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WHAT CAN AN INTERSTELLAR PROBE MISSION AT LARGE HELIOCENTRIC DISTANCES ACHIEVE WITH REMOTE IMAGING AND *IN SITU* DUST MEASUREMENTS? C.M. Lisse¹, M.B. Zemcov², A.R. Poppe³, J.R. Szalay⁴, B.T. Draine⁴, M. Horanyi⁵, R.L. McNutt, Jr.¹, A. Corcoros¹, P.C. Brandt¹, M.V. Paul¹, V. Sterken⁶, A.C. Lvasseur-Regourd⁷, R. Lallement⁸, C.A. Beichman⁹, ¹JHU-APL carey.lisse@jhuapl.edu ²RIT College of Science ³Space Sciences Laboratory, Univ. of California Berkeley ⁴Princeton University ⁵Laboratory for Atmospheric & Space Physics and Dept. of Physics, Univ. of Colorado ⁶Univ. Bern ⁷Sorbonne Université ⁸Observatoire de Paris ⁹NASA Exoplanet Science Institute, CalTech

Introduction. Here we present the scientific potential of using an Interstellar Probe (ISP) telescope traveling to > 500 AU from the Sun to observe the brightness, shape, and composition of the dust in our solar system's debris disks and to detect, for the first time, ISM dust interacting in the heliosheath and heliopause.

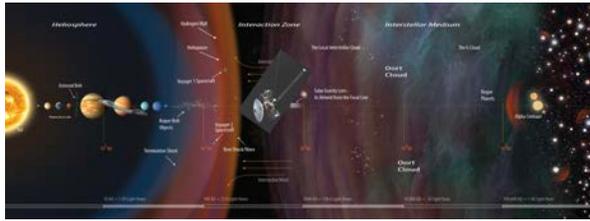


Figure 1 – Interstellar Probe Explorer payload at its design goal location of 1000 AU with respect to the planets, the heliopause, Alpha Centauri, and the Oort Cloud.

Discussion. Planetsimal belts and dusty debris disks are known as the "signposts of planet formation" in exo-systems. The overall brightness of a disk provides information on the amount of sourcing planetsimal material, while asymmetries in the shape of the disk can be used to search for perturbing planets. The solar system is known to house two such belts, the inner Jupiter Family Comet (JFC) + Asteroid belt and the outer Edgeworth-Kuiper Belt (EKB), and at least one debris cloud, the Zodiacal Cloud, sourced by planetsimal collisions and comet evaporative sublimation.

However, these are poorly understood *in toto* because we live inside of them. E.g., it is not understood well how much dust is produced from the EKB since the near-Sun comet contributions dominate the inner cloud and only one s/c, New Horizons, has ever flown a dust counter through the EKB. New estimates from the NH results put the EKB disk mass at at 30 – 40 times the inner disk mass [1]. Better understanding how much dust is produced in the EKB will improve our estimates of the total number of bodies in the belt, especially the smallest ones, and their dynamical collisional state. Even for the innermost Zodiacal cloud, questions remain concerning its overall shape and orientation with respect to the ecliptic and invariable planes of the solar system - they are not explainable from perturbations caused by the known planets alone.

Imaging Studies. Using new technologies and passively cooled detectors, a suitable low size, weight and

power system VISNIR spectrometer/FIR imager + 10 cm class primary has been specified using a CubeSat study baseline design [2]. The VISNIR spectrometer could provide maps of the cloud's dust particle size and composition, while FIR imagery would map the dust cloud's density. 3-D cloud Mapping would occur during flythrough via tomographic inversion, and via lookback imaging once the s/c is beyond 200 AU. The lookback imaging will allow ISP to measure for the 1st time in history the entire extent of the Zodiacal Cloud, and determine whether its inner JFC/asteroidal & outer KBO parts connect smoothly, as predicted by Stark & Kuchner [3-4] and detected by Piquette, Poppe *et al.* [5-8] (Figs. 2-3). This would also allow direct comparison of the solar system's debris disks with those observed around other nearby stars, and test theories that suggest that our solar system is planet rich but dust-poor [9].

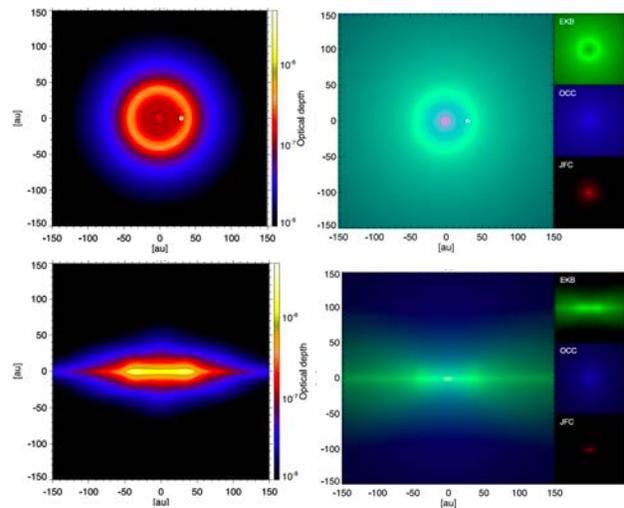


Figure 2 – Predicted dust cloud morphologies arising from solar system JFC (JFC) & Oort Cloud (OCC) comets & Kuiper Belt (EKB) sources. (Top) Looking down on the solar system. (Bottom) Looking through the plane of the solar system. After [1].

Observing at high phase angle by looking back towards the Sun from >500 AU, we will be able to perform deep searches for the presence of rings and dust clouds around discrete sources, and thus we will be able to search for possible strong individual sources of the debris clouds - like Planet X, the Haumea family of icy collisional fragments, the rings of the Centaur Chariklo, or dust emitted from spallation off the larger KBOs. The same remote sensors will be used to map the surfaces of

KBOs encountered along the way. Large-scale structure determination of the cloud should help inform us of ancient events like planetary migration and planetesimal scattering (as in the LHB), and measurement of the cloud's total brightness will allow improved removal of its signal in near-Earth cosmological measurements looking out into the Universe.

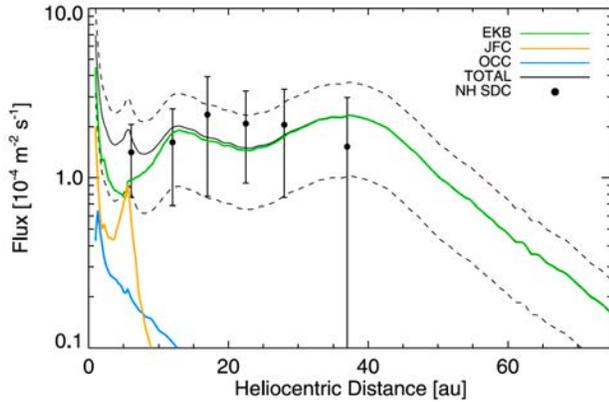


Figure 3 – In situ measurements (black data pts) and predicted dust flux contributions (colored curves) for the solar system's debris disks [1,8]. Some care should be taken in interpreting this plot, as the PIONEER 10 fluxes are for 1-100 um grains while the NH grains are 0.2 – 10.0 um in size. **Regardless, the overall relative shapes scale well and** the predicted crossover at ~10 AU from JFC dominated to EKB dominated is seen. ISP will help us determine if another crossover from EKB dominated to OCC dominated occurs at ~100 AU, and if the EKB dust is ice, rock, & organics rich like KBOs and comets.

First Ever Outer Solar System *In Situ* Dust Characterization. ISP can also carry the first ever *in situ* dust chemical analyzer past the orbit of Saturn. Based on the *Europa Clipper* SUDA instrument [10], it will compositionally and directionally characterize the solar system's dust clouds and will help isolate their sources, like the rocky asteroidal dust bands and the icy Haumea family fragments. Using measured dust particle masses and velocities, dust input & loss rates from these sources will be derived. Direct dust sampling will return the first ever *in situ* chemical analysis of EKB dust, the first ever *in situ* sampling of dust beyond 200 AU, and provide calibrated ground truth for cloud models produced from our imagery. It should also resolve the tension between the expected makeup of inflowing ISM microdust as determined by remote sensing and the measured ISM dust component found at Jupiter and Saturn by Galileo, Ulysses, and Cassini [11].

Understanding a G2V's Astropause ISM Bowshock. The role dust plays in shaping and energizing our solar system's boundary with the local galactic medium is almost completely unknown. Estimates range up to 1/3 of the energy density in the heliopause and heliosheath to be in the dust. Current models of the heliopause &

sheath do not allow for the physics of a dusty plasma because the dust component is so poorly known. We do know that submicron sized dust is streaming into the solar system from the ram direction the solar system is taking through the local ISM, and the discrepancy between remote sensing models of local ISM dust and ISM dust measured inside the solar system suggests a large amount of energy is involved in diverting much of the impinging dust around the edges of the solar system in the heliosheath.

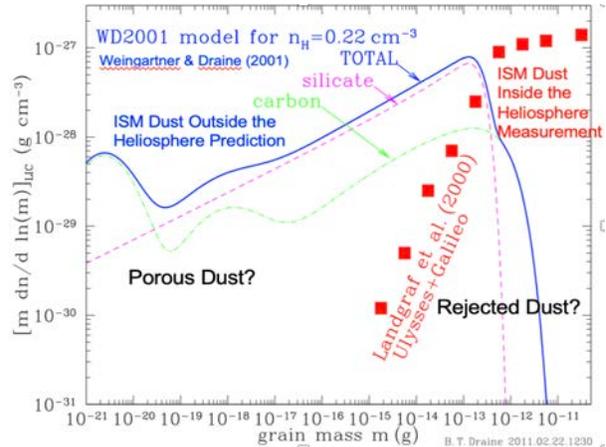


Figure 4 – Disconnect between the nearby ISM dust size distribution predicted from remote sensing measurements (blue) and ISM dust counts measured inside the solar system (red). After [11].

Conclusions. The expected scientific return of measuring the solar system's circumsolar dust out past 500AU is large. The contributions from the Edgeworth-Kuiper Belt and the Oort Cloud, normally obscured from the Earth by locally dominant JFC and asteroid belt contributions, will be imaged and sampled. The galactic and extragalactic background VISIR fluxes will be measured cleanly, without foreground contamination, for the 1st time, as will the role of dust in the heliosheath.

References: [1] Poppe, Lisse, *et al.* 2019, *ApJ Lett* **881**, L12 [2] Zembcov+ 2019, *American Astronomical Society*, AAS Meeting #233, id.#171.06 [3] Stark & Kuchner 2009, *ApJ* **707**, 543 [4] Stark & Kuchner 2010, *AJ* **140**, 1007 [5] Poppe *et al.* 2010, *Geophys.Res.Lett.* **37**, L11101 [6] Poppe & Horányi 2012, *Geophys.Res.Lett.* **39**, 1 [7] Poppe 2016, *Icarus* **264**, 369 [8] Piquette *et al.* 2019, *Icarus* **321**, 116 [9] Greaves 8 Wyatt 2010, *MNRAS* **404**, 1944 [10] Kempf *et al.* 2014, *EPSC Abstracts* **9**, EPSC2014-229 [11] Weingartner & Draine, *ApJ* **548**, 296; Draine & Hensley 2016, *ApJ* **831**, 59