Planetary Science White Paper

Instrumentation for Producing Groundbreaking Planetary & Astrophysical Science on an Interstellar Probe Mission

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Abstract: Astrophysical measurements at distances outside of 50 AU from the Sun enable transformative science that are impossible to obtain from inner system platforms, such as a: *Complete census of all interplanetary dust and ice* permeating the solar system, and direct comparison of its distribution to exo-circumstellar disks; *Stable time-domain astronomy of exoplanet transit lightcurves, exoplanet microlensing events*, supernova explosions, and black hole mergers; and *Measurement of all the light created by planets, stars, and galaxies over the entire history of the Universe*. A single powerful instrument could be used to obtain these measurements, and to perform *New Horizons-style flybys of dwarf planets & KBOs, potentially doubling the number of these kinds of worlds that have been visited and studied in great detail [1]*. Though likely transformative, opportunities to fly instrumentation capable of these measurements are rare, and a mission to the distant solar system that includes instrumentation expressly designed to perform astrophysical science *has never been flown*. The *proposed Interstellar Probe Mission* (ISP; [2-5]) provides just such an opportunity for launch in 2030. In this White Paper, we describe an instrument concept to ride along on a Heliospheric Division Interstellar Probe Mission that would enable groundbreaking science via cross-divisional collaboration and cooperation within NASA (c.f. [6]).

1. Context. The outer solar system is a unique, quiet vantage point from which to observe the universe around us. At VISIR (visible through infrared, 0.4 – 100 μm) wavelengths, the sensitivity of an instrument near the Earth is limited by scattered light and thermal emission light from the circumsolar dust cloud. Reductions in this bright foreground permit tremendous gains in sensitivity and temporal stability that permit new kinds of observations of both the solar system, and the universe beyond it [7]. *However, to date there has been only one mission, New Horizons (hereafter NH; [8]) that has ever carried active VISIR imaging instrumentation past 50 AU*. In this White Paper we make the case that a purpose-built instrument designed for both Planetary and Astronomical observations can enable a wide range of virtually untapped science while also providing the rich data return in the manner of the NH flybys of Pluto and MU69.

2. Novel Astrophysics & Planetary Science From a Unique Vantage Point

2.1 Understanding the Solar System’s Dust Cloud. Both the composition and structure of our circumsolar dust cloud is relatively well understood locally to the Earth [e.g. 9–12]. Instruments on solar orbiting spacecraft such as *Spitzer* have helped by providing Zodiacal Light (ZL) measurements along alternate lines of sight that are not constrained to originate at the Earth, and have highlighted the presence of local density enhancements in the ZL dust cloud at 1 AU [13]. However, beyond 1 AU we have little understanding of the structure of the interplanetary dust (IPD) cloud. This is a major hindrance as we begin to probe the equivalent structures in exoplanetary systems [e.g. review by 14]. Models indicate that there should be structures associated with Neptune and the Edgeworth-Kuiper Belt (EKB; Fig. 1 *bottom center*; [15]), to which we see many analogs in the circumstellar disks around other stars. We have virtually no understanding of how these disks map to our own, where we can hope to study composition and small-scale structure directly. Observations probing IPD emission at a variety of wavelengths along different sight lines, as we pass through and emerge from the cloud, are necessary to develop a three-dimensional understanding of the morphology of our own dust disk and to contrast it with those of exoplanetary systems.

Figure 1 – A wide range of unique, transformational science can be done from an Interstellar Probe spacecraft heading out of the solar system with modern purpose-built instrumentation - including close flybys of outer solar system planetesimals, imaging of our solar system’s entire circumstellar debris disk and planets as exoplanets, and accurate measurement of the Cosmic Background light. (See text for details.)

2.2 Distant Look-Back Observations of Solar System Planets as Exoplanets. In the next decade we will also begin to find and characterize Earth-like planets orbiting other stars, and one of the most important validations available is the suite of observations that simulate the Earth as an extrasolar planet, including direct observations [e.g. 16], Earthshine [e.g. 17], instrument calibration [e.g. 18-19], spacecraft flybys [20-21], and publicity shots from 40 AU [22]. **Viewing the Earth from a large distance (Fig. 1 bottom center) is the best analog to exoplanet observations [e.g. 23], and allows for the validation of both forward models and model retrievals using locally known ground-truth.** Adding large-separation spectrographic data would represent the only ground-truthed, close-to interstellar observations of a habitable – and inhabited – Earth-like planet [24].

2.3 Time Domain Astrophysics: Exoplanet Lightcurves, Exoplanet Gravitational Microlensing, & Transient Follow-up. Though already many instruments take advantage of the quiet environment away from the Earth at the L2 point of the Earth-Sun system (e.g. *WMAP*, *Herschel*, *Planck*, *Gaia*, with *JWST*, *Euclid*, and *WFIRST* planned), larger physical separations and even smaller temporal variability can be achieved elsewhere in the solar system. ***A platform away from Earth offers the possibility of a uniquely quiet and stable environment from which to make observations.*** Any observation requiring stability on long time scales (exoplanet detection, gravitational microlensing, SN light curves, variable star photometry) would benefit from access to the outer solar system. The stable thermal and RF environment permit highly sensitive measurements by instruments that are not affected by fast diurnal and slow annual variations that can be present [e.g. 7, 25-27]. In addition, the long baseline from Earth provides unique information for observations like gravitational microlensing that require different viewpoints of an event (e.g., a $1 M_{\odot}$ object at 4 kpc microlensing a source at 8 kpc can be viewed within a $r = 4.0$ AU region wherein observers at different positions in the solar system will see the object lens the source star with different maxima and times of peak magnification. An observatory further out in the solar system is sensitive to much larger masses, with a $10 M_{\odot}$ black hole at 4 kpc lensing a source at 8 kpc having a characteristic radius of 25 AU).

Table 1: Summary of Astrophysical Science Cases and Requirements

Science Topic	Type	Wavelength Range	Angular Resolution	Heliocentric Distance
Solar IPD Structure	Spectrographic Survey	Optical/Near-IR	$\sim 10''$	< 10 AU
EKB Disk	Spectrographic Survey	Far-IR	$\sim 10''$	> 10 AU
Earth Imaging	Pointed Spectro-photometry	Optical/Near-IR	$< 1''$	> 100 AU
Absolute EBL	Spectrographic Survey	UV to Sub-mm	$\sim 10''$	> 5 AU
Microlensing	Pointed Photometry	Optical/Near-IR	$< 1''$	Any
Transient Follow-Up	Pointed Spectro-photometry	Optical/Near-IR	$\sim 1''$	Any

2.4 Extragalactic Backgrounds. The Extragalactic Background Light (EBL) is the ***cumulative sum of all radiation produced over cosmic time***, including light from the first stars and galaxies and planets, as well as any truly diffuse extragalactic sources [Fig.1 bottom right; 28-29]. Measurements of the EBL can constrain galaxy formation and the evolution of cosmic structure, provide unique constraints on the Epoch of Reionization, and allow searches for beyond-standard model physics [30]. The absolute brightness of the EBL has been established from Earth at many radio and X-ray wavelengths, but at most infrared, optical, and UV wavelengths a precise assessment of the sky brightness has been hampered by reflected and emitted light from IPD, which

results in an irreducible $> 50\%$ uncertainty (and at some wavelengths significantly larger) on the absolute emission from the EBL [e.g. 31]. By observing beyond the interplanetary dust, *observations from the outer solar system can eliminate these uncertainties and definitively determine the absolute brightness of the EBL.*

2.5 New Horizons-like Planetary Flyby Science. Now add to all this exosystem-cosmic background astrophysical science the rich planetary science data return from a close Jupiter flyby (baselined in all ISP mission trajectories), and targeted flybys of outer system Centaurs, KBOs, and dwarf planets (as detailed in [1]; *Fig.1 bottom left*). The instrument suite roughed out above for purpose-built faint source astrophysical imaging and spectral mapping can, if carefully built, conduct NH/MVIC-style [32] surface geological and compositional mapping of Centaurs, KBOs, and dwarf planets encountered along the flight path at km/pixel spatial resolution. Intensive observing campaigns built around ± 10 days of closest approach of these objects will produce science data returns similar to the spectacular findings of the NH mission at Pluto and MU69, so we can expect multi-compositional maps co-registered to high angular resolution geological relief maps of these new worlds. Like the NH results, these maps will revolutionize our understanding of the formation and evolution of these bodies with measurements unobtainable except via close ($< 10,000$ km distance) flyby. The main difference between the astrophysical and planetary requirements will be the inclusion of high-speed (msec to sec) readout times, rapid slew and pointing capability ($> 1^\circ/\text{sec}$ and $< 5''$), and high precision pointing stability ($< 1''$ over 10 sec) to resolve landforms. These can either be included in a gimbal instrument or as augmentations of the s/c bus; for the sake of this WP, we will assume they are provided as part of a standalone gimballed instrument.) The envisioned flybys will also produce large amounts (10 – 100 Gbytes) worth of spectral imaging data over the short course of ~ 10 days which must be stored adequately and then downloaded, putting stress on the C&DH of the ISP system 2 to 4 times during the mission (depending on the number of outer system planetary flybys planned). For example, for a nominal ISP flight plane staying in the ecliptic plane and flying out towards the heliospheric nose, dwarf planet Quaoar is a prime target, as will be a small inner belt KBOs at ~ 40 AU. *In summary, the potential science return from a single instrument capable of making these measurements at distances of 50 to 500 AU from the Sun is immense.*

3. Strawman Instrument Concept. The measurements described above could all be made using a VISNIR spectral mapper flown on ISP (hereafter VISNIR mapper) based on a CubeSat-class instrument for measuring the ZL from near Earth out to at least 4 AU, the Smallsat Planetary & Extragalactic Light Experiment (SPECLE; PI Mike Zemcov, RIT). This instrument design is realizable for a 2030 launch using COTS components.

Our conceptual instrument is illustrated in Figure 2. It includes a modest 7 cm telescope, 1-D spectroscopic + 4-channel photometric detector FPAs, and all of the flight systems required to measure VISIR cosmic backgrounds and planetary surfaces in a < 3 kg, < 5 W package. Its imaging capabilities are similar to those flown as the NH/MVIC+LEISA instrument package to Pluto and MU69 [32], but with a greatly expanded longer wavelength range out to 100 μm . We plan to use a $10\text{cm} \times 20\text{cm} \times 20\text{cm}$ volume to house the scientific instrument, and rely on the spacecraft for data telemetry, power, and attitude sensing and control subsystems. We would minimize risk by using commercially available, high-heritage, flight-tested systems, components and subsystems, requiring no new technologies. Low resolution NIR spectrophotometry ($R=300$ corresponds to

0.0055 μm spectral resolution at the 1.65 μm crystalline water absorption feature) will be performed through the use of linear variable filters, and the telescope and detector can be cooled to $< 10\text{ K}$ through entirely passive means. Integration times will be configurable from msec to ksec in order to obtain 4 orders of magnitude sensitivity on cosmic backgrounds and planetary surfaces. Planetary observations will be performed in TDI mode, with active control of the fine instrument pointing, implemented either through a scan mirror or a gimble. Data will be stored and returned as giga-byte sized 1K x 1K hyperspectral cubes. The overall instrument specifications are given in Table 2.

Figure 2: Schematic representation of our strawman VISIR mapper instrument design. The telescope uses an off-axis 3-element design and couples to a standard VISNIR HgCdTe detector patterned with an LVF for spectroscopic mapping, with the option for broad-band FIR channels through the use of a beamsplitter. Nested thermal shields efficiently reject radiant heat and help passively cool the FPA to below 10 K. The instrument would weigh $< 3\text{ kg}$ and require $\sim 5\text{ W}$ to power. The current TRL of the instrument's components would support a 2030 launch.

Table 2. Visible-Infrared Spectral Mapper (VISIR Mapper) Specifications	ISP-VISIR 0.5 – 100 μm Baseline Design	VISIR NIR- 0.5-10 μm Only Descope
	0.5 – 10 μm Imaging Spectrometer + Multi-band FIR Mapper	0.5 – 10 μm Imaging Spectrometer
Primary Aperture	7 cm	
Pixel Size at 0.55 μm	2 arcsec (10 μrad)	
Pixel Size at 100 μm	6 arcmin (1.7 mrad)	
Mass	$< 3\text{ kg}$	
Min. Solar Elongation	90	70
Detector Temperature	$< 4\text{ K}$	$< 30\text{ K}$
Filter Set	0.5 – 10 μm + 40/60/100/150 μm	0.5 – 10 μm
Spectral Resolution	$\lambda/\Delta\lambda=300$ (NIR), $\lambda/\Delta\lambda=3$ (FIR)	$\lambda/\Delta\lambda=300$
Interplanetary Dust Science	$< 70\text{ AU}$	$< 10\text{ AU}$
Extragalactic Background Science	$> 10\text{ AU}$	$> 10\text{ AU}$
KBO Flyby Science	Yes	Yes

The VISIR mapper instrument will use an off-axis free-form telescope design with three optical elements, as shown in Figure 3. With a 7.0 cm effective aperture, we calculate this telescope can

image, at best resolution, 2'' pixels over a $1^\circ \times 1^\circ$ field of view. We will specify a standard 2048 x 2048 pixel H2RG detector [33] or equivalent to increase flight heritage. The detector and telescope will be passively cooled to $< 10\text{K}$ (beyond 50 AU) using radiation shields, which have a high heritage for astrophysics applications [e.g. 34]. We will use a SIDECAR-ASIC [35] to clock and readout the detector at the ambient temperature, simplifying the data processing chain. **The current instrument TRL at the component level is 9 except for the optics design where TRL = 5 until the SPHEREx launch in 2024 raises it to TRL = 9.**

Figure 3: A schematic representation of the ISP VISNIR mapper optical chain. Low spectral resolution is achieved with a linear variable filter (LVF) that will be flipped into or out of the optical path as needed. shutter in the filter mechanism than could be used to verify the dark current of the system, and (space permitting) broad band filters for calibration purposes.

A custom on-board flight computer would be responsible for the following tasks: (i) processing the detector output; (ii) passing the processed data to the spacecraft computers for later telemetry; and (iii) executing a pre-programmed observing sequence. The on-board

processing would be based on that described in [36], and the data storage would be based on that developed by the Zemcov group for various sounding rockets [37]. We expect that commercially available radiation-hard FPGAs would be more than adequate to meet our computational requirements. Most of the rest of the spacecraft subsystems are available from the ISP bus: data telemetry, power generation and storage, and attitude control during science observations.

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