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An ADvanced SOLar Probe Experiment Module (AD SOLEM)

R. L. McNutt, Jr., R. E. Gold, E. P. Keath, D. M. Rust, S. M. Krimigis, L. J. Zanetti, C. E. Willey, B. D. Williams
The Johns Hopkins University, Applied Physics Laboratory, Laurel, MD 20723-6099

W. S. Kurth, D. A. Gurnett
Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242

M. H. Acuna, L. F. Burlaga
Goddard Space Flight Center, Greenbelt, MD 20771

G. Gloeckler, F. M. Ipavich
Department of Physics and Astronomy, University of Maryland, College Park, MD 20742

A. J. Lazarus, J. T. Steinberg
Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

G. Brueckner, D. Socker
Naval Research Laboratory, Washington, D.C.

T. E. Holzer
NCAR/HAO, Box 3000, Boulder, CO 80307

P. A. Bochsler, R. Kallenbach
University of Bern, Physikal Inst, Sidlestrasse 5 CH-3012, Bern, Switzlerland

A. Roux
Centre d'Etudes des Environnements Terrestre et Planetaires (CETP/UVSQ),
10 / 12 Avenue de l'Europe 78140 Velizy, France

ABSTRACT

A small, low-power suite of fields and particles and imaging experiments is required for fulfilling the critical science objectives for a near-sun flyby mission. We discuss how an integrated instrument suite using novel sensors and advanced detector/microelectronics/packaging techniques can be implemented for such a payload. Critical tradeoffs between science requirements, measurement strategies and these resource limits are discussed, and critical enabling components are identified. The instrument suite consists of 6 major investigations, some with multiple sensors, power conditioners for both high and low voltages and a common DPU. The concept design is essentially a dress-rehearsal of how a payload could realistically make the measurements needed to answer the critical science questions while operating within a real-world physics, engineering and technology context.

Keywords: Spacecraft, Instrumentation, Solar Probe

1. INTRODUCTION

For decades, space scientists have anticipated a Solar Probe mission to the inner frontier of the heliosphere. A near-Sun flyby will provide *in situ* measurements of the outer solar corona and high resolution pictures and magnetograms of the photosphere and solar atmosphere. Such measurements can be obtained in no other way, yet are absolutely necessary for unraveling the mystery of solar wind acceleration and origin, understanding the physics of coronal heating of both the Sun and other stars, and providing the "ground truth" for interpreting remote measurements from solar imaging missions 1 AU from the Sun. A near-Sun flyby mission addresses two broad science themes within NASA's Office of Space Science: the Sun-Earth Connection and the Exploration of the Solar System.

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A near-Sun flyby probe must answer these compelling questions:

What produces the solar wind and how is it accelerated?
What produces the million-degree solar corona?
Where and how are energetic particles produced near the Sun?
What role do plasma turbulence and waves play in the above processes and structures?

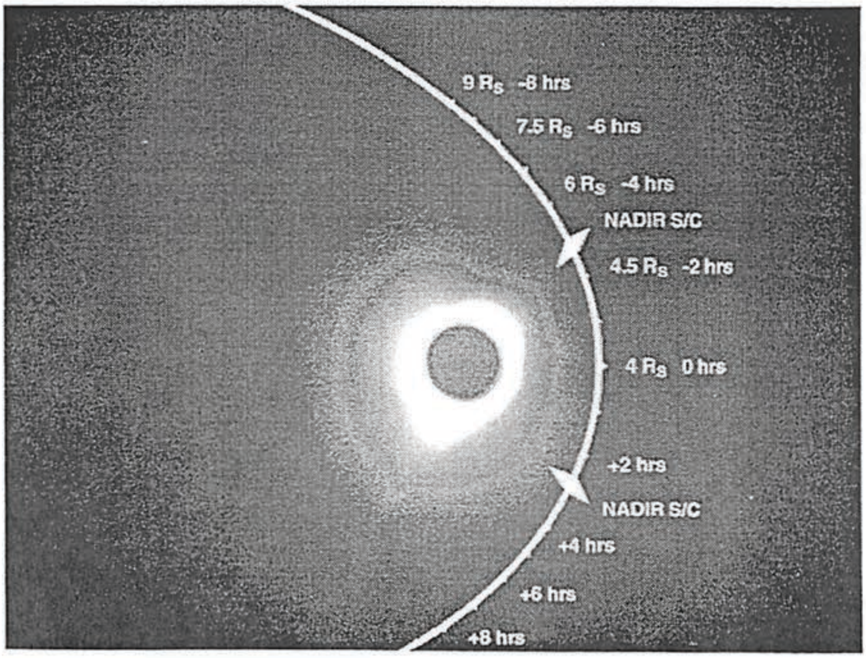
The answers will provide fundamental advances in our understanding the structure, origin, evolution and current state of the Sun and solar system.

A near-Sun flyby mission using available launch vehicles will require a small, low-power suite of fields and particles and imaging experiments. Strawman required measurements and science payloads have been discussed in a variety of recent studies [1-6]. Here we address the challenge of making the key measurements within the mass, power, data rate and financial constraints of the FIRE mission[1].

We have begun a conceptual experiment package design for such a mission. ***A payload is more than the sum of the scientific instrumentation carried; therefore, a crucial requirement for a resource-constrained solar flyby mission is demonstration of an integrated payload concept.*** By relying on creative and innovative sensor design, electronics and packaging, we believe that the required science goals can be met within NASA-mandated resource restrictions. In spite of current fiscal limitations, we believe a near-Sun flyby mission will blaze a pathway enabling humankind to solve some of the oldest, yet most puzzling and persistent, science questions of the Space Age.

1.1 The Solar Probe Concept

Serious consideration of a probe to the near vicinity of the Sun has been underway since 1978[4-5,7-9]. The current NASA baseline mission concept confirms extensively studied mission guidelines: probe approach to 4 solar radii* of the center of the Sun in an orbit inclined 90° to the plane of the ecliptic[4-5,11]. The spacecraft reaches 0.5 AU at 10 days prior to closest approach and spends only ~14 hours traversing from the north to south solar pole (Plate 1). The encounter is timed to provide passage over the west limb of the Sun; the area traversed by the probe will have been "previewed" during the same solar rotation by Earth-based observers.



Photograph by R. L. McNutt, Jr.
Graphic by Jet Propulsion Laboratory

Plate 1. Representative near-Sun flyby trajectory as viewed from Earth superimposed on eclipse photograph of the Sun taken on 24 October 1995 north of Ho Chi Minh City (Saigon), Vietnam.

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* One solar radius is 1 $R_S \equiv 6.9599 \times 10^5$ km and one Astronomical Unit (AU) is 1.495979×10^8 km or 214.94 R_S[10]. The semimajor axes of the orbits of Mercury and Venus are 0.387 and 0.723 AU or 83.2 and 155 R_S, respectively. The Helios spacecraft penetrated to within 0.3 AU or ~65 R_S and remain the source of our "innermost" *in situ* measurements of solar wind properties.

2. SCIENTIFIC OBJECTIVES

A Solar Probe mission has the ultimate scientific objective of understanding the atmosphere of the Sun. To achieve this requires sensor techniques, technologies and payload integration appropriate for enabling a near-Sun flyby mission while remaining within very real and very limiting programmatic and fiscal constraints

2.1 In Situ Near-Sun Science

What we know about the solar atmosphere near the Sun is fairly detailed in an observational sense, but key physical questions remain unanswered. Heating of the chromosphere[2] and corona remain outstanding problems. Coupled to coronal heating/energy transport is the process of the acceleration of the solar wind. While it is generally agreed that the Parker model[12] is qualitatively correct, fundamental questions remain. In particular, an additional energy source is required to power the high speed wind[13-15] now known to be associated with coronal holes[16]. Representative solar wind and interplanetary magnetic field parameters from the prime baseline mission as currently defined by NASA are plotted in Figure 1. These are, and will remain, only best guesses until a mission to the corona is actually flown.

Recent interplanetary scintillation (IPS) measurements suggest a filamentary structure to the corona, with a large range (~400 km/s) of solar wind speeds on adjacent flux tubes and a sonic critical point within 4 R_S on some of these[17]. Measurements with the Spartan payload suggest the presence of very hot plasma at several solar radii[18]; the recently launched Solar and Heliospheric Observatory (SOHO)[19] will greatly extend remote observations. As with all remote sensing, SOHO line-of-sight integrated measurements require model assumptions to sort out. Spatial and temporal structures cannot be uniquely separated, yet these structures are related to the fundamental physics and outstanding mysteries of the coronal and solar wind dynamics. Near-Sun coronal fine structure can only be resolved by *in situ* exploratory measurements from a properly instrumented near-Sun probe.

2.2 Cruise Science

In addition to the near-Sun (prime) phase of the mission at distances $<100\ R_S$, the probe will spend significant amounts of time between 0.5 and ~5 AU. However, constraints currently rule out measurements outside of the prime mission. Hence, the discussed instrument suite has been fine-tuned for operation within 0.5 AU, although it would have utility at larger distances.

3. RELEVANCE TO OFFICE OF SPACE SCIENCE PROGRAMS

The near-Sun flyby mission will address many of the fundamental scientific objectives of the Office of Space Science at NASA[20]. The FIRE and Minimum Mission baseline payloads concentrate upon the questions of solar wind acceleration, energetic particle dynamics, turbulence, and interpretation of remote measurements. Imaging investigations have been added to complete the survey of phenomena between the spacecraft and the photosphere, a region into which the most optimistic probe design cannot penetrate. Oft discussed measurement objectives focus the science upon (1) prime unanswered basic questions with relevance to other astrophysical settings and (2) applied questions with relevance to the solar-terrestrial connection. For a resource-constrained

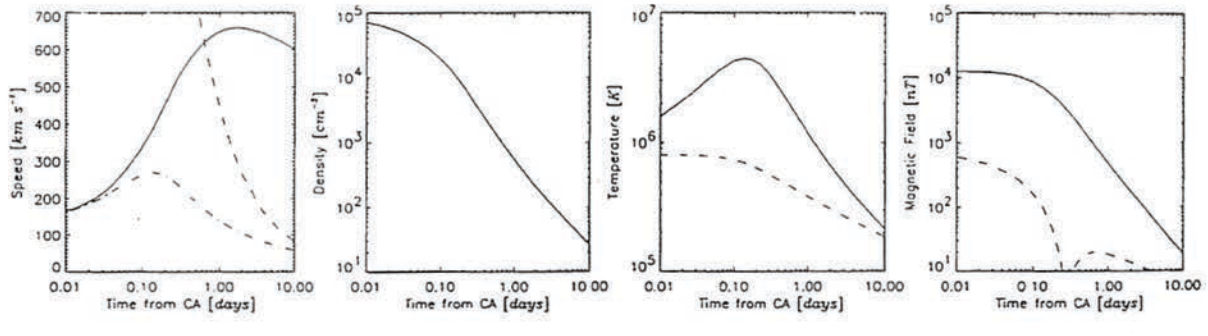

Figure 1. Representative values of solar wind parameters during the prime mission of the near-Sun probe (-10 days to +1 days from a closest approach of 4 R_S from the center of the Sun). The first figure shows the solar wind speed (solid), Alfvén speed (dashed), and proton thermal speed (dot-dashed). The second figure shows proton density, the third electron temperature (solid) and proton temperature (dashed), and the fourth the magnitude of the radial magnetic field component (solid) and the azimuthal component (dashed). Approximate formulas from work by Hansteen[26] have been convolved with the trajectory to be followed by the 4 R_S probe.

mission, the guiding principle ***must be*** to limit the payload requirements to those consistent with an affordable, doable and timely mission that can accomplish the key science objectives.

The same science questions keep recurring and always with a high priority for NASA. The *Space Physics Strategy-Implementation Study*[21] in §1.2 the Report of the Cosmic and Heliospheric Panel (Executive Summary) and the Solar Physics Panel in its executive summary (§1.5.5) both make an eloquent case for a solar probe mission. The scientific case has recently been reemphasized by many investigators[3,5,6,22-25].

4. IMPLEMENTATION

A near-Sun flyby mission will likely be a single exploratory mission, much like that of Voyager 2 to Uranus and Neptune or like Pioneer 10 to Jupiter or Pioneer 11 to Saturn (before the Voyager encounters). An additional Russian spacecraft has been discussed[23,24], but prudence suggests that a payload for the 4 R_S spacecraft should be self-contained and fully capable of carrying out the primary science mission by itself (this concept of prudent planning pertains to Russian plans *vis-a-vis* an American effort as well!). This mission offers the best opportunity to advance our fundamental understanding of the corona. ***Only a focused, highly integrated payload can enable real advances within constrained financial resources.*** We have mapped out a preliminary payload suite and development strategy that achieves the synergy required for answering the focused science questions. To remain within a realistic estimate of the spacecraft resources, we have studied a target of 10 kg/10 W/2000 bps, *which includes* sensors, structure, data processing and power regulation, supply and distribution (the instruments alone require 7.0 kg and 8.25 W).

An integrated science payload not only offers many advantages to this mission ***but is necessary for this mission to be implemented.*** Contrary to uninformed opinion, ***a tightly integrated payload can significantly reduce costs and,*** even more importantly for NASA, it can greatly reduce ***cost risk.*** Lower costs come from the use of common elements and subsystems among multiple instruments. The cost risk is much lower since the compatibility and integration of the entire payload is assured at the time of integration with the satellite. There is then no need for an implementation phase of the program to revise the spacecraft and instruments in order to form a coherent observatory. This phase of the mission has often been the interval in which the complexity and cost have grown most rapidly. A ***fully integrated payload***, because of its use of common subsystems and the physical economies of a single structure rather than many separate boxes, can ensure that the full set of science objectives can be met by allowing the complete required set of instrument types to be included at a very low cost in resources for each one.

Such a task presupposes taking advantage of several breakthrough technologies in electronics, packaging and individual instrument design. Taken together, this approach can result in a science payload that achieves a factor of 10 reduction in resources from early concepts and greater than a factor of three reduction from recent "focused" payloads[5].

Within the limits discussed above, we have further broken out preliminary targets as follows:

TABLE 1. Conceptual Instruments and Projected Resources

INSTRUMENT	*MASS (kg)*	*POWER (W)*	*DATA RATE (bps)*
Wave	2.25	3.50	282
Plasma	1.9	1.85	320
Fast Plasma	0.1	0.15	62
Energetic Particles	0.5	0.5	256
Magnetometer	0.25	0.25	80
Imager System	2.0	2.0	1000
Instrument Sub-Total	7.0	**8.25**	**2000**
Data Processing Unit	0.1	1.0	-
Power Supply	0.4	0.75	-
Structure	2.5	-	-
Support Architecture Sub-Total	3.0	**1.75**	-
Total	10.0	**10.0**	2000

4.1 Science

Science: Maintain balance in covering key science objectives.
Innovation: *Incorporate global perspective as part of instrument detailed design.*

Science requirements must lead and guide a fully integrated scientific spacecraft design. A concentrated effort must be made to set instrument requirements (viewing, resolution, bit rate) as needed to cover the required science objectives. We expect that engineering realities will lead to conflicts that must ultimately be settled in a manner consistent with minimizing spacecraft resource use while still accomplishing the required measurements.

4.2 Integration

Innovation: *Integrated structure, on-board data processing, low-dissipation power supplies; miniaturized electronics; novel deployment package; concurrent instrument design eliminates interference and cross-talk.*

Integration must includes the perfection of new technologies and the development of common subsystems as required to enable the mission. The new technologies include: (a) custom VLSI; (b) chip-on-board construction techniques; (c) advanced anisotropic composite materials for structures and thermal control.

(a) The new VLSI technology allows integration of nearly all the analog and digital functions of an entire instrument onto a single chip. This will greatly reduce the electronics part count of several of the instruments in this suite.

(b) Chip-on-board (COB) is a new electronic packaging scheme in which individual silicon die are mounted directly to an organic board with wire bond interconnects and proprietary passivation. COB alone can reduce the size of existing circuit boards by a factor of 7 to 10 in area and a factor of 5 in mass.

(c) Advanced composites have been developed with high strength and a 100:1 ratio in their thermal conductivities along and perpendicular to the surface.

All instruments should be designed to feed and be controlled by a common Data Processing Unit (DPU), share common high and low voltage power supplies (LVPS; HVPS) and be built into either the optics structual unit (OSU) or fields and particles structural unit (FPSU). The mechanical and thermal design of these structural units must also be inclueded as integral parts of an overall intgration approach.

We have considered a preliminary design for the OSU and FPSU. The only deployable/moving parts are associated with the magnetometer/wave sensors launch lock and with the deployable mirror option of the imaging instrument. The design includes all sensors discussed below and is shown in both stowed and deployed configurations (Figure 2).

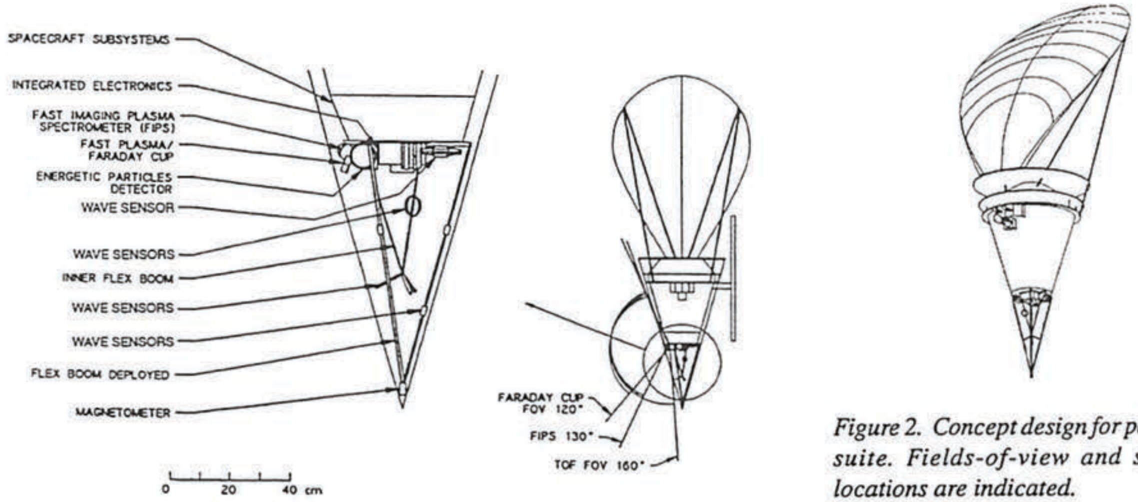

Figure 2. Concept design for payload suite. Fields-of-view and sensor locations are indicated.

Our proposed operating power limit of 10 W is equal to the projected total heat rejection capability of the spacecraft for the payload. ***Our concept calls for no holes in the thermal shield in order to significantly reduce*** spacecraft thermal design and instrument accommodation and their associated ***costs***. Such holes have been advocated to meet current science requirements for the mission (cf. Appendix D of reference 2). ***The limitations on the measurements imposed by this configuration and possible compromises of the science objectives may be the price the science community must pay in order to have any data whatsoever from near the Sun.***

4.3 Wave

Science: Solar wind heating, acceleration and origin; energetic particle production.
Measurement: Determine plasma wave turbulence characteristics.
Innovation: Small sensors, electronics miniaturization, clean interface with subsystems and magnetometer.

Concepts for miniaturized instrumentation must be developed to measure the plasma turbulence and other wave modes that may be responsible for the heating and acceleration of the solar wind. ***The discovery nature of the probe mission necessitates a complete survey of the plasma wave spectrum in the vicinity of the Sun.*** The Wave package will also identify other important contributors to the dynamics of the solar wind plasma and generation of energetic particles and will provide independent determinations of the electron density that are immune to the effects of the ablation cloud from the thermal shield.

Other measurements consistent with the available resources for these tasks can also be made, e.g., remotely sense solar radio emissions near their source and survey the dust environment near the Sun via the impacts of micron-sized dust.

A Wave investigation should survey the plasma wave spectrum from 1 Hz to 10 MHz (Alfvén waves to Langmuir waves) with at least one electric and one magnetic wave component. Our baseline concept instrument includes a variety of sensors and high and low-frequency receivers. It focuses especially on the frequency range below 10 kHz with multiple measurements in order to fully characterize Alfvén turbulence and kinetic Alfvén waves. Such an instrument will also provide at least two methods of determining the total plasma density.

Because of the low mass and small size of the sensors, their close proximity to the spacecraft and its electromagnetic interference, and the largely unknown effects of the ablation cloud from the spacecraft thermal shield, absolute sensitivity of this package will be limited compared with similar (but heavier!) investigation on other missions. However, most estimates of field strengths for various wave phenomena suggest that fields will be large and dynamic range may be more of a challenge than sensitivity. The estimated sensor mass is of the entire instrument is a mass of 2.25 kg; the instruement would require 3.50 W of power.

The low frequency receiver (LFR) includes bandpass filters and a signal processor to calculate fast Fourier transforms (FFT) and time-average over a few seconds for each channel The compressed data rate from the LFR will be ~210 bps. Actual waveforms will be transmitted periodically to verify the onboard analysis, e.g., one waveform set every five minutes.

The high frequency receiver provides spectral information on waves in the frequency range from 10 kHz to 10 MHz. The sweep frequency receiver can provide a complete spectra from 10 kHz to 10 MHz. The compressed data rate is ~72 bps.

4.4 Magnetometer

Science: Solar wind heating, acceleration and origin.
Measurement: Determine characteristics of in situ *magnetic field.*
Innovation: Sensor probe; electronics miniaturization, magnetically clean mounting.

For a nominal 5 nT radial component of the field at 1 AU, we expect a background field (almost completely radial) of about 500 nT at 0.1 AU and 10,000 nT, i.e., about 0.1 G at 4 R_S. Very long-period, large-amplitude Alfvén waves could possibly be present in the region between 4 R_S and 0.1 AU, and their magnetic field could be indistinguishable from the background field. It is unlikely that $\Delta B/B$ for these waves is greater than order unity, so the nonradial components of the background magnetic field should have the magnitude of the radial component as an upper limit. Given the central role that may be played by Alfvén waves in the solar wind problem, we believe it is required that one plan for a sensitivity to much smaller nonradial components.

The magnetometer has a three-axis fluxgate sensor and accompanying electronics on a single card. Its objective is to achieve accurate measurements of the three components of the solar magnetic field in the vicinity of the spacecraft. Sufficient sensitivity is currently incorporated in our concept and should allow a definitive study of the Alfvén wave environment within the prime region of the mission (0.5 AU into 4 R_s). The sensor has a mass of ~50 g and will be mounted at the end of the tripod structure containing elements of the Wave investigation (Figure 2). This will place it as far as possible into the tip of the umbral cone to minimize the background field associated with spacecraft systems. Placement close to preamplifiers for the Wave investigation can be accomplished by a careful screening and selection of the Wave instrument materials and parts.

The current electronics design uses a single 17.8 cm board with a mass of about 200 g. It requires 250 mW of power. Mass savings are anticipated by changing to the smaller common card design and by the extensive use of surface-mount parts and/or chip-on-board.

4.5 Plasma

Science: Solar wind heating, acceleration and origin.
Measurement: Magnetized plasma characteristics, plasma dynamics and composition.
Innovation: New sensor concept (FIPS); new measurement scheme (FC); miniaturized electronics; innovative scheme to eliminate holes in thermal shield.

That a Solar Probe mission without a plasma investigation is not worth doing is generally accepted by all of the space science community. The central role of and need for both bulk propertiy measurements as well as differential and compositional measurements in understanding the nature of the origin of the solar wind ***have been debated, studied and argued about since the initial Solar Probe studies.*** In our concept, in order to carry out these obviously required measurements, the plasma package consists of the compact time-of-flight Fast Imaging Plasma Spectrometer (FIPS) and a miniaturized Faraday Cup (FC). FIPS resolves solar wind electrons, protons, alpha particles, C^{+5}, O^{+6} as well as Si and Fe ions, under all conceivable conditions (see Figure 3) and measures their three-dimensional distribution functions from ~0.05 to ~20 keV/q over ~2π steradian once every second. The FC provides ion and electron density and bulk and thermal speeds at comparable time resolution. Both bulk parameters (see Figure 1) and distribution functions of various ion species provide crucial clues to the heating and acceleration of the solar wind[26,27].

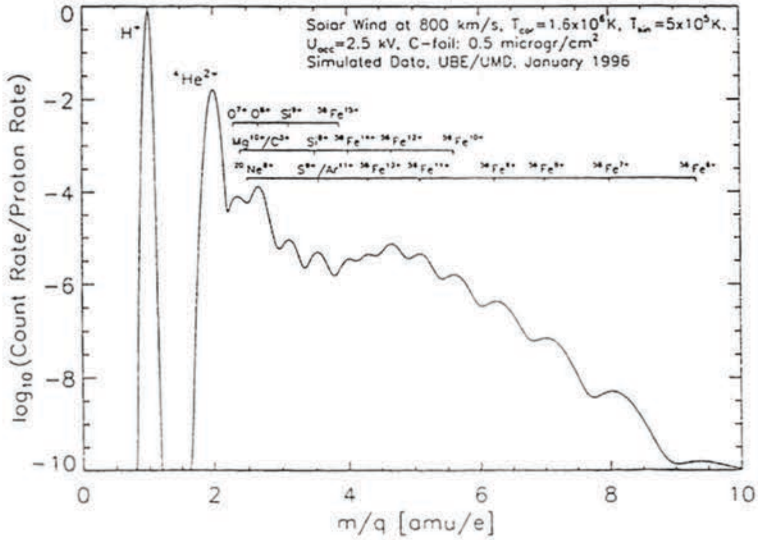

Figure 3. Simulation of the FIPS instrument response for a solar wind with a bulk velocity of 800 km/s. The element abundances and charge states are given for a coronal temperature of 1.6×10^6 K[28]. Energy loss, energy straggling and angular scattering of the ions in a 0.5 μg/cm² carbon foil as well as the timing resolution of the instrument have been modeled according to calibration data of similar space instruments (ACE, SOHO and ULYSSES).

4.5.1 Fast Imaging Plasma Spectrometer

The conceptual design for the innovative time-of-flight FIPS is based upon a series of collimating baffles and flight-tested time-of-flight analysis schemes. A solar wind particle passes into a deflection system and then is accelerated before passing through a carbon foil. Secondary electrons (SEs) from the foil at the entrance of the time-of-flight (TOF) system are accelerated to 1 kV and reflected by an electrostatic mirror onto the start chevron MCP assembly, while the more energetic solar wind particle passes through the mirror and is stopped by the stop MCP. The position of impact of the SEs on the start MCP is measured, thus recording the entrance direction and relative energy/charge (E/q) of the particle. The time-of-flight and the E/q of the particle (known from the deflection voltage at the time of the start signal) give the mass/charge (m/q) of the ion.

The electronics include three power supplies (Deflection, Acceleration, and MCP) which supply indicated time varying, synchronized voltages to the various electrodes of FIPS. The signal processing electronics generate for each ion or electron detected one time of flight and threeposition-related pulse height analyses (PHAs). The DPU provides all the control functions (synchronized, analog wave forms) for the FIPS power supplies and performs data reduction and compression.

4.5.2 Fast Plasma/Faraday Cup

Although out of favor with some less knowledgable members of the space physics community, a low-mass, low-power Faraday cup system can efficiently and accurately provide high-time-resolution measurements of the basic solar wind parameters: bulk velocity, density, and thermal speed (see Figure 4). These complement (and cross check!) the differential measurements of the plasma distribution function and solar wind composition provided by FIPS (or any other inherently differential plasma instrument).

The concept configuration is a scaled-down version of the mechanical configuration of a similar cup on the WIND spacecraft. The size is about the smallest that will permit sufficient high voltage on an energy/charge determining grid without shorting the grid via field emission *in vacuo*. The Faraday cup can use a circular collector plate split into three, 120° segments. Onboard data reduction (in the common DPU) will return nine numbers: solar wind velocity vector (three components), ion number density, observed electron number density, ion thermal speed and alpha particle density, temperature and speed differential (along the magnetic field) with respect to the protons (the Faraday cup intrinsically integrates the distribution function transverse to the cup entrance aperture). These parameters are returned at the same rate as magnetic field measurements. A data rate of about 62 bps should suffice for these data. Full spectra will be transmitted occasionally to verify the onboard analysis.

Work recently completed at MIT (funded under NASA Grant NAGW-3941) has shown that a measurement scheme similar to that employed on traditional retarding potential analyzers (RPAs) can be used to decrease the system electronics mass and power consumption while still allowing a clean separation of the solar wind signal from the photoelectron background The required circuits could be fit on one or two chips.

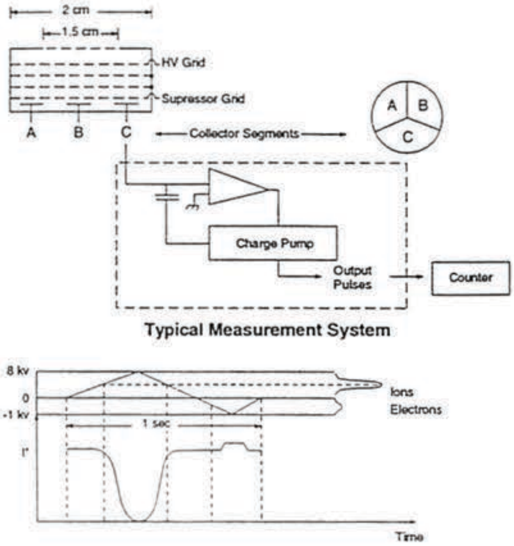

Figure 4. Fast Plasma/Faraday cup configuration and operation. The sweep grid's high voltage allows particles of greater energy/charge to reach the collector plate and be measured. The suppressor grid reflects secondary electrons back to the collector plate; the latter switches between -100 V in the ion mode to spacecraft ground in the electron mode; in the electron mode the collector plate as well as the amplifier reference are biased to +30 V in order to measure all electrons that can reach the aperture through the plasma sheath of the spacecraft. If illuminated by sunlight, large photocurrents are present on the collector plate. This large but constant offset is rejected by numerically differencing the counts taken every 30 ms (the effective measurement resolution) as the high voltage is swept with time. Even at 4 R_S *the measured currents remain above the limit set by the shot noise in the system.*

4.6 Energetic Particles

Science: *Acceleration, storage and transport of energetic particles.*
Measurement: *Spectrum and composition of energetic particles.*
Innovation: *New sensor concept; miniaturized electronics.*

As is the case with plasma measurements, the need for measurements of the energetic particle environment near the Sun is as essential as it is obvious and beyond debate. Turbulence in the upper corona and transient events at lower altitudes provide appropriate conditions for particle acceleration[9,22] including: (1) stochastic (second-order Fermi) acceleration via scattering from magnetohydrodynamic (MHD) waves, (2) shock (first-order Fermi) acceleration from shocks produced by transient, explosive processes, and (3) inductive acceleration associated with current sheet disruption produced during magnetic reconnection. All of these mechanisms can produce similar high-energy particle spectra. Finding the correct one will depend on knowing the underlying particle populations and wave environments, their spatial extent and dynamical evolution. Measurements of energetic ions and electrons down to 4 R_S will remove uncertainty due to propagation effects and extend the usefulness of remote observations for monitoring solar activity.

The Energetic Particles sensor design is based upon an ongoing NASA-funded effort in the Planetary Instrument Definition and Development Program (PIDDP; NASA Grant NAGW-4547). The objective of that work is to produce a breadboard particle detector for the Pluto Fast Flyby mission. The Pluto design goals of total instrument mass and power of <0.5 kg and 0.5 W (not including power supplies) have been adopted for the concept design presented here.The same basic design can be used in a solar flyby mission as well as many others in the solar system. The principal change from a Pluto-oriented design is "retuning" the energy and species sampling scheme, adding electron detection, and going to significantly shorter accumulation times.

The detector will measure the energy spectra, mass composition and detailed pitch angle distributions of energetic ions and electrons in the range of ~10 keV/nuc to ~3 MeV total energy. The telescope has two main components: a time-of-flight (TOF) section (Figure 5) and a solid state detector (SSD) array. A collimator, not shown in the figure, defines the acceptance angles for the incoming ions while the time-of-flight and solid state detector sections measure the velocity and energy of the ions, respectively. Electrons have TOF's in the instrument lower than the most energetic ions we will be measuring, and so can be recognized by an essentially zero time-of-flight.

Each SSD can measure an eight-channel energy spectrum for four species, e.g., electrons, protons, alpha particles and ions in the CNO group. Other configurations would allow measurement of heavier ions, e.g., Fe and Si. With one SSD readout per second 4 (species) x 8 (energy channels) of 8-bit words will contribute 256 bps to the data rate. All six channels on two detectors would be read out in 12 seconds. More details of the design and current status in the development work are given in the companion paper by *McNutt et al.*[29] in these Proceedings.

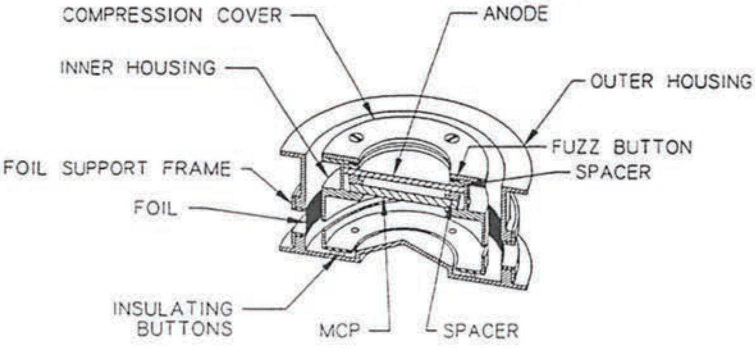

Figure 6. Cross section through the TOF section of the conceptual Energetic Particles detector.

4.7 Imaging

Science: *Solar wind heating, acceleration and origin; coronal origin.*

Measurement: *High resolution images of coronal and photospheric structure; optical context for* in situ *measurements; polar imaging; photospheric magnetic fields.*

Innovation: *New thermal design; compact, lightweight optical train; high resolution combined with wide field-of-view; new magnetograph concept; new miniaturized detectors (camera).*

Magnetic reconnection probably supplies the energy for coronal heating, solar wind acceleration and solar flares. Skylab and Yohkoh have shown that this process commonly occurs in the solar corona. However, those large scale observations do not reveal much about the details of the reconnection process.

A key property of the solar corona is its high electrical conductivity, which inhibits reconnection on the large scale; hence the key to coronal heating is likely to be found by considering very fine spatial structures[30]. *Parker*[31] proposed that these structures would produce very fine-scale, flare-like events that he termed nanoflares. The means by which the relatively large scale photospheric motions are then converted to small scale structures in the corona is a major question. To make significant progress on this fundamental topic, it is necessary to observe coronal structures on the finest possible scales—at least an order of magnitude below the 1 arc-sec resolution (~140 km on the photosphere from 1 AU) that can be anticipated with spacecraft experiments currently in orbit or in development.

Careful attention to materials selection, fabrication techniques and the use of the technologies desbribed below can enable an appropriate imaging investigation to be implemented that matches the limited resources allocated in Table 1. ***Preliminary engineering work shows these goals to be realistic and not simply "wishful thinking."***

4.7.1 EUV Optical Design

One imager can cover the corona-transition region boundary and structures inside coronal holes using the 1.3 x 10^6 K FeIX 171 Å and FeX 174 Å emission lines. A second can cover the chromospheric network and coronal holes using the 8.0 x 10^4 K HeII 304 Å emission line. Such imagers could point near nadir or along the direction of spacecraft motion so that time sequences of exposures could be acquired for any selected location on the solar disk.

We have studied the optical design of two such imagers which are identical, except for passband. The optical configuration is a zero-dispersion, slitless spectrograph similar to the one developed for the High Resolution Telescope and Spectrograph (HRTS) which has flown on Spacelab 2[32] and repeatedly on sounding rockets[33]. The primary advantage of this configuration is that it rejects the high heat load of the incoming visible and infrared radiation by reflecting it along the plane grating normal, in zero order, back toward the entrance aperture. The visible reflectance of the plane grating canbe raised above the R ~ 0.5 normally obtained with a Si/Mo multilayer to R ~0.9 by using a multilayer with an Si top and coating this inert layer with an Al overcoat. A reflective baffle system coated with Al_2O_3/SiO_x[34] can be included to reject the solar input radiation in much the same way.

The EUV imagers would be mounted transversely, behind the inner thermal shield (see Figure 2), with their optical axes perpendicular to the spacecraft orbital velocity. The solar disk is viewed over the side of the spacecraft by means of an extendable folding mirror/radiator. The mirror/radiator is extended only during the 1s exposures, which are few in number and have a low duty cycle. Only the mirror is irradiated by the solar disk when the unit is extended. The trade-off is an additional reflection from a metallic folding mirror and a compensatory increase in entrance aperture area. ***Preliminary calculations indicate that the heat load and transients can be accommodated by the mirror radiator system, especially in view of the limited number of operating cycles required.*** This configuration also simplifies integration and solves unaddressed thermal problems in the SDT "light pipe" concept.[2] The substrate polish micro-roughness, coating, figure stability and thermal design of the mirror/radiator assembly constitute a new technology applicable to the near-Sun environment.

The imager and folding mirror can be rolled to accommodate the apparent systematic motion of the solar disk under the spacecraft over the duration of an exposure. It can also be used to point off-normal, along the solar travel path to allow a time lapse image sequence for selected regions of the solar disk. The total width of the field of view is about 3-4 supergranular cells across; high quality images can be obtained with a temporal resolution ~1 second.

4.7.2 Camera Detector

An imaging system has been partially developed at JHU/APL with IRAD funds and has recently been selected for continued funding under the NASA PIDDP. Tthis camera system could be used as the detector for both EUV imagers. The design, using chip-on-board (COB) technology, is a miniature four-chip version of the imager camera on the JHU/APL Near Earth Asteroid Rendezvous (NEAR) spacecraft, including a CCD chip, two Application Specific Integrated Circuits (ASICs) and a Field Programmable Gate Array (FPGA) . The camera now in fabrication uses a 488 by 575 pixel TH7866 CCD. The funded PIDDP effort will upgrade the CCD to a 1024 by 1024 frame transfer device. DPU transfer and compression schemes can be used to keep the average data rate of the combined EUV Imagers/Magnetograph to <1000 bps (Table 1). Application of these technologies can be used to easily approach the low-mass and low-power goals for such an imaging system.

4.7.3 Magnetograph

Photospheric magnetic fields are composed of ropes of magnetic flux. Their size distribution is thought to peak at ~100 km, but there may be a very substantial component of flux at even smaller scales. It is important to study flux ropes with the highest possible spatial resolution because they almost certainly play a fundamental role in coronal heating by reconnection or as energy conduits.

To get true magnetic polarities and fluxes and to correlate these with coronal heating, which can best be detected in the EUV, a novel magnetograph can be coaligned with the EUV imagers and capable of a ~20 km resolution near closest approach. ***An alternate approach*** to detecting flux tubes is to make filtergrams at a wavelength that is sensitive to small photospheric temperature differences, e.g., the CH bandhead at ~4310 Å. However, this ***is unlikely to lead to a real advance in understanding coronal heating because it cannot be used to distinguish between the conduit and reconnection models.***

Our approach is to implement recent advances in holographic gratings in bulk photorefractive crystals, such as doped lithium niobate. Practically any desired grating pattern can be created and fixed inside the crystal. In particular, a 0.25 Å H-alpha filter for solar observations has been in daily use at the Big Bear Solar Observatory for several years. With internal funding, JHU/APL has made several holographic filters with the goal of fabricating a voltage-tunable filter.

For the probe payload, a holographic filter could diffract and focus many wavelengths at once. The objective is to overcome the low throughput and consequently long exposure times that have been a problem with magnetographs. The filter will not only sample many magnetically sensitive lines in the solar spectrum, it will simultaneously act as an off-axis reflecting telescope because the gratings will be curved.

The design uses a dichroic mirror transparent to all wavelengths except approximately 100 Å near 600 nm. Exposure times are 20-50 ms. Only about 2 Å of the 100 Å-wide band is diffracted toward the secondary mirror. The rest of the light (and energy) passes through the crystal. Only about 0.0005 of the incident solar energy (2.5 x the incident energy of sunlight at Earth) hits the detector which could be a CCD camera-polarimeter called an Integrated Dual Imaging Detector (IDID)[35]. Typical dimensions for the filter-telescope elements to achieve 20 km resolution are 75 mm. Crystals of this size are now commercially available.

We have demonstrated filter operation in the laboratory. The many-line approach to the filter-telescope increases the throughput at the desired wavelengths quite dramatically and would allow one to achieve the short exposure times required by the fast flyby of the Sun. The IDID measures circular polarization by integrating a quarter-wave plate and a polarizing beamsplitter with an advanced CCD image sensor. The result is a single unit that weighs only ~50 grams. A prototype IDID is running at JHU/APL.

4.8 MANAGEMENT CONSIDERATIONS

If run in a "traditional" manner, management of this type of tightly coordinated effort of various investigators potentially spreads across the world could result in costly delays and design changes. Prudent and sensible uses of electonic mail, the World Wide Web, teleconferencing, and other modern communications tools easily minimize the number of co-located meetings. The latter incur delays and additional costs to a project such as envisioned here, and are, therefore, no longer an "acceptable" way of doing business. Just as the telephone and fax machine were parts of developing, designing, and implementing space hardware in the 1980's and before, use of modern, available telecommunications tools and management techniques are an integral part of such endeavors in the 1990's. ***New management styles and paradigms are as essential to the successful completion of such a project as are the miniaturization of hardware and tight integration of packaging.***

5. CONCLUSION

In addition to a mission to the Sun, other deep-space missions with either primary or secondary space physics objectives have from time to time been discussed, all of which require miniaturization of current instrumentation if they are to be implemented. A particle-and-fields package integrated with appropriate imagimg instruments would provide fundamental science on a small solar probe, Pluto flyby, Mercury orbiter, or near-interstellar probe mission. Such instruments could also play a significant role in Discovery-class missions, e.g. a small mission to a comet.

The described instrumentation is necessary to the continued experimental viability of *in situ* space science on a broad range of missions. Given the current trend toward less massive spacecraft, "off-the-shelf" designs and concepts will no longer suffice for small mission payloads. Our on-going development work supports realistic demonstrations of what space physics can contribute even in tightly resource-constrained environments. The mission to the Sun is an excellent example of a mission with such constraints and to which the space physics discipline can contribute in a fundamental way to the wealth of human knowledge.

6. ACKNOWLEDGMENTS

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