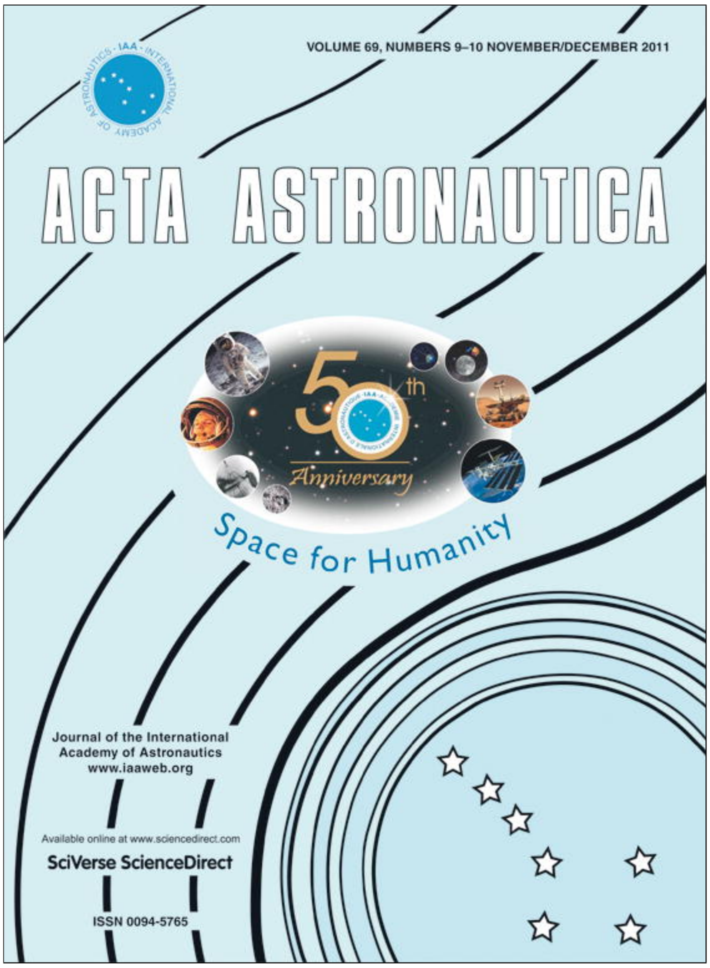
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Interstellar Probe: Impact of the Voyager and IBEX results on science and strategy ☆

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ABSTRACT

The ongoing Voyager Interstellar Mission (VIM) and recent observations from the Interstellar Boundary Explorer (IBEX) and Cassini missions are providing significant new information about the interaction of the heliosphere with the very local interstellar medium (VLISM). With new observations have come significant new puzzles for describing the interaction physics. Direct measurements of the shocked, solar-wind flow speed are now possible (from Voyager 2) and show the flow remains supersonic. This is one more piece of evidence supporting the idea that the bulk of the energy density in the plasma resides in a non-thermal component that extends to very high energies. There are both quantitative and qualitative implications for the overall heliospheric structure. Observations of energetic neutral atoms (ENAs) by IBEX (in Earth orbit) from the interaction region(s) of the solar wind and the VLISM show unexpected structure on a variety of scales. In addition to the general "glow" of the sky in ENAs, IBEX data show a relatively narrow "ribbon" of atomic hydrogen emission from ~200 to ~6 keV, roughly circular, but asymmetric in intensity, and centered on an ecliptic longitude ~221 degrees and ecliptic latitude of 39 degrees. The ribbon may be ordered by the interstellar magnetic field. It passes through, rather than being centered on, the "nose" from which the local, neutral interstellar wind enters the Heliosphere, indicating that the flow is not the primary driver of the system as had been thought previously. The neutrals from both the glow and ribbon are also characterized by non-thermal distribution functions. ENAs are observed at higher energies as well by the Ion and Neutral Camera (INCA) on Cassini (in orbit about Saturn). A "belt" of emission,

Abbreviations: ACR, anomalous cosmic ray; AU, astronomical unit (mean Earth–Sun distance of $1.4959787066 \times 10^{11}$ m); CME, coronal mass ejection; ENA, energetic neutral atom; GPHS, General Purpose Heat Source; HGA, high-gain antenna; IBEX, Interstellar Boundary Explorer; IHP/HEX, Interstellar Heliopause Probe/Heliospheric Explorer; IIE, Innovative Interstellar Explorer; IKAROS, Interplanetary Kite-craft Accelerated by Radiation Of the Sun; INCA, Ion and Neutral Camera; JAXA, Japan Aerospace Exploration Agency; LH2, liquid hydrogen; KBO, Kuiper Belt Object; NASA, National Aeronautics and Space Administration; NEP, nuclear electric propulsion; NIAC, NASA Institute for Advanced Concepts; pc, parsec (206,264.806 AU); NSSDC, National Space Science Data Center; REP, radioisotope electric propulsion; RPS, radioisotope power system; RTG, Radioisotope Thermoelectric Generator; STEREO, Solar TErrestrial RElations Observatory; VIM, Voyager Interstellar Mission; VLISM, very local interstellar medium

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broader than the ribbon but similar to it, is seen up to $\sim$50 keV. These observations emphasize the need for in situ measurements to understand the global nature of our local galactic environment, which is much more complex than previously thought. Only an interstellar probe with modern instruments and measurement requirements better defined by these recent observations can provide the new information required. Even more importantly, the broader scale of the interaction as revealed in these measurements suggests much greater flexibility in scientifically allowable, asymptotic trajectories from the heliosphere for the probe. This is a significant relaxation in the trajectory requirements that open up the trade space for Jupiter gravity assists to increase the flyout speeds.

1. Introduction

From the beginning of recorded history – and likely before – humans have speculated about and sought to understand our position in the Universe. Notions of the architecture of the cosmos as governed by physical laws have only developed over the last century, and for the first half of that only via telescopic observations combined with the advances of quantum mechanics and general relativity.

Davis [1] first called attention to the possible modification of the local interstellar medium by solar activity prior to the postulation [2] and confirmation [3] of the near-constant supersonic solar wind. The effects of this action on the nature of near-Sun space has been a subject of scientific speculation ever since [4,5].

There are currently five spacecraft with speeds sufficiently high to escape the solar system. All five are planetary missions, but they do include instrumentation capable of making *in situ* particle and/or field measurements relevant to probing the nature of the Sun's interaction with the very local interstellar medium (VLISM), generally taken as 0.01 parsecs (pc) or 2063 astronomical units (AU) so as to be outside the limit of influence of the Sun [6].[5]

The earlier two spacecraft, Pioneer 10 and 11, launched 2 March 1972 and 5 April 1973, fell silent on 23 January 2003 and 30 September 1995, respectively [7], while both were still in the supersonic region of the solar wind. Voyager 1 and 2, launched 5 September and 22 August 1977, continue to return data, now from the heliosheath, having crossed the termination shock of the solar wind at 94.0 AU on 16 December 2004 [8] and at 83.7 AU on 30 August 2007 [9], respectively. Both continue to return data and should continue to do so until at least $\sim$2020 [10]. Voyager 1 is the fastest ($\sim$3.6 AU/year[6]) and most distant of the five. Finally, the New Horizons spacecraft launched to Pluto on 19 January 2006, remains on course for that object and an Kuiper Belt Object (KBO) beyond at roughly the same heliographic longitude as Voyager 2, but near the plane of the ecliptic [11].

Following the Pioneer 10 and 11 Jupiter flybys, there was an initiative for flying a dedicated "interstellar precursor mission" [12–16]. Subsequently, the scientific rationale for such a mission has been repeated in a number of National Aeronautics and Space Administration (NASA) and National Academy of Sciences documents (a recent summary can be found in Ref. [17]). However, the ongoing *in situ* measurements by the Voyagers in the heliosheath, coupled with remote measurements of energetic neutral atoms (ENAs) from the interaction region have shown that the scientific need for new measurements with modern instruments from the remote reaches of the heliosphere are even more compelling than had been thought.

2. New science

The ongoing Voyager Interstellar Mission (VIM) and recent observations from the Interstellar Boundary Explorer (IBEX) [18–23] and Cassini missions [24–26] have revealed the interaction of the heliosphere with the VLISM to be much more complex than heretofore assumed by our present day concepts. These discoveries call for a major revision of the strategy for the Interstellar Probe mission. With new observations have come significant new puzzles for describing the interaction physics.

Other in situ instruments on Voyager 1 and Voyager 2 continue to reveal significant fluxes of energetic particles in the heliosheath, including a well-defined suprathermal ion "tail" in which the differential intensities fall off $\sim E^{-1.5}$ above $\sim$30 keV [27]. At even higher energies ($\sim$100 MeV), there is no "unfolding" of the energy spectrum of the anomalous cosmic rays (ACRs), thus pointing to a more remote location for the modulation region and source [28]. Most strikingly, direct measurements of the shocked, solar-wind flow speed obtained from Voyager 2 revealed that the flow remains supersonic in the heliosheath beyond the termination shock [29]. All of these particle observations, taken together, unambiguously imply that the bulk of the energy density in the plasma resides in a non-thermal component that extends to very high energies. Strong implications, both quantitative and qualitative, follow from this fact for the overall heliosheath structure. We have never encountered a large-scale plasma regime in which the non-thermal ion pressure dominates the thermal pressure and overwhelms the magnetic field stresses. The closest parallel regime lies in localized regions of planetary magnetospheres during extremely disturbed conditions, but in the heliosheath these conditions always exist everywhere. This means that no simple equation of state (neither maxwellian nor "kappa" distribution) is adequate to describe the essential physics.

[5] For units $c = 2.99792458\times10^{8}$ m s^{-1}; 1 (Julian) year = 365.25 d = 8766 h; 1 AU = 1.495 978 706 6 $\times 10^{11}$ m; 1 pc = 206 264.806 AU.

[6] 1 AU/(Julian)yr = 4.740470461 km/s.

This is why even sophisticated MHD models failed to predict anything like the striking new features that have just been observed in the last two years.

However, there was a foretelling of this recent revelation. For decades, there had been a clear, but under-appreciated, indication that the "standard" theoretical models of the heliosheath were seriously lacking the essential physics. A series of Voyager 1/2 radio observations beginning in 1983 and continuing to the present had detected remarkable long-lasting emissions in the 1.6–3.4 kHz range that were identified with major disturbances in the heliosheath produced by giant coronal mass ejections (CMEs) associated giant (X-class) solar flares [30]. The higher frequency emissions were localized, coming from and extended arc confined to the hemisphere toward the interstellar flow (i.e., the "nose" of the heliosheath), and lying close to, but not actually in the galactic plane [31]. These authors noted that the arc could perhaps be the curve on the heliopause (the boundary between shocked solar wind and interstellar plasma) where the interstellar magnetic field was normal to that surface ($\mathbf{B}\cdot\mathbf{n}=0$), in accordance with the "hydrogen deflection plane" defined by the $\sim 4^\circ$ difference between the arrival directions of interstellar H atoms [32] (affected by charge exchange in a heliosheath deformed by the interstellar magnetic field) and the unaffected interstellar He atoms [33].

In 2009, remote sensing of the heliosheath proton population using images formed in energetic neutral atoms (ENAs) by IBEX and Cassini/INCA revealed stunningly unexpected structures on a variety of scales [21,26]. In addition to the general "glow" of the sky in ENAs, IBEX data show a relatively narrow "ribbon" of atomic hydrogen emission from $\sim$200 to $\sim$6 keV, roughly circular, but asymmetric in intensity, suggesting that it is ordered by the interstellar magnetic field. It passes through, rather than being centered on, the "nose" at which the local, neutral interstellar plasma flow around the heliosphere stagnates, suggesting that the flow is not the primary driver of the system as has been thought, but rather it is the pressure of the interstellar field that configures the heliosheath. The neutrals from both the glow and ribbon are also characterized by non-thermal distribution functions. The Ion and Neutral Camera (INCA) on Cassini sees at higher energies (10 s of keV) a "belt" of emission in ENAs, broader than the ribbon and tilted significantly away from it and exhibiting a much steeper energy spectrum than observed in the IBEX energy range [25] (Fig. 1). More recently, particle anisotropy measurements by the Low Energy Charged Particle (LECP) instrument on Voyager 1 suggest that spacecraft may have entered a heliosheath transition layer. The negligible flow velocity of the in situ particles suggests proximity to the heliopause [34].

Attempts to explain consistently all the afore-mentioned fascinating observations are currently roiled in controversy, with no clear trend towards a consensus. All the diverse *in situ* and remote observations obtained to date only serve to emphasize the need for a new generation of the more comprehensive measurements that will be required to understand the global nature of our Sun's

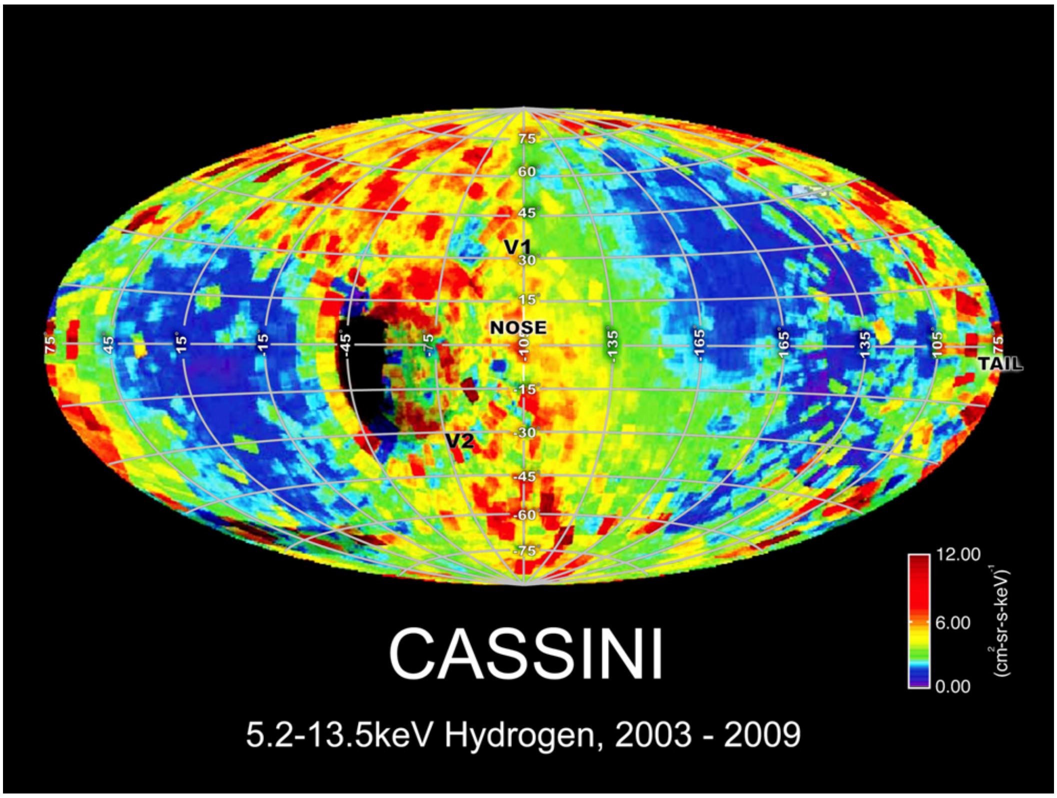

Fig. 1. ENA map from the INCA instrument on Cassini. The map is an equal-area projection that shows the emission "belt." The nominal "nose" of the heliosphere from which there is a general flow of neutral atoms is indicated along with the outgoing asymptotic trajectories of Voyager 1 (V1) to the north and Voyager 2 (V2) to the south, respectively, of the plane of the ecliptic.

interaction with the local galactic environment. Only an interstellar probe with modern instruments and measurement requirements better defined by these recent observations can provide the new information required. We now know that we are dealing with a strongly non-thermal plasma, and that the complex large and small scale structures in the heliosheath are produced by physical processes yet to be adequately described by theory or simulation. As exciting as the scientific prospects are, we must realize that in order to provide a sufficiently fast flyout speed from the heliosphere, careful trades must be done taking into account instruments masses, measurement capabilities, and mission scientific requirements.

3. Implementation approaches

3.1. Mission design

Voyager 1 is the fastest object escaping the solar system by virtue of its double gravity assists by Jupiter and Saturn. The synodic period of these two bodies is just under 20 years, but with an added constraint of the asymptotic trajectory being confined to a small range of ecliptic latitude and longitude, such mission opportunities become rarer [35]. It has typically been assumed in the scientific community that for such a dedicated effort to be worthwhile, an asymptotic speed at least double that of Voyager 1 – and preferably higher still – is a prerequisite for the mission. Hence, some form of "advanced" propulsion has always been viewed as enabling for such a mission.

The use of nuclear electric propulsion (NEP) was favored initially, but such systems tended to be large [15,36,37]. More recent work using the Project Prometheus architecture [38] came to the conclusion that the specific mass (kg/kWe) – as well as the gross mass – of that technical implementation was too large to offer the fast transit times required [39]. Such characteristics have been common for attempts to design fission systems for space [40].

Ballistic, powered, near-Sun, gravity assists [13] were recognized as offering a different potential solution, but with challenges in the high-thrust propulsion capability required [41]. More detailed studies have studied how best to supply such a capability. Specific impulses $\sim$1000 s at high thrust are required and solar-thermal propulsion offers a solution [42–47]. However, the approach required a very-low probe mass ($\sim$150 kg) along with a combined perihelion engine whose function was mission critical, could not be tested in the most stressing environment, and required long-term (3+ year) storage of liquid hydrogen (LH2).

Low-thrust approaches included solar sails [48–51] and RTG-powered electric propulsion [41], the latter now known as radioisotope electric propulsion (REP) [52,53], with solar electric propulsion seen as having limited value. Both of these have limitations driven by materials and mass issues.

3.1.1. Solar sails

Solar sails make use of the radiation pressure inherent in the electromagnetic nature of sunlight. At 1 AU, the solar constant is 1367.2 Wm^{-2} with an associated momentum flux of p_{sun}=4.5605 μNm^{-2}. The relevant physical parameter is the lightness number λ where, for a sail oriented with its normal at an angle β with respect to the direction toward the Sun's illumination, and assuming specular reflection

$$\lambda \equiv \frac{\text{solar radiation pressure force}}{\text{gravitational force}} = \frac{2\eta p_{Sun} A_{sail}\cos^2\beta/r^2}{GM_{Sun}\sigma_{sail,eff}A_{sail}/r^2} = \frac{2\eta p_{Sun}\cos^2\beta/r_0^2}{GM_{Sun}\sigma_{sail,eff}/r_0^2} = \frac{2\eta p_{Sun}\cos^2\beta}{\sigma_{sail,eff}\,a_0 r_0^2} = \frac{1.539\eta\cos^2\beta}{\sigma_{sail,eff}[\mathrm{gm^{-2}}]} = \frac{a}{a_0} = \frac{a[\mathrm{mms^{-2}}]}{5.922} \quad (1)$$

where a_0 is the local heliocentric acceleration at r_0, $\sigma_{sail,eff}$ is the total spacecraft mass divided by the sail area (also referred to the as the "sail loading" [54]), η is the "sail efficiency factor" (an efficiency for effective reflectivity of the sail), and a is the outward acceleration at 1 AU.

Rearranging Eq. (1) we have for normal incidence

$$\sigma_{sail,eff}[\mathrm{gm^{-2}}] = \frac{1.539\eta}{\lambda} = \frac{9.114\eta}{a[\mathrm{mms^{-2}}]} \quad (2)$$

where we also have

$$\sigma_{sail,eff} \equiv \frac{m_{total}}{A_{sail}} = \frac{m_{sail,bare}+m_{sail\ hardware}+m_{observatory}}{A_{sail}} = \sigma_{bare}+\sigma_{sail\ hardware}+\frac{m_{observatory}}{A_{sail}} > \frac{m_{observatory}}{A_{sail}} \quad (3)$$

Here $m_{observatory}$ is the mass of the spacecraft and payload and associated subsystems, such as attitude control, avionics, data handling, power, thermal control, and communications, while $m_{sail\ hardware}$ is the mass of the hardware associated with the sail itself, including booms, attitude control, and deployment-associated hardware that remains with the system. The mass of the sail material itself is m_{bare} with an areal density of σ_{bare}. While solar sailcraft are typically referred to as "propellantless" systems, Eq. (3) suggests a rough analogy to other low-thrust systems with $m_{sail,bare}$ corresponding to the initial propellant loading and the effective areal density $\sigma_{sail\ hardware}$ corresponding to the specific mass of the power plant (typically with units of kg/kWe).

For a sail pointed normal to the Sun's illumination and λ=1/2, the probe escapes the Sun on a parabolic trajectory. For λ=1, the force of gravity is exactly nulled out and the probe executes simple rectilinear motion from the Sun. Hence, a release at Earth, i.e., the launch vehicle deploys the probe to Earth escape speed and then the solar sail is deployed face on to the Sun, the probe will execute rectilinear motion at $\sim$Earth's average orbital speed of 29.7859 km s^{-1}=6.28332 AU yr^{-1}. At such a speed 200 AU would be reached in $\sim$32 years. To decrease the speed to oft-cited requirements of $\sim$15 years, the initial speed would need to increase by a factor of $\sim$2.12 to $\sim$63 km/s. This would require an initial orbit with a radius $\sim 1/(2.12)^2 \sim 0.22$ AU, an estimate in accord with previous detailed calculations [50,51].

This approach is not optimal; a better approach is to set the sail at some angle with respect to the illumination of the Sun for which optimized trajectories can be calculated [55]. Two different approaches have been pursued, both of which begin from a minimal launch vehicle that accelerates the probe to a C3 of 0, and then use the sail to change both the angular momentum and energy of the spacecraft, with a component of the reactive sail force along the velocity vector of the trajectory, such that the craft can fly close to the Sun where the acceleration to higher terminal speeds is possible [56,57]. Both cases require numerical integration of the equations of notion. The solutions both use close approaches to the sun, one with prograde orbits and the other with retrograde.

The "obvious" approach is to tilt the sail such that it first gains both energy and angular momentum, taking the spacecraft through two aphelia and two perihelia as the orbital energy is increased to allow for escape [48,58]. For a characteristic acceleration at 1 AU of 1.0 mm s^{-2}, a point design yields a sailcraft mass with margin of 520 kg using a square sail of 246 m $\times$ 246 m with a sail film density of 1.9 g m^{-2} and a sail loading of 8.6 g m^{-2}, in fairly close accord with Eq. (2). The speed at 5 AU (shortly prior to sail jettison) is 10.4 AU/yr after a travel time of 6.7 years. After an additional 20.3 years (27.0 years total), the spacecraft passes 200 AU [58], comparable to what can be accomplished using a Jupiter gravity assist and radioisotope electric propulsion [59]. The trajectory is predicated upon a second perihelion pass of 0.25 AU and a thermal environment that cannot be tested prior to actual flight. Smaller characteristic accelerations require Jupiter gravity assists to keep flight times low.

A second set of solutions exist as well for which the energy and angular momentum both initially decrease, with the angular momentum reversing sign [54,60]. However, the required sail loading for these solutions is $<$2.2 g m^{-2} if the flyout times are to be kept to less than $\sim$20 years with the perihelion kept above $\sim$0.25 AU.

Values of λ in excess of unity would yield a net acceleration on an outgoing hyperbolic trajectory. For a sufficiently large value, a "launch" from $\sim$1 AU could be contemplated, but this further strains the technological requirements.

While the trajectory scenarios require numerical evaluation, Eq. (3) sets a lower limit on the required area of the sail for a given probe mass. For example, the IHP point design [58] has a nominal bare-sail areal density of 1.9 g m^{-2} (calculated value is 2.0 g m^{-2}) and a sailcraft loading of 8.6 g m^{-2}. The difference is divided between the observatory (2.7 g m^{-2}, with the payload accounting for 0.35 g m^{-2}), the sail-deployment hardware (1.7 g m^{-2}), the launch adapter (0.7 g m^{-2}), and the 20% mass margin (1.4 g m^{-2}). The overall total can be decreased at the expense of a larger sail (the sail mass and sail hardware mass both increase while the other masses remain the same); the film areal density provides only a lower limit to the sailcraft loading.

This approach also suffers the same engineering problem faced by that of near-Sun powered maneuvers: a full-scale test of (deployed) mission-critical hardware is not possible under realistic (thermal) conditions.

Recently the Japan Aerospace Exploration Agency (JAXA) and NASA carried out dedicated tests of solar sailing for primary thrust using the IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) spacecraft [61] and NanoSail-D2 [62]. While both missions were successful, the implied sail loadings are very large: 1575 g m^{-2} for IKAROS and 400 g m^{-2} for Nanosail D-2, two to three orders of magnitude larger than the requirement for an Interstellar Probe.

3.1.2. REP

A "small" interstellar probe requires power for the onboard electronics and instruments, which will be, at a minimum, $\sim$150–200 watts of electricity (We). This requirement, in turn, is most easily fulfilled at large solar distances with a radioisotope power supply (RPS) (rather than with a nuclear fission reactor, the distances being so large as to make solar arrays totally inapplicable). By increasing the power supply one can, in principle, provide power to run ion engines, providing a constant thrust to the spacecraft.

This approach implies that a power conditioning system, ion engines, larger power supply, and appropriate propellant must all be supplied. Such an approach has been studied for implementation on both a Delta IV Heavy [63–65] and an Ares V launch vehicle [17]. With an Ares V and a Centaur upper stage the flyout time to $\sim$200 AU remains $\sim$28 years for a realistic technologies. About 5 years can be trimmed off this amount by also including a gravity assist at Jupiter. For a specific target region on the sky, this also implies limiting the optimal launch windows to about every 12 years.

Launch vehicles used to date for solar-system-escaping spacecraft are shown in Fig. 2, along with the conceptual Areas V and Saturn V for comparison.

3.2. Spacecraft

The five solar-system-escaping spacecraft all share the use of a high-energy "kick stage"; a large, spacecraft-fixed high-gain antenna (HGA), an RPS powered by plutonium-238 (^{238}Pu); redundant, fault-tolerant spacecraft electronics; low on-board propulsive capability; and, single-string instruments. Similar features characterize the Innovative Interstellar Explorer (IIE) concept, with the exception of the lack of large-onboard propulsion capability [17,65] (Fig. 3). The Pioneer 10 and 11 spacecraft far outlasted their 900-day mission requirement, and the Voyagers their five-year mission requirement; New Horizons is now in its fourth year of flight in a nominal 16-year mission [66].

The Voyager spacecraft were the heaviest and also had the most massive payloads, driven largely by planetary, remote-sensing requirements (Table 1). The Pioneer probes had less-capable planetary, remote-sensing instruments than did the Voyagers and this is reflected in the lower spacecraft and payload masses while still maintaining a comparable payload fraction. A single General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) [67,68] powered both the Ulysses and New Horizons spacecraft. Ulysses carries only fields and particles instruments and has far less maneuvering capability on board.

3.3. Payload

The mass limitations inherent in designing a spacecraft for fast solar-system escape imply the need for judicious

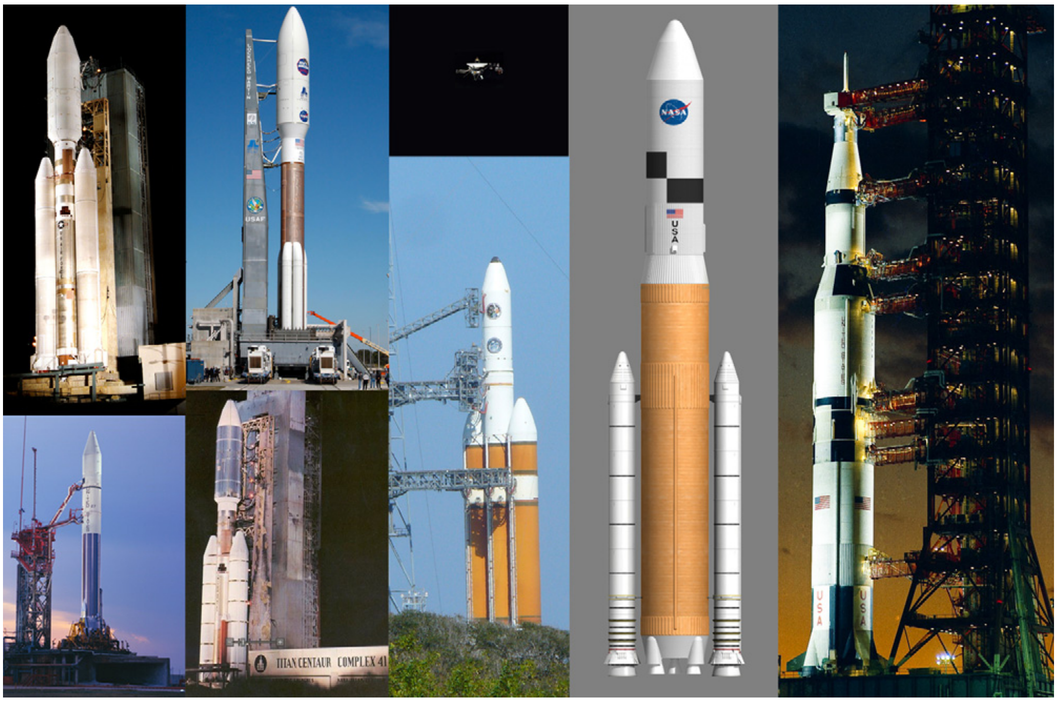

Fig. 2. Launch vehicles used for outer-solar-system and solar-system-escaping spacecraft and comparison with larger vehicles. Vehicle sizes are approximately to scale. Lower left is the Atlas-Centaur used to launch Pioneer 10 and 11. Next system at bottom to the right is the Titan 3E Centaur used to launch Voyagers 1 and 2. Left top is the Titan IV Centaur used to launch Cassini to Saturn and to the right is the Atlas V 551 used to launch New Horizons to Pluto. At the bottom center is the Delta IV Heavy and above it the Voyager spacecraft to scale. Next to the right is the Ares V, and on the far right is the Saturn V used on the unmanned Apollo IV mission test. Top center shows the largest of the solar-system-escaping spacecraft, Voyager, to scale (dominated by its white 3.66-m diameter high-gain antenna). Of these systems, only the Atlas V 551 and Delta IV Heavy are currently in production (photographs and illustrations from Wikipedia; not subject to copyright).

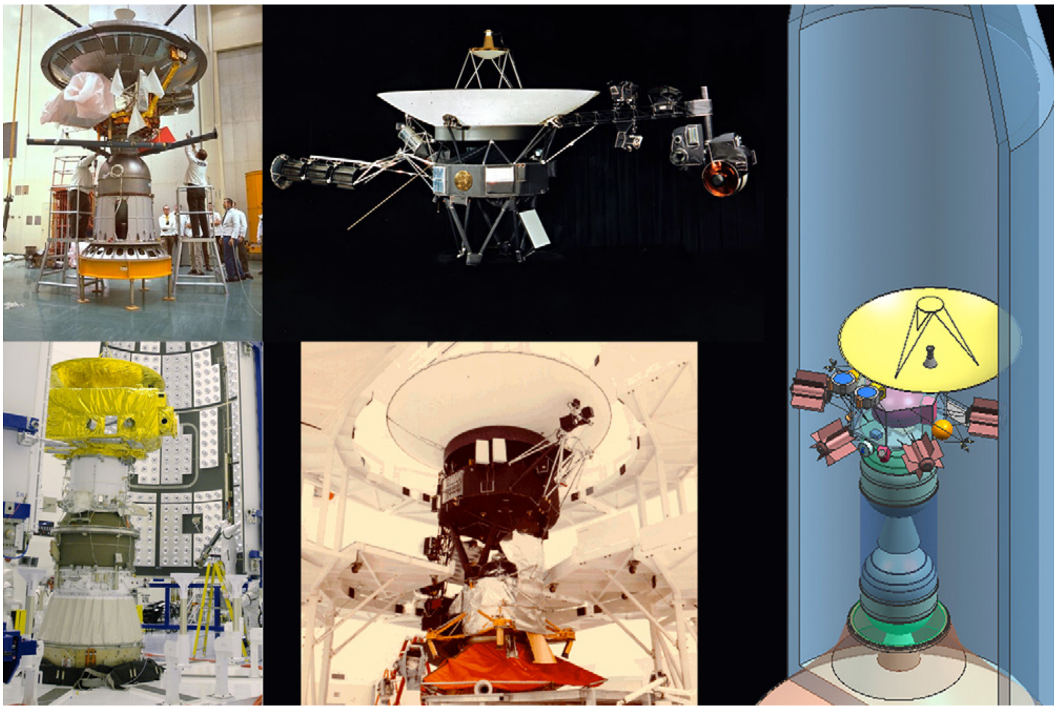

Fig. 3. Solar-system-escaping spacecraft. Top center shows the largest of the solar-system-escaping spacecraft, Voyager, to scale (dominated by its white 3.66-m diameter high-gain antenna) as in Fig. 2. Bottom center shows Voyager in the Spacecraft Assembly and Encapsulation Facility 2 at Kennedy Space Center prior to flight. Pioneer 10 sits atop its upper stage engine at the top left and New Horizons at the bottom left. At the far right, the illustration shows the IIE concept atop a two-stage stack using two Star 48A solid engines (photographs and illustrations from Wikipedia; not subject to copyright).

selection of payload instrumentation. The new Voyager, IBEX, and Cassini results provide better insight into the types of instruments to fly and the magnitude of the expected signals.

Prior to these results, a sample payload was worked out for IIE [65], based largely upon results for the Pioneers, Voyagers, Ulysses, and other field-and-particles robotic spacecraft.

For that concept, the mass is heavily biased by the antenna and boom requirements for plasma-wave and magnetometer experiments, respectively. These requirements are driven by the low signal levels that are, nonetheless, critical for understanding the interaction region of the solar wind and VLISM. Pioneer 10 and 11 had no plasma-wave antennas and a far shorter magnetometer boom, and to a certain extent the latter trades against the spacecraft electrical power.

Other instrument resources in the IIE payload need to be rethought, given the new measurements and ongoing instrumentation developments. For example, one would like to include neutral-atom imagers of similar sensitivity to those on IBEX, but the latter are relatively heavy, 25.21 kg including all electronics [69].

Table 1
Deep-space spacecraft, instruments, and their mass fractions.

Spacecraft	Instruments		Spacecraft (dry) (kg)	Payload mass fraction (%)
	Number	Mass (kg)		
Voyager	10	104.32	721.9	14.45
Pioneer	11	28.98	251.79	11.51
New Horizons	6	28.43	385	7.38
IHP	12	25.6	517	4.95
IIE	10	35.2	516.2	6.82

Notes: Voyager and New Horizons totals are from the National Space Science Data Center (NSSDC). Pioneer totals are from *Pioneer H Jupiter Swingby Out-of-the-Ecliptic Mission Study*, NASA Tech. Mem. NASA-TM-108108 (1971), Interstellar Heliopause Probe/Heliospheric Explorer (IHP) totals are from Ref. [47] and IIE totals (option 2) are from Ref. [55]. The small mass fractions on IIE and IHP are driven by dry mass associated with the propulsion systems. Dry masses are not readily available for the other spacecraft listed in Table 2.

Table 2 lists the fields and particles instruments from the ongoing Voyager Interstellar Mission, as well as relevant instruments from other flight missions. A comparison with the notional IIE payload is provided as well.

Table 2 clearly shows that functionally there are instruments masses close to what is required for a mass-constrained interstellar probe. However, not everything listed could be made to fit and choices are required. In addition, viewing angles, energy coverage and resolution, and geometric factor/integration time all comes into play. For example, just the five instruments now used on Voyager for the Voyager Interstellar Mission (VIM) (the top five entries) have a mass of 39.6 kg, already on the heavy side. Inclusion of IBEX-like detectors with the VIM instruments would add up to 64.8 kg, heavier than the Ulysses payload, and heavy enough that the flyout speed would be seriously impacted for any of the implementations discussed.

4. Summary

The passage of the Voyager spacecraft from the supersonic solar wind to the heliosheath also marked a passage in our knowledge of the world around us. Following the unexpected levels of energetic particles in the space outside the termination shock of the solar wind, more recent observations by IBEX and Cassini of energetic neutral atoms from the interaction region have revealed a totally unexpected structure in the "ribbon" and "band" of those emissions. With dated instrumentation and a dwindling power supply, the twin Voyagers will continue – for a

Table 2
Instrument masses on deep-space, robotic spacecraft.

Instrument	Spacecraft								
	IIE	IHP	Helios	Pioneer	Voyager	New Horizons	Ulysses	IBEX	STEREO
Vector helium magnetometer	8.81	1.5	4.40	2.7	5.6		2.332		
Fluxgate magnetometer			4.75	0.3			2.4		0.27
Plasma wave sensor	10.0	5.8	NA		9.1		7.4		13.23
Plasma	2.00	2	15.696	5.5	9.9	3.3	6.7		2.37
Plasma composition		1.5					5.584		11.4
Energetic particle spectrometer	1.50	3.0	3.50	3.3	7.5	1.5	5.8		1.63
Cosmic-ray spectrometer: anomalous and galactic cosmic rays	3.50	3.5		3.2	7.5		14.6		1.92
Cosmic-ray spectrometer: electrons/positrons, protons, helium	2.30	1.5	7.15	1.7					1.98
Geiger tube telescope				1.6					
Meteoroid detector			8.93	3.2					
Cosmic dust detector	1.75	1.1		1.6		1.6	3.8		
Solar X-rays and gamma-ray bursts							2.0		
Neutral atom detector	2.50							12.1	
Energetic neutral atom detector	2.50	4.5					4.3	7.7	
Lyman-alpha detector/UV measurements	0.30	1.2		0.7	4.5	4.4			
Infrared measurements				2.0	19.5				
Imaging photopolarimeter				4.3	2.6	8.6			
Imaging system			8.93		38.2	10.5			48.1
Common electronics, harness, boom, etc.								5.4	19.1
Totals	35.2	25.6	72.2	30.1	104.4	29.9	54.9	25.2	100.0

Notes: Instrument names are from IIE (Table 2 of Ref. [62]). Equivalences to payload elements on other spacecraft are notional and sometimes very divergent with respect to capabilities; they provide a rough guide only. Pioneer instrument masses are from *Pioneer H Jupiter Swingby Out-of-the-Ecliptic Mission Study*, NASA Tech. Mem. NASA-TM-108108 (1971); Voyager masses from the NSSDC; New Horizons masses from *Space Sci. Rev.* 140 (1–4) 2008; Ulysses masses from *Astron. Astrophys. Suppl. Series*, 92, 207 *et seq.*, 1992; IBEX masses from Ref. [60]; STEREO masses from *Space Sci. Rev.* 136 (1–4) 2008; Helios masses from *Raumfahrtforschung*, Band 19, Heft 5, September/October 1975 (not all are available; marked "NA"); and, IHP masses from Ref. [47].

while – to supply new knowledge of that far region. However, these new discoveries not only have not abated the oft-repeated reasons for the scientific need for an interstellar precursor mission, an Interstellar Probe, these discoveries have amplified them.

At the same time, various studies over recent years have exposed how difficult such a mission will be. Speed is of the essence, but the implied desired flyout times are sufficiently high to be just at the edge of our technological means. Nuclear electric propulsion, near-Sun powered maneuvers, and planetary gravity assists alone all have their drawbacks. There are issues not just of technology development, but also of prudent implementations that can be tested for success for what will not be an inexpensive robotic space mission. At the same time, the possible use of low-thrust propulsion based upon solar sails or radioisotope power supplies, augmented with capable launch vehicles and/or planetary gravity assists, appears to come close to enabling a doable, affordable, and compelling scientific investigation of the environment around out home.

Hardware choices are required, informed by a knowledge base that did not exist a decade ago. Some novel implementation schemes still require serious study, e.g., a large solar sail combined with a Sun-approaching trajectory or an REP craft boosted by an international combination of Centaur and Fregat upper stages, may, or may not provide better performance.

The scientific case for an Interstellar Probe mission has been strengthened by new and puzzling results. It is a gauntlet we can, and should, pick up. "Ah, but a man's reach should exceed his grasp, or what's a heaven for?"

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