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INNNOVATIVE INTERSTELLAR EXPLORER

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ABSTRACT

An interstellar “precursor” mission has been under discussion for over 25 years. Many fundamental scientific questions about the nature of the surrounding galactic medium and its interaction with the solar system can only be answered by in situ measurements that such a mission would provide. Therefore, the challenge is the development of a science probe that would reach a heliocentric distance of at least 200 astronomical units (AU) in 15 years or less with an average speed almost four times the 3.6-AU/yr speed of Voyager 1. Previous studies have looked at the use of a near-Sun perihelion propulsive maneuver, solar sails, and large fission-reactor-powered nuclear electric propulsion systems (NEP) for the enabling propulsion. We present here an alternative approach - the Innovative Interstellar Explorer (IIE) - based on Radioisotope Electric Propulsion (REP). The required speed is achieved by a high-energy launch, using current launch vehicle technology, followed by long-term, low-thrust, continuous acceleration enabled by a kilowatt-class ion thruster. The electric power is provided by advanced Stirling radioisotope generators (SRGs) based on Pu-238 General Purpose Heat Sources (GPHS). We discuss the science, payload, ongoing trade studies, and development of this approach to an interstellar probe.

"Great trees grow from the smallest shoots; a terraced garden, from a pile of earth, and a journey of a thousand miles begins by taking the initial step. " - Lao-Tze, *Tao Te Ching*.

INTRODUCTION

Travel to the stars has been a staple of science fiction for a great part of the last century. But after the successes of Pioneer 10 and 11 in their flybys of Jupiter, and prior to the Voyager launches, a scientific conference on "Missions Beyond the Solar System" was held at NASA's Jet Propulsion Laboratory (JPL). This 1976 conference[1] outlined the role for such missions in coming to terms with the engineering problems of a true interstellar mission and also the science that a "precursor" mission could accomplish.

Following this original discussion in the science community the so-called interstellar precursor missions, or Interstellar Probe, have continued to be discussed by individual authors,[2-5] as well as identified as a scientific priority by consensus documents in the science community (Table 1).

Today, Pioneer 10 and 11 and Voyager 1 and 2, all have speeds in excess of the escape speed from the Sun and will penetrate into interstellar space. Powered by Radioisotope Thermoelectric Generators (RTGs), the spacecraft all have a finite lifetime due to the half life of the ^{238}Pu fuel (89 years) as well as degradation of the Si-Ge convertors in the RTGs. The Voyagers now form the Voyager Interstellar Mission with the goal of penetrating the termination shock of the solar wind, thought to be located ~100 astronomical units (AU)[*] from the Sun.

The Voyagers will unlikely reach the "undisturbed" interstellar medium prior to falling silent. There are many fundamental science questions, however, that can only be addressed by instrumentation that actually penetrates outside of the heliosphere.[3-10] The specific goals of such in situ investigation include:

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). For example, measurements of rotation measures and dispersion measures of pulsars suggest a large scale magnetic field of ~1.4 μG,[11] but we have no idea of the field structure or its variations within 0.1 or even 0.01 light years (LY). Similarly, the properties of the nonthermal portion of the medium (including the low-energy galactic cosmic rays) remain unknown.

Explore the structure of the heliosphere and its interaction with the interstellar medium. The Voyager Interstellar Mission may establish the distance to the termination shock, but a farther-ranging probe is required to understand the dynamics of the interaction and how it is influenced by the conditions in the VLISM.

Explore fundamental astrophysical processes occurring in the heliosphere and the interstellar medium. Shock acceleration of particles has profound impacts upon many branches of astrophysics. In addition, the structure of the solar wind interface with the VLISM has analogs in many other astrophysical settings.

Determine fundamental properties of the Universe. Measurements of ^{3}He, D, and ^{7}Li would give constraints on big-bang nucleosynthesis and on how these key indicators have been processed in the interstellar medium.[12] Extremely accurate tracking of a probe can be used to look for gravitational waves and a non-zero cosmological constant, and/or other anomalous forces such as that inferred to be acting on several deep-space missions.[13,14] Polarization measurements of the downlink carrier can be used to

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[*] Distance scales: one solar radius is 1 $R_S = 6.9599 \times 10^5$ km and one AU is 1.495979×10^8 km or 214.94 R_S; one light year (LY) is 63,240 AU; one parsec (pc) is 3.26 LY or or 206,000 AU. Alpha Centauri, the closest star system is 4.3 LY or 272,000 AU away. Voyager 1 and 2, now constituting the Voyager Interstellar Mission, should be able to continue to relay data until power margins drop too low about the year 2020.

TABLE 1. Community Reports

NASA Studies	National Academy Studies
Outlook for Space, 1976	Physics through the 1990's - Panel on Gravitation, Cosmology, and Cosmic Rays (D. T. Wilkinson, chair), 1986 NRC report
An Implementation Plan for Solar System Space Physics, S. M. Krimigis, chair, 1985	Solar and Space Physics Task Group Report (F. Scarf, chair),1988 NRC study Space Science in the 21st Century - Imperatives for the Decade 1995-2015
Space Physics Strategy – Implementation Study: The NASA Space Physics Program for 1995-2010	Astronomy and Astrophysics Task Group Report (B. Burke, chair), 1988 NRC study Space Science in the 21st Century - Imperatives for the Decade 1995-2015
Sun-Earth Connection Technology Roadmap, 1997	The Decade of Discovery in Astronomy and Astrophysics (John N. Bahcall, chair)
Space Science Strategic Plan, The Space Science Enterprise, 2000	The Committee on Cosmic Ray Physics of the NRC Board on Physics and Astronomy (T. K. Gaisser, chair), 1995 report Opportunities in Cosmic Ray Physics
Sun-Earth Connection Roadmaps, 1997, 2000, 2003	A Science Strategy for Space Physics, Space Studies Board, NRC, National Academy Press, 1995 (M. Neugebauer, chair)
NASA 2003 Strategic Plan	The Sun to the Earth -and Beyond: A Decadal Research Strategy in Solar and Space Physics

look for inherent anisotropies in the structure of space.[15]

Within the last few years, two approaches have been pursued in some detail: the use of a solar sail at low-thrust with a gradual build up of escape speed within a few AU from the Sun[6,8,16] and the use of a powered solar gravity assist.[4,7,17-25] More massive schemes based upon nuclear electric propulsion (NEP) have also been discussed[26] and were the original basis for the interstellar precursor mission,[27-29] as well as for the Thousand Astronomical Unit (TAU) mission.[2]

Current observations suggest the termination shock is ~100 AU away, with the heliopause, the boundary separating solar and galactic plasmas, somewhere at 150-200 AU in the heliospheric nose direction. So, the minimum required distance to reach the interstellar medium is 200 AU[3,6,9,10] with a flyout time of 15 to 25 years, a half of a professional life time of a scientist and engineer. We note that to the unperturbed, “virgin” interstellar medium is expected to be found only at the distances beyond 300-400 AU. Further distances (~1000 AU) for longer times (~50 years) are preferred[1,25] but pose significantly more demands on both propulsion and spacecraft.

MISSION CONCEPT

Previous efforts have focused on most of the proposed scenarios for propelling a spacecraft to a high velocity from the solar system: near-Sun powered perihelion maneuvers (chemical and solar thermal propulsion, or STP), solar sails, and nuclear electric propulsion (NEP). Nuclear thermal propulsion (NTP) schemes based upon small reactors have also been considered.[30] More exotic propulsion means include laser-pushed lightsails,[31,32] fusion,[33,34] antimatter propulsion,[36,37] magnetic sails,[38] and propulsion based upon "breakthrough physics" concepts[39] that are at very low technology readiness levels (TRL) and not appropriate for actually implementing sometime within the next 25 years.

The one other "near-term" approach that has been noted but typically rejected for mass issues is that of Radioisotope Electric Propulsion (REP).[40] Given many advances in hand, as well as now in progress, under NASA's Project Prometheus, REP may actually be enabling for a realistic interstellar precursor mission in the right time and for the right price. This article describes a thorough system study of such a mission and spacecraft, an effort in progress.

Technology and Science

The Innovative Interstellar Explorer concept will provide a foundation for a mission planning and identify the required technology advancement strategy. Mass and power budgets present a special challenge for a mission to interstellar space. In addition, particular attention should be paid to potential interference between the REP propulsion system and spacecraft subsystems and instruments, including required clear fields of view of the instrumentation and electromagnetic interference and electromagnetic compatibility.

Our spacecraft concept is solely robotic and no astronaut intervention is required for either assembly or deployment. In fact, due to the presence of nuclear materials on board, only Earth escape trajectories ($C_3 > 0$) are considered, offering a significant safety and programmatic advantage over heavier fission-reactor-powered NEP systems that cannot be placed directly in escape trajectories with the current space launchers.

The science objectives of the Innovative Interstellar Explorer are aligned with the fundamental science objectives of NASA’s Sun-Earth Connection Theme identified by NASA Strategic Planning and can be traced from the top-level NASA questions, vision, and mission down to specific requirements for our mission.

Table 2 shows the science payload of the Innovative Interstellar Explorer. The science objectives are based on the 1999 report of NASA's Interstellar Probe Science and Technology Definition Team (IPSTDT).[6,8,9] These strawman instruments are compared with instruments at TRL 9, i.e., present-day instruments on flight spacecraft.

TABLE 2. Model Science Payload

Material Measured	Number of instruments	Notional instrument from 3rd Interstellar Probe Science and Technology Definition Team meeting, 17-19 May 1999, JPL			Comparable performance of instrument at TRL of 9 (An example ideal payload)		
Instrument Resources		Mass (kg)	Power (W)	Data Rat (bps)	Mass (kg)	Power (W)	Data Rate (bps)
Fields	2	1.0	1.3	3.6	12.77	12.00	95,760
Plasma; suprathermal particles	3	8.5	6	12	12.17	10.75	1,503
Energetic particles	3	6.4	4.6	7	103.1	63.0	3,224
Neutral material	3	7.3	6.5	1.4	51.01	46.98	5,324
Photons	2	3.4	0.9	0.6	40.65	105.1	1,900
Totals	13	26.6	19.3	24.6	219.7	237.83	107,711

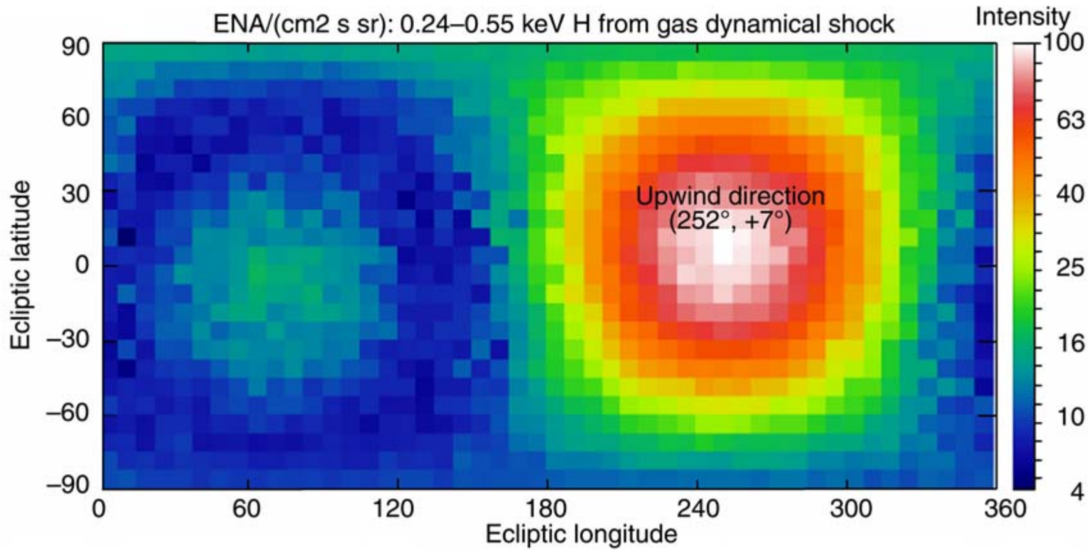

Fig. 1. Simulated all-sky image[40] in fluxes of 0.24<E<0.55 keV hydrogen energetic neutral atoms (ENAs) produced by charge exchange of protons heated in an axi-symmetric gas-dynamical termination shock. Intensity is color-coded in ENA/cm^2-sr-s.

Many required key measurements can only be made from a space probe in transit form the outer heliosphere to the VLISM. Global heliosphere imaging experiments[40-42] collapse a three-dimensional objects into two-dimensional images and in-situ, ground-truth measurements are essential to resolve ambiguities. As an example, when viewed in fluxes of energetic neutral atom (ENA) hydrogen from inside the termination shock (Figure 1), a strong (gasdynamical) solar wind termination shock[43] will produce a peak intensity in the upwind direction of interstellar gas flow relative to the Sun.[40] From a probe trajectory, the ENA distribution over the sky will dramatically change, but the intensities will remain approximately the same. A weak shock or magnetic effects will produce a markedly different distribution of ENA intensities, enabling those observations to probe the interaction. Another example is the detection of the heliospheric radio emission from the interaction of solar wind transients and the heliospheric structure[44-46] and determining the location and nature of its source. The most important measurement is, of course, a definitive identification of the termination shock[47] and later of the heliopause, the boundary separating the solar and galactic plasmas.[10,42,48]

Mission Significance

An interstellar probe mission to explore the heliosphere on its largest scale and the interaction between the Sun and the galaxy can only be accomplished with (1) measurements at the spacecraft itself when in the appropriate location and (2) remote measurements that are not blocked from the observer by the properties of the interplanetary (or interstellar) medium itself. Such measurements can be made in no other way and will go begging until an interstellar probe mission can be carried out. The interstellar probe mission together with the complementary future experiments to remotely (from 1 AU) image the heliospheric interface region in ENAs[40,41,49] and EUV[42,50,51] will comprehensively explore the sun's interaction with the surrounding galactic matter.

In addition, such a space mission into the interstellar medium will be the first, obviously modest, step toward truly interstellar flight of the future. Needless to say that it would be an important moment in the history of the planet Earth with the human race embarking on exploration, and ultimately expansion, beyond the boundaries of its home stellar system.

While Project Prometheus, perihelion maneuvers, and solar sailcraft also suggest a solution to this conundrum, all of these alternatives have drawbacks. Large, low areal density sails capable of withstanding high temperatures are needed or significant solar thermal propulsion technology development is needed for two of these approaches.[16,21] The spacecraft capable of carrying significant fission-reactor power to run NEP systems are inherently large and massive[26,28,29,52] including those discussed for Prometheus, and can just reach low-Earth orbit or nuclear-safe orbits with current launch vehicles. With the Jupiter Icy Moons Orbiter (JIMO) highlighted as the first reactor-driven Prometheus mission in ~2012, it is not at all clear when a second mission could be launched for an interstellar probe mission.

The cost reality of launching heavy spacecraft points to an unavoidable requirement of achieving a significant reduction in cost of access to space. Our Innovative Interstellar Explorer thus offers a significant programmatic advantage of enabling this important mission sooner rather than later.

MISSION EXAMPLE

The basic equation that governs spaceflight is the rocket equation:

$$M_{0I}/m_{final} = R = \exp\left(\Delta V/I_{sp}g\right) \qquad (1)$$

where $\Delta V = I_{sp}g\ \ln(R)$ is the change in speed; $g = 9.81\ m/s^2$ is the standard free fall acceleration; I_{sp} is the specific impulse ($I_{sp}g$ is the propellant exhaust velocity); R is the mass ratio, and M_0 and m_{final} are the initial mass (including propellant) and the mass following the speed change (the "dry" mass after "burnout"), respectively. To attain high speeds efficiently, exhaust velocities also need to be high.

For a constant mass flow rate and specific impulse (i.e. constant thrust) and in absence of a gravitational field, the distance traveled during the change in velocity ΔV is found by integrating Equation (1):

$$X = gI_{SP}\tau\left[1-\frac{\ln R}{R-1}\right] \qquad (2)$$

where τ is the flyout time to the end of the acceleration period.

For a mass ratio of R = 2.5, the initial propellant mass fraction would be 0.6, a large fraction for a deep-space probe. For a mass flow rate of 54.6 mg/day, a load of propellant lasting for 15 years of acceleration would be 300 kg of xenon (Xe), and the initial probe mass would be 500 kg. After 15 years at a realistic specific impulse of ~9700 s, the probe will have reached a distance of X = 117 AU with an achieved velocity of ~18 AU/yr. The distance to travel and time required thus set the required engine performance, regardless of the power supply. One does better by accelerating deeper within the Sun's gravitational field, launching at a C_3 in excess of gravitational escape from the Sun at the location of Earth (C_3 ~ 152 km^2/s^2), using a Jupiter gravity assist,[2] or some combination of all three.

"Large" NEP systems (that use reactors) are governed by the same general equations. In principle, they can accommodate larger propellant mass fractions, although NEP systems also carry more dry mass ("structural mass") in the form of the reactor, radiators, etc.

Ion engine specific impulses range from ~3000 s to ~20,000s at the limits.[53,54] Hence for any idealized low-thrust system, there is a parameter space of "reasonable" initial mass ratios of ~2.5 and ~5.0, and limits of 3000 to 20,000 s for the specific impulse. The range of mass ratio then determines a range of required specific impulses to reach a given distance in a given time at constant mass flow, governed by Equation (2). The mass flow rate and propellant choice along with the specific impulse then determines the required power output. The latter scales with the dry mass of the spacecraft and is a function of the technology and architecture employed.

In a specific example of a possible mission the spacecraft is launched on 16 July 2011; it reaches a heliocentric distance of 100 AU in 14.25 years on 11 October 2025. The spacecraft bus, science, and non-power, non-propulsion mass is taken as 267 kg.[55] The power and propulsion system are 131 kg for a dry mass of 498 kg. Launch mass includes 193 kg of the Xe propellant. With an I_{sp} of 4807 s and a mass flow rate of 54.6 mg/day, the ion engine requires 1 kW of electrical power that can be supplied by 9 SRGs, each providing 114 W at beginning of life (BOL). Two burn arcs are used to target a Jupiter gravity assist (JGA) on 1 August 2012, sending the spacecraft in the heliospheric nose direction. The engine operates for 3556 days (~85,000 hours) out of a total mission time of 5201 days. An Atlas V 551-Star 48V places the spacecraft in Earth escape with a $C_3 = 145\ km^2/s^2$. A Jupiter gravity assist adds 25 km/s, and the electric propulsion system adds an equivalent of 15.4 km/s. At 100 AU, the probe is traveling at 52.8 km/s (11.1 AU/year) and so would require an additional ~9 years to reach 200 AU. These performance numbers are similar to those obtained in heliospheric NEP studies.[57]

Although the flyout time to 200 AU in this example is longer than the desired nominal 15 years, both the mass ratio and the specific impulse are conservative and represent what can be accomplished without significant new technical development. That a simple example can get us within a factor of two of the desired flyout time using conservative assumptions gives confidence that the Innovative Interstellar Explorer is feasible. In addition, realistic technology advances will likely further improve mission performance.

Spacecraft - Current Design and Changes

The starting point for the spacecraft design is the concept for the probe section that we have completed under contract from the NASA Institute for Advanced Concepts (NIAC).[23-25] This mission design - Realistic Interstellar Explorer, or RISE (shown in Figure 2) - provided a perihelion propulsive burn deep in the Sun's gravitational well at 4 solar radii. In the present design, we build upon the RISE's optical communications and attitude control concept,[57] incorporate updated instrument concepts (Table 2), and modify the power and propulsive system. The latter are based on the new generation of power supplies (multimission thermoelectric generators, MMRTGs, and SRGs), and concepts for the NASA Glenn Research Center 8-cm ion thruster.[55,58,59] The projected lifetimes of the power sources are at least 14 years, and ion engine lifetime has been demonstrated to well over 3 years.[60,61]

The RISE spacecraft is designed as a spinner to accommodate ultraprecise pointing for downlink (from out to 1000 AU) as well as all-sky scanning for the fields and particles instruments and spectrometers. This philosophy is adopted for our Innovative Interstellar Explorer as well but with some instrument changes. The RTGs will be increased in number and ion engines and appropriate support subsystems, e.g., power processing units (PPUs) added. The original cold-gas nitrogen (GN_2) tanks will be resized for Xe for the propulsion phase. The basic structure and optical system will remain intact as will the basic layout for the MMRTG/SRG mountings, the plasma wave and magnetometer accommodation, and the low-gain radio frequency (RF) dishes for communications during the optical-communications-system checkout.

The spacecraft layout (similar to that of Ulysses) is designed to provide a favorable moment of inertia for spin stabilizing the system. With the ion engines operating most of the time, it is important for the instrument observations to be compatible with engine and power-supply interference, e.g. the SRGs operating while making magnetic field measurements. By sweeping both the plasma wave antennas and the magnetometer booms away from the engine plumes and

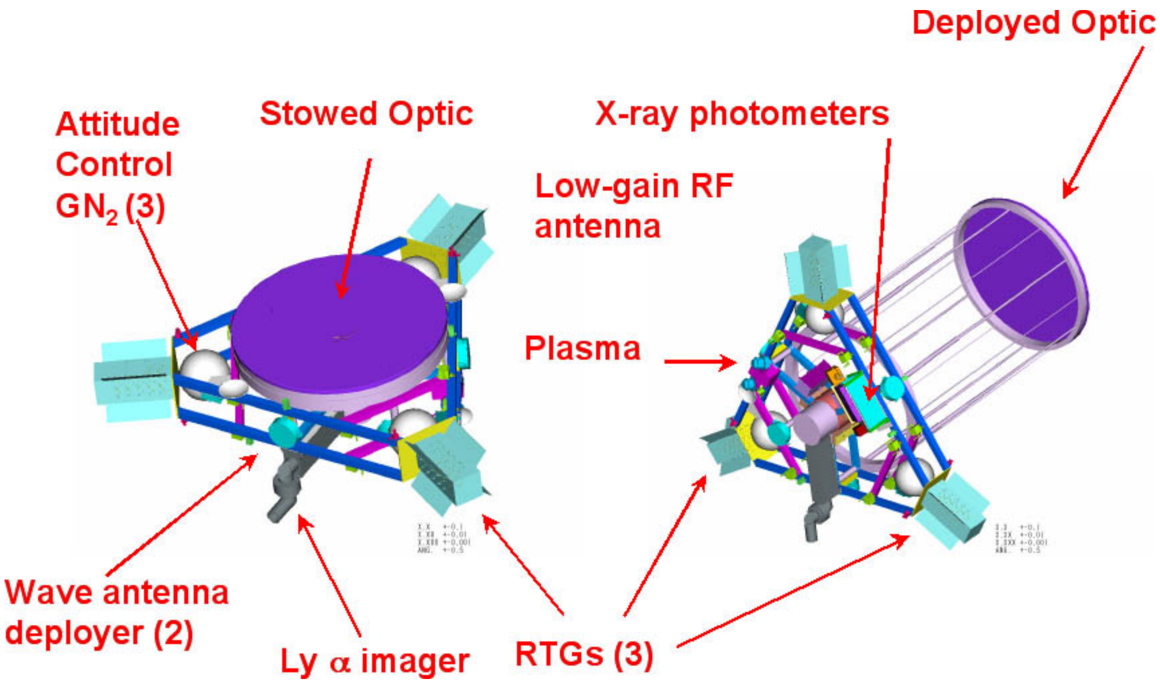

FIGURE 2. The RISE probe concept developed under NIAC.[25]

into the direction of motion, the interference can be minimized while allowing for direction finding with the plasma wave antennas. It is envisioned to incorporate in our spacecraft significant advances in autonomy via a "wireless bus" and multiple microprocessors and extremely low-power operation using ultra-low power components while operating.

The IIE power system includes nine ^{238}Pu units, nominally SRGs. The total of ~9 kg of plutonium would be packaged in units of about 13.5 kg each (second generation unit). The physical length of these units will likely require a deployment mechanism so that the unit can fit within the launch vehicle shroud.

The IIE cruise configuration is shown in Figure 3.

Communications. We base the IIE communications system on the system designed for RISE, with the link to up to 1000 AU. To keep the power down and provide a reasonable bitrate, we will likely stay with an optical downlink - a mission enabling technology – as on the RISE spacecraft.[57] To keep the mass down (both for the "high gain antenna" as well as the structural mass) we have chosen a 1-m diameter as a starting point. The RISE downlink optical antenna of 1-m diameter and receiver telescope aperture of 4 m enabled a bit rate of 500 bps in a burst mode and required pointing accuracy of 400 nrad (1-σ); bit error rate 10^{-6}; mass 10 kg; effective prime power of 15 W intermittently available). The pointing error requirements, in turn, necessitate the integration of the downlink system with the guidance and control system, including the star cameras.

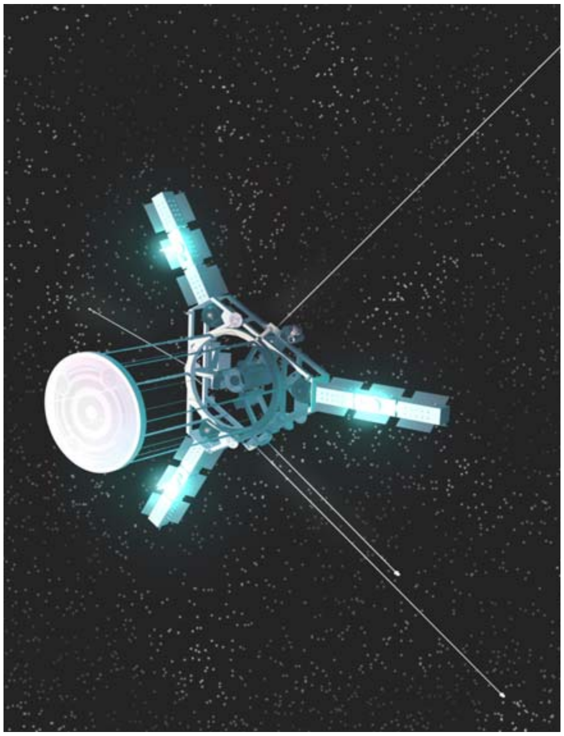

FIGURE 3. The Innovative Interstellar Explorer underway. The probe is dominated by the deployed dielectric Fresnel plate used to focus the optically downlinked data. The structure is dominated by the two swept-ahead 50-m long plasma wave antennas and the inboard (25m) and outboard (50m) magnetometer booms (not to scale). The blue glow is from the three 300-W ions thruster xenon plumes. Spacecraft systems run on 100 W at cryogenic temperatures.[23] For this study, we consider a more traditional harnessing approach. Thermal control is accomplished by using the truss structure as a *de facto* heat pipe. The RISE approach posited use of an all-beryllium structure, but the brittleness makes the survival of launch loads problematic. For this work, we consider the use of aluminum and lighter alternatives such as aluminum-lithium and Albumet® (aluminum-beryllium mixture).

Propulsion. All propulsion is carried out with gimballed ion thrusters. The baseline propellant is Xe as krypton (Kr) will require some degree of active and passive cooling and mercury (Hg) or cesium (Cs) (both of which have severe handling and contamination issues) will require heating. A trade study at the systems level points to xenon as the most promising propellant. The baseline ion engines are the 8-cm ion thrusters under development at Glenn Research Center.

Power System. For missions in the next two decades ^{238}Pu fueled systems based upon General Purpose Heat Sources (GPHS) remain the realistic power baseline for low-mass, low-power systems. The GPHS structures have undergone significant testing and certification for safety and, hence, are the reliable building blocks for any current radioisotope power system. We base our power and mass estimates on the "2nd generation" units, with "1st generation" as a fallback.

Software and Autonomy. Collection of data by IIE begins at 30 days after launch and will last as long as contact with Earth (downlink) can be maintained. The basic operation will be to gather data repetitively and broadcast back to Earth on a predetermined and automatic schedule. As part of our ongoing study, we will quantify the data acquisition rate, downlink rate, onboard storage, downlink frequency, and autonomy requirements.

Science Instruments

As shown in Table 2, nominal instruments for such a mission that are at a TRL of 9 far exceed the available resources for an interstellar precursor mission. Mass and power can be addressed by miniaturized electronics, by smaller geometrical factors in the sensors, and smarter instrument design.[10] Data downlink requirements can be minimized by onboard computing and lower time resolution than for the sample TRL-9 instruments. This is consistent with reduced geometrical factors for the particle instruments.

Time Resolution. For pickup ions and interstellar plasma, time resolution of 10 days or more is sufficient. This will give us all the important basic information about these populations. For the solar wind 1-day resolution will still catch all the important structures, especially in the outer heliosphere beyond 10s of AU.

Plasma, Charged Particles, Magnetic Field. For small but capable charged-particle instruments required on an interstellar probe, an enhanced Fast Imaging Plasma Spectrometer (FIPS) can do all the necessary solar wind, interstellar plasma and pickup ion measurements. The MESSENGER Energetic Particle Spectrometer (EPS) (which with FIPS constitutes the MESSENGER Energetic Particle and Plasma Spectrometer) and a simple solid state telescope instrument, such as the Voyager Cosmic Ray detector system (CRS), may be adequate for most of the higher-energy measurements.

Neutral Particles. A Low Energy Neutral Atom (LENA)-type instrument is needed to detect directly the interstellar gas (e.g., the hydrogen wall). A Medium Energy Neutral Atom (MENA)-type instrument is needed to detect ENAs when the spacecraft penetrates the interface region.

Dust. Dust particles bombarding the spacecraft may be detected and characterized by measuring the effects of the hot plasma produced by such impacts.[62] The whole spacecraft could serve as one large detector of certain properties and processes in space. One approach is that of the polyvinylidene fluoride (PVDF) dust sensor such as flying on NASA's Stardust Discovery mission.

Radio Science. "Radio" science is an important goal of the mission. Precise tracking of the spacecraft may provide for study of fundamental physical effects.[14] Combining required tracking with the optical downlink approach will be studied.

Radio and Plasma Waves. Identification of the source and mechanism of VLF radio waves is a significant part of an interstellar probe mission. Hence, direction finding capability is required. Implementation depends upon mass and spacecraft dynamics trade-offs.

Instrument Accommodation. A joint study of the spacecraft and the instruments allows the effect of the mission implementation (SRG/MMRTG) on measurements to be quantified. This also includes effects of the plasma wave antenna configuration and magnetometer boom configuration on spacecraft dynamics and optical downlink performance. Ion engine placement and plume effects must also be considered as well as SRG stray fields.

THE TIME IS RIGHT

We may be in the beginning phase of a paradigm shift. Observations from Voyager 1 at >85 AU and N34° heliolatitude during the past year have raised questions about the conventional concepts of the termination of the solar wind. The present paradigm, developed during the last 50 years, is minimally constrained because of the paucity of definitive observations. Backscatter of solar Lyman-α, modulation of galactic cosmic rays, anomalous cosmic rays, interstellar helium gas, interstellar pickup ions, 2-5 kHz radio events, and energetic neutral atoms are all global phenomena in which the effects of the heliosphere interacting with the local interstellar cloud are integrated over huge volumes of space ~100 AU and sometimes over periods of several years.

Consequently, it should have come as no surprise that the Voyager *in situ* observations beginning at 85 AU in mid-2002 do not fit the neat theoretical picture of a single global termination shock. While the interpretations are presently the subject of intense discussion,[47,63,64] it is clear that if we take the measurements at face value, there is no apparent reconciliation with conventional models of the termination of the solar wind.

These observations dramatically highlight the critical role of *in situ* measurements, even in a system as large as the heliosphere and its boundary regions. How much more critical will be the powerful combination of *in situ* observations and global remote sensing from outside the heliosphere, complemented by remote observations from 1 AU? The required *in situ* measurements and the unique viewing perspectives can be obtained in no other way.

The proposed concept of the Innovative Interstellar Explorer, with the right support, can be firmed up and technology advanced, making the mission launch possible by 2015.

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