COMPARATIVE PLANETOLOGY BEYOND NEPTUNE ENABLED BY A NEAR-TERM INTERSTELLAR PROBE.
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Summary: A properly instrumented Interstellar Probe could enable flyby geoscience investigations of a Kuiper belt dwarf planet, advancing comparative planetology in the trans-Neptunian region.

Introduction: Comparative planetology among KBO dwarf planets A) should be a priority for future NASA missions; and B) could be partly addressed by a targeted flyby of a dwarf planet by an interstellar probe leaving the Solar System, such as described by McNutt et al. (2019). This abstract is based on a near-term white paper to be submitted by mid-2020 to the National Academies Planetary Science Decadal Survey Panel. Please contact the first author to be added to the white paper signatory/co-author list (kirby.runyon@jhuapl.edu).

NASA's Heliophysics division is currently (as of early 2020) investigating the near-term feasibility of a pragmatic Interstellar Probe to investigate the outer heliosphere and the local interstellar medium using current or near-term technology (Brandt et al., 2019). Opportunistic reconnaissance of a dwarf planet by Interstellar Probe enhances the value proposition of such a mission but would benefit from interdisciplinary, cross-divisional support within NASA's Science Mission Directorate [see white paper by Kathleen Mandt et al., 2020]. For example, NASA's Planetary Science Division could treat a Heliophysics Division-run mission as a Mission of Opportunity (MoO) and provide funds and other support for planetary-specific instruments and operations.

As discussed elsewhere (McNutt et al., 2019, Brandt et al., 2020 Decadal White Paper; Mandt et al., 2020), the current concept for NASA's pragmatic Interstellar Probe would involve a 50 year prime mission for a low-mass spacecraft launched on a powerful rocket (e.g., the Space Launch System), conducting a gravity assist by a giant planet, and leaving the solar system significantly faster than Voyager 1 (3.6 AU/year) or New Horizons (3 AU/year) on a primary mission to study the outer heliosphere's interaction with the local interstellar medium. With a technology-readiness launch date of January 1, 2030, Interstellar Probe would leverage existing or very near-term technology. While planetary science opportunities abound during Interstellar Probe's giant planet gravity assist, we here focus on the compelling comparative planetology investigations awaiting us among the trans-Neptunian dwarf planets.

Science Objectives in Comparative Planetology: To date, only four dwarf planets have been explored in situ (Ceres, Triton, Pluto, Charon). All four offer surprising differences despite water having played a substantial role in the surface and subsurface of each planet (e.g., Prettyman et al., 2017; Prockter et al., 2005; Nimmo and Pappalardo, 2016; Beyer et al., 2019). With the long time frames and relative difficulty in reaching trans-Neptunian planets, Interstellar Probe could advance the field via in situ exploration of just one more planet, such as Quaoar, "Gonggong" (officially 2007 OR10), or another.

A camera-instrumented Interstellar Probe could target high resolution images of a dwarf planet's surface, similar to *New Horizons'* flyby images of Pluto, Charon, and Arrokoth (2014 MU69). Multispectral images and/or infrared spectrometers would reveal compositional variations across a planet, and magnetometers could reveal an intrinsic magnetic field. We discuss these in more detail below.

Questions in Comparative Planetology (Figure 1):

- What are the variability of landforms and compositions across dwarf planets?
- What geologic and atmospheric processes control the evolution and current state of trans-Neptunian planets?
- What fraction of these planets likely have or once had liquid water? If they had water, how long was it liquid before freezing? How is this related to the planet's timeline of habitability?
- What can the study of our solar system's trans-Neptunian dwarf planets teach us about dwarf exoplanets?

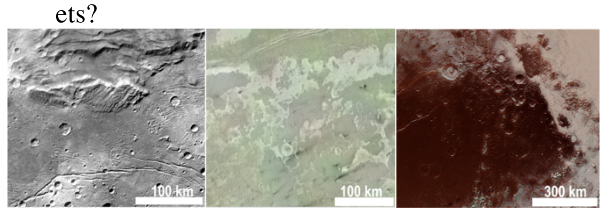

Figure 1. Charon (left), Triton (Center), and Pluto (right) reveal the broad geophysical and evolutionary diversity across Kuiper belt dwarf planets. If Interstellar Probe is instrumented with a multispectral imager, flyby reconnaissance of another dwarf planet would advance trans-Neptunian comparative planetology. Pluto/Charon image credit: NASA/SwRI/Johns Hopkins APL. Triton image credit: NASA/JPL.

Geomorphology: Seeing a new planet "up close" for the first time is perhaps the most viscerally satisfying aspect of planetary exploration. Images that resolve landforms—typically at pixel scales better than a few km or few 100 meters per pixel—reveal the geologic diversity of a world's surface and hint at the surficial and interior geophysical processes and timescales necessary to create those landforms. For instance, *New Horizons'* reconnaissance of Pluto and Charon revealed mountains, glaciers, craters, grabens, moats, frozen seas, and even sand dunes (Stern et al., 2015). The embayment relations between blocks and the surrounding smooth plains on Charon, together with the moon's hemispheric dichotomy, suggest past water and ice flows at the surface (Beyer et al., 2019). Drifted sand dunes on top of a convecting nitrogen ice glacier reveal sand-transporting winds on present-day Pluto (Telfer et al., 2018). Statistics of crater sizes on Pluto and Charon showed a paucity of craters smaller than 13 km, revealing that 1-2 km-diameter impactors were scarce in the early Kuiper Belt (Singer et al., 2019). On Triton, recent and ongoing geyser-like eruptions deposit wind-blown dark material on the surface (Hansen et al., 1990) while Europa-like curvilinear ridges cross the surface (Prockter et al., 2005). Comparing all three instances of explored Kuiper belt dwarf planets shows surprising morphological and evolutionary diversity. Future surprises among other worlds beckon further exploration in this region of the solar system.

Geophysics: Geophysical investigations of planetary interiors can address whether a given planet is or was an ocean world and possibly if it is or ever was habitable. Images of Pluto revealing the spherical shape, fracture orientations, ice loading, and crater depths implicate true polar wander and the existence and partial freezing of a subsurface ocean, possibly topped with insulating gas clathrates (Keane et al., 2016; Nimmo et al., 2017; Kamata et al., 2019). Magnetometer measurements on *Galileo* and *Cassini* revealed induced magnetic fields at Europa and Titan, respectively, consistent with conducting subsurface liquid water oceans (Kivelson et al., 2000; Wei et al., 2010). A magnetometer on Interstellar Probe could infer an intrinsic field around a planet and the accompanying geophysical properties and history.

Composition: While images can reveal landforms and hint at geologic processes and the subsurface geophysics, understanding the surface composition gives a more holistic understanding of a planet's current state and evolution. Visible and near-infrared multispectral imaging provides compositional constraints, and more detailed spectrometers could provide very specific compositions. For instance, the LEISA hyperspectral imager onboard *New Horizons* allowed mapping of CH_4, N_2, CO, and H_2O across Pluto and Charon, with a notable absence of CO_2 (Grundy et al., 2016). Including spectrometers or a multispectral camera on Interstellar Probe would advance this cause.

Recommendations: In our white paper, we will recommend that the Decadal Survey panel acknowledge that

- Comparative planetology among the solar system's most common type of planet—trans-Neptunian dwarf planets—can fundamentally inform solar system formation, evolution, and the timelines of habitability;
- The understanding of our solar system forms the basis for understanding exoplanetary systems, with implications for habitability;
- Implementing the Interstellar Probe concept mission with appropriate instrumentation and flying by a trans-Neptunian dwarf planet would significantly advance comparative planetology in the trans-Neptunian region; and
- Interstellar Probe could create a new paradigm for interdisciplinary, cross-divisional support among the divisions in NASA's Science Mission Directorate.

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