacecraft are clean and simple. The cryostat girth ring provides a rigid structural attachment point on the instrument which is attached to the spacecraft via a set of struts. These struts also provide thermal isolation between the instrument and spacecraft. This approach facilitates independent development of the instrument and spacecraft. The electrical interface between the instrument and spacecraft consists of unregulated power, a MIL STD 1553 bus, and an RS-422 serial link. As described above in §D.2.a.2.c., the instrument will require no dedicated processors and all instrument control software will be implemented in the spacecraft control computer.

F.5. Launch Vehicle

The launch vehicle for M4 will be a standard SELVS II, with Fairing A. The only known constraints on launch site are the requirement to be able to easily manage cryogen loading into the instrument prior to launch.

F.6. Ground System & Communications

During the launch, performance verification, and early operations phase, satellite scheduling will be done by the BU/SOC and relayed to GSFC for checking and uplink to M4 via existing NASA ground stations. Data downlink will route back through GSFC and on to the BU/SOC for processing and analysis.

Commands to control the M4 spacecraft and instrument will be generated and uplinked at least once daily, with a goal of two uplinks per day. Each uplink of commands will contain enough information to cause the satellite to execute two days of AOT-based observations. Data to be downlinked from the satellite will consist of spacecraft and instrument housekeeping information and instrument science data. The downlink requirement is at least one 2 minute downlink at 4Mbps per day, with a goal of two such downlinks per day.

The low data rate and robotic operation of M4 generate such light communications requirements that ground station details have been deferred to Phase A. We will use existing NASA facilities, on a fee-for-use basis, and have reserved over 0.25M$ of Phase E funds (about 100 times the cost expected using the tables in the AO – this represents another cost margin). We have also deferred to Phase A development of a detailed plan for GSFC-supplied services, but have reserved about 0.84M$ in the ground support budget for GSFC. GSFC duties will include monitoring of satellite safety, spacecraft health, and satellite schedule checking. GSFC will receive science observation schedules from BU/SOC, modify those schedules as necessary to include spacecraft commands needed to achieve the science goals and maintain satellite safety and health, and transmit the final schedule to the NASA ground station(s) for uplink. GSFC will accept downlinked data from the ground station(s) and transmit Level 0 (and/or Level 1) data to BU/SOC.

F.7. Margins Summary

Mass margins to the 500km altitude circular orbit are 11-18% (25-50kg). Power margins are 26-36% (44-61 W). Date rate margins are 200-300% (M4 will require 2min of data downlink per day, with up to 6min of data downlink available for one overhead pass). The current thermal model indicates a 4.4 month lifetime for the 110L of cryogen. This allows a minimum cryogen lifetime margin of 15%, as called out in Table 2 under the Prime Mission. The Extended Mission is understood to be carried out “at risk” and depends on extraordinary cryogen lifetime (as was recently seen in the 10 month [55%] addition to the 18 month designed *ISO* lifetime).

F.8. Potential Risks and Mitigations

There are some areas of potential risk for the M4 mission. The major area of technical risk is the ejectable cover. It is required on the ground and during orbit ascent to maintain the cryostat vacuum (to minimize loss of superfluid helium) and to prevent contamination. It will be ejected on orbit. Previous missions (*IRAS*, *COBE*, *ISO*) have used ejectable covers and the technology is straightforward, yet M4 presents risk because the cover is ejected from inside the forward light shield. To mitigate this risk, additional engineering resources will be allocated to designing and developing an ejection mechanism that will ensure safe removal of the cover. Building and testing a prototype of this mechanism will be needed to verify the design.

Cost and schedule have been identified as areas of programmatic risk. Designing, building, and integrating the instrument, cryostat, light shield, and S/C subsystems within the SMEX budget and schedule constraints presents considerable challenge. To mitigate these risks, we will have a tightly integrated product development team (IPDT) including the M4 BU/SOC, the M4 Science Team, the Ball design and development team, and NASA project managers and reviewers. By working together at early stages to identify cost and schedule critical elements in the design and development of the M4 mission and focusing resources on these areas, we will minimize unexpected costs and schedule delays.

Table 5: M4 Instrument: Mass and Power

System	**Mass**			**On-Orbit Power**		
Subsystem basis	**[kg]**	**[kg]**	**[%]**	**[W]**	**[W]**	**[%]**
Instrument Totals	**115**		**100.0%**	**30**		**100.0%**
Cryostat	***86***		***74.8%***			
Cryostat Tank		10	8.7%			
Vacuum Shell & Ejectable Cover		26	22.6%			
Vapor Cooled Shells (2)		4	3.5%			
Girth Rings and Support Straps		20	17.4%			
Valves, Manifolds, Burst Disks, Tubing		10	8.7%			
110 liters of Superfluid Liquid Helium		14	12.2%			
Multilayer Insulation (MLI)		2	1.7%			
Forward Light Shield	***11***		***9.6%***			
Inner Winston Cone		3	2.6%			
Outer Cones		5	4.3%			
Mounting Brackets		2	1.7%			
MLI		1	0.9%			
Telescope Assembly and Analysis Optics	***6***		***5.2%***			
Primary & Secondary		1	0.9%			
Supports, Secondary Spider, Structures		2	1.7%			
Baffles		0.1	0.1%			
Collimator and Mount		0.3	0.3%			
Beamsplitter and Mount		0.2	0.2%			
Camera Mirrors and Mounts (2)		0.4	0.3%			
Flat Mirror and Mount		0.1	0.1%			
Fold Mirrors and Mounts (2)		0.3	0.3%			
Detector Arrays and Heat Straps (2)		1.4	1.2%			
Stimulator and Heat Straps		0.2	0.2%			
Electronics	***9***		***7.8%***	***30***		***100.0%***
Detector Arrays Driver Circuit Boards (2)		1.8	1.6%		10	33.3%
Instrument - Spacecraft Interface Board		1.4	1.2%		5	16.7%
Instrument Power Conversion and Distrib.		2.8	2.4%		15	50.0%
Cables and Connectors		1	0.9%			
Electronics Housings		2	1.7%			
Star Tracker Support Structure	***3***		***2.6%***			

Table 6: M4 Spacecraft Options: Mass and Power
for Ball-Jr and SMEX-Lite Spacecraft

System	**Mass**		**On-Orbit Power**	
SMEX-Lite Subsystem Basis	**Ball-Jr**	**SMEX-Lite**	**Ball-Jr**	**SMEX-Lite**
	[kg]		**[W]**	
Spacecraft Totals	**129.0**	**109.7**	**95.0**	**79.0**
Structure & Mechanisms	***51.0***	***30.6***	***0.0***	***0.0***
Mechanical Structure		21.9		0.0
Separation Ring		4.0		0.0
Spacecraft Harness		4.7		0.0
Power Generation and Distribution	***32.0***	***46.2***	***21.0***	***8.0***
Solar Panel (1.5 sq. m) 13 "platelets"		35.8		0.0
Battery (Launch Power only) 5 Ah		5.0		0.0
Power Node		5.4		8.0
Command & Data Handling (Computer System)	***19.0***	***7.3***	***30.0***	***20.5***
RAD 6000 32-bit RISC Processor		4.5		13.5
200 Mbytes DRAM		0.5		2.0
Utility Node		2.3		5.0
Communications	***5.0***	***4.9***	***5.0***	***10.0***
Antenna Assembly		0.4		0.0
Transmitter (5 Watt)		3.6		6.0
Receiver		0.9		4.0
Thermal Control System	***2.0***	***1.6***	***7.0***	***15.0***
Attitude Control System	***20.0***	***19.1***	***32.0***	***25.5***
Ball CT631 Star Tracker		2.5		8.2
Sunshade for Star Tracker		0.2		0.0
Magnetic Torquers		1.5		1.3
Reaction Wheels (3)		13.5		15.0
Sun Sensors (coarse)		0.9		0.9
Magnetometer (3-axis)		0.5		0.1

G. MANAGEMENT AND SCHEDULE

G.1. M4 Project Management

The M4 project lead organization is Boston University (BU). Within BU, the Principal Investigator, Professor Dan Clemens will have responsibility and authority for the project. In support of the M4 mission, the BU M4 Science Operations Center (BU/SOC) will be established to act as the day-to-day managing unit. The PI will oversee the BU/SOC, and chair the BU/SOC senior management team, consisting of the Deputy Principal Investigator (DPI, Jones – ex officio BU/SOC member), the Project Manager (PM), the Business Manager (BM), the Education/Outreach Manager (EOM), and the Computer Facilities Manager (CFM). The PI will also act as the Science Manager for the BU/SOC.

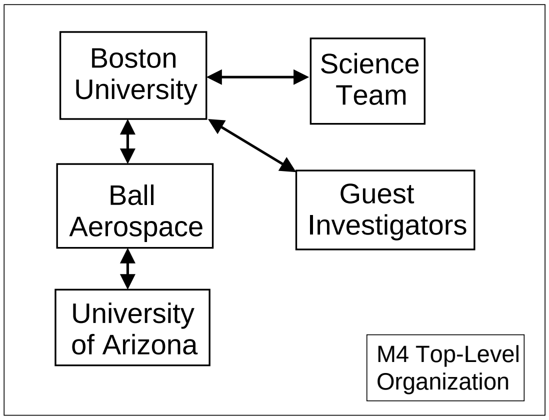

Figure 12: M4 Top-Level Organization Chart

The two major management tasks for the BU/SOC are to oversee the procurement of the M4 satellite from Ball Aerospace and to manage Mission Operations and Data Analysis during Phase E. The former is more challenging and will require significant attention to monitoring Ball to insure that the M4 procurement remains on schedule and on budget.

G.1.a. Organizational Structure

The top-level organization of the M4 project is shown in Figure 12. BU will be the lead organization. Ball Aerospace will be under subcontract to BU to supply the M4 Instrument, the M4 Spacecraft, to perform Integration of the two, and to support launch vehicle integration, launch, and on-orbit checkout. Ball will in turn subcontract to the University of Arizona for delivery of the detectors. Science Team members will be supported by BU subcontracts to assist in systems engineering and technical reviews (DPI Jones), data processing algorithm development and application (Lord), and science data analysis and interpretation (full Science Team). Guest Investigators will receive BU subcontracts to perform data and science analyses.

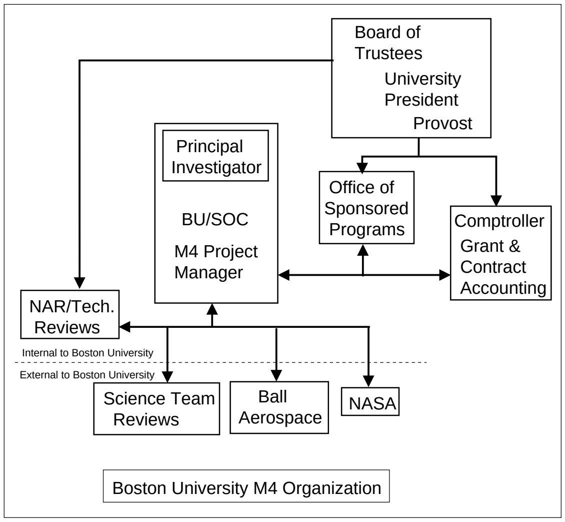

Figure 13: Boston University M4 Organization Chart

The Boston University organization is shown in Figure 13. The PI is the project authority, and delegates actions and tasks to the BU/SOC members. Fiscal oversight is provided by a combination of functions from the Office of Sponsored Programs and by Grant & Contract Accounting. These units advise on issues of sponsor requirements and contract and subcontract provisions. They in turn receive authority from the PI to release funds to subcontractors. The M4 PM will act with the authority of the PI as a single point of contact between these BU units and the subcontractors for most day-to-day activities.

The NAR/Tech Reviews box represent internal periodic (see Schedule, below) reviews of the cost, schedule, technical, and managerial aspects of the project. The NAR/Tech. reviews are meant to assist the PI in maintaining project momentum and to update the University regarding its interests in the project.

All external agencies will conduct normal day-to-day business through the BU/SOC, either directly with the PM or with the BM.

G.1.b. Project Responsibilities

The PI has overall project responsibility and authority. The PI represents the project to NASA, and is the single point of contact for receiving guidance back from NASA regarding the conduct of all aspects of the project. The

PI oversees the BU/SOC, chairs the Science Team, and represents the project to the Boston University Central Administration.

All top-level (major systems level or above) decisions are made by the PI, generally in consultation with the Science Team and the BU/SOC senior management team. The PI will continue to act as the BU/SOC Systems Engineer. The PI will also act as the BU/SOC Science Manager, mentoring the postdoctoral researchers, graduate students, and undergraduates.

Project Managers at BU receive their authority from Principal Investigators and are responsible directly to their PIs. PMs do not act independently, nor under authority of other offices at the University. The M4 PM will have responsibility for developing and updating project schedules and budgets (with the assistance of the Business Manager). The PM is expected to review the details of subcontractor costs and schedule performance, and will travel frequently to Ball Aerospace to execute these reviews. The PM will act as the normal day-to-day single point of contact between the BU units (Office of Sponsored Programs and Grant & Contract Accounting) and the subcontractors for matters of cost and schedule. The PM will be responsible for organizing the internal reviews (NAR/Tech.) and the external reviews (Science Team and NASA). The PM will help develop policy recommendations, remedies to project problems, and summarize future actions identified in reviews and will communicate these to the PI.

[At the present time a PM for the M4 BU/SOC has not been identified. The Department of Astronomy is currently advertising for a Satellite Engineer/Project Manager. It is expected that the M4 PM will be in place at the beginning of Phase B.]

G.1.c. Reviews and Management Tools

The M4 project is a large endeavor for Boston University and the PI. Nevertheless, the recent experience of developing the *TERRIERS* STEDI satellite here has shown the effectiveness of detailed schedule development and the importance of frequent project reviews. For the M4 project, we have planned four levels of reviews. At the lowest level, the PI+PM and DPI will travel to Ball Aerospace almost every month to hold informal reviews, identify problems, and recommend solutions. These informal reviews foster teaming between the scientists and the engineering staff, permitting higher level trades and systems level solutions. The next level of reviews are the internal NAR (non-advocate reviews)/Technical reviews to be conducted at BU. These will be used to review project technical aspects before local satellite and science experts (with MIT and Harvard consultants, as needed), and to review the cost, schedule, and management aspects before Astronomy Department, College of Arts and Sciences, and University representatives. The third level of review by the M4 Science Team will review progress at Ball Aerospace and at BU. The final level of reviews are the formal NASA reviews. These take place at the end of Phase A, Phase B (PDR), Phase C (CDR), Phase D (Flight Readiness Review), and Phase E (Project Summary Review).

In the schedule, the PI/PM/DPI trips to Ball are not shown, but the NAR/Tech., Science Team, and NASA reviews are all indicated. In general, the Science Team reviews are scheduled at 6 month intervals, shifted to allow examination of progress within any Phase near its middle, and toward its completion. NAR/Tech. reviews are placed between the Science Team reviews, with a NAR/Tech. review placed one month in advance of each NASA review.

At the BU/SOC, management planning and tracking will utilize the Microsoft Project software, with cost and budgets developed using Microsoft Excel. These represent continuations of existing tool usage.

Ball's proven utilization of project management tools for overseeing their internal management of M4 design and development is expected to continue, also. Ball's experience in *IRAS*, *COBE*, *SWAS*, and in *SIRTF* development all attest to their superb qualifications for developing M4. Ball is currently moving toward ISO9000 certification.

The Science Team is similarly highly qualified for this mission, with direct experience in designing and developing *IRAS*, NICMOS, *SIRTF* and *SIRTF* instruments and in fielding state-of-the art polarimeters on a wide variety of telescopes.

G.2. Schedule

The top-level schedule is shown as the following fold-out page (Figure 14). The overall phase breakdown is as follows: a 5 month Phase A Concept Study; a 12 month Phase B

Design Study; a 8 month Phase C Definition Study; a 17 month Phase D Development, including the launch date of 1 March 2001; and, a 42 month Phase E Mission Operations and Data Analysis period.

The overall philosophy used in developing this schedule was to include as many design and review cycles as possible before beginning hardware development. Risks can be reduced and reliability enhanced if all design aspects are fully developed and rigorously examined prior to construction. The difficulty is that the construction phase is then very short.

On the fold-out, the major activities and milestones are listed within each phase, followed by the planned internal and external reviews. Within Phase D, the instrument and S/C developments are listed independently, and their integration to each other and to the launch vehicle specifically called out.

In Phase E, the data delivery activities are identified by data Level. Reviews in Phase E are held frequently around the Mission Operations portion, and less frequently during the Data Analysis portion.

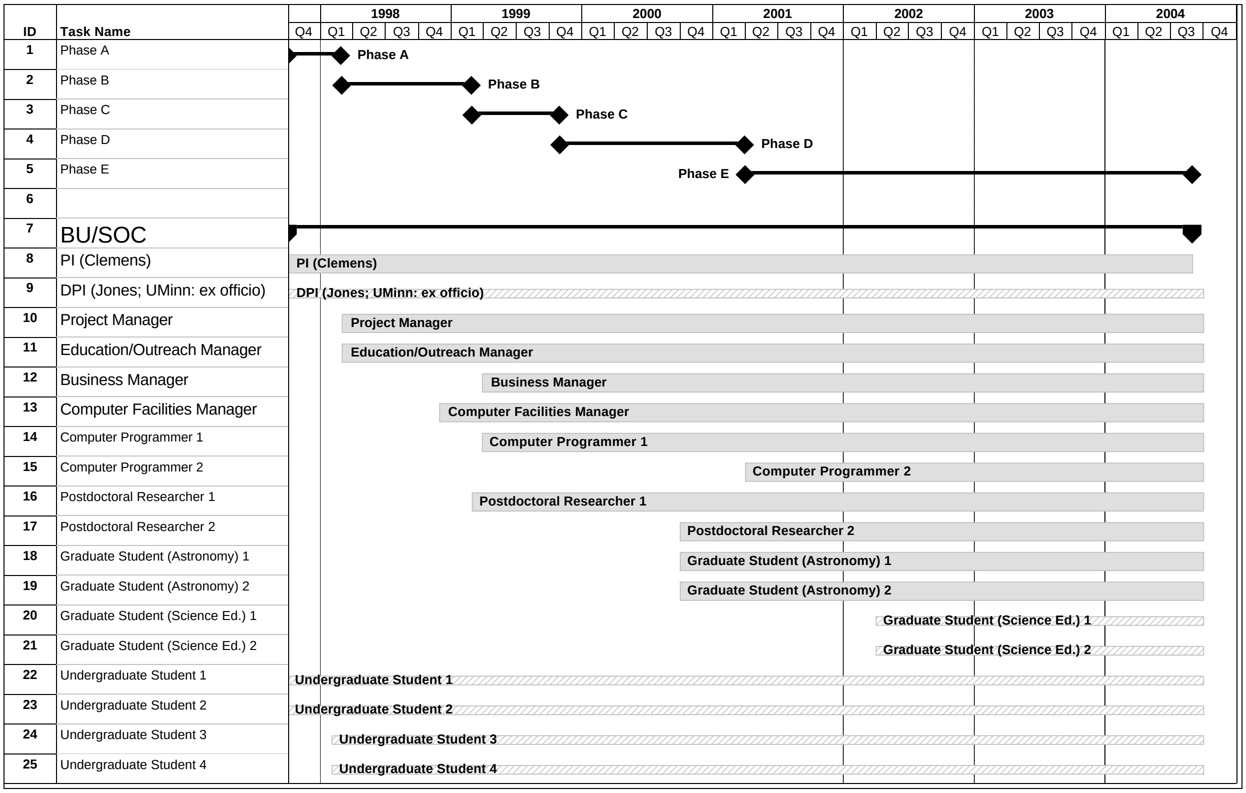

Figure 15: Timeline of BU/SOC staffing levels versus M4 project phase and date. Full-time (or equivalent) positions are indicated as solid bars, part-time as hatched bars. The BU/SOC senior management team consists of the PI, DPI, PM, BM, EOM, and CFM.

G.2.a. BU/SOC Development Schedule

The M4 Science Operations Center (BU/SOC) will be established at BU beginning with Phase B. The BU/SOC staffing plan versus time is shown in Figure 15. This chart shows the deployment of senior management positions (PI, DPI, PM, EOM, BM, and CFM) and the staff positions (CP1, CP2, PD1, PD2, GSA1, GSA2, GSE1, GSE2, UG1-4). Although the DPI is called out in the BU/SOC staffing, he will continue to reside at the University of Minnesota.

This phased staffing meets the twin management requirements of: (1) providing sufficient oversight of Ball Aerospace with early staffing of senior management lines in the BU/SOC, and; (2) providing sufficient personnel in the lead up to launch, during mission operations, and during data analysis in order to effectively operate M4 and to perform required levels of data processing an analysis.

H. COST AND COST ESTIMATING METHODOLOGY

A top level summary of the cost plan for the M4 mission is shown in Table 7. In the following, the cost methodologies and bases are discussed, and actions called out by project phase.

H.1. Methodologies Discussion

Boston University Costing Methodology The costing for BU activities is based on the full expected costs associated with a phased BU/SOC development and a full E&PO program. In our costing, each trip, person, and major purchase were delineated, based on recent travel, hiring, and procurement experience. All 23 subcontracts were costed including partial IDC burdening.

As part of this proposal, Boston University proposes to become a partial sponsor of Phase E activities. The form of this contribution is a waiver of the IDC burden on the Guest Investigator subcontracts. **This allows all M4 GI funds to flow directly to the Guest Investigators.** This contribution totals $253,125 of indirect cost support. Additionally, Boston University maintains a voluntary program of tuition remission for graduate students on stipends from on-campus research grants. For the two Astronomy graduate students hired in Phase E, the total for this voluntary support is $153,790. NASA costs have been offset by the amount of the GI support, but not by the amount of the voluntary support.

Ball Costing Methodology (for attached M4 ROM) The costing methodology for the Ball M4 Price ROM is based on a two-level approach. The first level involved a roundtable discussion of the M4 mission with senior Ball engineers and program managers with extensive experience and history with the many space instruments and missions. Based on the M4 mission requirements and an approximate schedule, a first level cost estimate was made.

The second level of price estimating was done by establishing a preliminary program schedule based on the requirements of the NASA SMEX AO and a 1 March 2001 launch date. A preliminary Work Breakdown Structure (WBS) was constructed, and a level of effort/equivalent personnel estimate was made for each of the WBS elements (except for the cryostat and spacecraft bus elements, see below). Where possible, comparisons and estimates for manpower and materials were made by using historical data from other Ball programs (e.g., *SWAS*). Appropriate labor, material, and burden rates were applied to produce estimates in 1997 dollars.

The cryostat ROM price was based on the actuals incurred for the Ball internal program to demonstrate current superfluid liquid helium dewar technology, as will be applied to *SIRTF*. The actuals were adjusted to reflect additional engineering to modify the dewar design to accommodate the M4 mission and to provide a flight qualified dewar.

The program was then broken into three subsystems: the cryostat/light shield, the instrument, and the spacecraft bus. The program management, system engineering, integration and test, and operations WBS elements were allocated to the cryostat/light shield, and instrument subsystems by their respective cost fractions. The costs for the spacecraft bus, and the costs for the spacecraft support required during integration and test and operations were separated from the instrument and cryostat/light shield to allow price estimates from other spacecraft sources to be compared.

The roundtable (first level) and detailed EP (second level) estimates agreed to better than 10%. No contingency has been built into the price ROM provided.

Boston University Modifications to Ball Cost Estimate The budget values contained in Table 7 do not perfectly reflect those contained in the Ball Price ROM. The non-spacecraft Ball values were decreased by 5%, while the spacecraft values were reduced by 15%. In the case of the spacecraft, significant cost savings are expected to be realized by procuring SMEX-Lite components from GSFC for the Ball-built spacecraft. The SMEX-Lite spacecraft costs published by GSFC represent a significant improvement over past SMEX spacecraft bus costs (e.g., *SWAS*). By migrating some of the highest performing components to the Ball spacecraft, costs should decrease.

Further, we have not seen the full bases for the instrument costs. Careful scrutiny during Phase A should uncover 5% of additional savings. A basis for this expectation can be found in the allocation of tasks during proposal preparation. The PI performed all of the optical design for the instrument, and undergraduates under the direction of the PI developed the M4 mission flight simulator used to test hardware and operations concepts. By identifying and migrating more of these types of tasks to the PI and Science Team members, cost savings of the order of 5% are expected.

Throughout each of phases B/C/D/E, a cost margin (contingency) of 6.75% is reserved in the Table 7 budget. During the flight phase, this contingency is increased to 25%.

H.2. Phase A

During the Phase A Concept Study, work will take place at BU and at Ball Aerospace, with a funding split of $89,354 for BU tasks and $160,000 for Ball Aerospace tasks. The costs at BU include release salary for the PI, plus funds for two undergraduate work/study students (Jason Wright and Paul Ilardi, the authors of the M4 Mission Operations Simulator). Travel funds will enable two PI trips and one DPI trip to Ball Aerospace to review Ball activities and to work on the Concept Study. Funds are included for one Science Team meeting in Boston to review the Concept Study report before release to NASA.

During Phase A Ball will:

1. Fully define the design and development phase (phase B/C/D) of the M4 instrument by: developing the system concept; supporting development of the operating plan; developing M4 instrument support requirements and interface agreements between the instrument and spacecraft; identify high risk items and potential alternatives; and support BU's preparation of the M4 implementation plan.
2. Support reviews and presentations: routine informal peer reviews with science team; and, mission definition and requirements review.
3. Prepare an M4 instrument performance requirements document as a basis for Phase B/C/D development and instrument acceptance.
4. Prepare and submit an M4 performance assurance plan.
5. Review and approve University of Arizona developed designs and plans (including program plans and performance assurance plans) for the focal plane arrays (and warm electronics).
6. Work with the University of Arizona in developing the detector subsystem designs and to establish detector subsystem costs.
7. Manage the M4 instrument definition program, including coordination with BU and the M4 team, liaison with NASA and provision of schedule and cost control and required reporting.

H.3. Phase B

The Phase B Design Study takes place at BU and Ball Aerospace. Additional subcontracts will be to the University of Minnesota (DPI time) and to IPAC (Co-I Steve Lord).

The BU/SOC computer system augmentation will begin, as will the full E&PO program. Data processing algorithm development will begin, and mission operations scheduling software will continue refined development. During this phase the Science Team will convene once in Boston and once at Ball Aerospace to review progress. PI and PM travel to Ball totals 13 person-trips, with three more DPI trips to Ball.

During Phases B and C Ball will:

1. Initiate the M4 instrument design and development in accordance with approved project plans and procedures. Work in close coordination with the University of Arizona in developing the detector subsystem designs.
2. Negotiate the development phase contract with BU and all related subcontracts.
3. Manage the program, including coordination with the M4 team, liaison with NASA and provision of schedule and cost control and required reporting.
4. Support reviews and presentations: routine informal peer reviews with science team; Systems Concepts review; Preliminary Design Review (PDR) with NASA; Critical Design Review (CDR) with NASA.
5. Manage the instrument design program, including coordination with BU and the M4 team, liaison with NASA on technical interface issues, provision of schedule and cost control, and support the planned project reviews (PDR and CDR).

H.4. Phase C

The Phase C Definition takes place at BUn, Ball Aerospace, and the University of Arizona (AU).

At BU data processing algorithm development and implementation takes place, scheduling software is implemented and verified. One Science Team meeting will take place in Boston. PI and PM travel to Ball totals 7 person-trips, with another 3 trips for DPI travel to Ball. PI and PM trips to NASA HQ and/or GSFC total two person-trips, plus one for the DPI.

H.5. Phase D

The Phase D Development period consists of three sub-phases: a 13 month construction phase, a 3 month flight integration phase (M4 satellite to SELVS II), and a one month launch and early operations phase. Activities will take place at BU, Ball, GSFC, and the launch site.

At BU, staffing of the BU/SOC remains constant relative to Phase C levels, up to the end of FY2000. At that time, in the run up to flight integration and launch, the PI level increases to 100%, a second Postdoctoral Researcher and two Astronomy Graduate Students are added to support preparations for flight and flight operations. During Phase D, the Science Team will convene once at Ball and once in Boston. PI and PM travel includes 16 person-trips to Ball and 4 person-trips to NASA. DPI travel is 4 trips to Ball and 2 to NASA.

During Phase D (Development) Ball will:

1. Develop a detailed instrument design incorporating the detector subsystem designs provided by the University of Arizona by subcontract.
2. Breadboard and test the critical instrument subsystems.
3. Fabricate, test and qualify the instrument subsystems and prepare and verify the instrument software.
4. Design, fabricate and verify all required ground support hardware and software including all test, handling, and shipping equipment.
5. Assemble, test, qualify and calibrate the M4 protoflight instrument and provide and qualify spares for critical components and subsystems.
6. Support the instrument - spacecraft integration at Ball.
7. Support integrated testing and shipment to the launch site.
8. Support pre-launch and launch operations at the launch site.
9. Support post-launch instrument checkout.
10. Support mission operations through launch plus 30 days.
11. Manage the instrument development program, including coordination with BU and the M4 team, liaison with NASA on technical interface issues, provision of schedule and cost control, and support the planned project reviews (pre-environmental review, pre-ship review, and flight readiness review).

H.6. Phase E

Phase E consists of two components. The first is a 6 month Mission Operations phase involving 3 to 5 months of M4 satellite operation plus up to 3 months of close-out activities archiving of Level 0 and Level 1 data. The second, Data Analysis phase, of duration 3 years, encompasses all Level 2 data generation, distribution, and archiving plus higher level data product generation, scientific analyses, and publication of findings.

Mission Operations In this phase, the PI level remains at 100%, and the BU/SOC will engage in almost 24 hour activity. We do not envision having any real-time satellite "operators," but will be able to respond quickly to changes in satellite operations or performance. During this phase, our normal level of project contingency funding has been increased to 25%, to allow for unanticipated needs.

Data Analysis Beginning during flight, and lasting through the end of the project, subcontracts to Science Team members and Guest Investigators will support scientific analyses of M4 data. The BU/SOC will take lead responsibility for initial data processing and delivery of scientifically useful data products to the Science Team, GIs, and to public archives in the most timely fashion possible. BU/SOC scientists and students will also conduct scientific analyses of these M4 data products, assist Science Team members and GIs in development of higher level data products and tools, and participate in the M4 E&PO plan.

Approximate Phase E direct funding levels are as follows: BU/SOC (all project phases) 4.2M$ (this includes 0.8M$ for E&PO); 12 Science Team members at 3.6M$; 15 Guest Investigators at 1.3M$. These funds have been scoped to provide support for approximately 15 Postdoc-years, 35 graduate student-years, plus some senior summer salary, computers, publications, travel, and overhead costs.

Table 7: Total Mission Cost Funding Profile

(FY Costs in Real Dollars, Totals in Real Year and FY 1997 Dollars)

Item	FY98	FY99	FY00	FY01	FY02	FY03	FY04	Total	Total FY '97
Phase A	$249,354	$0	$0	$0	$0	$0	$0	$249,354	$247,058
Phase B/C/D	$7,775,573	$16,795,836	$10,490,576	$6,097,338	$0	$0	$0	$41,159,324	$37,731,259
Instrument (Cryostat+Instrument)	$4,640,065	$9,994,339	$5,262,999	$2,441,766	$0	$0	$0	$22,339,169	$20,565,860
Spacecraft	$2,946,057	$6,347,009	$3,346,862	$1,554,172	$0	$0	$0	$14,194,100	$13,067,029
MSI&T	$115,379	$322,432	$1,743,192	$2,011,175	$0	$0	$0	$4,192,178	$3,703,604
Education & Public Outreach	$74,071	$132,056	$137,524	$90,225	$0	$0	$0	$433,876	$394,765
Ground System Development	$0	$0	$538,038	$304,763	$0	$0	$0	$842,800	$743,750
Launch Services	$0	$13,000,000	$7,000,000	$2,000,000	$0	$0	$0	$22,000,000	$19,000,000
Phase E	$0	$0	$0	$2,101,137	$2,706,138	$2,858,834	$2,928,891	$10,595,001	$8,641,662
MO&DA	$0	$0	$0	$1,994,948	$2,473,839	$2,618,159	$2,676,930	$9,763,877	$7,971,217
E&PO	$0	$0	$0	$106,189	$232,299	$240,675	$251,961	$831,124	$670,445
NASA Mission Cost	**$8,024,926**	**$29,795,836**	**$18,028,613**	**$10,503,238**	**$2,706,138**	**$2,858,834**	**$2,928,891**	**$74,846,478**	**$66,363,728**
E&PO Total	$74,071	$132,056	$137,524	$196,414	$232,299	$240,675	$251,961	$1,265,000	$1,065,210

Contributions by Organization to:

Phase A/B/C/D	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ground System Development	$0	$0	$0	$0	$0	$0	$0	$0	$0
Launch Services	$0	$0	$0	$0	$0	$0	$0	$0	$0
Phase E	$0	$0	$0	$134,802	$196,778	$54,969	$57,122	$443,671	$406,915
Boston University	$0	$0	$0	$134,802	$196,778	$54,969	$57,122	$443,671	$406,915
GI Program Indirect Costs [1]	$0	$0	$0	$109,294	$143,831	$0	$0	$253,125	$253,125
Graduate Student Tuition Support [2]	$0	$0	$0	$25,507	$52,948	$54,969	$57,122	$190,546	$153,790
Contributed Costs (Total)	**$0**	**$0**	**$0**	**$134,802**	**$196,778**	**$54,969**	**$57,122**	**$443,671**	**$406,915**
								Mission Totals	**$66,616,853**

Notes:

[1] Underrecovery of indirect costs on the initial $25,000 of each GI subcontract (15 total).

[2] Boston University voluntary program of tuition support for graduate student research assistants supported on grants.

I. APPENDICES

I.1. Short Resumes of PI and Science Team

A key element for the successful design, development, integration, testing, operations, and data analysis of a project as comprehensive as M4 is a strong, resourceful, and effective team of investigators. In this section, we review the credentials, experience, and focus areas of the M4 Team leaders and Team members. The form of this discussion is a set of short summaries and primary responsibilities.

Principal Investigator – Dan Clemens is a broadly trained scientist with degrees in Electrical Engineering, Physics, and Astronomy. He has had design, development, and testing experience with cryogenic maser amplifiers for millimeter wavelength applications, implementation experience with liquid nitrogen cooled optical silicon CCDs as imaging polarimetric detectors, and design, development, testing and scientific application experience with millimeter wavelength linear polarimeters. He has designed and built instrumentation computer controllers, and designed, written, and implemented large software systems for analysis of polarization data. He has been PI on 15 NASA and NSF projects and Co-I on another two. He is author of over 100 scientific articles and presentations and editor of one book. He is an Associate Professor of Astronomy at Boston University, where he has been on the faculty for nine years.

Deputy Principal Investigator – Terry J. Jones is an internationally known infrared astronomer, Professor of Astronomy at the University of Minnesota, and Assistant Director of Mt. Lemmon and O'Brien Observatories. He has a wide range of experience in astronomy and is best known for his work in infrared instrumentation and infrared polarimetry. He built an infrared polarimeter for his thesis observations and has built both the Minnesota Infrared Polarimeter (MIRP) and the SpectroPolarimeter for InfraRed (SPIR) since joining the infrared group at Minnesota. While at Mt. Stromlo Observatory, Australia, he built the Cooled Infrared Grating Spectrometer (CIGS) using a novel cylindrical optics design. He was also a central figure in the design of the Fabry Perot Infrared Grating Spectrometer (FIGS) for the Anglo Australian Observatory. He has been an unpaid consultant on infrared polarimetry for the *SIRTF* photometer and camera teams. Jones has produced six Ph.D. students and is currently Director of Undergraduate Studies in the Department of Astronomy. He has been both PI and CoPI on numerous research grants from NASA, NSF, AFOSR and private industry. He has authored over 90 publications in refereed journals.

As Deputy PI, Terry Jones is responsible for working directly with the PI on the overall scientific and technical progress of the project. Specific tasks, particularly in technical areas, that need attention at the PI level will be assigned to him.

Alyssa Goodman is recognized for her successful program of measuring magnetic field strengths and structures in the interstellar medium. She and her collaborators have mapped several regions using both optical and near-infrared polarization techniques. These studies, which have demonstrated that magnetic fields in star-forming regions are well-ordered, form the foundation for many of the questions to be answered by M4. Goodman has shown, through extensive observation of the Zeeman effect at radio wavelengths and theoretical modeling, that the magnetic field is energetically significant in many regimes of the interstellar medium. She is currently an associate professor of astronomy at Harvard University and has won numerous honors and awards including the prestigious Newton Lacy Pierce Prize from the American Astronomical Society.

Alyssa Goodman is responsible for collecting and communicating the input of the Science Team to the PI and the rest of the M4 project. She is also responsible for investigating the performance of M4 in mapping the magnetic field geometry deep in the interiors of dark clouds and star forming regions.

Benton Ellis is a PhD-trained scientist and engineer at Ball Aerospace with extensive instrument design experience. He was responsible for the design and construction of a high-vacuum ion beam instrument as a graduate student. As a postdoctoral research associate he built both a near-infrared polarimeter for use at NASA's IRTF and a near-infrared array camera used at McDonald Observatory and other facilities. In addition, Ellis is experienced in the acquisition and analysis of data from narrowband and broadband far-infrared instrumentation. As a systems engineer at Ball Aerospace, he has been responsible for requirements definition and systems level performance modeling for diverse space instruments. As systems analyst at Ball Aerospace for the Submillimeter Wave Astronomy Satellite (*SWAS*), Ellis was responsible for flow down of the science requirements and tracking of the instrument performance, from the start of the project through testing and delivery of the completed instrument.

Steve Lord is experienced in the design and development of analysis tools for astronomy. He has developed a successful deconvolution package for *SIRTF* (*SIRTF* originally planned for polarization capabilities) which solved for Stokes Parameters in noisy fields through numerical deconvolution techniques. He has developed several data analysis packages for far-infrared astronomy. He is the Cognitive Scientist for IPAC's IRSKY, the author of ATRAN (Earth FIR Atmospheric Transmission Modeling Tool) and is a co-designer of ISAP, the *ISO* Spectral Analysis Package. All of these packages have gained widespread usage. He is currently the *ISO* Long Wavelength Spectrometer Support Scientist for the U.S., keeping him in active contact with about 40 far-infrared spectroscopy teams using the *ISO* LWS.

Steve Lord will be primarily responsible for simulating the data acquisition scheme for M4. He will determine the optimum algorithms and techniques to extract high precision polarimetry from the M4 data stream.

George Rieke holds a joint appointment as Professor of Astronomy and Planetary Sciences at the University of Arizona, where he is also the Deputy Director of Steward Observatory. Rieke is author or co-author of numerous scholarly publications and of a text on astronomical radiation detectors. He leads the team that developed the focal plane detectors in the far-infrared for *SIRTF* and is Principal Investigator for the Multiband Imaging Photometer for *SIRTF*. Rieke has led development of a broad variety of instrumentation, including two high performance polarimeters.

The primary responsibility of George Rieke along with Erick Young will be supervision of the detector development for M4.

Erick Young is an associate astronomer at the Steward Observatory, University of Arizona. He has had extensive experience in space infrared astronomy, having participated in a number of major missions. He had the lead responsibility for focal plane development on the Spacelab II Small Infrared Telescope. As a member of the *IRAS* Science Team, he participated in the characterization of low-background photoconductors. He also was the Science Team member in charge of the processing and public release of the *IRAS* Pointed Observations. Dr. Young is a co-investigator on the Short Wavelength Spectrometer for *ISO*. He is a Co-Investigator on the NICMOS instrument for the Hubble Space Telescope. He is also Deputy Principal Investigator for the Multiband Imaging Photometer for *SIRTF* (MIPS), and he leads the detector development activity for that instrument. Young was the winner of the Van Biesbroeck award in 1982.

Bruce Draine is an internationally known theoretical astrophysicist. He is recognized as an expert in the dynamics and chemistry of the interstellar medium, in particular the interaction of dust particles with the gas, magnetic field and radiation field of the ISM. He was a member of the Scientific Organizing Committee for the Conference "Polarimetry of the Interstellar Medium", held at R.P.I. in 1995 and he is a co-Investigator on the Far-Infrared & Submm Space Telescope Mission Proposal.

Bruce Draine will be responsible for investigating the extent to which M4 will be able to strongly constrain current models for grain alignment by the Galactic magnetic field.

George Field is a Senior Physicist at the Smithsonian Astrophysical Observatory and the Robert Wheeler Willson Professor of Applied Astronomy at Harvard University. A member of the National Academy of Sciences and the recipient of the Joseph Henry Medal of the Smithsonian Institution, he is widely recognized for his pioneering work on the interstellar medium. He has served on numerous committees for NASA, NRL, NSF and other funding and policy organizations including the Space Science Panel of the President's Scientific Advisory Committee and the Astronomy Survey Committee, National Academy of Sciences - National Research Council. He was also Chairman, National Academy of Sciences - National Research Council Astronomy Survey.

Carl Heiles is a member of the National Academy of Sciences and recipient of the Heineman Prize from the American Astronomical Society. He has been a member of numerous organizing committees for meetings including "Physics of Gaseous and Stellar Disks of the

Galaxy" and "The Physics of the Interstellar Medium and Intergalactic Medium." He was the Associate Director of the Radio Astronomy Laboratory at the University of California, Berkeley. He is well known for his work on the statistical description of the interstellar magnetic field in the Milky Way.

Carl Heiles will be responsible for studying the use of M4 for investigating the magnetic field geometry in the very diffuse high latitude clouds (the Infrared Cirrus) in the Milky Way. He, along with Ellen Zweibel, will also investigate the extent to which M4 will be able to significantly constrain statistical models of the Galactic magnetic field.

Roger Hildebrand is the Samuel K. Allison Distinguished Service Professor in the Department of Physics and the Department of Astronomy at the University of Chicago. He has served as director of the Enrico Fermi Institute, Chairman of the Department of Astronomy, and Dean of the College. He has also served as Associate Director of Argonne National Laboratory, where he was responsible for construction of a 12 GeV synchrotron. He has been Chairman of the Airborne Observatories Users Group, a member of the Committee on Space Astronomy and Astrophysics of the Space Science Board, and Chairman of the consulting group for SOFIA.

Hildebrand has supervised the Ph.D. theses of 24 students. Together with his students, Hildebrand is responsible for the discovery of polarized submillimeter emission from a molecular cloud and the first mapping of the magnetic field configuration in dense interstellar clouds. Hildebrand and his students developed the premier instrument for far-IR polarimetry, STOKES, a 32-pixel array for the Kuiper Airborne Observatory.

Roger Hildebrand will be responsible for investigating and defining the relationship between the data set to be obtained by M4 and the higher spatial resolution observations of selected areas that can be made using airborne techniques (SOFIA).

Christopher McKee is a member of the National Academy of Sciences and a pioneer in theoretical studies of the interstellar medium. He has been a Fannie and John Hertz Foundation Fellow and a Sherman Fairchild Distinguished Scholar. He is currently a Professor of Physics and of Astronomy and Director of the Space Sciences Laboratory at the University of California, Berkeley.

Chris McKee will be responsible for investigating the performance of M4 in determining the interaction between the Galactic magnetic field and dynamic structures such as shock fronts, wind blown bubbles, and ionization fronts.

Philip Myers is an experienced observer of molecular clouds and their young stars using spectral lines, and in continuum observations at radio, centimeter, millimeter, submillimeter, far infrared, and near-infrared wavelengths. He has observed and analyzed properties of magnetic fields through measurements of the Zeeman effect in lines of OH and H I, and through measurements of optical and infrared polarization. He is responsible for: analyses of magnetic energies in molecular clouds and cloud cores, showing that many regions have comparable magnetic, kinetic, and gravitational energy densities; models of interstellar polarization, showing that the interstellar magnetic field has similar energy density in its uniform and nonuniform components, and; models of magnetic nonthermal motions in molecular clouds and cores, showing how nonthermal motions set the density structure in clouds, and the gravitational infall time for collapsing cores.

Philip Myers will be responsible for investigating the performance of M4 for mapping the magnetic field geometry in dark clouds. Of particular interest will be the ability of M4 to map the transition regime where the field within the cloud connects to the general Galactic field in the diffuse ISM.

Ellen Zweibel is a plasma astrophysicist with academic degrees in mathematics and astrophysics. She has a broad research program which includes both solar and interstellar astrophysics and includes basic problems common to both disciplines such as magnetic reconnection, dynamo theory, and particle acceleration. She has been Principal Investigator or Co-Principal Investigator on numerous NASA and NSF grants and has authored or co-authored numerous articles in refereed journals. She served as Chairwoman of the Astrophysical, Planetary, and Atmospheric Sciences Department at the University of Colorado from 1989 to 1992. She was elected a Fellow of the American Physical Society in 1991 in recognition of her accomplishments in plasma astrophysics. Zweibel has held visiting appointments at Cambridge University, Princeton University, Harvard, the University of Chicago, and the University of California at Berkeley. She has supervised or co-supervised 5 PhD dissertations, one MS thesis, and 4 postdoctoral research associates.

Ellen Zweibel will be responsible for investigating the extent to which M4 will be able to place strong constraints on theoretical models of the Galactic magnetic field.

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