Innovative interstellar explorer

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ABSTRACT. An interstellar "precursor" mission has been under discussion in the scientific community for at least 30 years. Fundamental scientific questions about the interaction of the Sun with the interstellar medium can only be answered with in situ measurements that such a mission can provide. The Innovative Interstellar Explorer (IIE) and its use of Radioisotope Electric Propulsion (REP) is being studied under a NASA "Vision Mission" grant. Speed is provided by a combination of a high-energy launch, using current launch vehicle technology, a Jupiter gravity assist, and long-term, low-thrust, continuous acceleration provided by an ion thruster running off electricity provided by advanced radioisotope electric generators. A payload of ten instruments with an aggregate mass of ~35 kg and requiring ~30 W has been carefully chosen to address the compelling science questions. The nominal 20-day launch window opens on 22 October 2014 followed by a Jupiter gravity assist on 5 February 2016. The REP system accelerates the spacecraft to a "burnout" speed of 7.8 AU per year at 104 AU on 13 October 2032 (Voyager 1's current speed is ~3.6 AU/yr). The spacecraft will return at least 500 bits per second from at least 200 AU ~30 years after launch. Additional (backup) launch opportunities occur every 13 months to early 2018. In addition to addressing basic heliospheric science, the mission will ensure continued information on the far-heliospheric galactic cosmic ray population after the Voyagers have fallen silent and as the era of human Mars exploration begins.

INTRODUCTION

The Innovative Interstellar Explorer (IIE) study [1-6] is one of several "Vision Missions" funded by NASA for studying in more detail missions that have been deferred in various strategy documents due to technical complexity. In particular, the idea of an "interstellar precursor mission" has been advocated in a variety of NASA and National Academy of Science documents for at least 30 years (Table 1).

Any robotic deep-space mission requires four elements: (1) compelling science, i.e., the rationale for the mission, (2) appropriate and developed enabling technologies, i.e., the means to implementation, (3) a strategy, i.e., advocacy by all current and potential stakeholders in the mission, and (4) programmatics, i.e., a "new start" in the U.S. Federal budget for NASA, with appropriate funds for development and implementation in the out-years and a plan for years after years further out in the planning process, as applicable to a given missions. A well-thought-out approach with all of these key elements is required to promote and accomplish a successful science exploration plan.

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Table 1. Sample Listing of Reports Calling for an Interstellar Probe

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. Negebauer, chair)
NASA 2003 Strategic Plan	The Sun to the Earth -and Beyond: A Decadal Research Strategy in Solar and Space Physics

For this mission concept, we have adopted a science formulation with appropriate instrumentation as vetted by the heliospheric science community over the years in general, and by our team in particular. We have identified the enabling technology, here radioisotope electric propulsion (REP) combined with advanced radioisotope power sources (RPS), with existing technologies. The goal of this approach is to provide a credible technological implementation while minimizing required technical innovations with their associated costs for both development and space-flight qualification.

Within these bounds, IIE is still "visionary" in the sense of reaching farther and faster than all previous excursions into space. At the same time, we believe the mission to be doable while representing one more of a long line of "firsts" adopted into the "banner" for the mission [6] that includes: The "all-seeing eye" with the visionary motto "Novus Ordo Seclorum" ("The new order of the ages"); the Pleiades - or "Seven Sisters" Messier 45; 425 L.Y; "If you seek our future, look to the stars" (Latin - cf. C. Wren); the Montgolfier brothers hot air balloon flight, Paris; 4 June 1783; Robert Goddard's liquid fueled roclet, 16 March 1926; the Wright Brothers first flight, 17 Dec 1903; Explorer I, the first U.S. orbital satellite, 1 February 1958 with Pickering, Van Allen, Von Braun; Pioneer 10 at Jupiter flyby, 3 Dec 1973; and Voyager 1 and 2, both launched in 1977.

THE FIRST TRUE STAR SHIP

Recently, the Voyager 1 spacecraft has returned data from the termination shock of the solar wind at a heliocentric distance of 94 AU [7-11]. Beyond the shock is the heliopause, the pressure-balance interface between the plasma components of the solar wind and of the interstellar medium. Beyond that interface there may be an external shock before one reaches the "undisturbed" interstellar medium, but the properties of the interstellar medium remain elusive [12-13]. To measure the properties of the VLISM, especially the magnetic field and low-energy cosmic rays, in situ sampling is required.

Many formulations of a science rationale have been made for an "interstellar precursor" mission that would probe the nearby interstellar medium [14-20]. In this NASA-supported Vision Mission study, we consider the implementation of a scientifically compelling precursor mission to the interstellar medium. Dubbed the Innovative Interstellar Explorer (IIE), the mission concept combines a compact payload, ~1000-kg (wet) class satellite, high launch energy, and electric propulsion. Four options are studied that combine various levels of risk and technical readiness for implementing this mission. Although not the first probe to escape the gravitational pull of the Sun, this would be the first mission for which the material between the stars is the destination. IIE will be bound for the stars, acquiring data on local interstellar conditions as long as it can. In this sense it really will be the first Star Ship.

Science Questions and Required Instruments

Four principal science questions are addressed. These are addressed by a set of ten carefully selected science instruments, listed with estimates of their required resources in Table 2. Detailed performance characteristics are given in the references [4,6]. How these trace through science objectives to science results are described in the traceability matrix [4,6], summarized in Table 3. The science questions are traced back to the third meeting of the Interstellar Probe Science and Technology Definition Team (IPSTDT) meeting held at the Jet Propulsion Laboratory (JPL).

Table 2. Instruments and Resource Estimates

Acronym	Instrument	Mass (kg)	Power (W)	Average acquisition data rate (bps)
MAG	Magnetometer	8.81	5.30	130.00
PWS	Plasma wave sensor	10.00	1.60	65.00
PLS	Plasma	2.00	2.30	10.00
EPS	Energetic particle spectrometer	1.50	2.50	10.00
CRS - ACR/GCR	Cosmic-ray spectrometer: anomalous and galactic cosmic rays	3.50	2.50	5.00
CRS - LoZCR	Cosmic-ray spectrometer: electrons/positrons, protons, helium	2.30	2.00	3.00
CDS	Cosmic dust sensor	1.75	5.00	0.05
NAI	Neutral atom detector	2.50	4.00	1.00
ENA	Energetic neutral atom imager	2.50	4.00	1.00
LAD	Lyman-alpha detector	0.30	0.20	1.00
Total resources		**35.16**	**29.40**	**226.05**

The additional instrument whose inclusion has been debated, is an infrared telescope capable of looking back toward the Sun to assess the solar system dust that causes IR extinction as we look outward from Earth. While such observations are important for understanding the structure of the solar system and this platform would provide a unique perspective from which to make such measurements, the required resources (mass, power) exceed what is available. We have judged the additional measurements to be worthwhile but below the science floor for the mission; hence, this instrument is not included in the baseline presented here. The corresponding questions, instrument, and analysis product are shown in light grey boxes in Table 3.

Table 3. Short Version of the Traceability Matrix

Science Questions 3rd IPSTDT Meeting, 17-19 May 1999	Objective Questions	Required Instruments	Analysis Product	Science Result
	From NASA's IPSTDT Report	THIS WORK		
What is the nature of the nearby interstellar medium?	How does the composition of interstellar matter differ from that of the solar system?	PLS, EPS, CRS	Interstellar medium composition	Composition differential between the solar system and current local interstellar
	What constraints do the interstellar abundances of ^{2}H and ^{3}He place on Big Bang and chemical evolution theories?	CRS - LoZCR		
	Is there evidence for recent nucleosynthesis in the interstellar medium?	CRS		
	What is the density, temperature, and ionization state of the interstellar gas, and the strength and direction of the interstellar magnetic field?	MAG, PLS	Thermodynamic and physical state of the very local interstellar medium (VLISM)	Physical state of the VLISM
	What processes control the ionization state, heating, and dynamics of the interstellar medium?	PLS, LAD, NAI, ENA	Energy inputs in the VLISM	
	How much interstellar matter is in the form of dust and where did it originate?	CDS, (PWS), PLS	Neutral matter assay for the VLISM	
	How much greater are cosmic ray nuclei and electron intensities outside the heliosphere, and what is their relation to galactic gamma ray and radio emission?	CRS, PWS	Low-energy galactic cosmic rays	
	What spectrum of 10-100 micron galactic infrared and Cosmic Infrared Background Radiation is hidden by emission from the zodiacal dust?	Not measured	IR absorption by solar system dust	
How do the Sun and galaxy affect the dynamics of the heliosphere?	What is the size and structure of the heliosphere?	MAG, PWS, PLS, EPS, LAD, ENA	Heliospheric spatial scales	Structure and dynamics of the heliosphere in upwind direction
	How do the termination shock and heliopause respond to solar variations and interstellar pressure?	MAG, PLS	Heliospheric temporal variably	
	How does the interstellar medium affect the inner heliosphere and solar wind dynamics?	PLS, EPS, CRS	Spatial and temporal variability of the interstellar medium properties	Effects of the VLISM on the heliosphere
	What roles do thermal plasma, pickup ions, waves, and anomalous cosmic rays play in determining the structure of the termination shock?	PLS, EPS, PWS, CRS - AGCR	Inputs from heliospheric interaction into the solar wind	
	What are the properties of interstellar gas and dust that penetrate into the heliosphere?	NAI, ENA, CDS	Properties of interstellar gas and dust in the outer heliosphere	

What is the structure of the heliosphere?	Does the heliosphere create a bow shock in the interstellar medium?	MAG, PWS, PLS	Determination of whether the solar system produces an external shock	**Impact of the solar system on the local composition and thermodynamic properties of the VLISM**
	What is the relation of the hydrogen wall outside the heliopause to similar structures and winds observed in neighboring systems?	NAI, ENA, PLS	Structure and properties of the predicted hydrogen wall	
	How do the Sun and heliosphere influence the temperature, ionization state, and energetic particle environment of the local interstellar medium? How far does the influence extend?	NAI, ENA, PLS, EPS, CRS	Penetration of heliosheath properties into the VLISM	
	How does particle acceleration occur at the termination shock and at other astrophysical shocks?	PLS, EPS, CRS - Autonomous burst	Characterization of particle acceleration at the termination shock	
How did matter in the solar system and interstellar medium originate and evolve?	Is there structure in the Zodiacal cloud due to dynamical processes associated with solar activity, planets, asteroids, comets, and Kuiper Belt objects?	PLS, CDS, (PWS)	Structure and dynamics of the Zodiacal dust cloud in the outer heliosphere	**Properties and dynamics of bulk matter in the outer solar system and VLISM**
	What does the distribution of small Kuiper Belt objects and dust tell us about the formation of the solar system?	CDS, PLS, EPS, (PWS)		
	How does the structure of the Zodiacal dust cloud impact infrared observations of the galaxy and searches for planets around other stars?	Not measured	Quantified extinction from Zodiacal dust	
	What are the origin, nature, and distribution of organic matter in the outer solar system and the interstellar medium?	CDS, PLS, EPS, (PWS)	Identification of *in situ* organic materials or fragments in the heliospheric boundary regions and/or VLISM	

THE SPACECRAFT

The baseline IIE spacecraft is a spinner using low-mass RTGs and a 1-kW ion engine that uses xenon propellant, an approach referred to as radioisotope electric propulsion (REP) [21]. A conceptual design based upon one of the technology options studied is shown in Figure 1. Key to the approach (as with solar sail approaches [19]) is keeping the mass of all components as low as their required functionality allows.

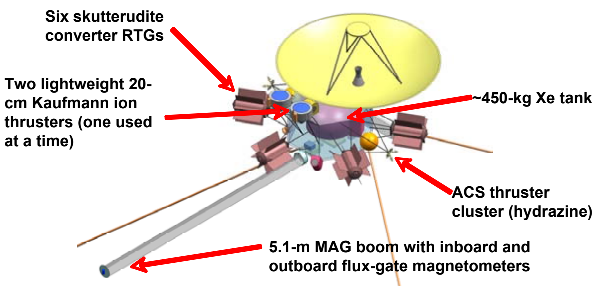

Figure 1. A concept for the IIE spacecraft. Technology Option 2 is shown. Option 1 baselined for flight has three ion engines (two plus a space and a slightly smaller high gain antenna (HGA) with a 2.1-m diameter.

Baseline Mission

The baseline mission was chosen following multiple mission design and spacecraft technology iterations with JPL's Team-X. All missions studied travel to an aim-point within 20° of the incoming interstellar wind direction by traveling outward from the Earth without Venus, Earth, or Mars gravity assists. A variety of mission scenarios were studied [22]. A Jupiter gravity assist was chosen as the baseline mission design. This design was iterated further as the spacecraft concept matured. Four technology options were devised with corresponding masses and power modes. For each a 30% mass contingency was added and the mission design reoptimized. Option 1, with the lowest level of new technology and selected as the baseline, reaches 200 AU in just over 30 years with an asymptotic speed of ~7.8 AU/yr (just over twice that of Voyager 1). Each option has a ~20-day launch window. Backups occur at ~13-month intervals (Nov. 2015, Dec. 2016, Jan. 2018) with the same spacecraft (and increasing flyout time to 200 AU), and the cycle repeats about every 12 years (Jupiter's orbital period) with the best opportunities in 2014, 2026, 2038, and 2050.

INTERSTELLAR PROBE AND HUMAN EXPLORATION

Solar energetic particle (SEP) events and galactic cosmic rays (GCRs) present a radiation threat to human explorers living and working outside low-Earth orbit. SEP events can be warned against and tend to occur near solar maximum. These solar outbursts help "tangle" the interplanetary magnetic field, decreasing the flux of GCRs penetrating into the heliosphere. The GCRs, especially those with heavy nuclei, cannot easily be shielded against. Current thinking suggests that GCR variability is controlled by solar activity. However, without actually reaching near-interstellar space and sampling the undisturbed GCR spectra, we cannot know for certain whether large investments in human infrastructure are appropriately designed for dealing with this potential hazard to human exploration of the solar system.

SUMMARY

The IIE is an exciting mission of exploration, discovery, and understanding. Primary issues are low-mass radioisotope power supplies, long-lived and low-power electric propulsion engines, communications infrastructure on the ground, available expendable launch vehicles with high-energy upper stages, and parts and subsystems that can be qualified for 30+ year missions. While all of these issues need attention and resources, implementation of the baseline mission for a launch in 2014 is possible as long as the serious planning starts now [23]:

> "The real journey will occur when we embark on an interstellar probe, with sufficient instrumentation and the capability to rapidly access the distant heliosphere. This journey will be one of the great explorations of humankind, when we leave the safety of our solar system and venture forth into interstellar space."

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REFERENCES

1. M. Gruntman, R. L. McNutt, Jr., R. E. Gold, S. M. Krimigis, E. C. Roelof, G. Gloeckler, P. L. Koehn, W. S. Kurth, and S. R. Oleson, Innovative Interstellar Explorer, 55th International Astronautical Congress, Vancouver, Canada, IAC-04-IAA.3.6.4.07, 2004.
2. M. Gruntman, R. L. McNutt, Jr., R. E. Gold, S. M. Krimigis, E. C. Roelof, J.C. Leary, G. Gloeckler, P. L. Koehn, W. S. Kurth, S. R. Oleson, D. Fiehler, Innovative Explorer Mission to Interstellar Space, 4th IAA Symposium on Realistic Near-Term Advanced Scientific Missions, Aosta, Italy, July 4-6, 2005; *J. Brit. Int. Soc., 59, 71-75,* 2006.
3. R. L. McNutt, Jr., R. E. Gold, S. M. Krimigis, E. C. Roelof, M. Gruntman, G. Gloeckler, P. L. Koehn, W. S. Kurth, S. R. Oleson, J. C. Leary, D. I. Fiehler, B. J. Anderson, M. Horanyi, and R. A. Mewaldt, Innovative Interstellar Explorer, *Proc. Solar Wind 11- SOHO 16, ESA SP-592,* 693-696, 2005.
4. R. L. McNutt, Jr., R. E. Gold, S. M. Krimigis, E. C. Roelof, J. C. Leary, M. Gruntman, G. Gloeckler, P. L. Koehn, W. S. Kurth, S. R. Oleson, D. Fiehler, Innovative Interstellar Explorer: Radioisotope Electric Propulsion to the Interstellar Medium, AIAA-2005-4272, 2005 Session 115-EP-25, Mission Systems Analysis, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, Arizona, 13 July 2005.
5. D. I. Fiehler and R. L. McNutt, Jr., Mission design for the Innovative Interstellar Explorer mission, IEPC-2005-211*, NASA/CR-2005-214017; in press J. Astron. Sci.*
6. http://interstellarexplorer.jhuapl.edu, accessed May 21, 2006.
7. L. A. Fisk, *Science*, **309**, 2016-2017 (2005).
8. E. C. Stone, A. C. Cummings, F. B. McDonald, B. C. Heikkila, N. Lal, and W. R. Webber, *Science*, **309**, 2017-2020 (2005).
9. R. B. Decker, S. M. Krimigis, E. C. Roelof, M. E. Hill, T. P. Armstrong, G. Gloeckler, D. C. Hamilton, and L. J. Lanzerotti, *Science*, **309**, 2020-2024 (2005).
10. D. A. Gurnett and W. S. Kurth, *Science*, **309**, 2025-2027 (2005).
11. L. F. Burlaga, N. F. Ness, M. H. Acuna, R. P. Lepping, J. E. P. Connerney, E. C. Stone, and F. B. McDonald, *Science*, **309**, 2027-2029 (2005).
12. W. I. Axford, "The interaction of the solar wind with the interstellar medium", in *Solar Wind*, edited by C.P. Sonnett, P.J. Coleman, and J.M. Wilcox, *NASA Spec. Publ., NASA SP-308*, 609-660, 1972.
13. G. P. Zank*, Space Sci. Rev.,* **89**, 1-275 (1999).
14. L. D. Jaffe and C. V. Ivie, *Icarus, 39*, 486-494 (1979).
15. T. E. Holzer, et al. *The Interstellar Probe: Scientific objectives for a Frontier mission to the heliospheric boundary and interstellar space*, *NASA Publication*, 1990.
16. R. A. Mewaldt, J. Kangas, S.J. Kerridge, and M. Neugebauer*, Acta Astron.,* **35, Suppl.,** 267-276 (1995).
17. R. L. McNutt, Jr., R. E. Gold, E. C. Roelof, L. J. Zanetti, E. L. Reynolds, F. W. Farquhar, D. A. Gurnett, and W. S. Kurth, *J. Brit. Int. Soc.,* **50**, 463-474 (1997).
18. R. A. Mewaldt, and Liewer, P.A., "Scientific payload for an Interstellar probe mission," *The Outer Heliosphere: The Next Frontier*, COSPAR Colloquia Series, Vol. 11, K. Scherer, H. Fichtner, H.-J. Fahr, and E. Marsch, eds., Pergamon, New York, 2001, 2001, pp.451-464.
19. P. C. Liewer, Mewaldt, R. A., Ayon, J. A., Garner, C., Gavit, S., and Wallace, R. A., "Interstellar probe using a solar sail: Conceptual design and technological challenges," *COSPAR Colloquium on The Outer Heliosphere: The Next Frontiers*, COSPAR Colloquia Series, Vol. 11, K. Scherer, H. Fichtner, H.-J. Fahr, and E. Marsch, eds., Pergamon, New York, 2001, pp.411-420.
20. http://interstellar.jpl.nasa.gov/interstellar/probe/introduction/objectives.html, accessed May 22, 2006.
21. R. J. Noble, R. J., *Acta Astron*., **44**, 193-199 (1999).
22. D. I. Fiehler, R. L. McNutt, Jr., "Mission design for the Innovative Interstellar Explorer mission", IEPC-2005-211*, NASA/CR-2005-214017; in press J. Astron. Sci.*
23. *Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report*, Committee on Solar and Space Physics, Space Studies Board, Division on Engineering and Physical Sciences, National Research Council of the National Academies, The National Academies Press, Washington, D. C., 2004, 56pp.