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A SOLE / AD ASTRA: FROM THE SUN TO THE STARS

RALPH L. MCNUTT, Jr., ROBERT E. GOLD, EDMOND C. ROELOF, LAWRENCE J. ZANETTI, EDWARD L. REYNOLDS, ROBERT W. FARQUHAR
The Johns Hopkins University Applied Physics Laboratory, Johns Hopkins Rd., Laurel, MD 20723-6099 U.S.A.

DONALD A. GURNETT AND WILLIAM S. KURTH
Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242 U.S.A.

We discuss a "standardized sciencecraft" design that can be launched in the 2003-2010 time frame using a maximal number of standard modules for implementing a Solar Probe (SP) and/or Interstellar Probe (IP) mission. Both missions must be low mass, operate close to the Sun and in deep space and require fields and particles instruments that must be miniaturized and can operate in the different environments by changing their integration times. By drawing on programmatic experience from the Near Earth Asteroid Rendezvous mission and upon the APL Integrated Electronics Module and other advanced spacecraft and sensor development work currently being conducted, we summarize concepts for both missions that will enable key science for minimal cost. Exclusive of launch vehicle, both of these missions probably remain toward the low end of the "large mission" category ($150M - $250M). A significant thrust of NASA and the new Science Theme structure is one of exploration. For decades a Solar Probe and an Interstellar Probe have been advocated by peer-review constituencies within the Space Physics community: Both of these missions are required to truly complete the "exploration of the solar system" and will add significantly to the wealth of human knowledge about our galactic environment. The proposed mission concept is of central and pressing relevance to continue the role of space physics in exploration and investigation of fundamental physics questions that cross many interdisciplinary boundaries.

1. INTRODUCTION

Two highly-ranked exploratory missions central to the discipline of Space Physics have eluded the grasp of NASA and the Space Science community for over 20 years. These missions would yield measurements of fundamental importance for our understanding of the galactic environment in which we live while enabling us to pursue long-standing questions of the state and evolution of our stellar environment and its implications for the possibility of life elsewhere in the universe. Both missions consist of probes carrying both remote sensing and *in situ* experiments designed to make measurements that can be obtained in no other way. One probe, the Solar Probe, would explore the inner boundary of our stellar environment; the corona of the Sun while the other, the Interstellar Probe, would probe the outer boundary: the Very Local Interstellar Medium (VLISM).

In spite of the very different environments to be sampled by these missions, there are nonetheless common requirements in both the instrument package and the spacecraft themselves. *In situ* measurements by fields and particles sensors are the core measurements required for both missions. Both spacecraft must be small so as to be compatible with available launch vehicles — including availability based upon current NASA policy and cost constraints. Both spacecraft require Jupiter assist flybys and both require operations near the Sun: the Solar Probe in order to make its required measurements and the Interstellar Probe in order to rapidly escape the solar system in order to reach rapidly the region of its required measurements. These and other requirements imposed by the science measurements themselves impose similar and significant engineering constraints on the required spacecraft.

We carefully examine the missions' requirements and seek design commonalities where they make sense in order to:

(1) enable serious consideration of actually launching these missions in the near term (2003-2010 time frame),

(2) minimize non-recurrent engineering costs on two very demanding missions by seeking common solutions to common problems and thereby minimizing mission cost, and

(3) minimizing the required spacecraft mass and power consistent with the required science measurements (the "sciencecraft" paradigm) in order to minimize the launch vehicle requirements and therefore a major cost driver while remaining consistent with the goals of these two fundamental science missions.

We discuss the science rationales, policy rationales, mission requirements and constraints, zeroth order designs of spacecraft to fulfill the requirements and constrains and end with a synopsis of work still required and the associated priorities and rationales. We do not discuss the instrument packages per se. These have been discussed and debated many times over; rather, we seek to define a mission concept that can link the required science, desired instruments and the realities of the fiscal and technological milieu in which NASA must operate if such missions are to become realities.

2. SCIENTIFIC OBJECTIVES

We have the ultimate scientific objective of understanding the atmosphere of the Sun and the properties of the local interstellar environment. The enabling missions are linked conceptually by seeking to understand the frontiers of our stellar system by looking both inward and outward. They are also linked technologically by both requiring small, yet capable spacecraft that can survive an extreme range of interplanetary thermal environments. To achieve this we propose to develop self-consistent spacecraft designs that can bring these missions to reality. At the same time, such detailed concept development will help to delineate the limitations on the science objectives that are implied by policy and fiscal realities. This type of iterative requirements versus design process is implicit in the sciencecraft paradigm: incorporation of limited, focused science objectives combined with specified and limited resources as a means to accomplish fundamental science objectives on fixed budgets.

2.1 Science Drivers

2.1.1 In Situ Near-Sun Science on Solar Probe

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 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 [1] is qualitatively correct, fundamental questions remain. In particular, an additional energy source is required to power the high speed wind [2-4] now known to be associated with coronal holes [5]. Representative solar wind and interplanetary magnetic field parameters from the current for the NASA prime mission are plotted in fig.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[1] on some of these [8]. Measurements with the Spartan payload suggest the presence of very hot plasma at several solar radii [9]; the Solar and Heliospheric Observatory (SOHO) [10] will greatly extend remote observations. As with all remote sensing, SOHO line-of-sight integrated measurements will 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.

2.1.2 Cruise Science on Solar Probe

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 instrument suite and its use of resources must be fine-tuned for operation within 0.5 AU, although it would have utility at larger distances.

2.1.3 Cruise Science on Interstellar Probe

The actual collection of data is envisaged to begin at the time the spacecraft passes 1 AU outbound on its way out of the solar system. The prime phase of the mission will last for at least a decade and possibly two depending upon the operational status of the Voyager Interstellar Mission spacecraft and their heliospheric locations at the time that the Interstellar Probe is launched. The basic data mode will be to gather data repetitively and broadcast back to Earth on a predetermined and automatic schedule in order to minimize mission operations costs. Autonomy will be a guiding principal in implementation of such a mission due to the large potential costs of operating a spacecraft over a ~20-year lifetime.

2.1.4 Science Rationale - A Sole ("From the Sun")

For decades, space scientists have anticipated a Solar Probe (SP) 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.

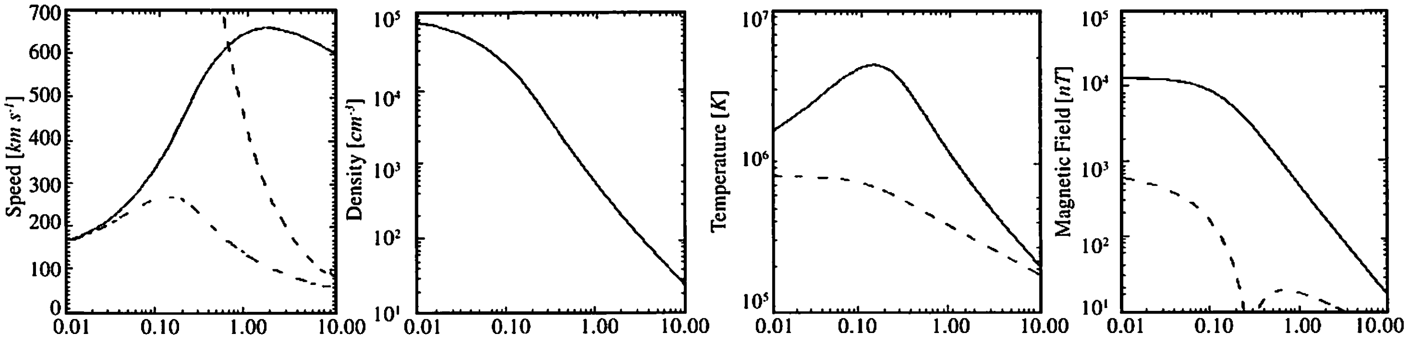

Fig. 1 Representative values of solar wind parameters during the prime mission of the near-Sun probe (-10 days to +1 days from a closest approach of 4 R_S from the center of the Sun). The first figure shows the solar wind speed (solid), Alfvén speed (dashed), and proton thermal speed (dot-dashed). The 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 [6] have been convolved with the trajectory to be followed by the 4 R_S probe.

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[1] One solar radius is 1 R_S 6.9599 x 10^5 km and one Astronomical Unit (AU) is 1.495979 x 10^8 km or 214.94 R_S [7]. 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. The termination shock of the solar wind is now thought to be ~80AU from the Sun. The VLISM lies more than 100 AU away.

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?*

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

Serious consideration of a probe to the near vicinity of the Sun has been underway since 1978 [15, 17-19]. We adopt 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 [14, 15, 20]. The spacecraft reaches 0.5AU 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.

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 [11-16]. We do not revisit these science closure issues in detail here; we do address the challenge of making the key measurements currently defined by NASA within the mass, power, data rate and financial constraints of what has become known as the FIRE mission (Delta II 7925 launch vehicle, Jupiter Gravity Assist 3.6-year trajectory, non-RTG power, and four solar radii flyby perihelion with real-time data link).

In addition to a complete experiment package design for this mission, ***a detailed conceptual design capable of carrying out the NASA FIRE mission, and perhaps extending it, is required. In particular, means of extending the onboard power and data capabilities of the spacecraft during the prime mission and also extending the mission by lowering the aphelion of the Solar Probe's solar orbit would significantly enhance the science return from the current FIRE baseline mission concept.*** The latter goal involves trade-off decisions that are not necessarily in consonance with current NASA policy and the current FIRE mission. However, these policies and scenarios could change before the mission is flown, and we believe it prudent, therefore, to consider such trade-offs. Also in this category is the use of a radioactive power source (RPS) similar to that currently baselined for the Pluto Express mission. Such a supply is required for the Interstellar Probe and, we believe, may be a matter of practical necessity for the Solar Probe - this issue is discussed in more detail as a common design element below.

2.2 Science Rationale - Ad Astra ("To the Stars")

For almost as long a period of time as a Solar Probe has been discussed, there have been similar, but less focused, discussions about an Interstellar Probe (IP) mission. Travel to the stars is the stuff that dreams and science fiction novels are made of. However, there is also a very scientifically compelling and serious side of the concept as well. Travel across the interstellar void or even to the relatively near Oort comet cloud is prohibitive in time and resources, but a mission to the local boundary of interstellar space is feasible and could yield a rich scientific harvest [21]. Already there is a "fleet" of four interstellar spacecraft: Pioneer 10 and 11 and Voyager 1 and 2 all have speeds in excess of the escape speed from the Sun and will

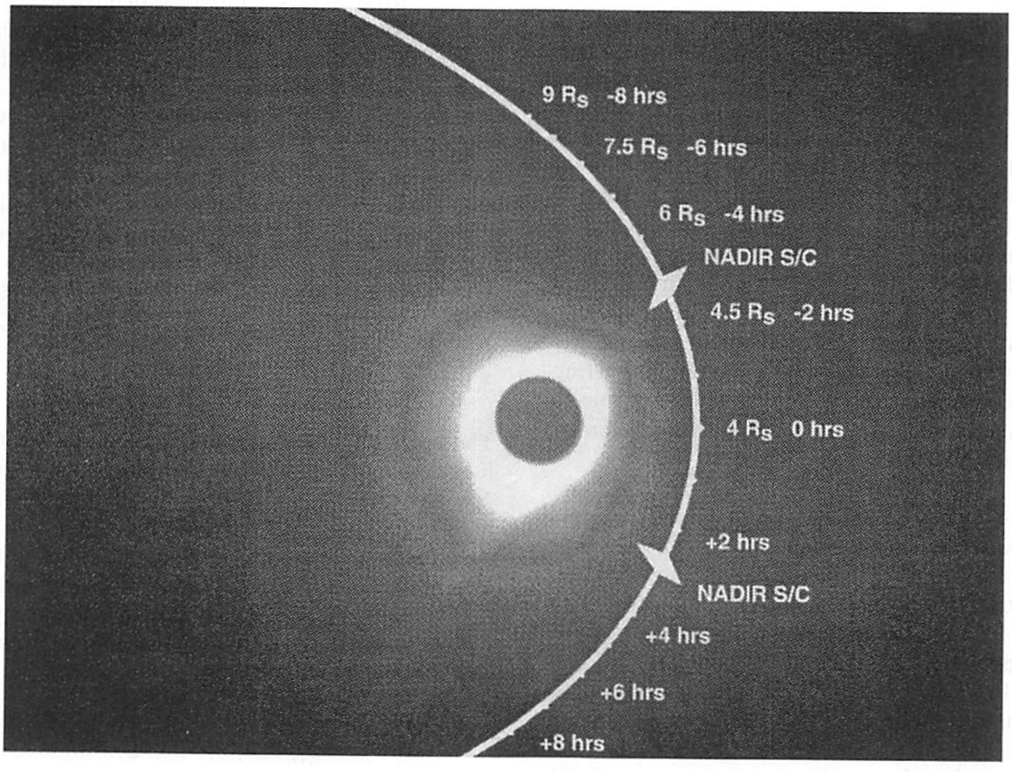

Plate 1. Representative near-Sun flyby trajectory as viewed from Earth superimposed on eclipse photograph of the Sun taken on 24 October 1995 north of Ho Chi Minh City (Saigon), Vietnam.

penetrate into interstellar space. Powered by Radioisotope Thermoelectric Generators (RTGs), the spacecraft all have a finite lifetime due to the half life of the Pu-238 fuel (89 years) as well as degradation of the Si-Ge convertors in the RTGs. Pioneer 11 has effectively been "switched off" (30 September 1995), and the same fate awaits Pioneer 10 in the near future as power margins continue to decline. The Voyagers now form the Voyager Interstellar Mission with the goal of at least penetrating the termination shock of the solar wind, which is thought to be located ~100 AU from the Sun [22,23,23a].

Whether the Voyagers will actually reach the "undisturbed" interstellar medium prior to falling silent remains unknown today. What is clear is that there are fundamental science questions that can only be addressed by instrumentation that actually penetrate outside of the heliosphere [24, 25]. The science goals include:

(1) ***Explore*** the nature of ***the interstellar medium*** and its implications for the origin and evolution of matter in the Galaxy. We know amazingly little about the nature of the Very Local Interstellar Medium (VLISM). Measurements of rotation measures and dispersion measures of pulsars [26] suggest a large scale magnetic field of ~1.4 uG; polarization of light from nearby stars suggests a direction of *l*II = 70° in the galactic plane (*b*II = 0°) [27]. However, there is also a random component apparently associated with local turbulence and a local cloud on interstellar material; in which the solar system has been embedded for a few thousand years [28]. High resolution spectroscopy of nearby stars has given us information on the flow velocity and temperature of the cloud, but its density and ionization fraction are not well constrained [28-30].

Similarly, the differential flux density and elemental and isotopic composition of the nonthermal portion of the medium (including the galactic cosmic rays) remain unknown, yet knowledge of these quantities, especially for the low energy portion of the cosmic ray spectrum, are important constraints for theories of cosmic ray production and evolution. The overall makeup of the medium similarly places constraints on theories of evolution of the medium and on cosmological nucleosynthesis and the baryonic component of galactic matter. The chemical makeup of the external medium - including the presence and extent of the Kuiper belt objects - reflect the original makeup of the solar nebula. The radiation environment of these objects, and, hence, of the original nebula, could provide clues to the effects of the heliospheric environment on the evolution of the nebula. Interesting possibilities are the radiation processing of organic to prebiotic material and local nucleosynthesis driven by local (in space and time) supernovae.

(2) ***Explore*** the structure of ***the heliosphere*** and its interaction with the interstellar medium. The Voyager Interstellar Mission will hopefully characterize the distance to the termination shock, the distance that can be used to find the fundamental scale length of the interaction between the solar wind and the VLISM. The interaction has been speculated about for some time [31, 32]. Our current best guess about the conditions in the VLISM suggest an asymmetric bubble in the local medium, controlled by the local ram pressure of the ionized component of the interstellar gas [33, 34], but influenced significantly by the momentum sink due to charge exchange between the cold neutral gas and the hot shocked solar wind [35-37]. By directly penetrating through the termination shock (of the solar wind), the heliopause (where the solar wind and interstellar pressures balance) and through an external interstellar shock (thought to exist), an Interstellar Probe would allow for the fundamental characterization of this interaction between the solar system and the VLISM. Motion of the termination shock and other structures as a function of the solar wind input would be characterized as well as the location and study of the region wherein the galactic cosmic rays are modulated by solar activity [23a, 38]. We would be able to actually study *in situ* the region of space responsible for the outer heliospheric Very Low Frequency (VLF) radio emissions [22] that are currently our best means of estimating the distance scale for the solar wind VLISM interaction [22, 23, 39].

The Interstellar Probe would also provide the first *in situ* investigation of the region of production of the anomalous cosmic rays, providing a test of the heliospheric shock acceleration theory [40]. Confirmation or rejection of this hypothesis has far-reaching results for our understanding of the production of the supra-thermal component of particle populations throughout the observable cosmos.

(3) ***Explore fundamental astrophysical processes*** occurring in the heliosphere and the interstellar medium. As just noted, shock acceleration of particles has profound impacts upon many sub-branches of astrophysics. In addition, the structure of the solar wind interface with the VLISM has analogs in many other astrophysical settings, including observations of the bow shock nebula surrounding the pulsar PSR 1957+20 [41]; similar structures produced by outflows from Herbig-Haro objects [42, 43] and outflows from cataclysmic variables [44]. Similar structures are also expected for other G (solar)-type stars that might have stellar systems similar to that of ours [45]. There is also the question of whether our own termination shock is modified by high-energy particles [46] and to what extent this may also be an ubiquitous feature of interacting stellar wind/interstellar medium systems. Finally, there is the question of interstellar dust grains, their origin, density and evolution, a question that may be partially answerable by measuring the properties of such grains *in situ*.

3. RELEVANCE TO NASA'S OFFICE OF SPACE SCIENCE PROGRAMS

3.1 A Sole

The near-Sun flyby mission will address many of the fundamental scientific objectives of the Office of Space Science at NASA [47]. The NASA-concept 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. 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.

The guiding principle must be to limit the payload and spacecraft 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* [48] 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 *Randolph* [49], *Galeev et al.* [50], *McNutt et al.* [15], *Marsch et al.* [16], *Axford et al.* [13], and *Oraevsky and Kuznetsov* [51].

3.2 Ad Astra

The Interstellar Probe or Interstellar Precursor Mission is less well-defined than the Solar Probe mission. It is generally agreed that the probe must leave the solar system as rapidly as possible in order to penetrate as far as possible into the interstellar medium in a "reasonable" length of time — that has typically been taken as ~20 to ~50 years due to the constraints of realism in selecting propulsion technologies.

Even the unmanned, but "realistic" Daedalus mission to Barnard's star in 50 years [52, 61] strains credulity from the perspective of the 20th century and its realities. At the other end of the spectrum the current interstellar fleet of spacecraft will probably not reach the undisturbed VLISM within their operational lifetimes. Pioneer 10 and 11 now have barely enough power to remain operational even without their science instruments turned on (the Pioneer 11 mission, as noted above, has already officially ended). Pioneer 10 will leave the solar system at about 2.5 AU/year and enter an orbit about the galactic center similar to that of the Sun (and solar system - escape velocity from the Milky Way from the Sun's location is ~360 km s^{-1} [page 283 in Section 134 of ref. 7]; these numbers can be compared with Voyager 1's speed of 3.5 AU/year = 16.6 km s^{-1}). Voyager 1 and 2, now constituting the Voyager Interstellar Mission and managed by the Space Physics Division of NASA, should be able to continue to relay data on the far solar wind, and the heliosphere interaction region until the year 2015. At that time Voyager 1 and 2 will have extended our reach to 129 and 107 AU, respectively, from the Sun [54, 55].

3.2.1 Evolution of the Concept

The idea of a dedicated interstellar "precursor" mission first surfaced at the conference "Missions Beyond the Solar System" held at the Jet Propulsion Laboratory (JPL) in August 1976. The baseline mission was to reach 370 AU in 20 years after launch and 1030 AU in 50 years after launch using a fission-based Nuclear Electric Propulsion (NEP) system [56, 57]. Key goals were *in situ* measurements of the solar wind, interaction region and the interstellar medium with the goal of characterizing near interstellar space. Given the location of the incoming direction of the interstellar wind (as well as it was then known), it was suggested to include a Pluto orbiter spacecraft and launch about the year 2000 [21]. This "precursor" mission would be a means to begin the examination of engineering problems that would be faced on a true interstellar mission.

In March of 1990, the mission concept was revived in a workshop held in Ballston, VA [24]. The mission was identified as one of three "frontier probes" to explore the global heliosphere and local interstellar space. Again the prime focus was *in situ* fields and particles measurements. The goal was scaled back to reaching ~200 AU within ~25 years with 13 science instruments. This instrument payload had a projected mass of 126 kg payload and required 96 W of power. The projected spacecraft mass was ~600 to 1000 kg. A "powered solar flyby" was advocated as a means of accomplishing a rapid escape from the solar system without requiring NEP. The 1990 Workshop concept emphasis is in contrast with the TAU (Thousand AU) probe using NEP as studied by JPL and oriented toward astronomical science. The Interstellar Probe was to "takeover" from the Voyager spacecraft just outside of ~100 AU if the launch occurred in ~2000 as the power from the Voyager RTGs deceased below operational limits, as discussed above.

In the *Space Physics Strategy-Implementation Study* [48] the Interstellar Probe mission was endorsed and called out for a launch shortly after 2010 "to reach a minimum distance of 200 AU within 25 years, requiring spacecraft velocities of ~10 AU/year." Such a mission would be primarily a "fields and particles" mission into near-interstellar space for the purpose of understanding the interaction of the solar wind with and characteristics of the Very Local Interstellar Medium (VLISM) (Volume 1, Section 2.5.1.2). The main enabling technology problem was viewed as the wedding of a large ΔV maneuver near the Sun (~4 R_S — the distance proposed for a near-solar probe) or otherwise providing the high velocity required. The mission has also been advocated by both the:

(1) solar and space physics panel and

(2) astronomy and astrophysics panel of an NAS/NRC study: *Space Physics in the 21st Century - Imperatives for the Decades 1995 to 2015* as well as previous NAS/NRC reports.

Such a mission continues to be discussed as a high-priority, exploratory science mission [25].

3.3 Summary

Solar Probe and Interstellar Probe together represent the best of NASA: The exploration of the unknown. Together they can enable us to: ***understand*** how stars with life-supporting planets couple to their environments; ***link*** remote observable solar physics and phenomena to the physics of the corona and solar wind; ***discover and explore*** our own cosmic neighborhood - the VLISM and global structure of the heliosphere; ***investigate*** big-bang nucleosynthesis and interstellar processing of elements and isotopes using ***in situ*** measured data; and ***explore*** what a life-bearing star system looks like from the "outside."

However, **NONE** of this can come about without some realistic engineering assessments of what is and is not really feasible and how it drives and is driven by the science requirements. It is such an assessment that we consider in a preliminary way in the following paragraphs.

4. SPECIFIC FEATURES

4.1 Overview

A near-Sun flyby mission and a mission to the interstellar medium will likely each be single exploratory missions, much like that of Voyager 2 to Uranus and Neptune. Although an additional Russian spacecraft has been discussed for the Solar Probe mission, prudence suggests that designs are required for a spacecraft that can operate by itself in providing the science mission (a similar caveat applies to Russian planners!). Hence, a payload for the 4 R_S spacecraft must be self-contained. This mission offers the best opportunity to advance our fundamental understanding of the corona. Similarly the Interstellar Probe offers our best opportunity to really explore our solar neighborhood. ***Only focused, highly integrated payloads can enable real advances within constrained financial resources and accomplish these tasks.*** We have mapped out preliminary payload suites for both missions, relying on current programmatic status and drivers for both programs. To remain within a realistic estimate of the spacecraft resources, we have adopted a target of 10 kg/10 W/2000 bps, *which includes* structure, data processing and power regulation, supply and distribution (the instruments alone require 7.0 kg and 8.25 W).

Integrated science payloads offer many advantages to both missions. 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 selection, and there is 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 development has often been the interval in which the complexity and cost have grown most rapidly. An integrated payload, because of its use of common subsystems and the physical economies of a single structure, 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. ***These arguments for cost savings and risk mitigation are strengthened further by adopting an integrated approach to the payload and spacecraft together.*** This approach was successfully implemented by JHU/APL for NASA on the Near Earth Asteroid Rendezvous (NEAR) spacecraft and mission; this approach has also been taken for other pending and future missions in the Discovery series of low-cost, planetary missions (NEAR was the first Discovery mission). This mission, managed for NASA Headquarters by JHU/APL and launched in February 1996, now has all payload instruments successfully turned on as the mission continues to a rendezvous with the asteroid 433 Eros in 1999.

For the Solar Probe, our proposed payload retains all key science capabilities [15]. We have sought to minimize payload differences between the two missions, consonant both with the common measurement objectives and the design-to-cost mission driver. Major differences are that the accumulation times will be longer for the plasma and particles instruments for the Interstellar Probe mission. Longer times will enable accurate measurements as long as the instrumental backgrounds are sufficiently low. This philosophy is also in accord with anticipated lower data rates at larger distances toward the end of the Interstellar Probe mission. We have broken out preliminary resource targets as follows:

For the Interstellar Probe, the Solar Probe Imager would be replaced by a Lyman-α imager, infrared imager (passively cooled detector), cosmic ray detector, gamma-ray burst detector or a dust detector. Only one of these probably could be incorporated into a small Interstellar Probe payload, and more community input on the minimal science requirements is needed.

Other accommodation differences between the two missions include the need for a boom for the magnetometer for Interstellar Probe in order to accurately measure the expected microgauss field strengths accurately. In addition, a significantly different plasma wave detector with much longer antennas is required. ***Measurements of the wave environment, and especially the heliospheric VLF radiation are of prime scientific importance for an interstellar mission.*** Longer antennas for the plasma wave investigation and a boom for the magnetometer may use up the entire mass savings gained by the deletion of the imager system included in the Solar Probe payload. Otherwise, we believe it appropriate to aim for a maximal commonality between the two payloads as a means of keeping systems cost to a minimum as a means toward implementing ***both*** of these missions.

TABLE 1: *Conceptual Instruments and Projected Resources for a Solar Probe.*

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

One set of mass and power goals for a conceptual small Interstellar Probe [25] are still a factor of two larger than what we have budgeted for. ***An integral part of future studies should include looking at the Interstellar Probe as an integrated sciencecraft system to see what instruments can realistically be accommodated.***

4.2 Mission Concepts

We consider a "standardized sciencecraft" design that can be built using a maximal number of standard modules for implementing either a Solar Probe (SP) or Interstellar Probe (IP) mission. Notable differences include the requirement for transmission near the solar pass for SP and the need for Radioisotope Power Supplies (RPS) and communications across much larger distances (up to several hundred AU) for IP. The real-time transmission requirement for the SP mission also requires a three-axis stabilized spacecraft. This is not a requirement for IP; making the latter a spinner may have overall system advantages for long term (~20 year stability); ***a detailed look at the level of commonality that can be used for a spinner and three-axis stabilized spacecraft while minimizing life cycle costs for both is another topic that requires further study.***

4.3 Mission Requirements

Both mission concepts considered here require a close solar passage, i.e., approach the Sun to within 4 solar radii of the Sun's center [*cf.* ref. 25 for a discussion of other options for IP]. No Earth flybys are allowed (they introduce a longer period of mission operations = added cost and also cannot be implemented as a matter of policy if there is any radioactive material on board), but a Jupiter flyby is required to lower the angular momentum of the spacecraft in order for it to reach sufficiently small perihelion distances.

For the baseline mission requirements, both spacecraft must be launched with a Delta II 7925 and approach within 4 solar radii of the Sun following a Jupiter flyby (Jupiter Gravity Assist — JGA) to remove the heliocentric angular momentum of the probes. With no other constraints, energy and momentum conservation set the required injection energy (C_3) required to pass close to the Sun. Orbital inclination between Jupiter and the Sun is 90°, and for launches in 2000-2003, the flight time is ~3.6 years. The final probe orbital period is ~4.5 years for the 2003 launch; it is this period that can be reduced with a rocket motor burn opposite to the spacecraft velocity at perihelion.

The Solar Pioneer study [14, 15] focused on the use of an Earth flyby (unpowered) in order to increase the overall mission payload and relax required miniaturization issues. We compare a $C_3 = 121$ km^2 s^{-2} case that corresponds to a 12-day launch window for the 2002 launch JGA mission with a $C_3 = 50.7$ km^2 s^{-2} case that defines a 12-day launch window for the 2000 launch 3$^+$ ΔVEJGA (ΔV Earth Jupiter Gravity Assist) mission (Table 2).

TABLE 2: *Solar Probe Injected Mass Limits*

Launch Vehicle	Upper Stage	Injected Mass (kg) 50.7 (Δ VEJGA)	at C_3 (km^2 s^{-2}) 121 (JGA)
Atlas IIA	Star 48B	934	307
Atlas IIAS	Star 48B	1132	364
Delta II-7925	Star 30C	528	178
Proton M-5	FREGAT	2458	672
Proton M	Star 27V	1990	365
Proton M	Star 48V	476	816
Shuttle	IUS/Pam D	1358	401
Titan IV	SRMU/Centaur	942	708
Titan IV	Centaur	2983	12

The nominal Solar Probe launch date now being carried by NASA is for the 2003 mission which has a comparable requirement for a 20-day launch window. It should be noted that the 2000 3$^+$ΔVEJGA mission and 2003 JGA mission both fly by Jupiter and arrive at the Sun at the same times: May 4, 2005, and July 8, 2007, respectively.

Due to cost constraints, only the Delta II 7925 can be considered as a realistic option (the Delta III, scheduled for its first flight in 1998 has capabilities similar to the Atlas IIAS but is currently estimated as costing ~$30M more than the Delta II 7925). Mission operations cost constraints and mission "timeliness" similarly limit the trajectory choice to JGA for SP. Use of radioactive materials (required for IP) also rule out Earth encounter trajectories. Based upon these considerations, we identify a maximum wet mass for the SP mission as 178 kg and use this as the basis for our spacecraft design concept.

The IP is far more demanding and requires that the SP act as a "pathfinder" for demonstrating that a spacecraft can survive a close perihelion pass. The requirement for the IP is that it leave the solar system "as fast as possible." As noted above, programmatic considerations in the past have suggested reaching 200 AU in ~25 years (IMP 8 has now been operating in Earth orbit for almost 23 years, the Voyagers have passed 19 years of operation and Pioneer 10 is now past 24 years of operations).

In 1929, rocket pioneer Hermann Oberth [58] recognized that a large rocket burn near the Sun was the most efficient means to leave the solar system as rapidly as possible. Measuring all speeds in km/s the asymptotic escape speed from the solar system is approximately

$$v_{escape} = (\Delta V)^{\frac{1}{2}} \frac{35.147}{r_p^{\frac{1}{4}}}$$

where r_p is the perihelion distance from the center of the Sun measured in units of solar radii. A speed of 1 AU/yr = 4.74 km/s, so to reach 10 AU/yr at 4 R_s perihelion we need a speed increase of 3.6 km/s. This value can be decreased by moving the perihelion closer to the Sun. However, the thermal shield temperature rises as the inverse square root of the perihelion location. Moving the perihelion distance inward implies that the thermal shield mass (and its outgassing rate) must increase, decreasing the available fuel fraction, and hence, the available ΔV.

The amount of rocket fuel delivered to the near vicinity of the Sun must come from the wet mass of the initial launch vehicle. For a JGA trajectory, the IP spacecraft can have a larger mass than the SP by flying a 3$^+$ ΔVEJGA trajectory. ***Further study needs to be done to determine whether (i) staging of the IP at the deep space ΔV maneuver and (ii) dropping the perihelion closer to the Sun can realistically increase the asymptotic flyout speed.***

Another possibility for raising the injected mass for both missions may be by using a Mars gravity assist to reach Jupiter. Such a gravity assist would be done "on the way" to Jupiter so as not adversely to impact the flight time. A flyby of Mars with radioactive materials on board also does not have the policy implications that an Earth flyby has. It is not clear without detailed study whether the phasing of the planets in their orbits would allow for such a scenario. ***Calculations of whether a Mars flyby could work are also needed but beyond the scope of this paper.***

If the injected mass for both a SP and IP mission could be increased, the same perihelion burn that ejects IP from the solar system, could be used to reduce the period of SP. Use of retractable solar arrays (versus simply jettisoning of them) as well as incorporation of a Solar Thermoelectric Generator could enable multiple close flybys of the Sun, significantly enhancing the science return with some increase in mission operations cost. Maintenance of the solar arrays during perihelion passage while remaining within the injection mass constraints is the most difficult enabling problem for this possibility. ***Again further quantitative engineering assessments are needed.***

4.4 Spacecraft Systems

We have assembled a rough conceptual design for the SP and IP configurations drawing upon our previous work on Solar Pioneer - a concept study for an inexpensive solar probe funded by the Space Physics Division of NASA [14,15].

Figure 2 shows a block diagram of the baseline concept for the sciencecraft probe we have been discussing. It combines some of the features that would be present on either the SP or IP. Details of the differences are illustrated in mass and power spreadsheets that follow, while the block diagram can be taken as indicative of desirable design goals. Salient points include the use of a conical carbon-carbon thermal shield, the use of an Integrated Electronics Module (IEM) with full system redundancy (not a "single-string" spacecraft), incorporation of a non-coherent communications system, and the attempt to avoid incorporation of radioactive materials as part of the power system. The baseline thermal shield is sized as a 1.8 x 3.5 m cone which, together with the secondary IR shield has an estimated mass of 36 kg and allows space for the system components. The shield mass increases by about 10 kg for the IP concept for shielding of the larger propulsion system. Table 3 shows the mass and power requirements for the 178 kg JGA SP version of the sciencecraft. Corresponding values for the IP (SP with aphelion lowering) are shown in Table 4.

TABLE 3: *Cold Gas Minimal System*

Component	Mass (Kg)	Power (W)
INSTRUMENTS (Allocation)	**10.0**	**10.0**
GUIDANCE AND CONTROL SYSTEM	**9.3**	**16.7**
REACTION WHEELS (2)	6.4	6.7
Chip On Board STAR CAMERAS (2)	0.9	1.9
DSAD(2)	0.5	0.1
GYRO UNIT/ACCELEROMETERS	1.5	8.0
COMMAND AND TELEMETRY SYSTEM	**4.1**	**20.0**
INTEGRATED ELECTRONICS MODULE	4.1	20.0
POWER	**17.0**	**2.5**
POWER SYSTEM ELECTRONICS & SWITCHING	3.4	2.5
SECONDARY BATTERY (4 A-H)	4.5	
75 WATT RADIOISOTOPE POWER SOURCE	9.1	na
PROPULSION & PRIMARY STRUCTURE	**82.4**	**0.0**
STRUCTURE/ADAPTER	21.4	0.0
MISC. STRUCTURES & FASTENERS	6.0	0.0
PRIMARY SHIELD/SECONDARY SHIELDS	35.5	
PROPULSION COMPONENTS (150 M/S Cold G	19.5	0.0
RF COMMUNICATIONS	**10.1**	**20.0**
DIPLEXERS (2)	0.3	na
PWR AMP (2)	5.4	na
DC/DC CONVERTER (2)	2.5	20.0
FANBEAM PLANAR ANTENNA (40¡ x 8¡)	0.7	0.0
LOW GAIN ANTENNAS (2)	0.3	0.0
COAX SWITCHASSEMBLY	0.5	0.0
COAX CABLES	0.4	0.0
THERMAL	**7.9**	**1.0**
SPACECRAFT HEATERS/THERMOSTATS	0.7	0.0
LOUVERS	1.2	0.0
BLANKETS	6.0	0.0
HARNESS	**6.0**	1.0
EXPERIMENT & SPACECRAFT BUS	**146.7**	**71.2**
DRY WEIGHT MAX. (Delta 7325)	178.0	
FUEL (Ox-H-He Mixture 150 Isp)	17.3	
TOTAL WET MASS	164.0	
RESERVE	**14.0**	

TABLE 4: *Biprop and Perihelion Thrust System*

Component	Mass (Kg)	Power (W)
INSTRUMENTS (Allocation)	**10.0**	**10.0**
GUIDANCE AND CONTROL SYSTEM	**9.3**	**16.7**
REACTION WHEELS (2)	6.4	6.7
Chip On Board STAR CAMERAS (2)	0.9	1.9
DSAD(2)	0.5	0.1
GYRO UNIT/ACCELEROMETERS	1.5	8.0
COMMAND AND TELEMETRY SYSTEM	**4.1**	**25.0**
INTEGRATED ELECTRONICS MODULE	4.1	25.0
POWER	**26.1**	**2.5**
POWER SYSTEM ELECTRONICS & SWITCHING	3.4	2.5
SECONDARY BATTERY (4 A-H)	4.5	3.0
Two 75 WATT RADIOISOTOPE POWER SOURCE	18.2	na
PROPULSION & PRIMARY STRUCTURE	**125.8**	**40.0**
STRUCTURE/ADAPTER	27.4	0.0
MISC. STRUCTURES & FASTENERS	7.9	0.0
PRIMARY SHIELD/SECONDARY SHIELDS	35.5	
PROPULSION COMPONENTS (Dual Mode)	55.0	40.0
RF COMMUNICATIONS	**16.9**	**35.0**
DIPLEXERS (2)	0.3	na
PWR AMP (2)	5.4	na
DC/DC CONVERTER (2)	2.5	35.0
0.75 METER ANTENNA	1.5	0.0
RF GIMBALLED PLATFORM	6.0	na
LOW GAIN ANTENNAS (2)	0.3	0.0
COAX SWITCHASSEMBLY	0.5	0.0
COAX CABLES	0.4	0.0
THERMAL	**11.8**	**9.8**
SPACECRAFT HEATERS/THERMOSTATS	1.0	8.0
LOUVERS	1.8	0.0
BLANKETS	9.0	0.0
HARNESS	**6.0**	1.8
EXPERIMENT & SPACECRAFT BUS	**209.9**	**140.8**
DRY WEIGHT MAX. (Delta 7325)	528.0	
FUEL (MMH-N2O4)	102.0	
STAR20B With TVC (Isp 288, 188 Kg burned)	216.0	
TOTAL WET MASS	527.9	
RESERVE	**0.9**	

4.4.1 Communications System

The RF system uses a X-band or Ka-band downlink. The latter has increased data rate and tends to minimize the effects of solar scintillations at the expense of degraded performance if there is rain over a receiving station, increased pointing accuracy requirements and questionable coverage at the Canberra and Madrid Deep Space Network (DSN) stations. By not using the JPL incorporated antenna/thermal shield concept [59] we (i) mitigate system risk by separating the shield and communications functions, (ii) eliminate the need to correct for solar light pressure torque on the asymmetric JPL design, (iii) eliminated the need for a high temperature feed for the antenna, and (iv) may save in fabrication costs (due to tolerances required on the antenna side of the shield).

In the SP design (Table 3), the RF power amps consume 20 W and broadcast 5 W of power. A 40° x 8° fanbeam antenna is employed. For the IP (Table 4), we increase the power amplifier input to 35 W (10 W output RF at Ka- or X-band) and go to a 30° gimballed platform with a 0.75 meter dish antenna. The IP uses the DVEJGA trajectory and, therefore, has some room for increasing the mass of pertinent subsystems to allow for the need to communicate over significantly larger distances.

By employing non-coherent navigation [60] one can significantly simplify spacecraft communications hardware. Here the uplink frequency is measured in the S/C receiver relative to an on-board precision oscillator. This measurement is accomplished with a simple set of counters, sent down in the spacecraft telemetry and used to correct the one-way Doppler measurement made by the DSN. The technique (i) provides coherent precision, (ii) does not require changes to DSN assets, (iii) permits direct measurement of the spacecraft oscillator frequency (this may permit periods of accurate one-way Doppler tracking when the DSN uplink is unavailable), (iv) does not necessarily require an ultra-stable oscillator (USO) on the spacecraft, and (v) allows elimination of two-way phase noise amplification in Doppler measurements if dual (e.g., X/Ka) frequency bands are used.

Spacecraft telemetry is required to provide the correction factors for the one-way downlink Doppler measurement (the current system is independent of the spacecraft telemetry); hence, mission operations must provide a path for the telemetry to be sent to the navigation team and this can be a disadvantage.

Although coherency is not really a "driver" for the spacecraft transponder design, this implementation provides a "top-level" way to provide miniaturization without requiring expensive technology investments (i.e., custom MMIC chips) that eventually result in asymptotically decreasing returns on investment. For example, JHU/APL is currently designing a lightweight "receiver-on-a-card" for the IEM (discussed in a following section) that does not require expensive technology advances and will permit non-coherent two-way tracking without requiring multiple ground stations or turn-around tones that require changes to the DSN assets to process. Our idea is differentiated by its simplicity and the fact that it does not require changes to DSN hardware.

The next-generation deep space transponders (now under development by Motorola) incorporate X-band uplink and dual X-/Ka-band downlink, but they are relatively heavy: 2.75 kg/unit (with two needed for redundancy). They require 10 to 16 W of power and require external power amplifiers. The currently estimated cost is $750 k/unit. By using the non-coherent scheme we can reduce the mass to ~0.5 kg/unit, the power to ~5 W and cost to ~$150 k/set. More importantly, this allows us to put all of the communications system, except the power amplifiers into the common IEM.

Data rates of ~5 bits per second are the "floor" due to power usage for traditional telecommunications schemes. Using narrow-band tones (proposed for beacon operation) and narrow-band filters for separating the signal from background noise may enable retrieval of data at rates as low as 0.1 bps and so keep down antenna and communications system masses and power for the IP at its large operating distances.

4.4.2 Propulsion

The baseline SP concept has a 150 m/s ΔV capability for course correction maneuvers and lining up the Jupiter flybys. The use of a biprop system similar to that implemented on the NEAR spacecraft is shown on fig. 2. Another solution is indicated in Table 3. By employing a cold gas mixture of He/O/H it may be feasible to achieve a reasonable specific impulse while eliminating the need for any heaters (this configuration uses a platinum mesh catalytic bed but requires no heating). Reaction wheels are used for pitch and yaw to keep the thermal shield pointed precisely at the Sun near perihelion while roll attitude would be controlled with jets run from the propulsion system.

For the IP (or SP employing an aphelion lowering burn), we would include a Star 20B with off-loaded fuel, removed nozzle and a thrust vector control nozzle assembly that a gives more compact volume. The biprop system as shown in the block diagram is employed for both the trajectory correction maneuvers and the large required deep space burn of 461 m/s on the ΔVEJGA trajectory.

Currently in this "first cut" (Table 4) we have room to supply a ΔV of 1.56 km/s at perihelion, about half of what is desirable. By decreasing the perihelion distance to 3 solar radii (with associated increased sublimation of the thermal shield, but potentially within structural failure limits), we can obtain an escape speed of ~7.0 AU/year. By staging the deep space propulsion system and searching for other mass-saving efforts it may prove possible to approach the desired design goal of ~10 AU/year with near-term technologies.

4.4.3 Integrated Electronics Module (IEM)

The "Integrated Electronics Module" or IEM is a spacecraft concept now being pursued as an internally-funded project at JHU/APL. The goal is to develop an integrated card cage with spacecraft subsystems miniaturized onto individual standardized cards. The concept system is redundant with an architecture that can be developed to the point of being flown in the near-future. The goals and drivers of this development program (begun in January 1995) are to (i) target smaller launch vehicles, (ii) increase the payload (science) mass fraction, (iii)

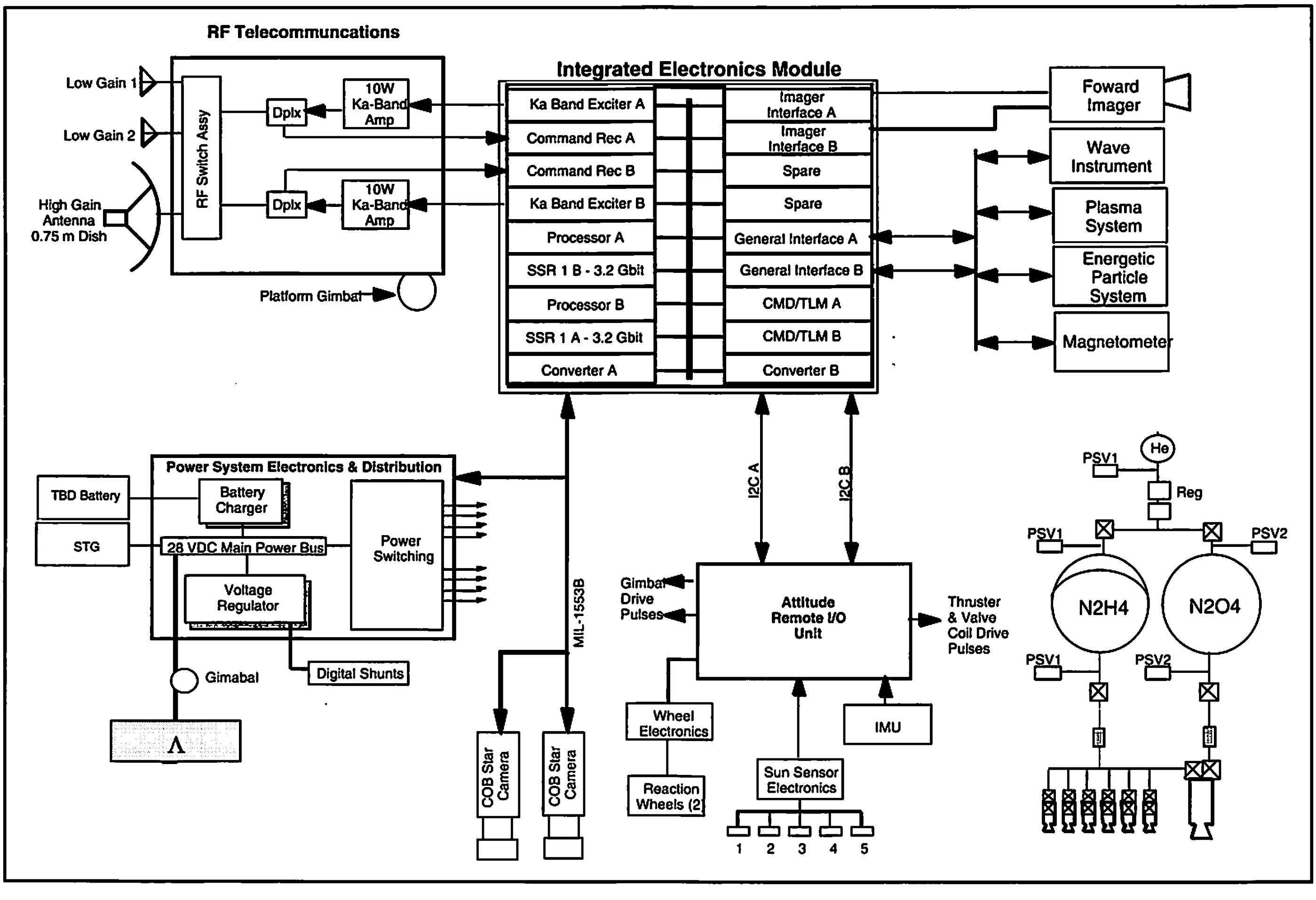

Fig. 2 SOLAR PROBE System Block Diagram

reduce development time while maintaining a flexible mission design capability, and (iv) reduce the "ground up" design on individual programs while minimizing parts types and parts so as to improve reliability and capability. Key supporting technologies now in development at JHU/APL include design of a serial bus ASIC chip, design of a remote I/O (RIO) mixed ASIC chip (the "housekeeping chip"), developing techniques for fully composite construction and demonstrating a receiver card and transmitter card fully integrating the communications subsystem with the other card level systems (the non-coherent system referred to in the communications section).

A technical review of the IEM concept and design was held internally on 15 March 1996. Figure 3 shows a block diagram of the current IEM concept. ***The IEM approach forms the core of the spacecraft designs for the Solar Probe/Interstellar Probe common design discussed here.***

4.4.4 Power System

Concern for costs associated with required reviews for flying spacecraft powered by and/or heated with radioactive materials has driven NASA to advocate a Solar Probe mission that is free of RTGs, RHUs (Radioisotope Heater Units) or any of their derivatives. In the case of the Pluto Express mission, an exception has been made (for the present) due to the extreme impracticability of flying even a low-powered mission to over 30 AU from the Sun on solar cells (or a battery!). Similarly an Interstellar Probe will require some form of radioactive power source for both power and heating during its 20 year + mission. The block diagram of the common system (fig. 2) currently shows a power system with solar panels, a Solar Thermoelectric Generator (STG), and a "to be determined" battery. However, for purposes of estimating a technically doable mission, we have used estimates for RTGs in the spreadsheets: one 75 W RTG with the small SP (Table 3) and two 75 W RTGs for the more massive IP design and power estimate (Table 4).

As part of our Solar Pioneer study [15] we considered a non-nuclear design based upon batteries and solar cells, but we found an unacceptable (negative) mass launch margin (with a 50 kg payload on an Atlas IIA). The current JPL minimum mission design shows a large negative mass launch margin for such a concept [59] even with high energy density batteries. Both of these exercises have demonstrated the severe limitations, including a hard finite mission operating time, that is imposed by a battery/solar cell power system for SP. To avoid the use of RTGs on a non-nuclear SP that also avoids power lifetime constraints, some form of STG is essential for providing perihelion power.

The current non-nuclear designs for SP do (barely) suffice for a limited initial reconnaissance of the upper corona. For a multiple-solar-orbit probe (a scaled version of the Ulysses mission with a much smaller perihelion), an STG or RTG/RPS is required. Current STG concepts suffer from too small a dynamic range of thermal operation. Obviously there is no lack

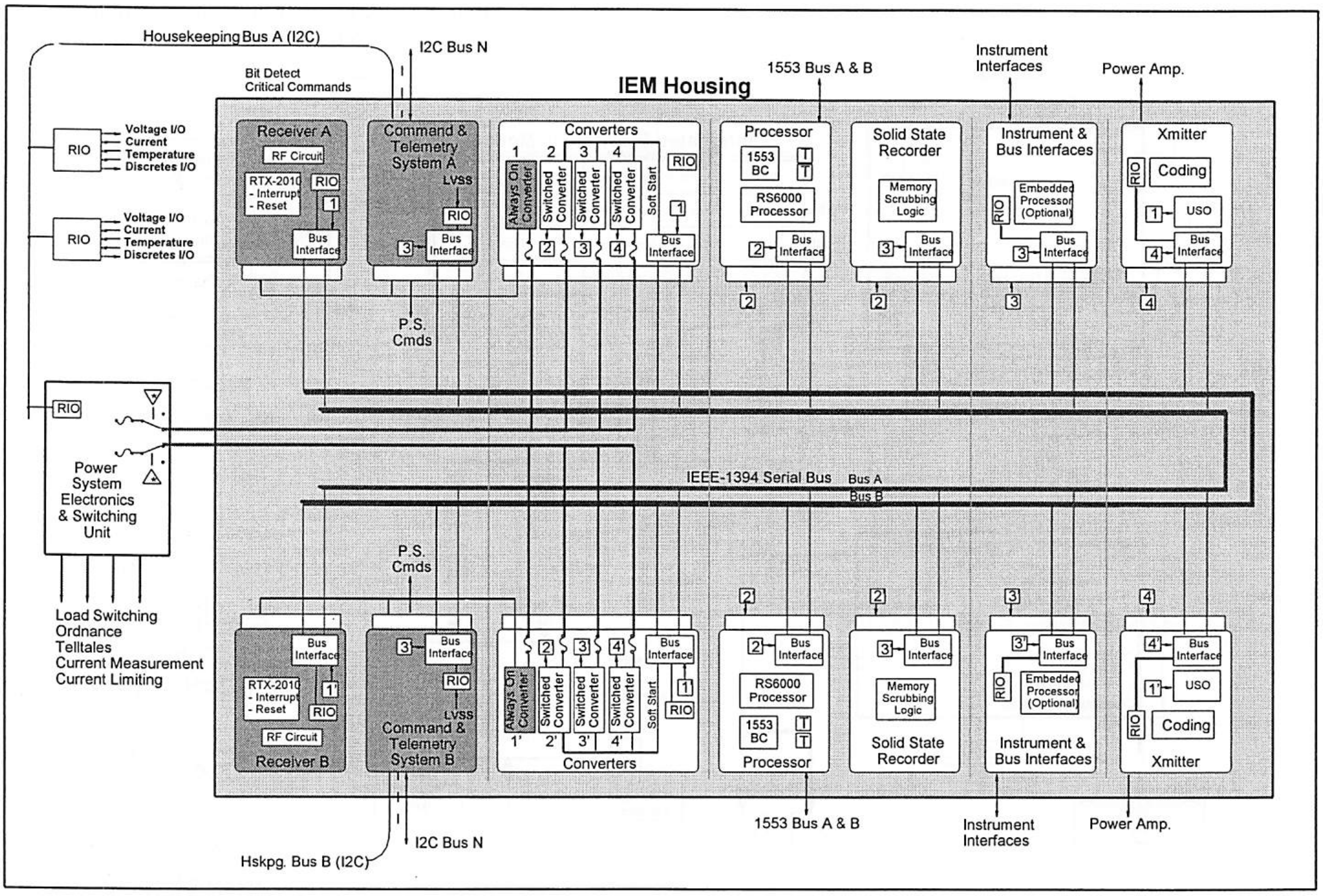

Fig. 3 Block diagram of the IEM concept currently under development at JHU/APL on IRAD funds. This redundant serial bus design is planned to standardize and reduce costs and mass while allowing implementation of core spacecraft task. The objective of this development program is to build a functioning card cage and bring the entire design to a mature level that can be credibly proposed for near-term implementation.

of solar power - the problem is that it changes too much and too rapidly during the time SP is within ~0.2 AU of the Sun. ***Further engineering study may - or may not - suggest a solution.*** In the near-term (~2003 launch) there may be no realistic option for a solar probe mission except for "one-shot" limited perihelion pass, except for no mission at all!

Unless a far more robust STG system can be designed, a multiple-solar-orbit SP mission may require the use of some form of RPS. As in the case of Pluto Express there is no other power supply option than an RPS for an Interstellar Probe.

5. CONCLUSIONS

Instrumented missions to the Sun and to near-Interstellar space have been discussed for over two decades. Usually characterized as *in situ* measurement missions, other high-priority science goals can be addressed only *via* the use of these unique platforms. Both missions require extremely capable spacecraft that can operate in extreme thermal environments. With current fiscal and programmatic constraints faced by NASA's Office of Space Science, both missions also require miniaturization of spacecraft systems and scientific payloads as well, if they are to happen.

We have outlined common requirements as well as requirements that are unique to both missions. In addition, we have sketched out how these requirements might be met and these missions implemented, pointing out that significant cost savings may be incurred on an Interstellar Probe (or other deep space mission) if some attention to commonality is paid during a Solar Probe development effort At the same time, such forward-looking, strategic thinking need not be an additional cost driver for a Solar Probe as some might think

Current Solar Probe requirements already provide a core for the approach to an Interstellar Probe design. An Interstellar Probe will ***require*** both an RPS power supply and a perihelion kick motor. Inclusion of these systems on an advanced solar probe would enable multiple orbits of the Sun, and a more bountiful return of knowledge and understanding about the nearest star. The programmatic and policy problems raised by the inclusion of an RPS on a Solar Probe mission might be alleviated with an advanced STG power supply, but more engineering research is required to full assess this possibility. In the meantime, a baseline FIRE-like mission can be built and will return significant new science, although a Discovery-like implementation is probably required in order to maintain the payload's scientific viability while remaining within mass, power, data rate and fiscal constraints.

In the midst of new fiscal challenges, our exploration of the cosmos must continue. Spacecraft missions to the inner and outer edges of the heliosphere remain exciting scientific priorities for obtaining data that can be obtained in no other way that is needed to answer fundamental questions about our cosmic environments. The frontiers beckon, the technology is in hand, and the time is now "...to strive, to seek, to find, and not to yield..." in our quest to increase the wealth of human knowledge *a sole ad astra.*

6. ACKNOWLEDGEMENTS

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