POSSIBLE CONTRIBUTIONS OF A FUTURE INTERSTELLAR PROBE MISSION TO PLANETARY SCIENCES. R. F. Wimmer-Schweingruber[1], R. L. McNutt Jr.[2], P. C. Brandt[2], E. A. Provornikova[2], [1]Institute of Experimental and Applied Physics, University of Kiel, Leibnizstr. 11, 24118 Kiel, Germany (wimmer@physik.uni-kiel.de), [2]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, United States.

Introduction: The discovery of a myriad of exoplanets in the past decades has revolutionized our understanding of our place in the Universe. How different are exoplanets and do some of them harbor life, just like Earth? To do so, their parent stars must drive a stellar wind and carve what we call astrospheres into the surrounding interstellar medium. Astrospheres are ubiquitous in our immediate galactic neighborhood and show similar structure to our heliosphere. The Voyager 1 and 2, Ulysses, Cassini, and IBEX space missions have shown that the interaction between interstellar medium and solar wind is much more complex and involved than previously believed. This stellar-interstellar interaction is key to understand astrospheres and the shielding they provide to the planetary systems they harbor. This paper informs about a substantial study [1] and number of whitepapers for an InterStellar Probe (ISP) that were submitted to NASA's 2023/2024 decadal survey which is being conducted by the US National Academies, and some of the opportunities such a mission would offer to the planetary science community.

Mission Description: Interstellar Probe is a ≥50-year-long deep-space mission with the goal to reach several hundreds of astronomical units past the heliospheric boundary and into the nearby interstellar medium (ISM) [1]. On its way it would provide new, unified measurements of the conditions throughout the heliosphere and its multiple boundary layers. These measurements would also stretch across almost five solar cycles and, as a result, would help ascertain and quantify how solar activity maps throughout the solar system, past the planets, into the Kuiper Belt, and into the ISM itself. After a Jupiter flyby Interstellar Probe would have acquired its final speed of ~ 7 astronomical units per year which is required to reach and investigate the nearby ISM within 50 years.

Opportunities for the Planetary Sciences: On its way to the nearby ISM, Interstellar Probe offers several opportunities for many scientific fields apart from the heliophysics community, some of which are summarized here. More information is provided in [1].

Flyby of a Kuiperbelt Object (KBO) or Transneptunian Object (TNO): An outward trajectory through the outer solar system provides natural opportunities for planetary science (and also astrophysics) with relatively modest augmentations to payload and mission architecture. The exploration of the outer solar system is just beginning to uncover the Kuiper Belt with discoveries that will revise our understanding of planetary system formation. Over 100 dwarf planets and thousands of planetesimals in the Kuiper Belt have now been detected using ground-based surveys such as the Deep Ecliptic Survey, Pan-STARRS1 (Panoramic Survey Telescope and Rapid Response System 1), the Dark Energy Survey, the Outer Solar System Origins Survey, and others, with the expectation of increasing the number of known objects by an order of magnitude in the 2020s. At Pluto, New Horizons revealed a planet that hosts active geological phenomena, atmospheric haze, and a potential subsurface ocean. The flyby observations of 2014 MU69 Arrokoth uncovered an oblate contact binary with far-reaching implications for planetary formation and the collisional history of the Kuiper Belt.

Any of ISP's fly-out directions dictated by the heliophysics aims of the mission will offer at least one flyby of a scientifically compelling planetesimal or dwarf planet in the Kuiper Belt. For example, Orcus with its moon Vanth lies ~80° west of the nose direction just some 20° south of the ecliptic and potentially hosts an icy world with cryovolcanism. Quaoar with its moon Weywot is ~40° east of the nose just 12° south of ecliptic and is believed to be a world that is in its final stages of losing its atmosphere. Multiple other flyby options exist, any of which would provide a tremendous increase in our understanding of the formation of our solar system by enabling comparative planetology among dwarf planets. Flying by one of the ~130 dwarf planets (bodies > 400 km) or countless small-body planetesimals would require the spacecraft to fly within several thousand to several tens of thousands of kilometers of its surface. Imaging the target across multiple visible and IR wavelengths would permit detailed geophysical studies of its surface, allowing to infer the target's evolutionary history and internal makeup. The flyby by New Horizons of Pluto and 2014 MU69/Arrokoth provides an excellent example for the concept of operations and types of measurements ISP could make at a dwarf planet. Closest flyby distance would be chosen to optimize image coverage and surface pixel scale. In the days to weeks leading up to closest approach to the dwarf planet, a VISNIR imager could search for previously undiscovered satellites and rings, both of scientific interest but also for documenting and avoiding hazards to the spacecraft. Rotation movies and photometry measurements of the body and any moons would also occur during this time. Repeat imaging with parallax offset would allow to derive 3D topography and terrain models required to answer geological and geodetic questions in the context of the formation of the solar system. Parallax caused by spacecraft motion will also allow multiphase-angle (Sun–target–spacecraft angle) images of the targets to better constrain the geology, composition, and photometric properties.

T*he circumstellar dust cloud*: Both the composition and the structure of our circumsolar dust cloud are relatively well understood locally, close to Earth. Instruments on Sun-orbiting spacecraft such as Spitzer have helped by our understanding by providing zodiacal light (ZL) measurements along alternate lines of sight that are not constrained to originate at Earth, and have highlighted the presence of local density enhancements in the ZL dust cloud at 1 au.

However, beyond 1 au, we have little understanding of the structure of the circumsolar dust disk. These regions are poorly understood because we live deep inside them. For example, it is not well understood how much dust is produced from the Edgeworth-Kuiper Belt (EKB) because the near-Sun comet contributions dominate the inner cloud and the only spacecraft to have flown any dust measurement capability through the EKB are New Horizons and the Voyagers via the Plasma Wave System. New estimates from the New Horizons results put the EKB disk mass at 30–40 times the inner disk mass. Better understanding how much dust is produced in the EKB would 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 plane of the solar system. Lack of knowledge of our own system is a major hindrance as we begin to probe the equivalent structures in exoplanetary systems [see, e.g., 2 for a review].

Properties of circum-solar and interstellar dust : As a planetary system accretes into larger bodies, it leaves behind an imprint of the formation processes in its large-scale dust disk surrounding the star. Recent observations of protoplanetary disks have revealed planetary formation taking place already at less than one million years from the birth of the star, which has necessitated a complete revision of planetary formation theories. The 4.6-billion-year-old dust disk which surrounds the solar system represents an example of a mature system. With the increasingly detailed information about processes in our own solar system, the large-scale distribution of our circumsolar dust disk, or “zodiacal cloud,” is extremely valuable in understanding the formation in other star systems. However, the distribution of the circumsolar dust disk is still largely unknown because observations thus far have only been made from the inside. An interstellar probe equipped with a dust analyzer and an infrared (IR) detector would provide one of the most critical observations to date in support of understanding planetary system formation.

Role of the interstellar medium for habitability of planetary bodies: At the outermost edges of our solar system, the role dust plays in shaping and energizing the heliosphere’s boundary with the local galactic medium is almost completely unknown. Estimates range to up to one-third of the energy density in the heliopause and heliosheath being in the dust. Current models of the heliopause and heliosheath do not allow for the physics of a dusty plasma because the dust component is so poorly known. We do know that submicrometer-sized interstellar dust is streaming into the solar system opposite to the direction the solar system is taking through the local interstellar medium (LISM), and the discrepancy between remote-sensing models of LISM 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. Because the solar system was built from ISM dust, measuring it in its pristine galactic condition would greatly improve our understanding of stellar and solar system formation.

Pristine galactic dust studies would also produce cosmological findings because species made in the early universe – such as ^{2}H, ^{7}Li, and ^{8}Be – could also be directly measured.

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References: [1] McNutt, R. L., et al., (2021), Interstellar Probe, NASA Solar and Space Physics Mission Concept Study for the Solar and Space Physics 2023–2032 Decadal Survey, NASA Task order NNN06AA01C, https://interstellarprobe.jhuapl.edu/Interstellar-Probe-MCR.pdf. [2] Hughes M., et al., Ann. Rev. of Astron & Astrophys 56, 541. doi:10.1146/annurev-astro-081817-052035