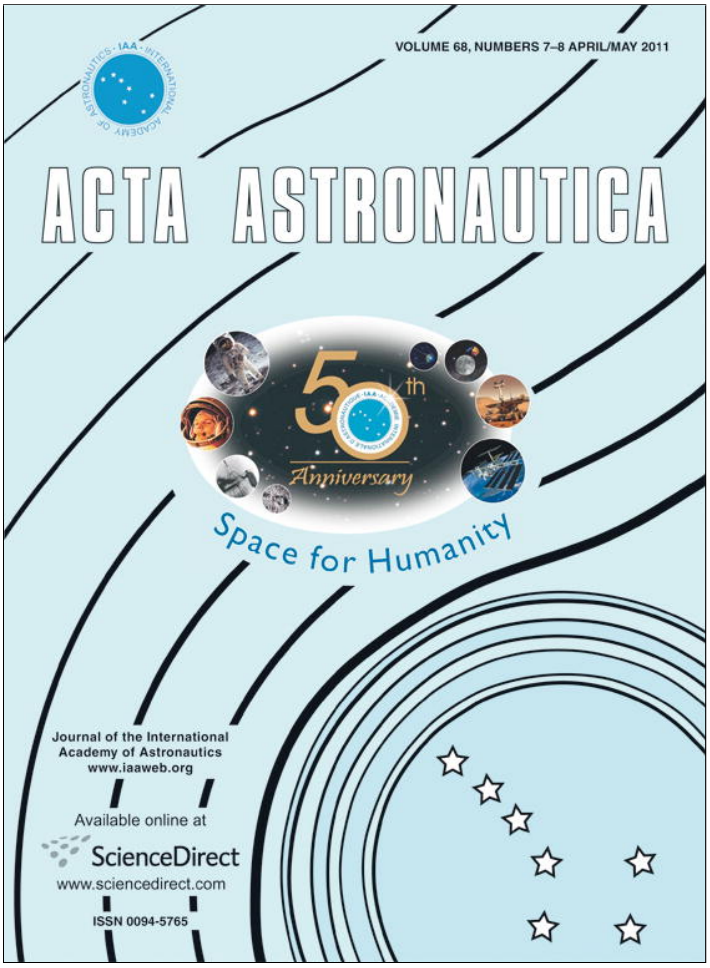
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Enabling interstellar probe

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ABSTRACT

The scientific community has advocated a scientific probe to the interstellar medium for over 30 years. While the Voyager spacecraft have passed through the termination shock of the solar wind, they have limited lifetimes as their radioisotope power supplies decay. It remains unclear whether they can reach the heliopause, the boundary between shocked solar wind and interstellar plasmas, and, in any case, they will not reach the undisturbed interstellar medium. As with most exploratory space missions, their ongoing observations continue to raise even more questions about the nature of the interaction of our heliosphere and the interstellar medium. Scientific questions including:

1. What is the nature of the nearby interstellar medium?
2. How do the Sun and galaxy affect the dynamics of the heliosphere?
3. What is the structure of the heliosphere?
4. How did matter in the solar system and interstellar medium originate and evolve?

can only be answered by an "interstellar precursor" probe. Such a mission is required to make in situ measurements in the interaction region and interstellar medium itself at distances far from the Sun, but in a finite mission lifetime. By launching a probe toward the incoming "interstellar wind," whose direction is known, the distance to be traveled can be minimized but is still large. The current consensus is that a scientifically compelling mission must function to at least a distance of 200 astronomical units (AU) from the Sun and return a reasonable stream of data during the voyage. The central problem is that of providing a means of propulsion to accelerate a probe from the Solar System. Even with a low-mass payload and spacecraft, achieving the high speeds needed, even with gravity assists, have remained problematic. Voyager 1, the fastest object ever to leave the system is now traveling ~3.6 AU/yr, and a credible probe must reach at least 2–3 times this speed. The use of an Ares V is an approach for enabling a

Abbreviations: ACE, Advanced Composition Explorer; ACS, attitude control system; AU, astronomical unit (mean Earth–Sun distance of $1.4959787066 \times 10^{11}$ m); bps, bits per second; BNTR, Bimodal Nuclear Thermal Rocket; CDS, command and data subsystem; DRM, Design Reference Mission; DSN, Deep Space Network; EDS, Earth Departure Stage; ESA, European Space Agency; HEF, high-efficiency (DSN antenna); HGA, high-gain antenna; IBEX, Interstellar Boundary Explorer; IHP/HEX, Interstellar Heliopause Probe/Heliospheric Explorer; IIE, Innovative Interstellar Explorer; IPSTDT, Interstellar Probe Science and Technology Definition Team; ISM, interstellar medium; lbf, pounds force (1lbf=0.00444822 kN); LH2, liquid hydrogen; kN, kilonewton (1 kN=224.809 lbf); Mb, megabit; MO&DA, mission operations and data analysis; NAS, National Academy of Sciences; NASA, National Aeronautics and Space Administration; NEP, nuclear electric propulsion; NEPA, National Environmental Protection Act; NERVA, Nuclear Engine for Rocket Vehicle Application; NIAC, NASA Institute for Advanced Concepts; NRC, National Research Council; NTR, nuclear thermal rocket; REP, radioisotope electric propulsion; RF, radio frequency; RFA, Research Focus Area; RISE, Realistic Interstellar Explorer; RPS, radioisotope power system; SOHO, Solar and Heliospheric Observatory; TRL, technology readiness level; ULP, ultra-low power; VIM, Voyager Interstellar Mission; VLISM, very local interstellar medium

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fast interstellar precursor mission. Maximum capability uses the combination of an Ares V, two-engine Centaur upper stage, close fly-by of Jupiter, and radioisotope electric propulsion (REP). Deletion of any of these pieces does not disable the mission, but does increase the flyout time to a given distance. This approach is more robust and provides a faster probe than an earlier alternative, designed for launch by a Delta IV 4050H plus twin Star 48A upper stages.

1. Introduction

The space science community has advocated the idea of an "interstellar precursor mission" to the interstellar medium (ISM) for over 30 years [1].[2] The series of initial studies baselined a large, nuclear-electric propulsion (NEP) vehicle with a comprehensive set of science instruments in the payload [2,3]. Such a mission was considered a "precursor" to interstellar travel, the idea being that such a mission would be able to answer scientifically significant questions about the interstellar medium, and the Sun's interaction with that medium [4–6]. Even as the twin Voyager spacecraft were following Pioneer 10 and 11 on voyages that would take all four U.S. spacecraft outside of the solar system, it was recognized that a very capable propulsion system was key to such a mission.

Various studies that followed considered near-Sun flyby trajectories with near-Sun propulsive maneuvers, larger NEP systems, solar sails, and REP (see, e.g., references in [7,8]). Following the birth and death of the NEP Prometheus Project and its initial promises[3] [11,12] and the realization of the problems inherent with near-Sun gravity assists, both NEP and all-ballistic systems have fallen from the discussion of technical alternatives. Solar-sail and REP systems have remained as potential contenders for addressing the propulsion problem, both requiring relatively low-mass spacecraft (~200 kg not including power and propulsion) similar to the masses of Pioneer 10 [13] and Pioneer 11 [14] of 258 kg including the payload.

2. Approaches

The baseline spacecraft used for discussions herein is described in some detail by McNutt et al. [15]. Subsequently, a(n unsuccessful) proposal for an Interstellar Heliopause Probe/Heliospheric Explorer (IHP/HEX), a similar mission with the same science goals, was submitted to the European Space Agency's (ESA) "Cosmic Vision 2015–2025" competition [16,17]. This latter approach uses a similar spacecraft bus, dominated by a high-gain antenna (HGA) and reliant upon a radioisotope power system (RPS) for electrical power. The propulsive means is a solar sail used in conjunction with a trajectory whose features include: (1) launch to low excess velocity (C3[4] $\sim 0\ \mathrm{km^2/s^2}$), (2) two orbits of the Sun prior to gaining hyperbolic escape speed from the solar system, (3) a closest approach to the Sun with the sail deployed at 0.25 AU from the Sun, and (4) final sail jettison at ~5 AU, some 6.7 years following the launch, at which point the primary science mission begins.

2.1. Solar sail

The current solar sail approach is similar to that studied in the U.S. by the Interstellar Probe Science and Technology Definition Team (IPSTDT) almost a decade ago [18–21]. The first difficulty with this approach is primarily the development and validation of a sufficiently "light-weight" (low-mass) sail including the reflective surface, deployment mechanism, and control means. Work to date has yet to result in a sufficiently light sail, but, at the same time, there are no obvious impediments to obtaining the required characteristics other than technology-development money. The second difficulty is that for the high-solar-system escape speeds to be obtained, the sail, and the rest of the spacecraft, must be designed to withstand the thermal environment at 0.25 AU from the Sun, some 16 times the solar input received at Earth. The previous Helios and current MESSENGER mission to Mercury [22,23] have demonstrated spacecraft survival for spin- and three-axis-stabilized spacecraft, respectively, to within 0.31 AU of the Sun. Hence, the possibility of flying a spacecraft to within 0.25 AU of the Sun is not, in and of itself, a problem. However, the thermal environment does result in mass addition to the thermal protection system and the properties of a solar sail for use at such a distance have yet to be studied in detail. For "sailcraft" the overall mass is a critical parameter, and, again, more technical study is required.

Advantages of this approach include potentially high asymptotic escape speeds from the solar system of up to 10–11 AU/yr, a relatively short acceleration period of less than 7 years, and transition to a "dull" science mode,

[2] In Table B-4 of the referenced report, mission 1069 is listed as: "Solar System Escape Spacecraft. Small spacecraft with particles-and-fields instrumentation launched in 1980 by Titan-Centaur plus high-performance upper stages on a trajectory escaping solar system in general direction of solar apex. If mission launched in late 80's, electric propulsion, solar sailing, and/or Jupiter swingby could be used to reduce transit time to Heliosphere boundary. Mission duration ten years or more."

[3] One of the "Vision Missions" studied for use as an interstellar probe relies on an NEP system [9]. However, the Prometheus system could not achieve the low mass-to-power ratio required to enable that mission [10].

[4] C3 is the excess energy per mass above that required for escape from the Earth's gravitational field; a spacecraft with a C3 of zero has just sufficient energy to escape, i.e., escape velocity of 11.2 km/s.

with all extraneous materials jettisoned at ~5 AU from the Sun. With most of the acceleration to very high speeds accomplished by the sail jettison at ~5 AU, a Jupiter gravity assist, and the associated fly through the Jovian radiation belts, is not an issue. With the speeds already reached by the time of the crossing of Jupiter's orbit, such a flyby would provide little additional advantage [16].

2.2. Ares V

First-order use and trades for an Ares V on enabling a fast, interstellar-precursor mission were initially presented to a committee of the National Research Council (NRC) on 21 February 2008 at the Keck Building, Washington, DC, evaluated by the committee, and commented upon in the resulting report [24]. Some of this material was also provided in a poster *Interstellar Explorer: An Interstellar Precursor Mission* at the NASA Heliophysics Town Hall Meeting: Planning Our Strategy for the Future, May 19–20, College Park, MD. More robust estimates of performance were provided at NASA Ames Research Center during the *Ares V—Solar System Science Workshop* of August 2008 [25].

Maximum capability uses an Ares V, two-engine Centaur upper stage (a NERVA-derived[5] upper stage is not credible and provides only a modest increase in performance), a close fly-by of Jupiter, and extended electrical propulsion at low thrust using REP. Deletion of any of these pieces does not disable the mission, but only increases the flyout time to a given distance. This approach has not been fully vetted against the payload and other mission architecture, which was designed for transport by a Delta IV 4050H plus twin Star-48A-propelled upper stages for use as the launch vehicle.

3. Current status

In the U.S. the scientific case for an interstellar precursor mission continues to be made in reports by both the National Aeronautics and Space Administration (NASA) and the NRC acting under the National Academy of Sciences (NAS). The latter have included:

1. Physics through the 1990s—Panel on Gravitation, Cosmology, and Cosmic Rays (D. T. Wilkinson, chair), 1986 NRC report
2. 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
3. Astronomy and Astrophysics Task Group Report (B. Burke, chair), 1988 NRC study Space Science in the 21st Century—Imperatives for the Decade 1995–2015
4. The Decade of Discovery in Astronomy and Astrophysics (John N. Bahcall, chair)
5. 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
6. A Science Strategy for Space Physics, Space Studies Board, NRC, National Academy Press, 1995 (M. Neugebauer, chair)
7. The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics, 2003
8. Exploration of the Outer Heliosphere and the Local Interstellar Medium, 2004
9. Priorities in Space Science Enabled by Nuclear Power and Propulsion, 2006

Past NASA documents and reports include:

1. Outlook for Space, 1976
2. An Implementation Plan for Solar System Space Shysics, S. M. Krimigis, chair, 1985
3. Space Physics Strategy-Implementation Study: The NASA Space Physics Program for 1995–2010
4. Sun–Earth Connection Technology Roadmap, 1997
5. Space Science Strategic Plan, The Space Science Enterprise, 2000
6. Sun–Earth Connection Roadmaps, 1997, 2000, 2003
7. NASA 2003 Strategic Plan
8. The New Science of the Sun—Solar System: Recommended Roadmap for Science and Technology 2005–2035, 2006

The most recent NAS/NRC document advocating the mission [24] in considering the implementation using an Ares V, described in more detail below, made the recommendation: "NASA should conduct further study of the following mission concepts, which have the most potential to demonstrate the scientific opportunities provided by the Constellation System: 8-Meter Monolithic Space Telescope, ***Interstellar Probe*** [emphasis added], Neptune Orbiter with Probes, Solar Polar Imager, and Solar Probe 2." The report notes further "Several of the missions named above, particularly the heliophysics missions, are well defined scientifically and do not require significant study of instruments or related issues. Further study should focus primarily on the relationship between the Ares V capabilities and the missions' propulsion requirements." Such study support has yet to materialize.

The explanatory note to the proposal team in the Cosmic Vision 2015–2025 competition explaining the rejection of the proposed solar-sail version of the mission (which included a substantial proposed NASA collaboration) notes: "The [reviewers] considered the concept of a mission to the outer heliosphere to be extremely interesting but a lower priority when compared to other proposals. The main issues are with the timeliness of the main science return from the mission, the technical feasibility of some of the elements and the need to preserve technical information across several generations of scientists/engineers." Technical feasibility concerns primarily centered on the 60,000 m^2 solar sail and what was seen as a required demonstrator mission to prove the concept and implementation. A secondary concern was

[5] The Nuclear Engine for Rocket Vehicle Application (NERVA) program had the goal of developing a nuclear thermal rocket (NTR) stage. The program developed several successful reactors but came to an end by 1973 with no flight articles.

the need for "very efficient" RPSs, which would be a NASA contribution. Nonetheless they noted that this is "…an innovative mission that addressed our place in the universe and which should be done at some stage… ."

With respect to the other objections raised, efficient RPSs remain a recognized issue, but that problem is being addressed [26] and the mission flyout time to a given distance is contemplated as being faster than that of the Voyagers, but it will still be long. On the other hand, other missions including those of the Voyagers, Ulysses, and the Solar and Heliospheric Observatory (SOHO) have demonstrated that the appropriate maintenance of corporate knowledge across multiple decades is a manageable problem [27].

Most recently, this mission was endorsed in NASA's Heliophysics Roadmap [28] as a potential mission for an international partnership: "The nature of composition and dynamics of the interstellar medium are among the highest ranked science questions in heliophysics. No international partnership opportunity to explore the interstellar boundary is known at this time. Were it to materialize, a spacecraft directly sampling the environment outside the heliosphere could address these questions.

The next logical step in exploration would be to directly sample the medium that lies beyond the extended solar atmosphere. The solar wind and magnetic field keep the unique plasma of the interstellar medium outside the heliosphere. A partnership mission to interstellar space would allow us to sample its unique dynamics and composition and to access the regime of low-energy cosmic rays that helps us understand cosmic particle acceleration processes for the first time." Indeed, "the [Roadmap] team identified one high-priority science target for a potential international partnership, interstellar mission… ." (p. 64 of [28]).

By whatever name it is called, a mission to probe the outer reaches of the heliosphere, the nearby interstellar medium, and the interaction of the two has an undisputed science rationale. The only real questions are (1) how to perform such a mission technically on what will be considered a reasonable budget and (2) how to fund a new round of engineering implementation studies to build upon the current knowledge base.

4. Scientific motivation

The exact formulation of the science questions has varied with particular studies. The formulation used with the NASA Vision Mission study (the Innovative Interstellar Explorer, IIE) is

1. What is the nature of the nearby interstellar medium?
2. How do the Sun and galaxy affect the dynamics of the heliosphere?
3. What is the structure of the heliosphere?
4. How did matter in the solar system and interstellar medium originate and evolve?

This set of questions (from the 3rd Interstellar Probe Science and Technology Definition Team Meeting, 17–19 May 1999) feeds into objectives and questions articulated in NASA's IPSTDT Report and can be used to establish a Traceability Matrix for the mission [15]. In the recent NASA Roadmap [28], the science context flows from Research Focus Areas (RFAs) under each of the three broad science objectives in that report, all of which couple to the priority investigations of determining:

1. What is the composition of matter fundamental to the formation of habitable planets and life?
2. How do the heliosphere and the interstellar medium interact?
3. What is the magnetic structure of the Sun–heliosphere system?

as well as to Decadal Survey Challenge 2: "Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium."

Along with the Voyager Interstellar Mission (VIM), comprised of Voyagers 1 and 2 launched in 1977, the Advanced Composition Explorer (ACE) mission launched in 1997, and the Interstellar Boundary Explorer (IBEX), launched in 2008, and now providing paradigm-shifting results [29–34], the Interstellar Probe is called out as fundamental to addressing these questions.

Similarly, the IHP/HEX mission has had the announced science goals of [16,17,27]

1. How do solar wind and interstellar medium interact to form the heliosphere and how does this relate to the universal phenomenon of the formation of astrospheres?
2. What are the properties of the very local interstellar medium and how do they relate to the typical ISM?
3. How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent, and incompletely ionized plasmas?
4. What is the cause of the Pioneer Anomaly? [35] (a potential "bonus" science goal).

While emphasizing different features and levels of detail, all of these formulations point to the science of our local neighborhood in the galaxy with an emphasis on what it, and the Sun's interaction with it can tell us about ourselves, our solar system, and the undiscovered country that lies beyond (Fig. 1).

5. Instrumentation

To meet the scientific goals of an Interstellar Probe mission, the focus of payload studies and payload examples has tended to focus on in situ measurements with various fields and particles sensors. While early studies also discussed possibilities of stellar measurements using parallax enabled by very long baselines, e.g., [4,36], the required telescopes have been absent from more recent studies for which mass allocations have been too small to allow accommodation.

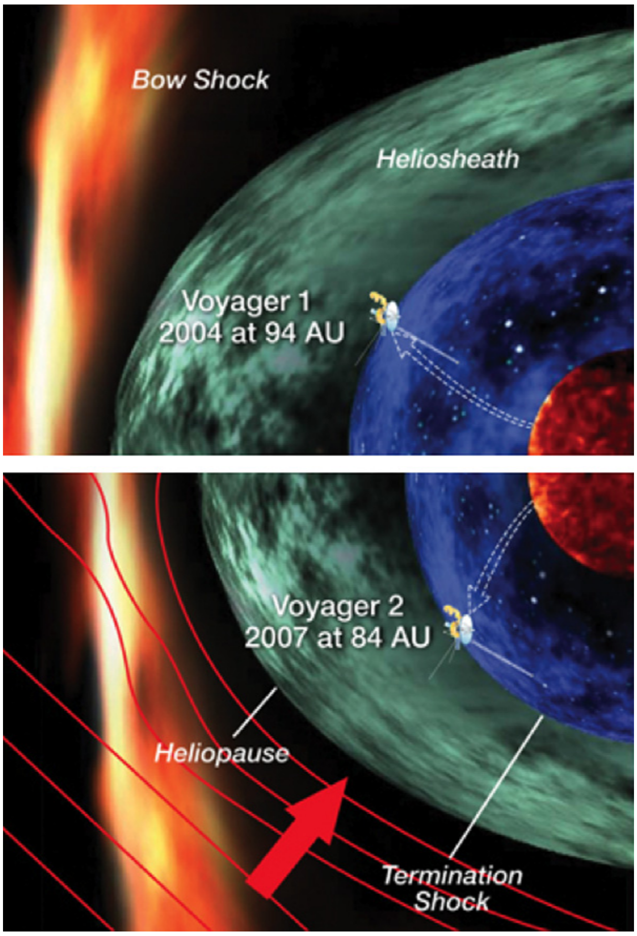

Fig. 1. Representation of the heliosphere in the "upwind" direction showing the relative locations of the termination shock crossings by Voyagers 1 and 2. The closer distance seen by Voyager 2 is thought to be due to the influence of the interstellar magnetic field [47]. Figure adopted from [28].

The Realistic Interstellar Explorer (RISE), carried out under competed funding from the NASA Institute for Advanced Concepts (NIAC), consisted of a miniaturized, ultra-low power (ULP) payload based upon a variety of technological extrapolations, such as a cryogenic spacecraft (also discussed by Jaffe et al. [2]). A goal of the study was to seek out technologies that would allow a fast, long-lived mission (at least 50 years) that could reach at least 1000 AU [37]. The baseline payload of eight instruments had an estimated mass of 2.16 kg drawing 1.87 W [38,39]; these can be compared with the initial baseline of six instruments with a mass allocation of 10 kg and a power allocation of 10 W [40]. Even with this limited payload, significant technology development would be required to realize such a payload, currently at a technology readiness level (TRL) not greater than 2.

The subsequent NASA-funded Vision Mission Study for the Innovative Interstellar Explorer (IIE) adopted a higher TRL payload, which is used as the baseline here. That ten-instrument payload has an estimated mass of 35.16 kg, a power consumption of 29.40 W, and collects data at an estimated rate of 226.05 bits per second (bps) [15,41,42].

Remote measurements that can take unique advantage of the spacecraft location are maintained. Such measurements include the detection of ultraviolet photons and neutral atoms from the interaction regions that are being measured. Similarly, many discussions of appropriate payloads have led to inclusion of infrared absorption measurements to map out the absorption due to solar system dust as the spacecraft recedes from the Sun. Instrumentation discussed for this purpose has been problematic due to the need for moderately large (and heavy) optics, active cooling (both a mass and a power item), and relatively large data rates. Such instrumentation is excluded in the current concept for these reasons.

The payload instrumentation goal has been to remain at less than ~45 kg and 40 W, including ~30% margins for ten instruments with data rates not exceeding 500 bps. Similar mass and power constraints existed for Pioneer 10, an RPS-powered, 258-kg spacecraft. Pioneer 10 carried eleven instruments with a mass of 33 kg and drawing about 24 W of power for operation. Spinning at 4.8 revolutions per minute, a 2.74-m diameter HGA provided a data downlink rate of 1024 bps from Jupiter during the Pioneer 10 flyby in December 1973 [13,14].

The nominal IHP/HEX spacecraft has a similar instrumentation baseline. Twelve instruments are envisioned with a mass of 25.6 kg using 23.8 W and producing 265 bps of data. The two model payloads make use of current, or near-current instrumentation and provide roughly the same overall measurement capability. The difference in instrument count lies in the details of how the measurement functionality is distributed in the two model payloads.

The NRC study examining the usefulness of Constellation architecture for robotic missions noted the overall maturity of these current Interstellar Probe studies [24]. Technical maturity of the science, instruments, and mission concept were all rated as "high" with the mission concept noted as "worthy of further study as a constellation mission" with a mission price estimate of between $1B and $5B Fiscal Year (FY) 2008 dollars. The authors noted "Further study is needed of the benefits of Ares V—in particular, of alternative propulsion options." The preliminary study that led them to these conclusions is documented here.

In what follows we consider some of the details of implementing the mission with a high-speed launch combined with a low-thrust, electric-propulsion system. The other major propulsion-option alternative is that of solar sails, the baseline of the IHP/HEX approach. Only the basic means of propulsion differentiates the two approaches. With the problems identified with the powered-solar-swingby-ballistic approach (the NIAC study) and the NEP approach using near-term, space-reactor technology, these are the only viable propulsion approaches remaining. The science, required measurements, supporting instrumentation – including mass, power, and data rate – and spacecraft mass, excluding systems associated with in-space propulsion, can be taken as identical at this level of study and comparison.

6. Mission requirements

The mission requirements for an Interstellar Probe have been to reach as high a solar-system escape speed as possible with an appropriate payload and do so as rapidly as possible. Typically, but not always, this has been further constrained by launching toward the vicinity of the incoming "interstellar wind, " a flow of neutral atoms that provides an asymmetry to the heliosphere and has been thought to mark the closest approach of the interstellar medium to such a probe, e.g. [43] and references therein.

The top-level mission requirements for the IIE Vision Mission are (1) launch the spacecraft to have an asymptotic trajectory within a 20° cone of the "heliospheric nose" (+7°, 252° Earth ecliptic coordinates) (this may be relaxed in light of IBEX observations), (2) provide data from 10 to 200 AU; (3) arrive at 200 AU "as fast as possible, (4) consider all possible missions that launch between 2010 and 2050, (5) use existing launch hardware (relaxed for use of Ares V), (6) use no "in-space" assembly, (7) launch to escape velocity, (8) keep new hardware and technology to a minimum, and (9) provide accepted "adequate" margins.

Requirements 1 through 3 are driven by the science goals and reaching a minimum heliocentric distance of 200 AU for the mission. Requirement 4 guided a detailed examination of what extra performance non-powered planetary gravity assists could – and could not – do in terms of increasing performance [15]. Requirement 7 is meant to deal with any safety concerns associated with the RPS on board. The other requirements are made to maintain a launch possibility of such a mission in the near future. In this case, the Ares V is the only new technology addition. The original baseline used a Delta IV H with a twin Star 48A stack – a novel combination requiring new interfaces but using well-tested components.

With respect to gravity assists, the REP (as well as a fully ballistic) spacecraft can gain significant additional asymptotic speed from a Jupiter flyby. This is unlike the case of using a solar sail, for which all acceleration will have occurred prior to Jupiter orbit. A combined Jupiter–Saturn flyby can provide extra capability still, but the geometry for reaching a fixed point in space (the incoming interstellar wind direction) occurs rarely, only once between 2010 and 2050. Windows for Jupiter flybys to a fixed point in space occur every 13 months for about 4 years in a 12-year cycle. Such flybys also require consideration of radiation exposure on spacecraft parts within Jupiter's magnetosphere, adding an additional consideration to the mass trade-space with a solar sail.

7. Spacecraft architecture

For the baseline spacecraft using REP, four different options were studied. These configurations include different levels of risk and technology aggressiveness. The different approaches were meant to stress the power required for the downlink data system and ion engines as well as the mass penalties for different HGAs, command and data subsystem (CDS) strings, and ion thrusters, the latter two items driven by the amount of redundancy required for a long-lived mission. For example, a requirement of data recording at 500 bits per second (bps) full time translates into 302.4 megabits (Mb) per week. To play this data back during two 7.25-hour passes (nominal 8-h pass plus lock-up time) would require transmission at 5.8 kbps from 200 AU as the most stressing case. The telecommunications system would have to be sized to provide such a downlink capability and this drives both mass and power for the spacecraft bus. Using a 2.1-m diameter HGA versus a 3-m-dia HGA requires more radio-frequency (RF) power but less antenna and structural (support) mass, as well as (potentially) decreasing the spacecraft moments of inertia, and, hence attitude control system (ACS) requirements. Smaller numbers of CDS strings and ion engines do not directly affect power, as only one is run at time (additional units are cold spares), but they do add mass while increasing mission reliability. Details are provided in [15] and are summarized in Table 1.

Table 1
Spacecraft configuration options.

Option	1	2	3	4
Data rate @ 200 AU (kbps)	5.8	5.8	0.5	0.5
HGA dia (m)	2.1	3.0	2.1	2.1
CDS strings	4	2	4	2
Ion engines (no./kW each)	3/1	2/1	3/1	2/0.75
Dry mass (kg)	586	518	571	465
Dry mass with margin (kg)	762	674	743	605
Wet mass (kg)	1283	1194	1263	1066

As with the Pioneer 10 and 11 spacecraft, typical spacecraft concepts are dominated by the HGA, a magnetometer boom, and here, plasma wave instrument antennas (Fig. 2).

8. Constellation approach

A rapid examination of Ares I and Ares V capability revealed two, unsurprising, conclusions. First, as compared with the Delta IV H data, available data for projected Ares I performance showed no advantage to be gained for mission performance using that launch vehicle. Secondly, the Ares V is not designed for providing large C3s for heavy spacecraft, and for a relatively small robotic probe, that launch vehicle is over-powered unless a high-energy stage is included in the stack. This type of "impedance mismatch" is well known and long ago led to energetic upper stage vehicles. The older Agena and newer Centaur upper stages are well known in the U.S., as is the Fregat in Russia, as examples.

For the first iteration, we consider an Ares V with a partially fueled Earth Departure Stage (EDS) topped with a Centaur upper stage (Fig. 3). For the first iteration of an optimized solution, we obtain C3 $\sim$270 km^2/s^2 and a corresponding asymptotic speed from the solar system of $\sim$19.0 km/s or $\sim$4 AU/yr. The Centaur upper stage is also built with two engines, providing higher thrust lower in the Earth's gravity field. This combination provides slightly higher performance for this mission.

For comparison New Horizons launched to a C3 of 158 km^2/s^2 and with a distant Jupiter flyby at $\sim$30 Jovian radii will perform a Pluto flyby at 13.8 km/s (2.9 AU/yr). With Jupiter and Saturn flybys Voyager 1's current speed

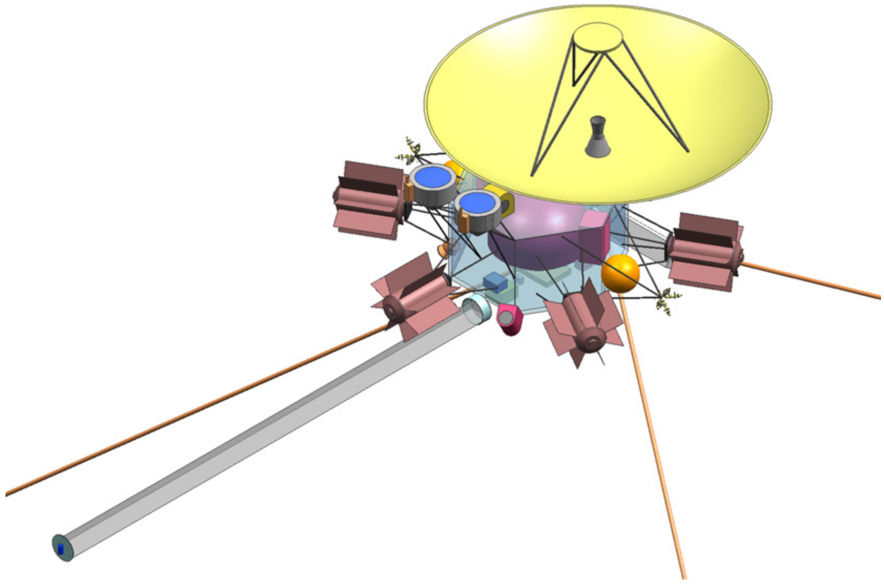

Fig. 2. A close-up, isometric of configuration option 3 (of Table 1). The three-plasma waves antennas, each 25 m long and mounted in mutually orthogonal directions are cut off at the edge of the figure and not visible in their entirety. The 5.1-m-long magnetometer boom extends to the lower left. Four of six RPSs are visible and can be located from their radiator fins. The two cylinders mounted to the side of the HGA and above the magnetometer boom are the 20-cm-dia ion engines associated with the REP system (used one at a time). The xenon tank is hidden within the spacecraft bus below the HGA.

is 3.6 AU/yr while that of Voyager 2 is 3.3 AU/yr (Voyager 2 also executed flybys of Uranus and Neptune, but the latter deceased the asymptotic flyout speed due to constraints imposed by the geometry of a near encounter with Neptune's moon Triton).

To reach 9.5 AU/yr (45 km/s) with only a (fully ballistic) launch from Earth would require C3 = 1016 km^2/s^2, an unachievable initial launch energy per mass with any foreseeable rocket technology. Hence, even with an Ares V, launch remains only one component of an interstellar-probe-mission solution.

To investigate how much farther one could push the technology, we have also made a preliminary investigation of the use of an upper stage powered with an NTR system. We have restricted the study to the use of a stage originally proposed under the NERVA program for which modern designs exist under the Bimodal Nuclear Thermal Rocket (BNTR) studies that have been conducted (Fig. 4).

Nuclear stage advantages include: (1) more performance than Centaur V1 and (2) lower mass, while maintaining an Earth-escape trajectory. However, such units have never been developed, and, in addition to development and flight qualification costs, the unit costs will also be higher for a nuclear unit. In addition, the uses of all liquid hydrogen (LH2) propellant means the unit will be larger (due to the lower LH2 volume). The stage will not have a solar-system escape trajectory, so its ultimate orbit must be taken into account as a potential, future hazard.

For performance numbers we used available specifications for the NERVA Gamma engine with a thrust of 81 kN (18,209 lbf) attached to a corresponding upper stage with a gross mass (wet) of 18,643 kg [44]. For comparison, specifications for a recent BNTR engine concept provided a thrust of 66.7 kN (15,000 lbf) with three of these baselined for the Mars Design Reference Mission (DRM) 4.0 of 1999. Further use of NTR components is not feasible. A nuclear EDS is not acceptable because it would not be on an Earth-escape trajectory. For a comparable thrust engine for a nuclear EDS, the NERVA 2 engine thrust specification was 867.4 kN (195 klbf) and the NERVA stage specifications 178,321 kg wet, 34,019 kg dry [45], which can be compared with those of the S IVB stage: 119,900 kg wet, 13,300 kg dry; J-2: 486.2 kN (109.3 lbf). While conceptually promising on a technical level, there are currently no development plans or identified requirements for any NTR upper stage. Hence, these concepts do not provide a credible approach and are included as a design point of reference only.

8.1. Performance comparisons

For the REP spacecraft we adopted a standard configuration close to that of our configuration option 3 with a dry mass of 790 kg, including reserves, and 440 kg of Xe for a 1.0 kW ion engine, yielding a total launch mass of 1230 kg for the REP system. Optimized trajectory and system performance for arrival 200 AU from the Sun within the established mission constraints is provided in Table 2.

The NTR/REP combination provides the best performance with a speed at 200 AU of 10.1 AU/yr after just over 22 years from launch, a transit time 8 years less than what is achievable with the Delta IV H stack. The burnout speed is just under 3 times that of the current speed of Voyager 1 (3.6 AU/yr). The Ares V/Centaur stack provides performance almost as good: 7 years saving over the Delta IV H stack capability and a speed in excess of that achievable with the Delta IV H by 1.9 AU/yr.

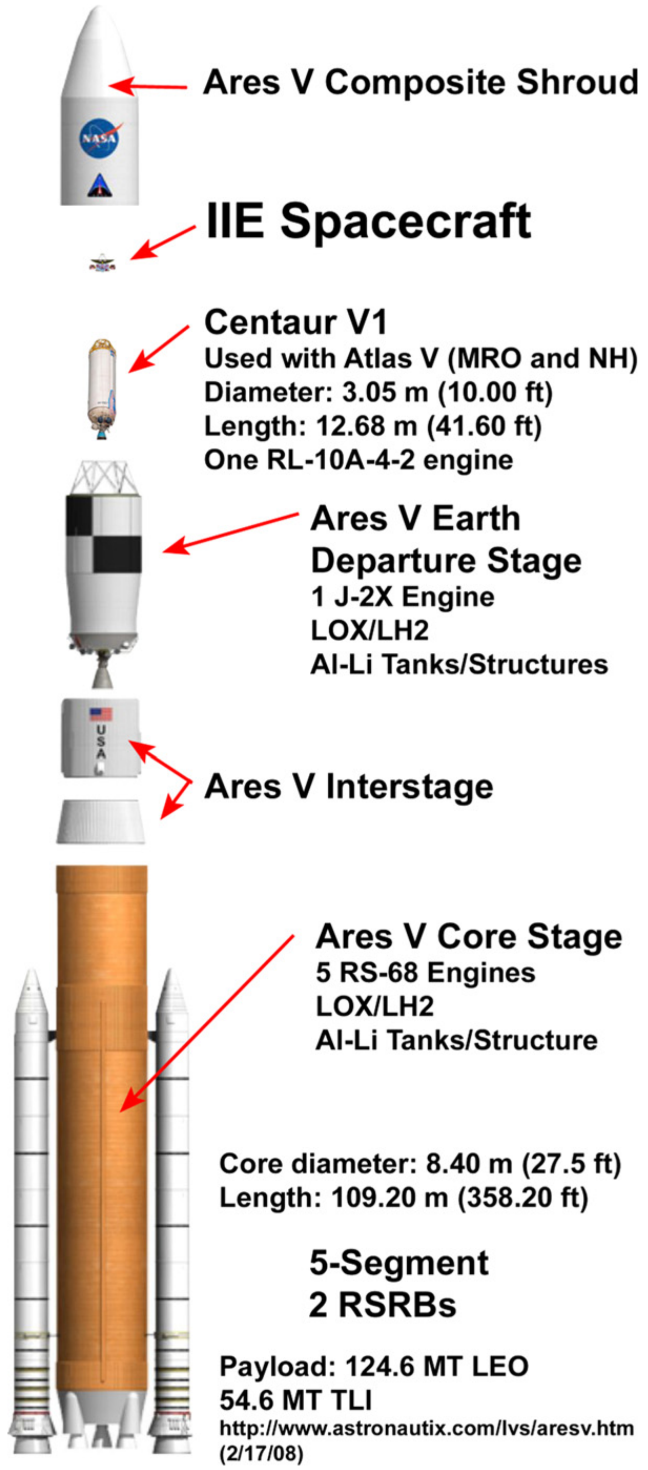

Fig. 3. Concept for Ares V with EDS and Centaur V1 used to propel an IIE spacecraft using REP. Drawings of Ares components © Mark Wade.

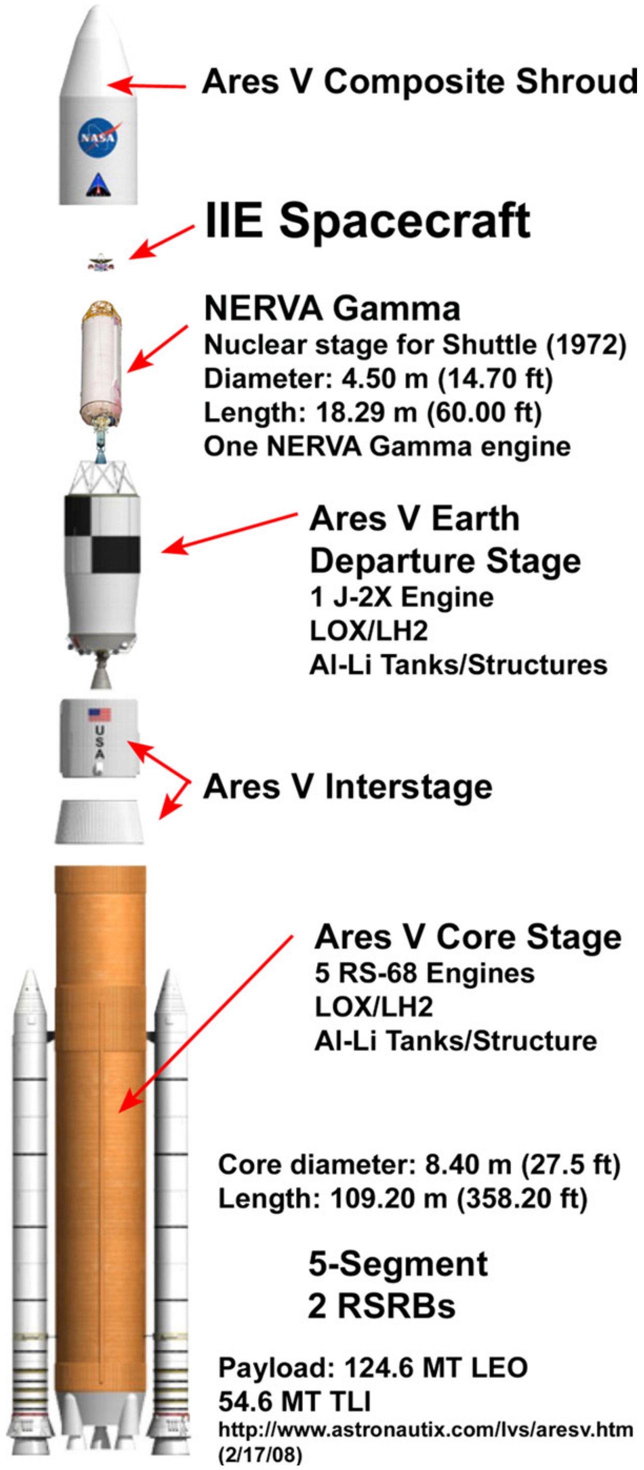

Fig. 4. Launch stack for an interstellar probe incorporating an NTR upper stage. Components, including the nuclear engine are approximately to scale. Drawings of Ares components © Mark Wade.

To probe the margins, calculations were also made for total mass of 1500 kg (final mass of 843 kg and Xe propellant mass of 657 kg). The increased mass affected the Centaur design less, the optimized REP system providing better performance (decreased flyout time of 0.2 year and increased flyout speed of 0.1 AU/yr). The NERVA design also had a decreased flyout time of 0.2 years and an increased flyout speed of 0.2 AU/yr. The optimization in both cases resulted in higher speed gain from the REP system.

Trades against various stack configurations and components are given for thirteen different variants in Figs. 5 and 6, all based upon the use of the Ares V and EDS as the baseline launch vehicle. Asymptotic-speed performance trends fall into four broad classes (Fig. 5): (1) ballistic launch from Earth, (2) ballistic launch with an REP upper

Table 2
REP performance trades to 200 AU.

Option	Delta IVH+2 Star 48A	Ares V Centaur	Ares V NERVA
Launch date	22 Oct 2014	3 Dec 2015	5 Dec 2015
Gravity assist body	Jupiter	Jupiter	Jupiter
Gravity assist date	5 Feb 2016	10 Oct 2016	19 Sep 2016
Gravity assist altitude	75,150 km	128,855 km	128,855 km
Gravity assist radius	2.05 Rj	2.80 Rj	2.80 Rj
Gravity assist, Δv	23.8 km/s	25.1 km/s	25.0 km/s
Burnout date	13 Oct 2032	3 Jul 2030	26 Nov 2029
Burnout distance	104 AU	116 AU	117 AU
Burnout speed	7.9 AU/year	9.8 AU/year	10.1 AU/year
Date 200 AU reached	31 Dec 2044	14 Feb 2039	27 Jan 2038
Minimum trip time to 200 AU	30.2 years	23.2 years	22.2 years
Speed at 200 AU	7.8 AU/year	9.7 AU/year	10.1 AU/year
Right ascension at 200 AU	263.8°	248.7°	242.6°
Declination at 200 AU	0.0°	0.58°	0.71°
Launch mass	1230 kg	1230 kg	1230 kg
Propellant mass	440 kg	440 kg	440 kg
Final mass	790 kg	790 kg	790 kg
Power	1.0 kW	1.0 kW	1.0 kW
Isp	3800 s	3410 s	3336 s
EP system efficiency	53.8%	53.5%	53.4%
Total stack C3	123.3 km^2/s^2	270.0 km^2/s^2	320.0 km^2/s^2
EP, Δv	16.5 km/s	14.8 km/s	14.5 km/s
Thrust time	18.0 years	14.6 years	14.0 years

stage, (3) ballistic launch with a Jupiter flyby, and (4) ballistic launch, Jupiter flyby, and REP upper stage. The time to 200 AU breaks into three families (Fig. 6) with the use of a Jupiter gravity assist trading against the use of an REP stage. The spread in arrival time to 200 AU varies from ~22 years to ~38 years across all thirteen options considered. Best performance comes from the synergistic combination of high launch energy, Jupiter gravity assist, and the use of an REP stage. None of the scenarios studied yielded a flyout time as short as 15 years to 200 AU, a goal of many of the previous studies. The shorter times are comparable to what has been found with initial engineering studies of the IHP/HEX solar sail approach that include a 0.25 AU perihelion [16].

8.2. Extended mission

The Voyagers may not remain on line much past the year 2020, some 43 years following their launches, due to the decay of the Pu-238 in their RPSs (assuming no other spacecraft system failures). For an option 1 (minimum new technology) configuration (cf. Table 1 and [15]) and a 2015 launch using an Ares V with a two-engine Centaur upper stage, an Interstellar Probe would reach 200 AU in 2038, some 22.3 years after launch. With an asymptotic speed of 10.2 AU/yr, the spacecraft would reach 300 AU some 32 years after launch and 1000 AU – well into the undisturbed very local interstellar medium (VLISM) – in 2116, just over a century after launch. Although 1.1 Pu-238 half-lives would have elapsed, plenty of power could still be present to run the spacecraft and downlink. Most of the power would be margin following the expulsion of the Xe through the REP system before the ~120 AU mark. Whether a spacecraft could be built to last for such a long time is questionable. Designing upfront for a century of use is not feasible, but such a craft would require an ~25-year design lifetime. This can be compared with the Voyagers, which have exceeded their design lifetimes of 5 years by over a factor of six.

8.3. Mission enablers and mission costs

An Interstellar Probe mission pushes the technical limits of the three enablers for any deep space mission traveling away from the Sun: a highly capable, yet "affordable" launch vehicle with a high-energy stage, kilowatt-class electric power from a low-specific-mass RPS, and reliable, sensitive, deep-space communications at Ka-band. All three elements of this robotic-mission-infrastructure triad are necessary for such a mission to take place.

Launch vehicle prices must be negotiated for any given mission and are contingent upon mission details. Delta IV H costs have likely not decreased from their reported level of $254M in late 2004 [46]. While Star 48A motors are available, the type of custom stack required for this application would require design work. The overall stack could likely be produced for less than $500M, including the National Environmental Protection Act (NEPA) costs associated with use of an RPS for spacecraft power. Recurring costs for an Ares V/EDS/Centaur stack are totally unknown, but could run as high as $1B, depending upon the Ares V production run and orders for its use. An appropriate launch vehicle for the IHP/HEX would likely be in the ~$100M or less category, provided that current mass and initial launch energy (C3 ~ 0) requirements hold.

From past usage of RPSs, we could guess at a price of ~$80M per unit with 6 required for the REP approach and 2 for IHP/HEX. Key to this and other deep-space robotic missions is restarting the production of Pu-238 [26].

Tracking and operations costs are, to first order, independent of the propulsion implementation. The

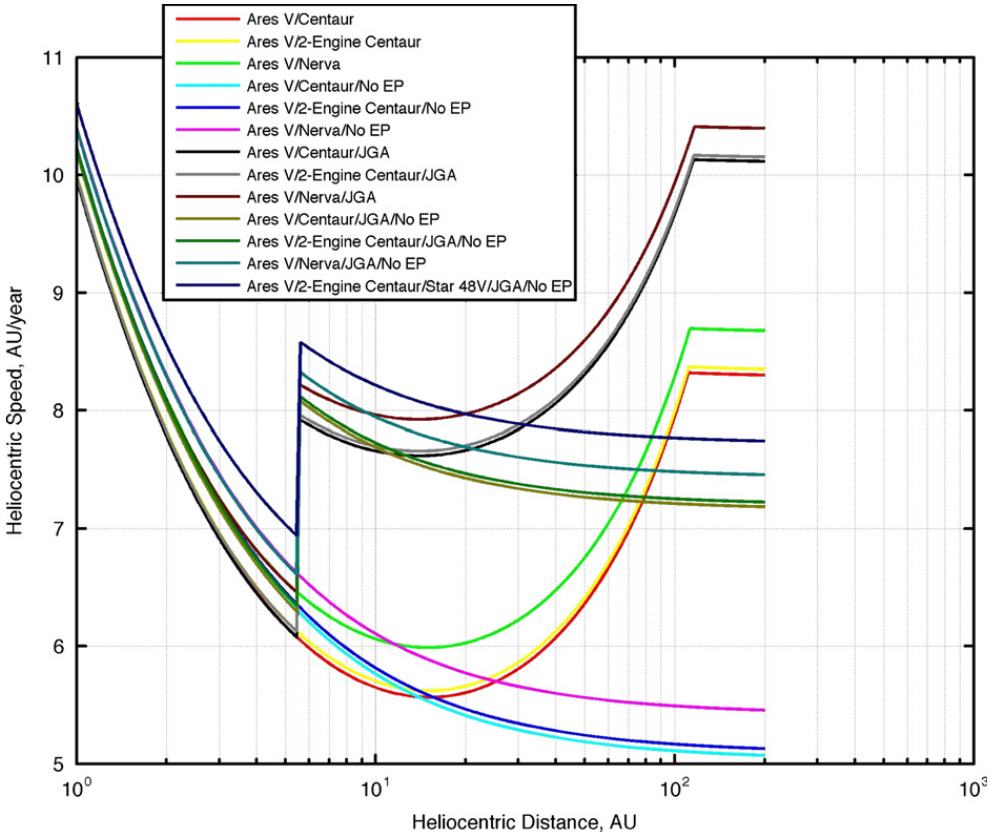

Fig. 5. Asymptotic heliocentric speed as a function of heliocentric distance for the thirteen different configurations considered. Note the slightly enhanced performance with the two-engine Centaur stage versus that for the stage with a single engine. The speed discontinuity at just greater than 5 AU is due to inclusion of a Jupiter gravity assist. "Burnout" of the REP stage can be identified by the slope discontinuities at just greater than 100 AU from the Sun.

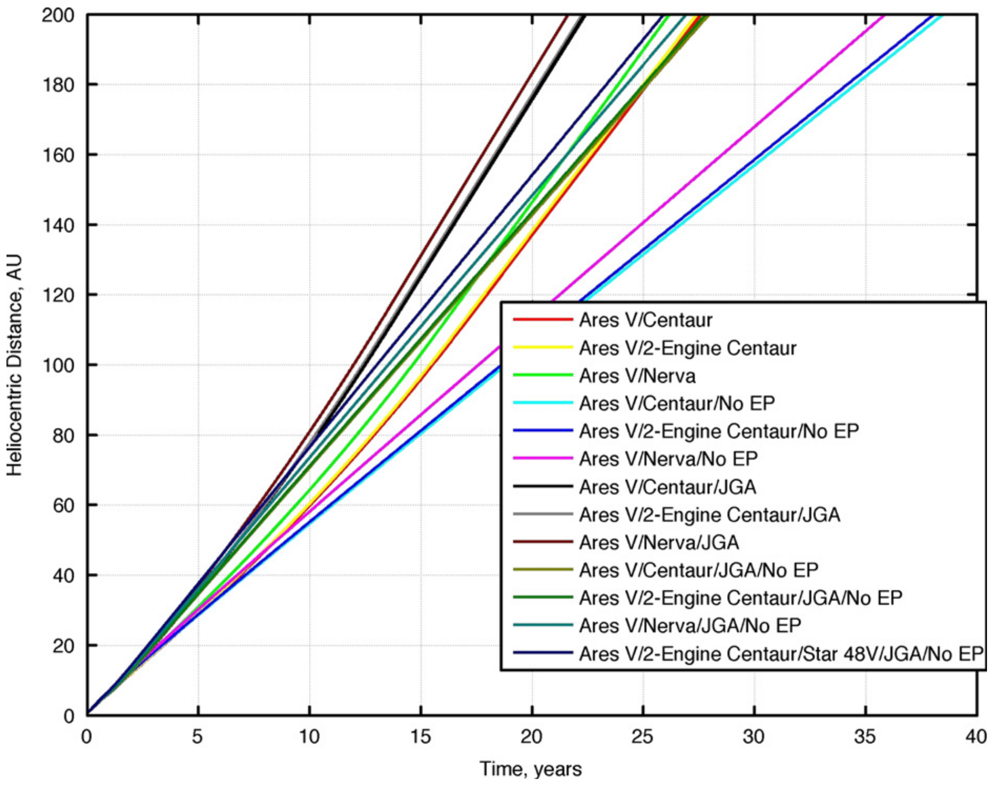

Fig. 6. Spacecraft heliocentric distance versus mission time for the same thirteen mission configurations used in Fig. 5.

aperture fee for use of NASA's Deep Space Network (DSN) can be estimated using a variety of NASA resource tools. Assuming three tracks/week with the 34-m high efficiency (HEF) antennas through 2032 with a switch to 70-m antennas (or equivalent) through 2044, we estimate 30-year tracking costs (real-year dollars) of ~$930M. For the cost of mission operations and data analysis (MO&DA) of ~$10M per year for 30 years at 3% per annum inflation rate, we derive ~$500M.

Spacecraft and instrumentation costs are also likely to be vaguely independent of implementation. For 12 instruments at an average cost of $15 mission each and $500M for the spacecraft bus, the basic unit should be buildable for less than $1B including healthy reserves. For a solar-sail implementation, we might guess that a ~$150M precursor mission with an additional ~$50M may be needed to prove out the required solar-sail technology.

Tallying these hypothetical costs for the two approaches suggests the Delta IV H/Star 48/REP mission could be built for ~$1.5 B (spacecraft+instruments+6 RPS) and launched for another $500M. The use of an Ares V/EDS/Centaur could provide more capability for an additional ~$500M. A solar-sail unit (spacecraft+instruments+2 RPS) could be built for $1.1B, qualified for ~$200M and launched for another ~$100M, a total of $1.4B. Running and tracking either mission for 30 years could total ~$1.4 B (a high number until one considers 30 years of 3% per year inflation being included). In this hypothetical example, a dedicated 30-year mission to interstellar space could be built and launched for no more than ~$1.5 B and operated for no more than this same amount, less than the cost of building the Cassini mission now in orbit about Saturn.

9. Summary

A robotic probe to the interstellar medium, humanity's first "star ship," continues to be one of the most scientifically profound, yet technically challenging, of feasible space missions. Some type of advanced propulsion is required to implement such a mission as far as 200 AU from the Sun in a time interval as short as ~25 years.

The use of a solar sail provides a conceptually efficient implementation. However, the required technological implementation remains unproven, and a precursor demonstration mission will be required to make a full evaluation of its potential. Difficulties include development of a sufficiently large sail with sufficiently small areal density that can also be deployed and controlled within 0.25 AU of the Sun. An efficient RPS power supply will be required in any event to power the spacecraft and instruments.

The use of a large launch vehicle in concert with an REP propulsion system and a Jupiter gravity assist appears to be more complex, yet the required technology advances to provide the same performance are closer at hand. Such an implementation trades more cost for less implementation risk. Even more performance can be achieved with the use of an Ares V launch vehicle including its upper EDS. A Centaur upper stage is still required to provide the needed performance, but the parts and technology are well proven for that stage. Cost, certification, and use of the Ares V remain significant unknowns, especially with regard to the inclusion of RPSs in the payload. While additional performance could be had with the use of an NTR stage instead of a Centaur, such stages remain on the drawing board and do not provide sufficiently increased performance to justify their development solely for this mission.

These still preliminary concepts do indicate that such a mission is possible, and the scientific bounty would be significant. With no other means of probing this aspect of our Sun's interaction with the galaxy beyond than by direct sampling with such a mission, an Interstellar Probe continues to remain a high scientific priority and will continue to remain so until it is successfully implemented.

The International Interstellar Probe Team is an open group of over 60 scientists from 13 countries on 5 continents dedicated to reaching the beginnings of interstellar space. With its beginnings in the last Cosmic Vision proposal [16] the group welcomes to its ranks scientists from all countries with an interest in bringing this important mission to fruition.

Acknowledgments

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