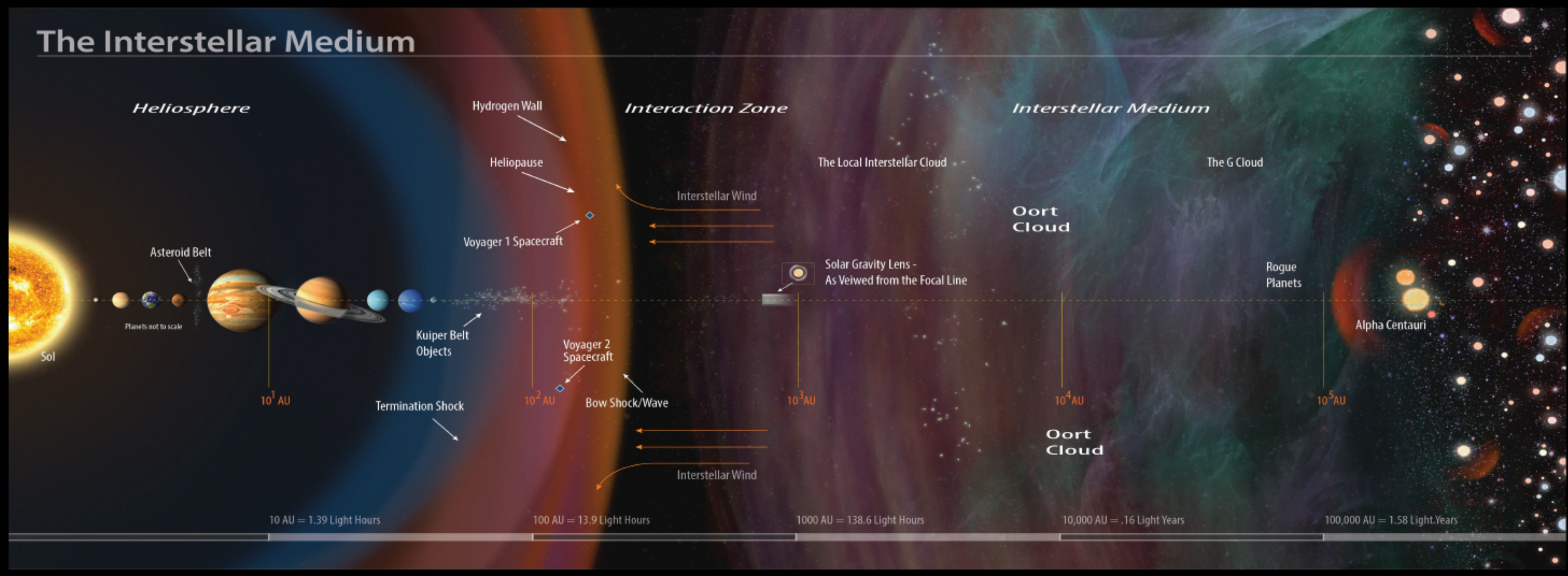
THE INTERSTELLAR PROBE MISSION: HUMANITY'S FIRST EXPLICIT STEP IN REACHING ANOTHER STAR.

P. C. Brandt[1], R. McNutt[1], G. Hallinan[2], M. Shao[3], R. Mewaldt[2], M. Brown[2], L. Alkalai[3], N. Arora[3], J. McGuire[3], S. Turyshev[3], A. Biswas[3], P. Liewer[3], N. Murphy[3], M. Desai[4], D. McComas[5], M. Opher[6], E. Stone[2], G. Zank[7], L. Friedman[8]

[1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA (pontus.brandt@jhuapl.edu)
[2]California Institute of Technology, Pasadena, CA 91125, USA
[3]Jet Propulsion Laboratory, Pasadena, CA 91109, USA
[4]Southwest Research Institute, San Antonio, TX 78238, USA
[5]Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA
[6]Boston University, Boston, MA 02215, USA
[7]University of Alabama in Huntsville, Huntsville, AL 35899, USA.
[8]Emeritus, The Planetary Society

As the Voyagers are crossing in to the Inter Stellar Medium (ISM) and the Kepler Mission has unveiled an abundance of Earth-like planets around other Suns, inevitably, we are faced with the question of how humanity will venture out through the vast space between our star and other potentially habitable planetary systems.
Such a venture requires new lines of voyages that each would expand our frontier of exploration of undiscovered worlds beyond our planetary neighborhood and unveil the workings and habitability of exoplanetary systems by bringing unseen views of our own astrosphere that harbors our solar system.
Here, we discuss the steps and questions NASA would have to consider to embark on a path that continually expand humanities frontier of exploration. Following the Voyagers, New Horizon and Solar Probe Plus, NASA is now in a position to take the first explicit step scientifically, technologically and programmatically on that path through the development of the first Interstellar Probe.

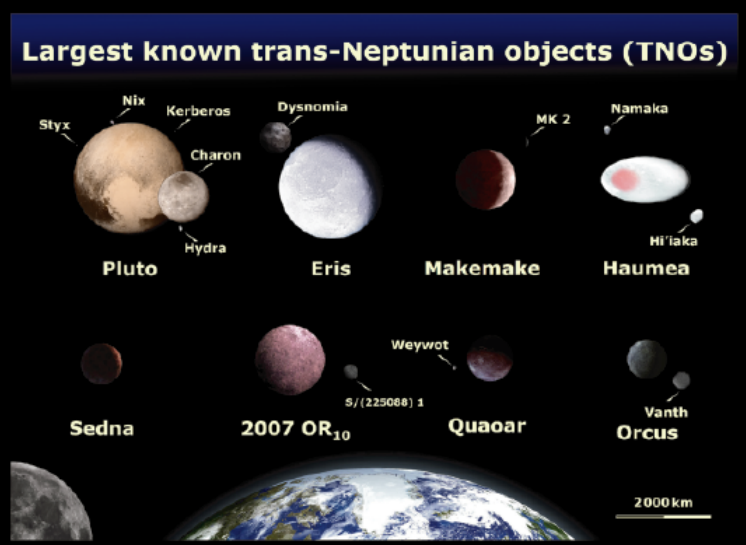


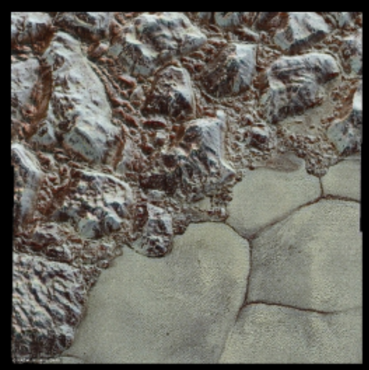
Enabling Steps

1. Conduct a study team with the objective to use current technologies to design a feasible mission to reach the interstellar medium by 2050
2. Trade-off studies would include trajectory analysis using existing launch and propulsion systems, integrated solutions for mass- and power-optimized science payload and communication subsystems
3. Publish definitive Interstellar Probe Study Report in time for mid-term Planetary and Heliophysics Decadal
4. Baseline use of General Purpose Heat Source RTGs used on Ulysses, Galileo, Cassini and New Horizons
5. Continue seeking international advocacy through, for example The COSPAR Panel on Interstellar Research

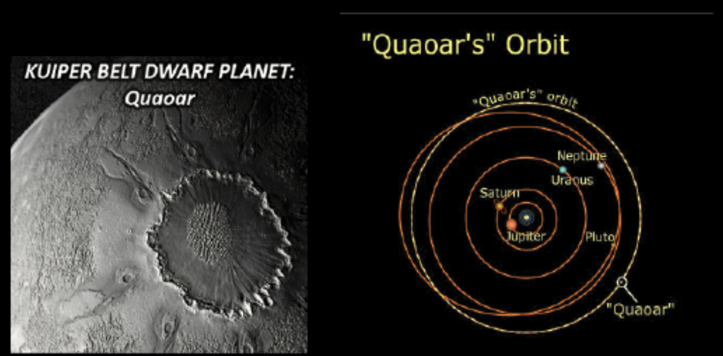
Interstellar Probe Science

Undiscovered Worlds Beyond our Neighborhood



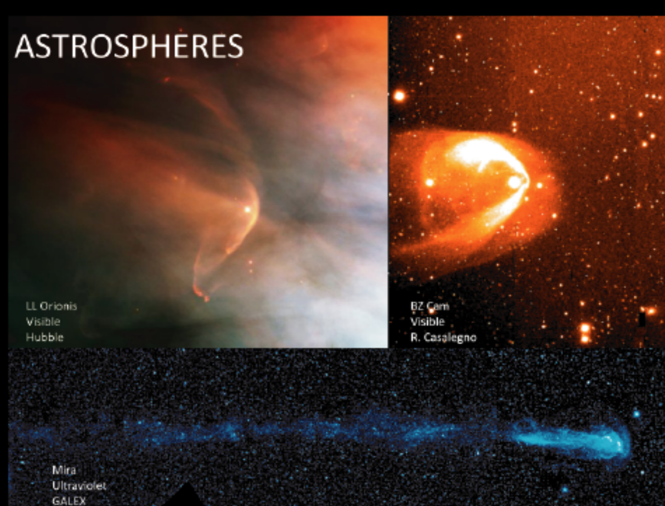


The New-Horizon discoveries of the alien landscape of Pluto have demonstrated what groundbreaking discoveries are awaiting beyond our planetary neighborhood.

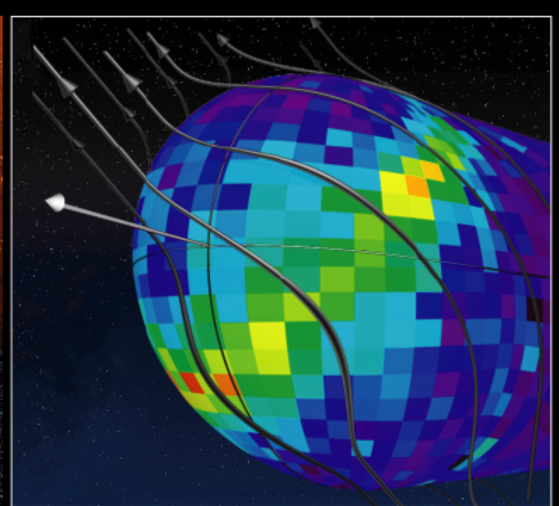


At 40-50 AU, conveniently lining up with the nose direction of the heliosphere of a flyby in the ~2030's, lies the dwarf planet Quaoar that is in the last stages of loosing its methane atmosphere. Surprisingly, crystalline ice has been detected on the surface implying cryo-volcanism active in the immediate past or even still active [1].

Astrospheres and Exoplanets

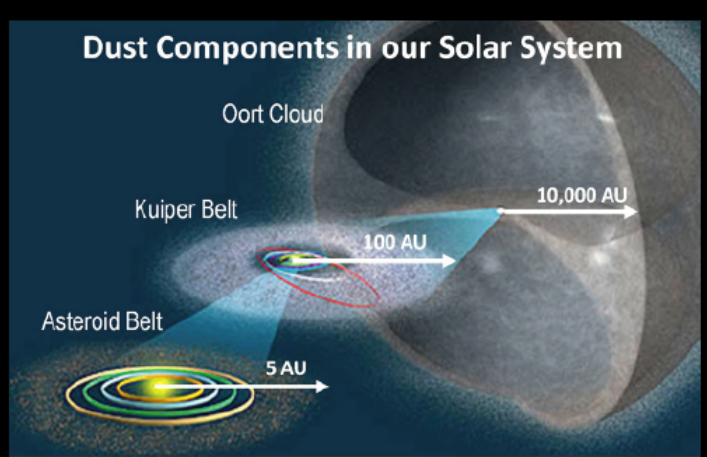


Planetary systems are encased in a magnetic bubble spanned by the outward stellar wind of its parent star. The global shape and nature of this astrosphere as it plows through its surrounding ISM, is directly constrained by the properties of the stellar wind and therefore reveals the habitable conditions governed by stellar-wind interactions responsible for the loss of planetary atmospheres.

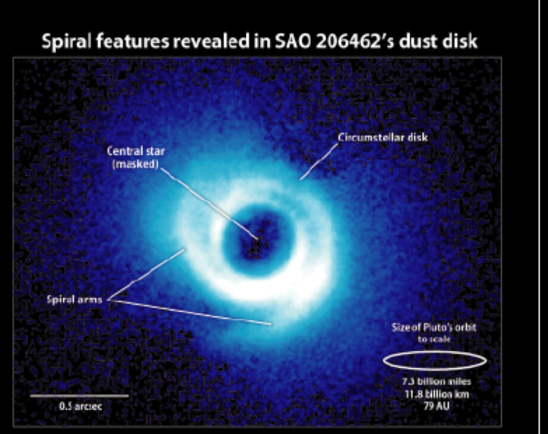


As Interstellar Probe traverses in to the pristine Interstellar Medium it will lay claim to the first historical view of our own astrospheres from the outside, allowing us to extrapolate and understand other astrospheres and the habitability of the planetary systems they harbor. Figure depicts our current understanding derived from Energetic Neutral Atom (ENA) images looking out from the inside our bubble from the IBEX Mission [2].

Evolutionary History of Planetary Systems

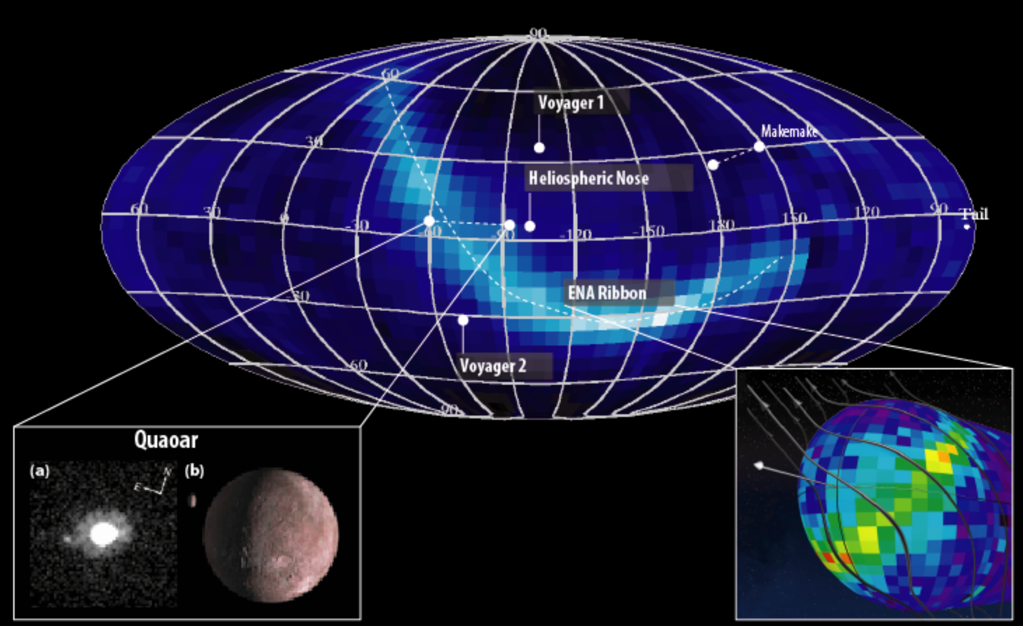


Keys to the evolution of our own and exo-planetary systems lie in the distribution of dust in the solar system out to the Oort Cloud. Dust is thought to be produced by Comets originating in the Oort cloud, asteroid collisions and also from collisions of KBOs. On its way out an Interstellar Probe will for the first time unveil the previously invisible dust distributions of the Outer Solar System to enable a first 3D map of our own circum-stellar dust disk that are common around other stars.



Circum-Stellar dust disks are commonly observed around other stars as tracers of planetary birth and formation that cannot be directly discerned in young systems due to the obscuring dust. In this image, unusual spiral features are believed to indicators of massive planets in formation [3].

Interstellar Probe Targets and Timeline



<2020	Trade-off studies Requirements definition Baseline Mission Design
2020s	Acquisition of RPS and SLS
mid-2020s	Launch window for exiting solar system towards nose and Quaoar
2030s	Quaoar Flyby
2050s	Arrival in ISM First External Images of Heliosphere First Data on circum-solar dust disk
>2050	Voyage in to the unknown

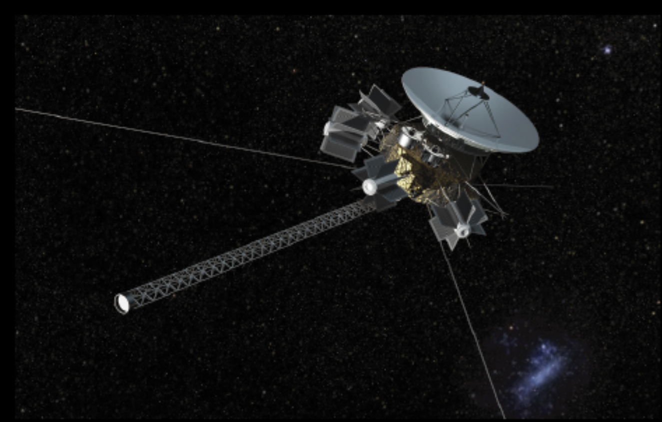
Interstellar Probe Mission Requirements

1. Launch the spacecraft to have an asymptotic trajectory within a 20° cone of the heliospheric nose
2. Collect data from 10 to 200 AU
3. Arrive at 200 AU as fast as possible
4. Consider all possible missions that launch between now and 2050
5. se existing launch hardware
6. Use no "in-space" assembly,
7. Launch to escape velocity
8. Keep new hardware and technology to a minimum
9. Use accepted "adequate" margins.

Interstellar Probe Trajectories and Trade Offs

Two mission scenarios are considered that could be developed and flown with today's technology: direct injection to an active Jupiter Gravity Assist [4], and one using Solar Gravity Assist [5]. The use of in-space propulsion including solar sails, nuclear electric propulsion (NEP), and radioisotope propulsion (REP) have all been problematic. The problems have included predicted masses and structural requirements, assembly, autonomy, and lifetime, and are therefore not consistent with these mission requirements.

Jupiter Gravity Assist



A 585 kg (including 30% margin) spacecraft launched on an SLS with a direct inject to an active Jupiter Gravity Assist would reach 200 AU in 29 years with an asymptotic velocity of 30 km/s. Spacecraft design by Boeing from previous study [4] using six RTGs, Ka-band High-Gain Antenna. During flyby phase the platform would be three-axis stabilized. During long cruise and exploration of ISM the platform would spin stabilized.

- Launch with SLS, Castor 30XL stage and Star-48 booster
- S/C mass: 450 kg plus 30% margin (New Horizons 485 kg)
- Direct inject to powered Jupiter Gravity Assist yielding 30 km/s.
- Quaoar flyby at 50 AU
- Arrival at Interstellar Medium 200 AU in 29 years at 30 km/s

Solar Gravity Assist

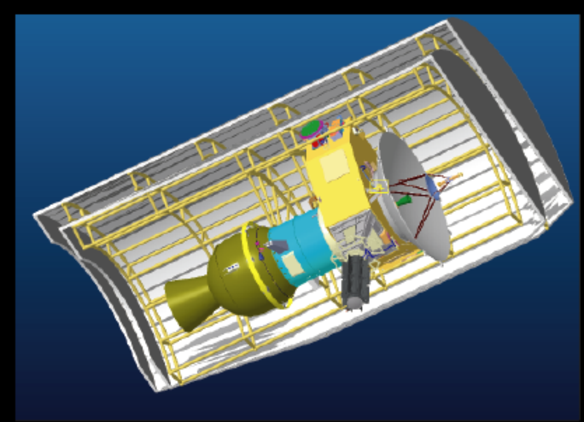


Figure from [6] assuming a New Horizons spacecraft with a 640 kg heatshield. A powered SGA at 9.4 solar radii would result in a flight time to 200 AU in 39 years with an asymptotic velocity of 26 km/s. The perihelion distance is dictated by the available launch energy without the need for an EGA. SGAs at closer distances can increase the asymptotic velocity significantly (up to a factor of two), at a price of stricter thermal requirements.

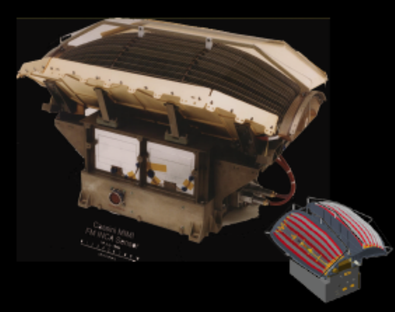
- Launch with SLS, Castor 30XL stage and Star-48 booster
- S/C mass: 450 kg plus 30% margin (New Horizons 485 kg)
- Heathshield mass: 640 kg based on Solar Probe Plus
- Direct inject to Jupiter Gravity Assist
- Solar Gravity Assist with active burn at 9.4 solar radii
- Quaoar flyby at 50 AU
- Arrival at Interstellar Medium 200 AU in 39 years at 26 km/s

Interstellar Probe Payload

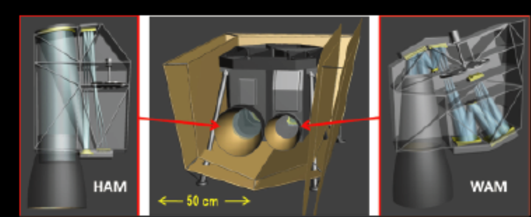
Payload mass and power cannot exceed 50 kg and 50 W in order to reach 200 AU in less than 30 years. Therefore, significant effort must be put in to trading off science and developing a highly integrated mass- and power-optimized payload. The science targets discussed here requires a payload as outlined below.

- Optical cameras for flyby imaging and astrometry
- IR camera for obtaining the 3D distribution of dust beyond our planetary neighborhood
- Suite for Exploring the Interstellar Medium and its Interaction with the Heliosphere
  - Energetic Neutral Atom (ENA) Camera
  - Energetic Particles/Cosmic Rays
  - Solar/Interstellar Plasma and Neutral Wind
  - Vector Helium Magnetometer
  - Plasma Wave

As examples of integrated solutions that optimizes mass, power and functionality, are the Multipurpose Imaging Science and Communication Instrument (MISCI) outlined in the KISS Technology Development Proposal [5], or the Zodiacal dust, Extragalactic Background, and Reionization Apparatus (ZEBRA) [7]. MISCI would combine deep-space and fast flyby imaging with IR imaging and a laser subsystem for optical communication and ranging. The ZEBRA imaging system combines optical with IR.



The ENA Camera INCA on board the Cassini mission and its second generation version developed for the ESA JUICE Mission [8]. The camera implementation for an Interstellar Probe mass would be less than 8 kg and dissipates about 5 W.



The ZEBRA instrument consists of the High-resolution Absolute Module (HAM) with a 15 cm telescope, and the Wide-field Absolute Module (WAM) with a 3 cm telescope. The instrument mass is 16.4kg and power dissipation is 12.4W, both including 30% margin.

Power

General Purpose Heat Source Radioisotope Thermoelectric Generators – GPHS RTGs have been used successfully on Ulysses, Galileo, Cassini and New Horizons and could be baselined. The Multi-Hundred Watt RTGs on the Voyagers still have 170 W after about 48 years en route (450 W at beginning of life).

The GPHS-RTG used on the Ulysses spacecraft weighed about 56 kg including 11 kg of Pu-238.

Communication

Ka-band communications with High-Gain Antenna (HGA) and DSN upgrade to phase-array dishes offers advantages in pointing requirements, but is restricted in bandwidth (Voyager 160 bps at 135 AU).
Optical communication offers advantages in bandwidth (1-10 kbps at 200 AU), but imposes very stringent pointing requirements (<μrad)
The MISCI concept implements laser communication and optimizes resources by combining it with deep-space, fast-flyby imaging capabilities and laser ranging
Core part of uplink could be achieved before the Interstellar Probe leaves the inner solar system, which would trade-off autonomy against the requirements to pick up an optical signal against the solar background

References

[1] Jewitt, D.C., and J. Luu, "Crystalline water ice on the Kuiper belt object (50000) Quaoar". Nature. 432 (7018): 731–3, 2004.
[2] McComas et al., IBEX: The First Five Years (2009-2013), ApJ, 213:20 (28pp), 2014.
[3] Muto et al., "Discovery of Small-scale Spiral Structures in the Disk of SAO 206462 (HD 135344B): Implications for the Physical State of the Disk from Spiral Density Wave Theory" ApJ, 748:L22 (7pp), 2012.
[4] McNutt et al., "Enabling Interstellar Probe With the Space Launch System (SLS)", 65th International Astronautical Congress, Toronto, Canada, 2014.
[5] Stone et al., "Science and enabling technologies for the exploration of the interstellar medium", Keck Institute for Space Studies, Pasadena, California, pp. 97, 2015.
[6] McNutt et al., "Interstellar Probe: Requirements", 67th International Astronautical Congress, Guadalajara, Mexico, 2016.
[7] http://zebra.caltech.edu Zodiacal dust, extragalactic background, and reionization apparatus mission concept study. Accessed 11 February 2012.
[8] Mitchell et al., "Energetic particle imaging: The evolution of techniques in imaging high-energy neutral atom emissions, J. Geophys. Res. Space Physics, 121, 8804–8820, doi:10.1002/2016JA022586, 2016.