Not Even Halfway There: New Horizons' Future Exploration of the Heliosphere, the Outer Solar System, and Beyond

Pontus C. Brandt, Heather A. Elliott, Matthew E. Hill, Peter Kollmann, Parisa S. Mostafavi, Ralph L. McNutt Jr., Fran Bagenal, Andrew R. Poppe, Veerle J. Sterken, Jonathan D. Slavin, Lawrence E. Brown, Tod R. Lauer, William M. Grundy, Anne J. Verbiscer, John R. Spencer, Carey M. Lisse, Kelsi N. Singer, S. Alan Stern, and the New Horizons Science Team

ABSTRACT

This article gives an overview of New Horizons' past, present, and future exploration of the heliosphere, including descriptions of the planned future investigations by the plasma and particle instruments Solar Wind Around Pluto (SWAP) and Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI). These investigations include the evolution of the solar wind, pickup ions, energetic particles, and galactic cosmic rays in the outer heliosphere, as well as the propagation of the solar disturbances throughout the heliosphere. The article also presents the observation plans for the ultraviolet spectrograph Alice, which consist of all-sky imaging in search for signatures of the hydrogen wall and interstellar clouds beyond the heliopause and also measurements of the hydrogen column density between New Horizons and other spacecraft in the inner solar system. In addition, it discusses the past measurements of circumsolar dust by the Venetia Burney Student Dust Counter (VBSDC) and the search for interstellar dust grains. Lastly, it presents an overview of the planned observations by the Long Range Reconnaissance Imager (LORRI), including of distant Kuiper Belt objects and the cosmic optical background.

INTRODUCTION

Our solar system was formed in a journey around the galaxy from the protosolar nebula plowing through interstellar space filled with gas, dust, plasma, and cosmic rays. After only a few ten million years, the Sun ignited and its magnetized solar wind carved out a vast magnetic bubble—the heliosphere. Since then our protective heliosphere has helped shape our solar system. It has been exposed to dramatically different interstellar environments and supernovae, at times leaving the entire solar system exposed to the interstellar medium, amplifying the central role of an astrosphere in the evolution of habitable systems.[1,2,3,4,5,6,7,8,9] After traversing the Local Interstellar Cloud (LIC) for the past 60,000 years, the Sun is now about to enter the unknown environment of the neighboring G-Cloud, which will continue to shape the evolution of our home.[10]

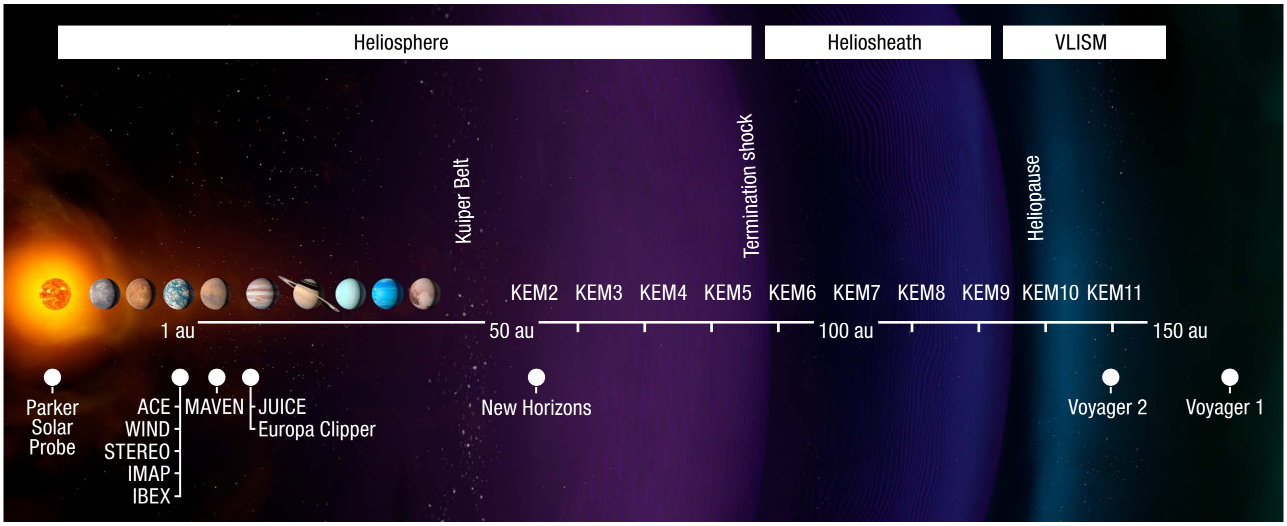


Figure 1. New Horizons Kuiper Belt extended mission (KEM) timeline. New Horizons has not yet reached the halfway point of its operational lifetime and is now embarking on its exploration of the vast heliospheric boundary, likely operating over the next two solar maxima.

Our vast protective heliosphere is created by the Sun releasing the solar wind with structures from the smallest kinetic scales to large-scale coronal mass ejections and stream interaction regions,[11] which are the compressions where fast wind particles run into slower ones emitted earlier. Fine-scale processes, such as magnetic reconnection, shock, and turbulent interactions, are at work throughout the heliosphere. Interstellar gas flowing through the heliosphere is ionized, creating interstellar pickup ions (PUIs)[12,13] that interact with the evolving solar wind and its embedded structures already ~3 astronomical units (au).[14,15,16,17] All these large- and small-scale processes have global consequences for the nature and character of the solar wind that upholds our entire heliosphere against the very local interstellar medium (VLISM).

New Horizons is the only spacecraft currently in the outer heliosphere (Figure 1), where its instruments Solar Wind Around Pluto (SWAP) and Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) are making first-time measurements of H^+ and He^+ PUIs that are decisive for the entire structure of the heliosphere—measurements Voyager was not equipped to make. With its simultaneous measurements of the solar wind, PUIs, suprathermals, and energetic particles, New Horizons is well equipped to investigate the outer heliosphere and provide the necessary understanding to incorporate the physical processes missing in global models.[18] Alice, New Horizons' ultraviolet (UV) spectrograph, provides remote diagnostics of interplanetary and interstellar hydrogen atoms (Lyman-α) with much higher sensitivity than the spectrograph onboard the Voyager spacecraft. Venetia Burney Student Dust Counter (VBSDC) measurements are intriguingly still dominated by strong fluxes of interplanetary dust created in the Kuiper Belt. Once those fluxes diminish, VBSDC is expected to make the first direct measurements in the distant region of interstellar dust (ISD) that penetrates the heliospheric shield.

EXPLORATION OF THE HELIOSPHERE AND ITS BOUNDARY TO THE VLISM

As New Horizons leaves the main part of the Kuiper Belt, it begins a new phase of exploration that will reveal discoveries central to understanding our global heliosphere. The next couple decades of exploration for New Horizons span solar cycles 25–27, for which each mission extension will have unique enduring science goals that will further heliophysics as a discipline.

Early in the next decade, New Horizons is expected to begin traversing the boundary region to the VLISM (Figure 2). It will take about 10 years to cross this region, which could be ~30 au thick. First New Horizons will encounter the termination shock (TS), estimated at ~92 au,[19] after which it will explore the heliosheath in varying solar-cycle conditions and make measurements to uncover plasma flows and dynamics. New Horizons has sufficient power to cross the heliopause (HP) in the early 2040s and probably enough to last until ~2050, enabling it to make critical measurements that will shed light on the mysteries left behind by the Voyager mission and to become the third operating mission to cross into the VLISM. With New Horizons in the outer heliosphere, Voyager in the VLISM, and the fleet of inner-heliospheric in situ and imaging missions, the science community is equipped with the most widely spaced constellation of spacecraft to date, offering a historic opportunity to understand how the Sun interacts with the VLISM.

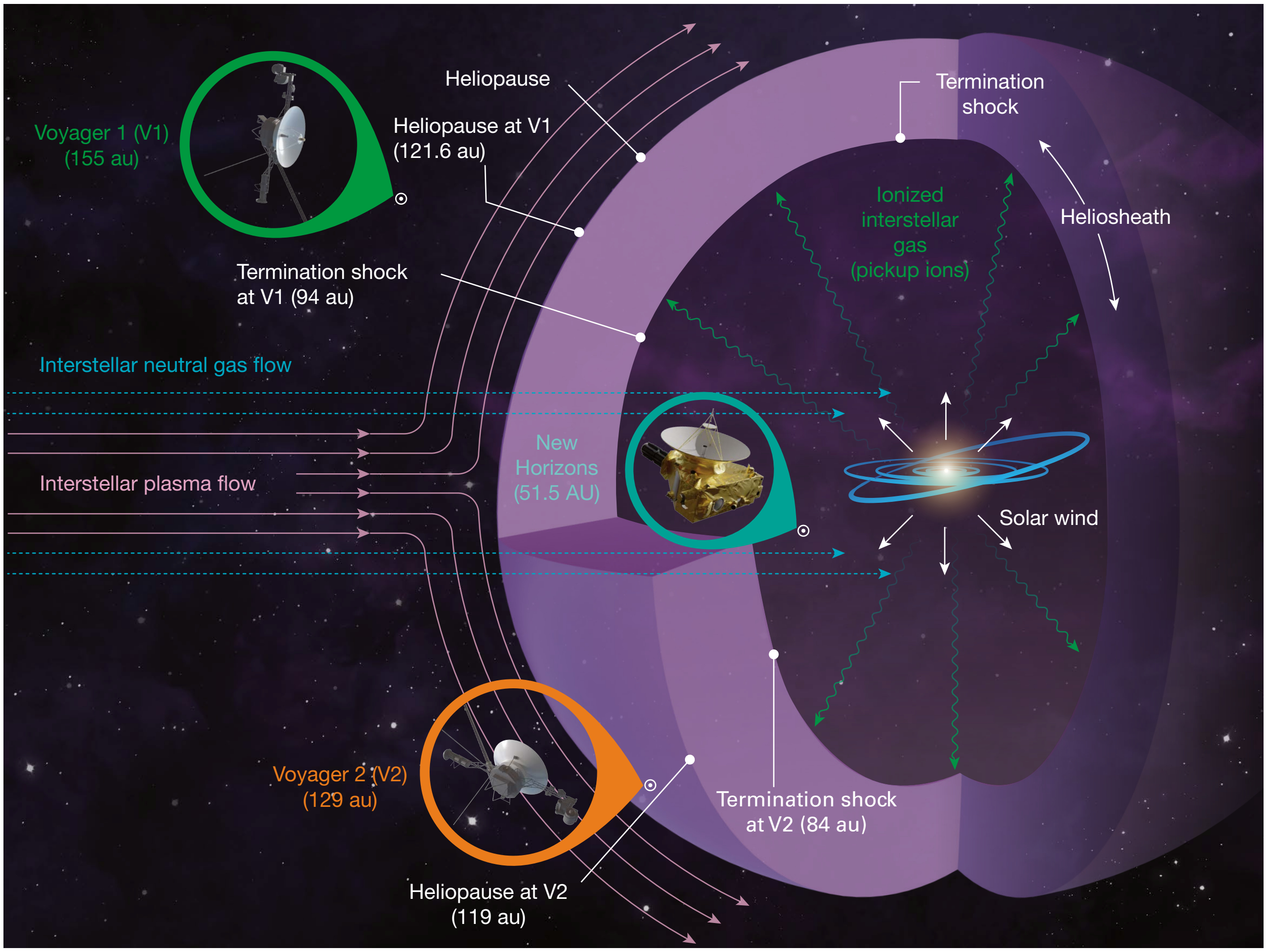


Figure 2. Spacecraft exploring the outer heliosphere and interstellar medium and their positions. As the Sun plows through the VLISM, the solar wind carves out a vast magnetic bubble—the heliosphere—which interacts with galactic cosmic rays, ISD, plasma, and gas. In its next extended mission period, New Horizons will enter a unique region 63–69 au from the Sun where the processes upholding the heliospheric boundary become more pronounced. As the only spacecraft now in the outer heliosphere, New Horizons has only begun its exploration. Its unique instrumentation enables new discoveries in heliophysics and possibly in astrophysics and planetary sciences. (Adapted from Krimigis et al.[20])

Solar Wind Evolution and Processes Shaping the Heliosphere

As the heliosphere moves through the VLISM, the surrounding interstellar neutral gas (mainly H and He) flows through the solar system and becomes photoionized by solar UV or charge-exchanged with solar wind protons. These newly created PUIs obtain an additional gyration velocity as large as the local solar wind bulk flow speed itself and, thus, are measured in the spacecraft frame of reference with speeds from zero up to twice that of the solar wind. In obtaining this speed, PUIs extract momentum from the solar wind, decelerating and heating it, as seen by SWAP.[17,19] PUIs are also likely heated by turbulence in the solar wind,[21] but it is not clear how PUIs evolve in the supersonic solar wind. PUIs dominate the energy density in the outer heliosphere[22,23] and therefore play a central role in shaping the heliosphere.

New Horizons is uniquely equipped to address this interplay between interstellar neutrals and the heliosphere. SWAP and PEPSSI have the capabilities to measure, for the first time, H^+ and He^+ PUIs in the important region of the outer heliosphere while also observing the solar wind evolution (Figure 3). Alice obtains remote line-of-sight measurements of Lyman-α emission scattered by interstellar hydrogen atoms streaming through the heliosphere (refer to the section on interplanetary and interstellar hydrogen).

In the next several years, New Horizons will approach the TS and enter a region where solar wind heating and slowdown by interstellar PUIs become increasingly pronounced[17,24] as the PUI distributions isotropize and transfer their energy to the solar wind through turbulent wave–particle interactions.[15] Solar disturbances in this region preferentially accelerate PUIs to suprathermal energies[25,26] along their path, likely resulting

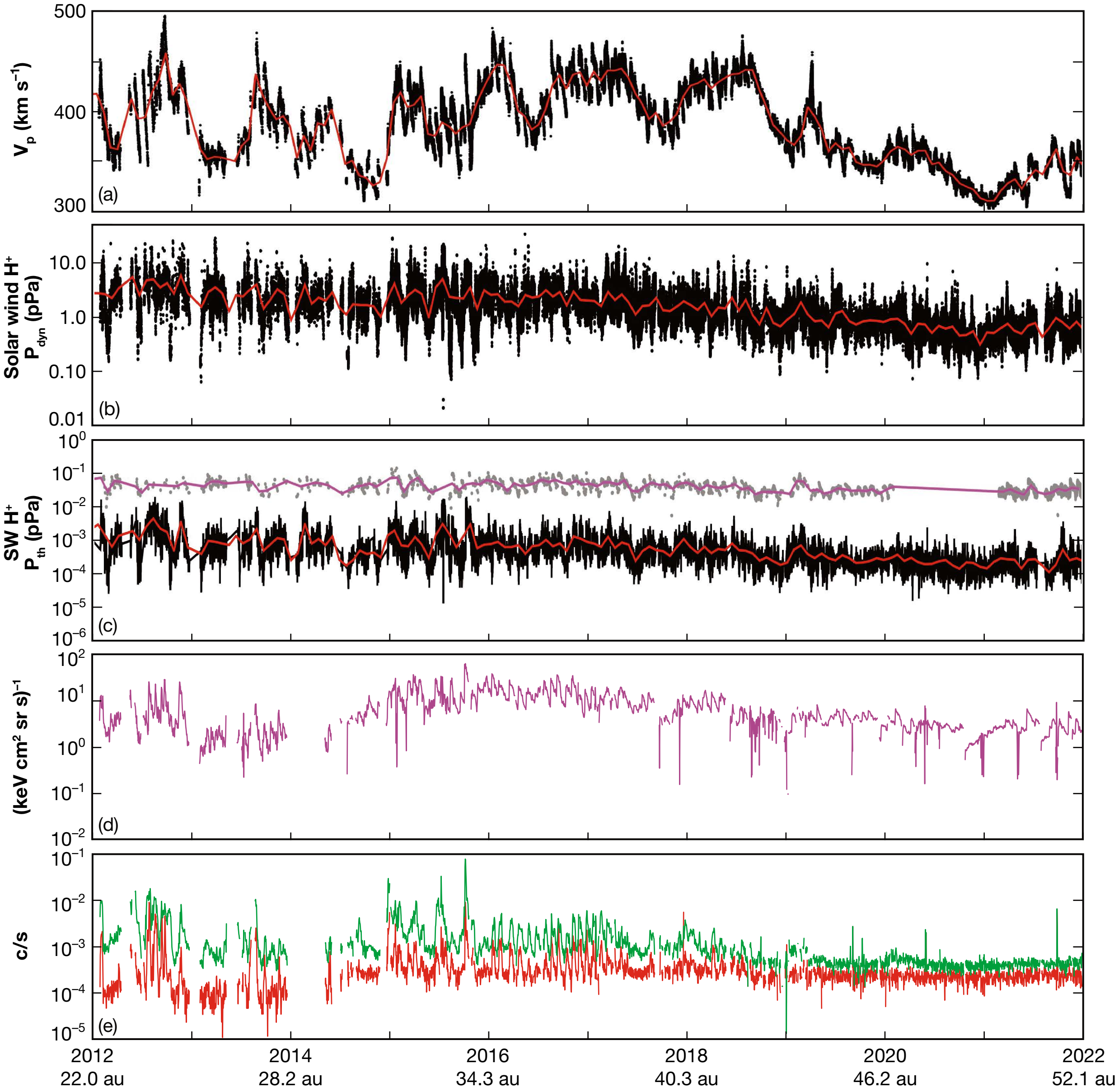


Figure 3. Solar wind and energetic particle measurements throughout the New Horizons mission. (a) SWAP solar wind proton speed. (b) SWAP proton solar wind dynamic pressure. (c) SWAP proton solar wind thermal pressure (black) and PUI pressure (purple). (d) PEPSSI He$^+$ 2–200 keV/nuc (purple). (e) PEPSSI 20 keV–1 MeV protons (green), 20 keV–1 MeV CNO (red).

in the PUIs dominating the thermal pressure in the outer heliosphere.[23]

PEPSSI resolves the He$^+$ PUI energy spectra well across its energy cutoff, enabling us to study their trends across the outer heliosphere. While H$^+$ PUIs can be well described through the phase-space-density spectrum that is relatively constant below the PUI cutoff energy,[19,27] heavier PUIs sometimes show rising phase space density, as measured by both PEPSSI at >5 au and Cassini's Magnetospheric Imaging Instrument (MIMI) and Charge Energy Mass Spectrometer (CHEMS) in the <10-au region.[25,28,29] These spectra may hold signatures of acceleration and transport processes in the outer heliosphere that are currently unknown or underappreciated.

Although New Horizons is headed along the same longitude as Voyager 2, it is remaining in the ecliptic headed toward the ribbon. During the recent solar minimum, the tilt of the current sheet was low, which directed slow wind toward New Horizons. New Horizons began to observe a solar wind slowdown at around 42 au,[30] which is reminiscent of the slowdown Voyager 2 observed starting near 53 au. This behavior may indicate a unique environment leading up to the crossing of the TS. As New Horizons moves away from the Sun, we need to combine data sets and use models to understand the context of what happens along the New Horizons trajectory. In analyzing the trend of the so-called solar wind power law index between the density and temperature determined with SWAP and comparing it with that estimated from Voyager 2, New Horizons' measurements can constrain the motion and location of the TS[17] to within about ±5 au. PEPSSI will determine ion anisotropies from ~40 keV to 17 MeV that come from field-aligned particles streaming Sunward from the TS. These could be used as an early indicator of the TS, similar to Sunward energetic particle streams Voyager 1 detected ~9 au before the crossing.[31,32] Not only are these measurements important for constraining the global structure of the TS, but they also provide valuable insight into how the PUI-mediated solar wind affects the location and motion of the TS. They will be compared with other estimates of the same—for example, from the Interstellar Boundary Explorer (IBEX) or the Interstellar Mapping and Acceleration Probe (IMAP).

Heliospheric models critically depend on New Horizons' measurements to quantify the effects of neutrals and PUIs, which are crucial for describing the heliospheric shape and structure.[15,33,34,35] These neutrals and PUIs also control the large-scale Energetic Neutral Atom (ENA) emission patterns, observed by IBEX, Cassini, and soon also IMAP.[36,37] While recent physical models of the outer heliosphere are progressing, they still overestimate the thickness of the heliosheath by a factor of two, requiring a new description of ion-neutral interactions that include PUIs and thermal plasma as two different components.[34] The importance of these measurements is amplified because New Horizons is traveling along the same longitude as Voyager 2 but is headed toward the middle of the so-called ENA ribbon. Thus, New Horizons provides measures of PUI densities and velocity distributions that are critical for understanding the physical processes currently missing in models, which consistently underestimate observed IBEX ENA intensities.[18]

Solar Disturbances Propagating through the Heliosphere

Corotating interaction regions (CIR) compressions and coronal mass ejections originate from the Sun and gradually slow down and merge into global merged interaction regions (GMIRs) that propagate through the TS and even out beyond the HP. Over the next several years, New Horizons is expected to observe 30–60 of these GMIRs, shock structures, or other variable solar wind structures that have propagated for nearly a year from the inner to the outer heliosphere. Here, PEPSSI and SWAP determine the detailed effects on H^+ and He^+ ions from keV to MeV energies (Figure 4). Using their

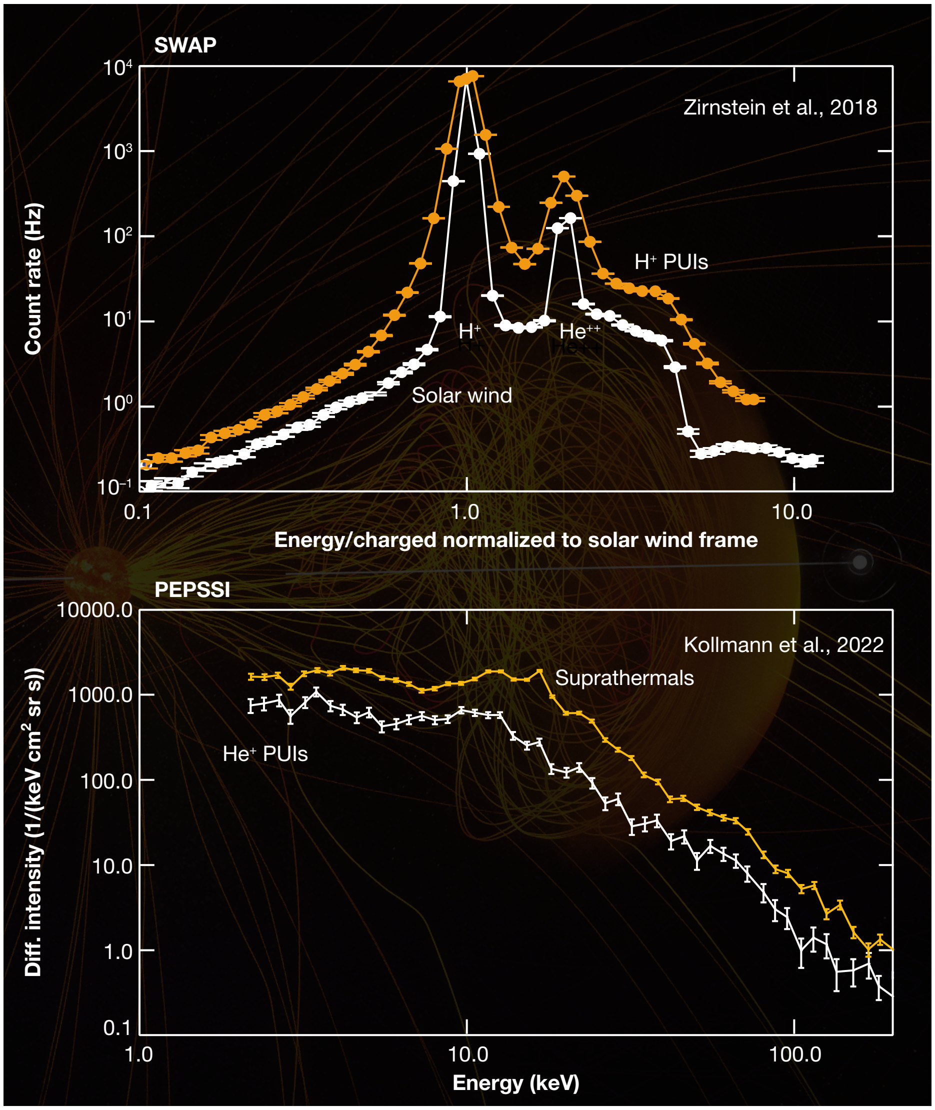


Figure 4. PUI observations by New Horizons. Upper graph, in addition to measuring the solar wind, SWAP measures the proton PUIs and how they are preferentially accelerated by an interplanetary shock. The white curve denotes conditions before the shock, and the orange curve denotes conditions after shock passage.[25] Lower graph, PEPSSI measures He^+ PUIs and how they respond to a passage of CIR. The white curve denotes conditions before CIR passage, and the orange curve denotes conditions during CIR passage.

newly (2021–2022) installed higher-time-resolution flight software capabilities, PEPSSI and SWAP[21] will provide new insights into particle interactions with propagating solar disturbances that can also be used as a diagnosis to constrain their nature. The new high-resolution observations are extremely important for understanding shocks in the outer heliosphere and especially the TS. In general, PUI-mediated shocks are common across many astrophysical systems. This makes New Horizons' observations unique and critical for developing a general physical understanding of this kind of shock for the broader community.

The next several years mark an important opportunity to combine data from the instruments on New Horizons, the only outer-heliosphere observatory, with Voyager data to investigate propagation of solar disturbances through the heliosphere and into the VLISM. From New Horizons, disturbances take about 4–6 years to reach the Voyagers. According to the current operational schedule of Voyager 1 and 2, 2025–2027 is the last opportunity to coordinate observations between New Horizons and Voyager before power is depleted on the Voyager spacecraft.

Although New Horizons lacks a magnetometer and therefore cannot characterize complete shock conditions, it uses signatures of solar wind speed and particles to characterize solar disturbances that in some cases may not be shocks. Recently, McComas et al.[21] used SWAP's new high-resolution observations to identify seven weak shocks during ~10 months. This new time resolution is sufficient to resolve the shock structures and quantify the particle heating across the shocks. Comparing the timing and strength of solar disturbances at New Horizons observed by PEPSSI and SWAP with the observations obtained by Voyager 1 and 2 places powerful constraints on propagation speeds and heliosheath properties between New Horizons and Voyager.

Propagating disturbances are all responsible for the global dynamics of the entire heliosphere, including motion of the TS, heating of the heliosheath, and perturbations of the HP and VLISM, as indicated by Voyager observations.[38,39,40] Despite these disturbances' importance for the global dynamics, the physics of the propagation and modification of these structures through the different heliospheric boundaries are far from understood (Figure 5).[41] The timing and characteristics of disturbances observed by New Horizons will be compared with in situ measurements from operating inner-heliospheric missions, such as Advanced Composition Explorer (ACE), Solar TErrestrial RElations Observatory (STEREO),[17,24] and IMAP. The continued remote ENA observations by IBEX,[42] and soon IMAP starting in 2025,[43] will enable new comparisons between IMAP ENA images and disturbances propagating across the heliospheric boundary measured by New Horizons[44] and Voyager.

One of the fundamental questions in space physics is how the charged particles found in space propagate and change energy. We know that particles in the magnetosphere of a magnetized planet perform to zeroth order a complicated motion that in essence drives them around the central body, further complicated through various scattering processes. In the heliosphere, it is obvious that the sub-keV solar wind plasma mostly moves away from the Sun. Yet there is no generally accepted theory on how the more energetic suprathermal particles move in the heliosphere. With their high energy, they are generally able to move in any direction, but for their *actual* movements, current theories were mostly tested in the inner heliosphere.[45,46] New Horizons' trajectory takes it through CIRs, and their stable and relatively well-defined structures provide a natural laboratory that is ideal for investigating the fundamental particle propagation processes. There has been little opportunity to study such CIRs in the outer heliosphere. While the Voyager spacecraft passed through that same region, they lacked instrumentation to cover the specific energy range of suprathermal ions. The first measurements of ions in this energy range beyond the orbit of Saturn were made by PEPSSI.[26] Only PEPSSI can provide continuous He^+ measurements from PUIs (~2–16 keV), through suprathermal ions (~16–100 keV), and into the energetic particle population (~100–1,000 keV). SWAP completes the energy coverage down into the solar wind plasma energy range. Therefore, both PEPSSI and SWAP can

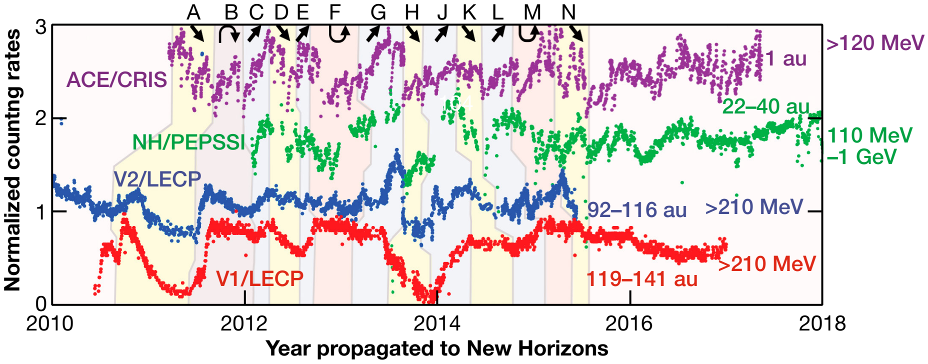


Figure 5. The variability of cosmic rays penetrating the heliosphere is a complex interplay between solar disturbances propagating through the heliosphere and even well beyond the HP. Daily averages of ≥100 MeV proton rates are plotted from ACE, New Horizons, to Voyager 1 and 2 and propagated to the position of New Horizons. The letters and respective colored regions mark different events, and arrows denote direction of variations. (Adapted from Hill et al.,[41] CC BY 4.0.)

track how the particle distribution functions change with distance to the CIRs and determine the different particle responses during different phases of the solar cycle. All these transitions are critical constraints to theories[26] that describe how the suprathermal particles in that region of the heliosphere propagate, which may be turbulent and diffusive[47,48] or—fundamentally different—nearly scatter free and deterministic.[49,50]

Interplanetary and Interstellar Hydrogen

The Alice UV spectrograph has been regularly mapping the distribution of Lyman-α emissions across the sky.[51,52,53] Most of these emissions result from the resonantly backscattered solar Lyman-α radiation off the interstellar H flowing through the heliosphere. Independent estimations of heliospheric neutral H densities are being planned for 2024 using Alice Lyman-α measurements in the same direction as observations from the inner heliosphere, such as those from the Imaging Ultraviolet Spectrograph (IUVS) on Mars Atmosphere and Volatile EvolutioN (MAVEN), the Lyman Alpha Mapping Project (LAMP) on the Lunar Reconnaissance Orbiter (LRO), and the Ultraviolet Spectrograph (UVS) on the Jupiter Icy Moons Explorer (JUICE). The technique was validated in 2021 with MAVEN and New Horizons. The initial results indicate an H density at New Horizons (at 51.3 au) of about three times higher than that at MAVEN in Mars orbit (~1.5 au), well inside the ionization cavity and therefore a very reasonable result given the strong depletion of H near the Sun.[54] More analysis is needed to account correctly for the observational geometries, and future opportunities with other spacecraft are planned.

New Horizons is gradually traveling beyond this foreground haze of interplanetary Lyman-α and has confirmed the galactic Lyman-α background of ~43 R,[53] which had been hypothesized for over half a century.[55] Given its 500 times higher sensitivity over the UVS spectrograph onboard Voyager, Alice is capable of detecting also the faint contribution (<10 R) from the H gas blanketing the nose of the heliosphere, the "hydrogen wall,"[56,57] which is a consequence of the slowdown of interstellar H through charge-exchange processes beyond the HP. Therefore, understanding the H wall is a core part of understanding how interstellar neutral gas interacts with the heliosphere. The H wall is also one of the outstanding features seen shielding other "astrospheres."[58] Stellar analogs to the heliospheric H wall are difficult to detect because of their relatively weak intensities, so heliospheric observations therefore remain the best way to understand astrospheres around G-type main-sequence stars.

Being now far away from the foreground "fog" of solar-scattered emissions from interplanetary H, Alice observations provide greater sensitivity to faint heliospheric and local interstellar medium (LISM) structures detectable in the optically thin wings of the Lyman-α profile. Upstream excess emissions (~10 R) from the H wall blanketing the heliosphere at ~300 au[59,60] should respond to solar-cycle variations, while the LISM clouds will instead display unchanging morphology. Alice's sensitivity to Lyman-α emissions is ~5 counts/s/Rayleigh, ~500 times more sensitive than Voyager's UVS, which first mapped Lyman-α emissions from large heliospheric distances.[61,62] In 2024, New Horizons will have obtained two complete Lyman-α sky maps at 2° resolution to search for morphological signatures of the H wall. The sky maps will be constructed by sweeping out great circles across the sky by slowly moving the spin plane of the spacecraft. The scan planes of the two sky maps are planned at 90° angles to each other to improve the angular resolution of the composite sky map. Depending on the results, an

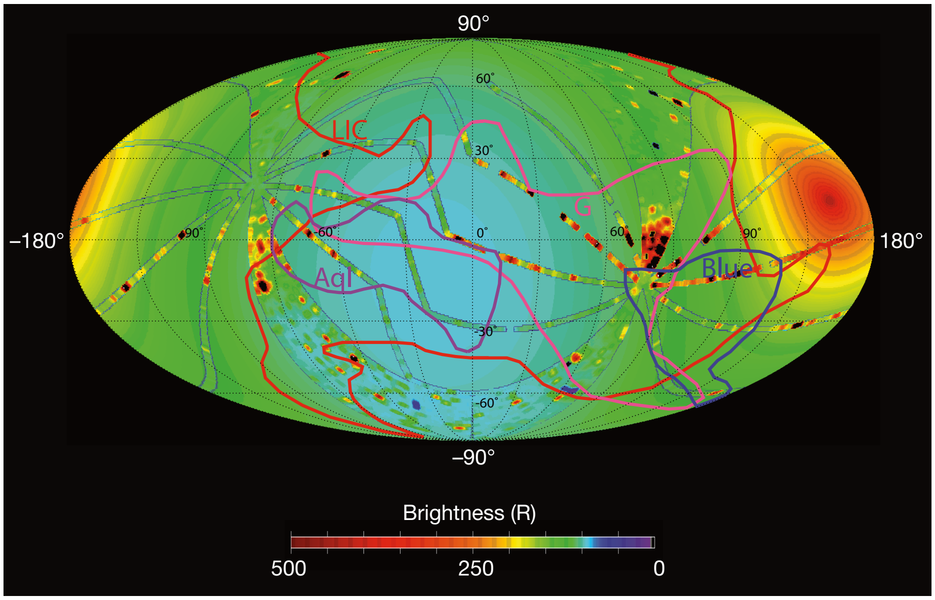


Figure 6. New Horizons' Alice will make two full Lyman-α sky maps with high resolution and sensitivity (expanding on the six great-circle scans and proof-of-concept 30°-wide contiguous sector shown here). The smooth background model includes multiple scatterings of solar Lyman-α and isotropic 43-R galactic background.[53] New Horizons is uniquely positioned to reveal the large-scale structure of the H wall and LISM cloud signatures (colored outlines of LIC, G, Blue, Aql, mapped by Redfield et al.[63])

additional sky map in 2027 will be obtained during the declining phase of solar cycle 25 (should NASA choose to continue to extend the mission), and this map will be contrasted against the previous ones obtained when the solar Lyman-α was more intense. Any temporal intensity of a morphological H-wall structure would follow the solar Lyman-α variation and could therefore be differentiated against the constant galactic and interstellar cloud Lyman-α emissions. Proof-of-concept great-circle scans were already performed in 2021, shown by the 30°-wide "pixelated" swath in Figure 6. This discrimination was not possible earlier, when only six great-circle Lyman-α scans were made.

Surrounding the Sun on parsec scales are several interstellar clouds that have very different gas and plasma densities and temperatures and are believed to be remnants from past supernovae. The Sun has spent its last 60,000 years traversing the LIC,[63] whose properties are governing the interaction, shape, and size of the heliosphere.[64] Already now the Sun may be in the transition region to enter the unknown environment of the G-Cloud,[65,66] which could drastically change the heliospheric shape and interaction. Most of the knowledge we have about our immediate interstellar neighborhood is based on average properties obtained from ~80 line-of-sight absorption measurements to the nearest stars. Despite the sparsity of these samples, a crude map of several clouds could be constructed.[63]

Following the same approach described above, all-sky maps obtained by Alice in 2027 will be contrasted with those obtained during 2023 and 2024 when the solar Lyman-α output was different. This will enable a search for any features that are constant over time and follow the outlines of interstellar clouds obtained by the Hubble Space Telescope, indicated by the contours in Figure 6. The core of the Lyman-α spectrum is optically thick over the distances relevant to interstellar clouds, and signatures are therefore not expected in this wavelength range. However, in the wings of the spectral distribution where emissions are optically thin, signatures may be present. To maintain a low data volume, the sky maps are spectrally integrated over the wavelength range. Any morphological signatures would appear as either an excess or reduction in overall intensity. Any such signatures would be the first continuous verification of neighboring interstellar clouds. Any reduction caused by obscuration or excess emissions would provide the important constraints on processes within the clouds themselves or in the interaction regions between clouds, as has been observed in x-rays.[67] Any findings may warrant more detailed follow-up observations in dedicated wavelength ranges. Using the galactic Lyman-α background as a measure by ISD absorption, Alice can also determine dust absorption coefficients to infer ISD properties.

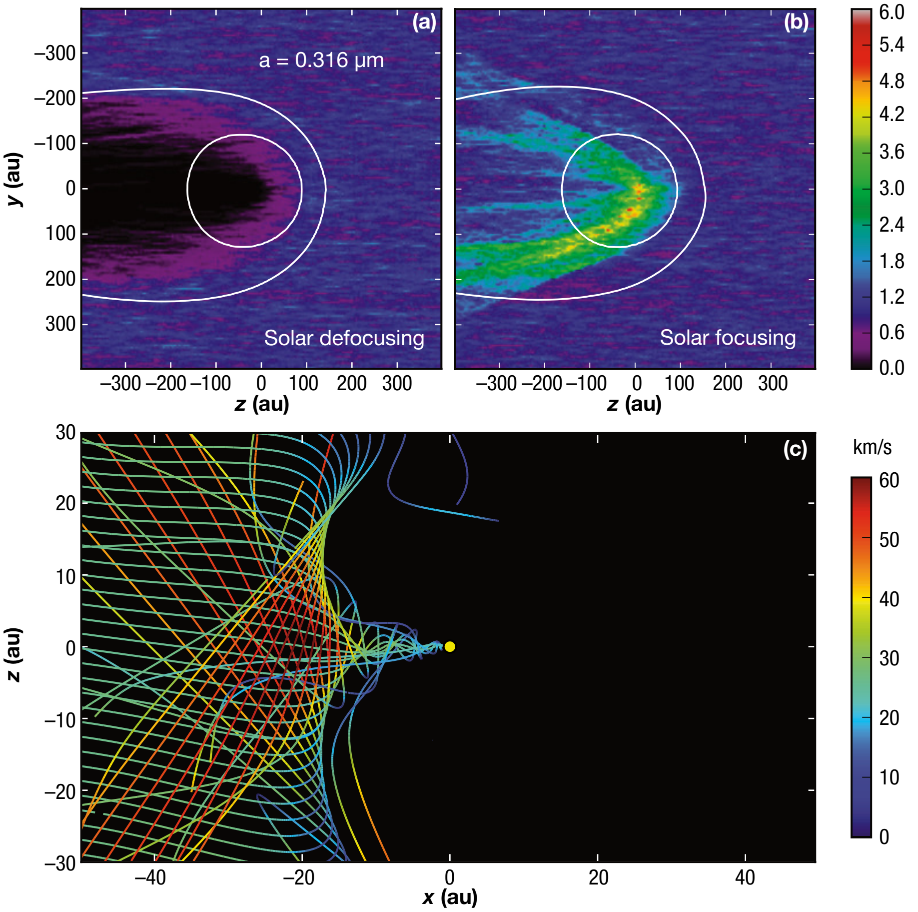


Figure 7. Simulated 0.3-µm ISD densities within the heliosphere during contrasting heliospheric conditions. (a) Each second solar minimum, the IMF polarity defocuses the trajectories of charged ISD grains. (b) During the focusing solar minima, the interplanetary magnetic field (IMF) polarity focuses the trajectories of charged grains. (Model of 0.316-µm grains adapted from Slavin et al.,[68] © AAS, reproduced with permission.) (c) For very small grains (~12 nm), trajectories become much more complicated and less intuitive. This can lead to higher concentrations in the solar system at certain times and positions, also described as "waves" of small dust "rolling" into the heliosphere. (Adapted from Sterken et al.,[76] CC BY 4.0.)

The Search for ISD

ISD grains penetrate the heliosphere, and their trajectories are modified by solar gravity, radiation pressure, interplanetary magnetic fields (IMFs), and the heliospheric boundary, depending on their mass-to-charge ratio.[68,69,70] ISD grains carry critical dynamical and compositional information about the VLISM and its interaction with the heliosphere.[71] Currently, there is no agreement between in situ measurements of ISD fluxes by the Ulysses and Galileo spacecraft in the inner heliosphere (<5 au)[72,73] and remote sensing observations of more distant ISD grain distributions.[74,75] A likely reason for this disagreement is the role the heliosheath plays in filtering sub-micrometer ISD grains as they interact with the heliosphere.[76]

Previous analyses show that ISD grain fluxes in the inner heliosphere display long-term modulations due to solar-cycle variations in the IMF.[77] Figure 7 shows simulated 0.3-µm ISD densities within the heliosphere during contrasting heliospheric conditions, demonstrating the strong modulation of ISD dynamics.[68] Fortuitously, New Horizons is heading nearly upwind into the incoming ISD flow, allowing VBSDC to record impacts of ISD grains. The IMF is currently switching toward a "focusing" orientation, which will reach its maximum in the solar minimum of the upcoming solar cycle 26 (ca. 2029–2030), whereby sub-micrometer ISD grains will be driven toward the heliospheric current sheet, increasing ISD densities.[68] However, ISD grains take a little more than one solar cycle to travel from the HP to New Horizons, and they also interact with the heliospheric boundary in a complex fashion. Therefore, it is difficult to predict any ISD fluxes accurately. Because of this complexity, three world-leading models[68,78,79] have not yet had data to fully incorporate the necessary physics, and any future VBSDC measurement may therefore provide useful constraints on this emerging field.

PLANETARY SCIENCE: UNCOVERING THE SECRETS OF SOLAR SYSTEM EVOLUTION

Exploration of the Kuiper Belt(s)

The distant vantage point of New Horizons has enabled unique observations of the photometric phase functions, rotational light curves, and binarity of Kuiper Belt objects (KBOs). Although New Horizons is now beyond the classical Kuiper Belt, KBOs observable by the spacecraft, primarily belonging to excited populations, continue to be discovered by Earth-based programs. These discoveries hint at a possible hitherto undetected and possibly massive population of planetesimals beyond the known Kuiper Belt.[80] If confirmed, they would increase the sample size of KBOs available to New Horizons and would allow sampling of solar phase curves and perhaps some rotational light curves that would provide shape constraints from new trans-Neptunian populations.

Since 2007, the telescopic Long Range Reconnaissance Imager (LORRI) imager onboard New Horizons has observed KBOs at high solar phase angles not attainable from Earth or Earth orbit. These consist mostly of KBOs from the cold classical Kuiper Belt population, like Arrokoth, that have low-eccentricity, low-inclination orbits close to where they formed in the protoplanetary nebula.[81,82,83] New Horizons has found that some KBOs exhibit both steep solar phase curves and rotation curves that increase in amplitude with increasing phase angle, similar to those of other small, dark objects (asteroids, comet nuclei, and many irregular satellites of giant planets). For KBOs closest to the spacecraft, high-resolution imaging by New Horizons has also found evidence for very close binaries.[84] Rotational light curves provide evidence for elongated and flattened objects, a discovery that indicates that Arrokoth's shape may be very common among the cold classical Kuiper Belt population and has important implications for planetesimal formation.[83]

High-phase observations from New Horizons constrain KBO surface scattering behavior and thus fine-scale surface texture, a source of information about processes driving surface evolution and potential compositional differences among the various classes of KBOs.[85] High-phase observations are also valuable for determining the energy balance between absorbed sunlight and thermal radiation and, thus, KBO temperatures and their abilities to retain volatiles.

The New Horizons ground-based KBO search team found dozens of KBOs that the spacecraft has already observed (Figure 8 plots all currently known KBOs with well-determined orbits). Two newly discovered KBOs are already known to be observable by LORRI in the coming years. Both are bright enough from New Horizons to obtain solar phase curves. By using ongoing ground-based searches, we expect that at least three to four more distant KBOs observable by LORRI will be discovered in the next couple years, and it is possible that some may appear bright enough to LORRI that rotational light curves can be obtained, providing shape constraints. These objects sample the dynamically excited subpopulations of objects that originally formed closer to the Sun before being perturbed outward early in solar system history, and this new Kuiper Belt population offers a major addition to the current data set. Each distinct Kuiper Belt population holds valuable information about the formation of planetesimals and planets in the outer solar system,[86,87] as well as subsequent events leading to the solar system's present-day configuration.[88,89]

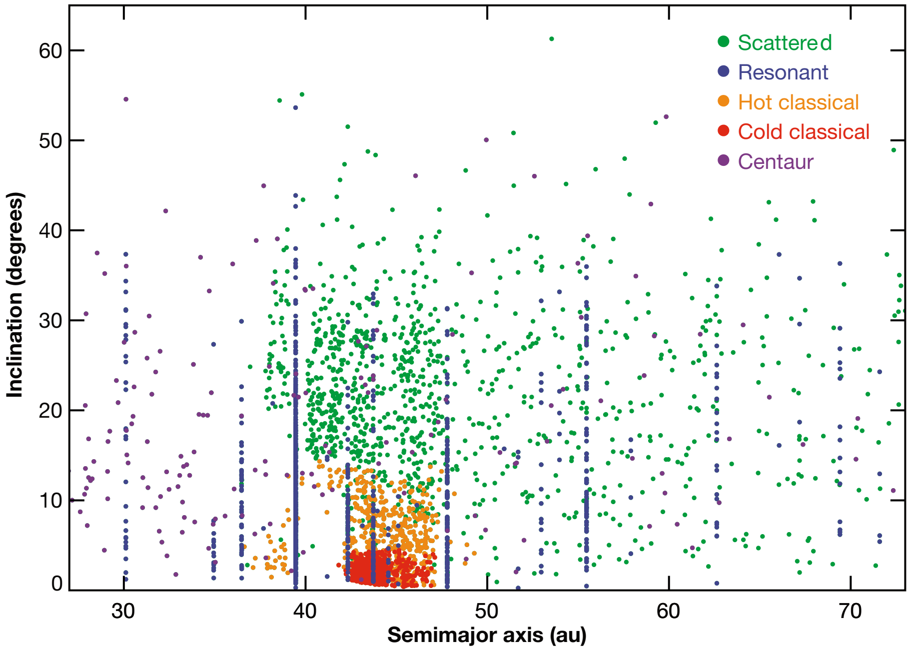


Figure 8. Currently known KBOs with well-determined orbits. KBOs are colored according to dynamical class according to the Deep Ecliptic Survey scheme.[90]

The Circumsolar Dust Disk

Planetesimal 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 planetesimal 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) with the asteroid belt and the outer Edgeworth-Kuiper Belt (EKB), and at least one debris cloud, the zodiacal cloud, sourced by planetesimal collisions and comet evaporative sublimation. It is not well understood how much dust is produced from the 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[91] and the Voyagers via the Plasma Wave System.[92] New estimates from the New Horizons results put the EKB disk mass at 30–40 times the inner disk mass.[93] Better understanding of 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.

VBSDC measures dust fluxes and number densities of micrometer-sized (10^{-14}–10^{-10} kg) interplanetary dust particles (IDPs) originating from the Kuiper Belt as well as ISD from the interstellar medium for sizes > ca. 300 nm.[91,94,95,96] Recent achievements include dust flux measurements extended to 52 au[91,97] (Figure 9), modeling of interplanetary dust densities drawing analogs to exozodiacal disks,[93,97,98] quantification of interplanetary dust mass fluxes to giant planet atmospheres with implications for photochemical equilibria,[99] and quantification of exogenous water deposition rates in the atmospheres of Pluto and Triton with implications for photochemistry and haze formation.[100]

VBSDC will extend its measurements of IDPs that are produced by KBO collisions and ejected from KBOs by ISD grains.[101,102] Its measurements will constrain dynamical models of the interplanetary dust environment in the outer solar system,[93,98] thereby indirectly characterizing the distribution of parent KBOs.

Figure 9a shows VBSDC measurements of grains with radii >0.63 μm to date, from 1 to >50 au, along with models for the expected fluxes of IDPs (solid lines[98]) and ISD model predictions.[77,97]

The solid red curve in Figure 9a denotes the best-fit IDP model to the VBSDC measurements considering only the main Kuiper Belt parent body components observed by Petit et al.[103] Recent stellar occultation measurements have suggested the possible presence of an extended tail to the Kuiper Belt heliocentric distance distribution, consisting of smaller more distant objects, which would in turn result in an extended region of IDP dust production and fluxes. Two additional curves (blue and purple) show IDP fluxes with the addition of two hypothetical distributions of KBOs extending to ~100 au (an "outer" Kuiper Belt). The presence of a putative outer Kuiper Belt region of dust production yields more extended tails to the IDP dust fluxes at distances >50 au. While VBSDC observed increasing dust fluxes out to ~40–45 au, measurements near ~50 au may have declined slightly, suggesting that New Horizons may have passed through the densest dust-producing region of the Kuiper Belt around 45 au. The most recent measurements seem to suggest yet another upward trend that may, or may not, be associated with a significant outer KBO population beyond the main belt. Thus, continued VBSDC observations into the mare incognitum beyond 55 au provide a unique opportunity to learn about the structure of the Kuiper Belt, including constraints on a possible extension of the KBO distribution >50 au, which may be difficult to detect otherwise.

Dust distributions in the outer solar system can also provide unique insights into the interpretation of remote observations of extrasolar debris

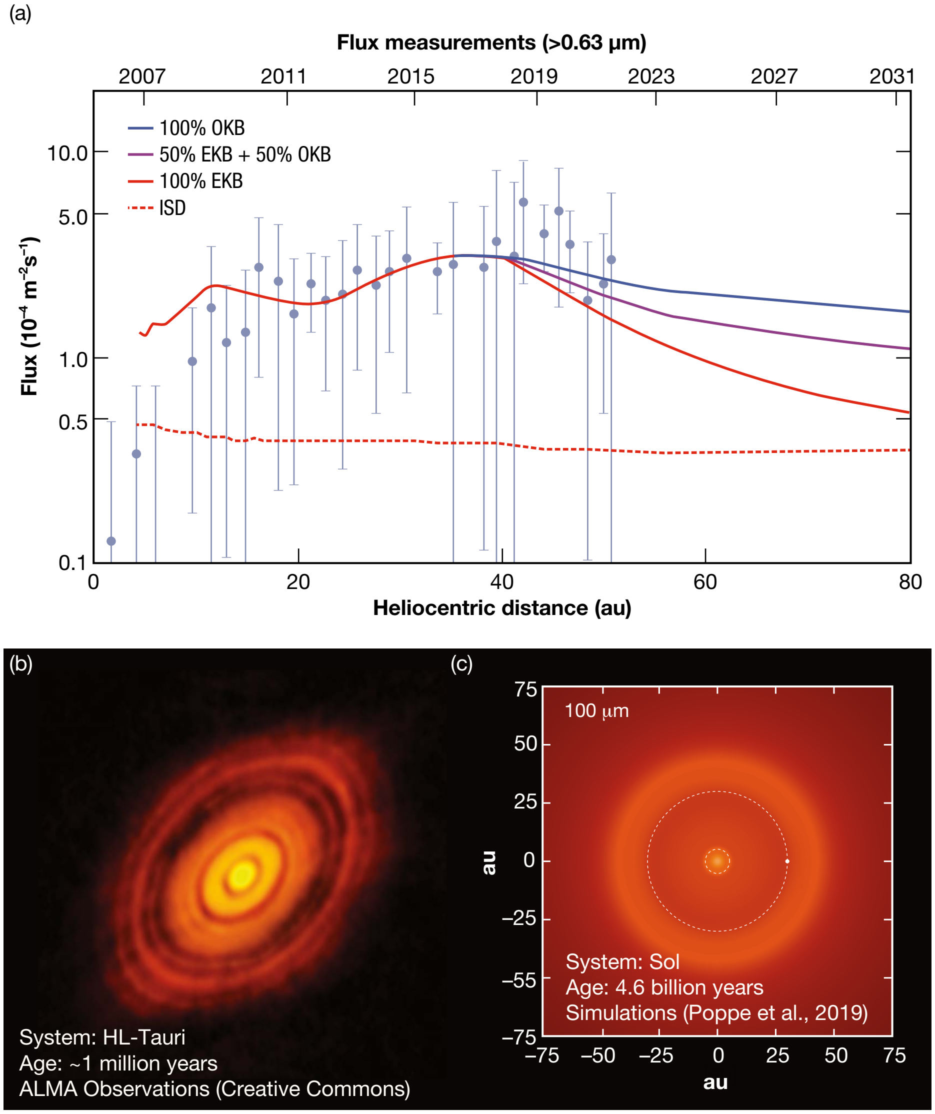


Figure 9. Dust measurements by New Horizons. (a) VBSDC flux measurements of >0.63-µm dust grains (filled circles) with different IDP and predicted ISD flux (lower red dashed line). (Adapted from Piquette et al.[91] and Bernardoni et al.,[97] CC BY 4.0.) (b) Atacama Large Millimeter/submillimeter Array (ALMA) image of the HL-Tauri system with indications of early planetary formation. (c) Simulation of our own circumsolar dust disk by Poppe et al.[93] (© AAS, reproduced with permission). New Horizons dust measurements will provide the best understanding to date of the Sun's dust disk, allowing us to better understand the formation of planetary systems in general.

disks.[104,105] The vast majority of these are exo-Kuiper Belts.[106,107,108,109,110] Mature exo-Kuiper Belts are not just products of the early protoplanetary disk structure, but, like the Kuiper Belt, are also affected by millions to billions of years of subsequent planetary migration and/or scattering events. Indeed, the brightest known exo-disks are formed in either highly stirred and dynamically excited exo-Kuiper Belts,[105] or systems plowing through locally dense interstellar medium dust concentrations at high relative velocities;[111,112] however, detailed knowledge of the dynamical structure and ISM dust influx in these systems remains sparse. By coupling VBSDC measurements of the distribution of Kuiper Belt dust with detailed knowledge of the solar system's Kuiper Belt population dynamics,[113] measurement-driven models of dust creation in the solar system can be built to apply to other systems, advancing understanding of how exozodiacal disks are formed and interact with unseen planets and influences from surrounding interstellar material; see comparison of the modeled solar system zodiacal cloud structure with remote observations of exozodiacal clouds (Figure 9b).

ASTROPHYSICS: PEERING INTO THE FORMATION OF GALAXIES

The discovery and characterization of cosmic background radiation that is not attributable to known sources has been a frontier of fundamental astrophysics since the discovery of the 3-K microwave background in the 1960s.[114] The analogous cosmic optical background (COB) may provide critical information on the evolution of galaxies over the age of the universe and perhaps even clues to the nature of dark matter. However, the COB has been exceedingly difficult to observe from 1 au. New Horizons can produce the most accurate and direct observation of the COB yet for the integrated flux from all extragalactic sources generating photons detected at optical wavelengths (accounting for any redshift). For LORRI, the measured flux samples redshifts z from $0 \leq z \leq 6$ (Lyman-α is redshifted out of the bandpass at earlier epochs).

The directly measured COB flux is a key diagnostic that can be compared with the integral over known sources of extragalactic light, such as integrated galactic light (IGL) described by multicolor counts of faint background galaxies[115] from the Hubble Space Telescope or, shortly, from the James Webb Space Telescope.[116] Any confirmed excess over known sources, as is hinted at by current measurements, particularly those from New Horizons, would potentially be a discovery of great importance. Explanations might include the existence of low-luminosity stellar systems unanticipated by simple extrapolation of the counts,[117] a large population of stars not closely associated with galaxies, or novel channels of photon generation.[118] Understanding additional flux sources is vital to understanding the complete history of star formation and active galactic nuclei output over the age of the universe.[115] Solving such problems is at the center of the Cosmic Ecosystems initiatives called out in the Astro2020 decadal report.[119]

Another compelling reason to measure the COB is to test attenuation models by visible photons of high-energy (~TeV) γ-rays emitted by distant active galactic nuclei. The observed γ-ray attenuation[120] is consistent with estimated IGL background levels. Any COB flux above the expected IGL (Figure 10a) would imply a corresponding reduction in γ-ray attenuation. This, in turn, might imply, for instance, that the γ-rays interact with axion-like particles, a hypothesized form of dark matter.[121]

Attempts to measure the COB from the inner solar system yielded fluxes several times larger than estimates of the IGL based on galaxy counts, though none with significance >95% (Figure 10a) from zero, because even at the ecliptic poles at 1 au, zodiacal light is over an order of magnitude stronger than the COB and is difficult to model.

New Horizons' great distance from the Sun allows unprecedentedly sensitive measurements of the COB,[122] because the spacecraft is far beyond most solar-illuminated dust. Using LORRI observations, Lauer et al.[123] derived a COB flux of 15.36 ± 1.40 nW m^{-2} sr^{-1}, which is in ~5σ conflict with the hypothesis that the IGL can account for the COB, as well as with the simplest models of the γ-ray attenuation. The excess over the IGL may validate arguments that the present galaxy counts have not included the full variety of stellar systems.[124]

In the next year, New Horizons will obtain COB measurements of multiple fields (Figure 10b) to establish that the fluxes are sufficiently accurate to provide a strong test of the COB fluxes *inferred* from galaxy counts and the attenuation of cosmologically distant very high-energy γ-ray sources. The number of the fields also allows them to be tested for homogeneity of the COB, a key diagnostic for whether the unknown component is generated on cosmological scales.

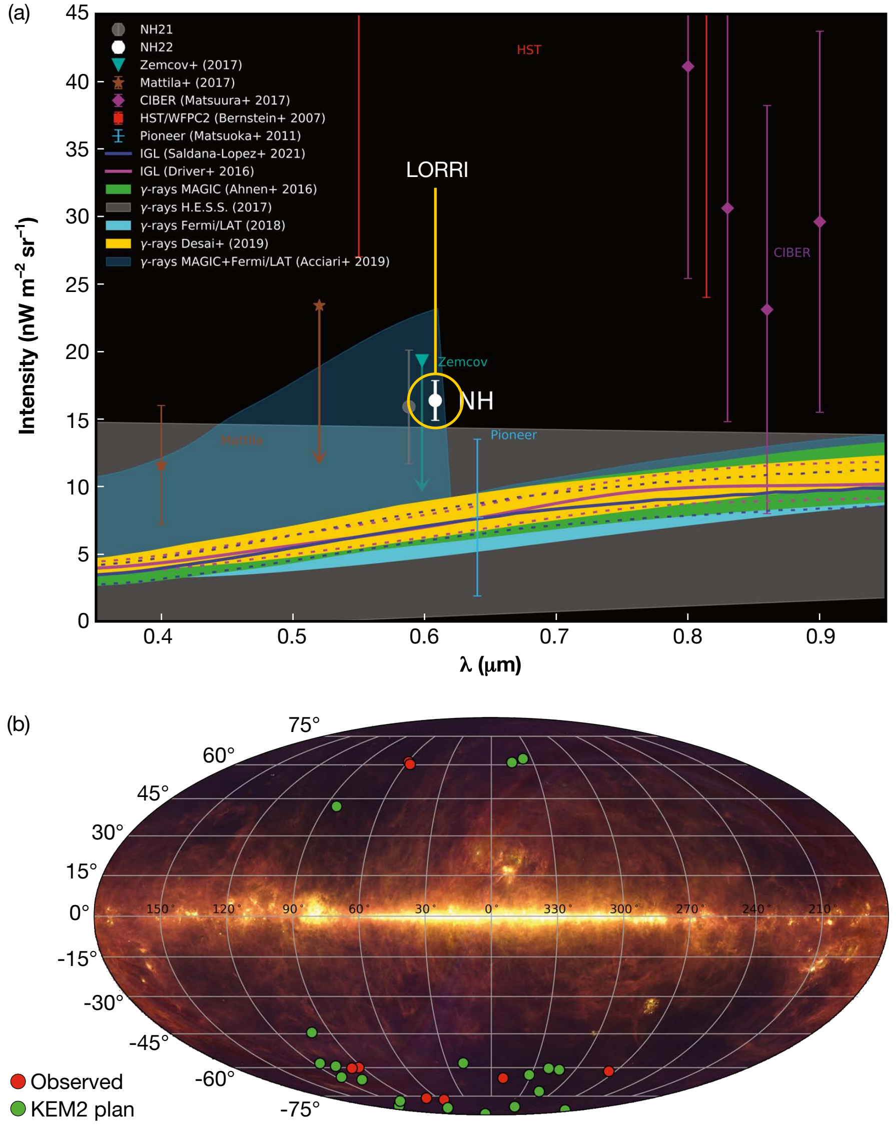


Figure 10. COB measurements by New Horizons. (a) New Horizons LORRI has observed a COB intensity that is in excess of current theories.[123] (b) In 2024, New Horizons will observe multiple additional dark fields to refine the estimates and test the homogeneity of the intensities across the sky.

New Horizons' large heliocentric distance also opens a unique window into cosmical UV background radiation from outside the heliosphere. The background UV spectrum observed is a combination of contributions from the outer heliosphere, the LISM, and more distant sources out to z<~1, which New Horizons can help to disentangle with a combination of Lyman-α imaging and spectroscopy. Data from the Galaxy Evolution Explorer (GALEX) in the range of $130 \text{ nm} < \lambda < 180 \text{ nm}$ obtained at 1 au suggested significant emission from unknown sources,[125] although Kulkarni[126] argues that about two-thirds of this unknown component can be explained as emission from weak shocks, H_2 fluorescence, or two-photon continuum emission. Given its distant position, New Horizons can test these contributions using Alice[127] to obtain deep spectra at several fields.

SUMMARY

New Horizons, currently at 56.5 au from the Sun (as of July 14, 2023), is the only spacecraft in the Kuiper Belt and outer heliosphere. SWAP's and PEPSSI's unique measurements of the solar wind, interstellar PUIs, and energetic particles are becoming increasingly important to understanding the formation of the heliospheric boundary that New Horizons may begin to cross into, perhaps as soon as the end of this decade (the 2020s). New Horizons may be past the densest peak of the Kuiper Belt, but there are indications (at the time of this writing) that the Kuiper Belt is much more extended than once thought, with possible secondary populations of KBOs, some of which may be sufficiently bright to be observed by the LORRI camera. Being beyond the foreground haze of interplanetary hydrogen and dust, the LORRI camera and Alice spectrograph are also making critical contributions to understanding the cosmic background, the heliospheric hydrogen wall and, potentially, interstellar clouds. New Horizons is projected to have sufficient power to make scientific observations until ~2050, which would make it the third operational spacecraft to reach the VLISM after the Voyager mission. New Horizons is therefore also a cross-divisional pathfinder for a future Interstellar Probe.[128,129]

ACKNOWLEDGMENTS: Work on the New Horizons mission was performed under NASA contracts NAS5-97271/TO30 (APL) and NASW-02008 (SwRI). V. J. Sterken received funding from the European Union's Horizon 2020 research and innovation program under grant agreement Nr. 851544.

REFERENCES

[1] A. Wallner, J. Feige, N. Kinoshita, M. Paul, L. K. Fifield, et al., "Recent near-Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe," *Nature*, vol, 532, pp. 69–72, 2016, https://doi.org/10.1038/nature17196.

[2] A. Wallner, M. B. Froehlich, M. A. C. Hotchkis, N. Kinoshita, M. Paul, et al., "^{60}Fe and ^{244}Pu deposited on Earth constrain the r-process yields of recent nearby supernovae," *Science*, vol. 372, no. 6543, pp. 742–745, 2021, https://doi.org/10.1126/science.aax3972.

[3] K. Knie, G. Korschinek, T. Faestermann, C. Wallner, J. Scholten, and W. Hillebrandt, "Indication for supernova produced ^{60}Fe activity on Earth," *Phys. Rev. Lett.*, vol. 83, no. 1, pp. 18–21, 1999, https://doi.org/10.1103/PhysRevLett.83.18.

[4] C. Fitoussi, G. M. Raisbeck, K. Knie, G. Korschinek, T. Faestermann, et al., "Search for supernova-produced ^{60}Fe in a marine sediment," *Phys. Rev. Lett.*, vol. 101, no. 12, art. 121101, 2008, https://doi.org/10.1103/PhysRevLett.101.121101.

[5] M. Opher and A. Loeb, "Terrestrial impact from the passage of the solar system through a cold cloud a few million years ago," arXiv, Feb. 3, 2022 (v1) and Feb. 18, 2022 (v2), https://doi.org/10.48550/arXiv.2202.01813.

[6] B. D. Fields, T. Athanassiadou, and S. R. Johnson, "Supernova collisions with the heliosphere," *Astrophys. J.*, vol. 678, no. 1, pp. 549–562, 2008, https://doi.org/10.1086/523622.

[7] A. Wallner, J. Feige, L. K. Fifield, M. B. Froehlich, R. Golser, et al., "^{60}Fe deposition during the late Pleistocene and the Holocene echoes past supernova activity," *Proc. Nat. Acad. Sci.*, vol. 117, no. 36, pp. 21873–21879, 2020, https://doi.org/10.1073/pnas.1916769117.

[8] D. Koll, G. Korschinek, T. Faestermann, J. M. Gómez-Guzmán, S. Kipfstuhl, et al., "Interstellar ^{60}Fe in Antarctica," *Phys. Rev. Lett.*, vol. 123, art. 072701, 2019, https://doi.org/10.1103/PhysRevLett.123.072701.

[9] L. Fimiani, D. L. Cook, T. Faestermann, J. M. Gómez-Guzmán, K. Hain, et al., "Interstellar ^{60}Fe on the surface of the moon," *Phys. Rev. Lett.*, vol. 116, art. 151104, 2016, https://doi.org/10.1103/PhysRevLett.116.151104.

[10] J. Linsky, S. Redfield, D. Ryder, and E. Moebius, "Inhomogeneity in the local ISM and its relation to the heliosphere," *Space Sci. Rev.*, vol. 218, art. 16, 2022, https://doi.org/10.1007/s11214-022-00884-5.

[11] N. E. Raouafi, "A journey to touch the sun," *Phys. Today*, vol. 75, no. 11, pp. 28–34, 2022, https://doi.org/10.1063/PT.3.5120.

[12] E. Möbius, D. Hovestadt, B. Klecker, M. Scholer, G. Gloeckler, and F. M. Ipavich, "Direct observation of He$^+$ pick-up ions of interstellar origin in the solar wind," *Nature*, vol. 318, pp. 426–429, 1985, https://doi.org/10.1038/318426a0.

[13] G. Gloeckler, J. Geiss, H. Balsiger, L. A. Fisk, A. B. Galvin, et al., "Detection of interstellar pick-up hydrogen in the solar system," *Science*, vol. 261, no. 5117, pp. 70–73, 1993, https://doi.org/10.1126/science.261.5117.70.

[14] H. A. Elliott, C. J. Henney, D. J. McComas, C. W. Smith, and B. J. Vasquez, "Temporal and radial variation of the solar wind temperature-speed relationship," *J. Geophys. Res.*, vol. 117, no. A9, art. A09102, 2012, https://doi.org/10.1029/2011JA017125.

[15] G. P. Zank, L. Adhikari, L.-L. Zhao, P. Mostafavi, E. J. Zirnstein, and D. J. McComas, "The pickup ion-mediated solar wind," *Astrophys. J.*, vol. 869, no. 1, art. 23, 2018, https://doi.org/10.3847/1538-4357/aaebfe.

[16] J. D. Richardson and C. W. Smith, "The radial temperature profile of the solar wind," *Geophys. Res. Lett.*, vol. 30, no. 5, art. 1206, 2003, https://doi.org/10.1029/2002gl016551.

[17] H. A. Elliott, D. J. McComas, E. J. Zirnstein, B. M. Randol, P. A. Delamere, et al., "Slowing of the solar wind in the outer heliosphere," *Astrophys. J.*, vol. 885, no. 2, art. 156, 2019, https://doi.org/10.3847/1538-4357/ab3e49.

[18] S. A. Fuselier, A. Galli, J. D. Richardson, D. B. Reisenfeld, E. J. Zirnstein, et al., "Energetic neutral atom fluxes from the heliosheath: Constraints from in situ measurements and models," *Astrophys. J. Lett.*, vol. 915, no. 2, art. L26, 2021, https://doi.org/10.3847/2041-8213/ac0d5c.

[19] D. J. McComas, P. Swaczyna, J. R. Szalay, E. J. Zirnstein, J. S. Rankin, et al., "Interstellar pickup ion observations halfway to the termination shock," *Astrophys. J. Suppl. Ser.*, vol. 254, no. 1, art. 19, 2021, https://doi.org/10.3847/1538-4365/abee76.

[20] S. M. Krimigis, R. B. Decker, E. C. Roelof, M. E. Hill, C. O. Bostrom, et al., "Energetic charged particle measurements from Voyager 2 at the heliopause and beyond," *Nature Astron.*, vol. 3, pp. 997–1006, 2019, https://doi.org/10.1038/s41550-019-0927-4.

[21] D. J. McComas, B. L. Shrestha, P. Swaczyna, J. S. Rankin, S. E. Weidner, et al., "First high-resolution Observations of interstellar pickup ion mediated shocks in the outer heliosphere," *Astrophys. J.*, vol. 934, no. 2, art. 147, 2022, https://doi.org/10.3847/1538-4357/ac7956.

[22] J. D. Richardson, J. C. Kasper, C. Wang, J. W. Belcher, and A. J. Lazarus, “Cool heliosheath plasma and deceleration of the upstream solar wind at the termination shock,” *Nature*, vol. 454, pp. 63–66, 2008, https://doi.org/10.1038/nature07024.

[23] K. Dialynas, A. Galli, M. A. Dayeh, A. C. Cummings, R. B. Decker, et al., “Combined ~10 eV to ~344 MeV particle spectra and pressures in the heliosheath along the Voyager 2 trajectory,” *Astrophys. J. Lett*, vol. 905, no. 2, art. L24, 2020, https://doi.org/10.3847/2041-8213/abcaaa.

[24] H. A. Elliott, D. J. McComas, P. Valek, G. Nicolaou, S. Weidner, and G. Livadiotis, “The *New Horizons* Solar Wind Around Pluto (SWAP) observations of the solar wind from 11-33 au,” *Astrophys. J. Suppl. Ser.*, vol. 223, no. 2, art. 19, 2016, https://doi.org/10.3847/0067-0049/223/2/19.

[25] E. J. Zirnstein, D. J. McComas, R. Kumar, H. A. Elliott, J. R. Szalay, et al., “In situ observations of preferential pickup ion heating at an interplanetary shock,’ *Phys. Rev. Lett.*, vol. 121, art. 075102, 2018, https://doi.org/10.1103/PhysRevLett.121.075102.

[26] P. Kollmann, M. E. Hill, R. L. McNutt Jr., L. E. Brown, R. C. Allen, et al., “Suprathermal ions in the outer heliosphere,” *Astrophys. J.*, vol. 876, no. 1, art. 46, 2019, https://doi.org/10.3847/1538-4357/ab125f.

[27] B. M. Randol, R. W. Ebert, F. Allegrini, D. J. McComas, and N. A. Schwadron, “Reflections of ions in electrostatic analyzers: A case study with New Horizons/Solar Wind Around Pluto,” *Rev. Scientific Instrum.*, vol. 81, no. 1, art. 114501, 2010, https://doi.org/10.1063/1.3499367.

[28] M. E. Hill, N. A. Schwadron, D. C. Hamilton, R. D. Di Fabio, and R. K. Squier, “Interplanetary suprathermal He^+ and He^{++} observations during quiet periods from 1 to 9 AU and implications for particle acceleration,” *Astrophys. J.*, vol. 699, no. 1, art. L26, 2009, https://doi.org/10.1088/0004-637x/699/1/l26.

[29] M. E. Hill and D. C. Hamilton, “Interim report on the power law index of interplanetary suprathermal ion spectra,” *AIP Conf. Proc.*, vol. 1302, pp. 58–63, 2010, https://doi.org/10.1063/1.3529991.

[30] J. D. Richardson, L. F. Burlaga, H. Elliott, W. S. Kurth, Y. D. Liu, and R. von Steiger, “Observations of the outer heliosphere, heliosheath, and interstellar medium,” *Space Sci. Rev.*, vol. 218, art. 35, 2022, https://doi.org/10.1007/s11214-022-00899-y.

[31] S. M. Krimigis, R. B. Decker, M. E. Hill, T. P. Armstrong, G. Gloeckler, et al., “Voyager 1 exited the solar wind at a distance of ~85AU from the Sun,” *Nature*, vol. 426, pp. 45–48, 2003, https://doi.org/10.1038/nature02068.

[32] R. B. Decker, S. M. Krimigis, E. C. Roelof, M. E. Hill, T. P. Armstrong, et al., “Voyager 1 in the foreshock, termination shock, and heliosheath,” *Science*, vol. 309, no. 5743, pp. 2020–2024, 2005, https://doi.org/10.1126/science.1117569.

[33] N. V. Pogorelov, J. Heerikhuisen, V. Roytershteyn, L. F. Burlaga, D. A. Gurnett, and W. S. Kurth, “Three-dimensional features of the outer heliosphere due to coupling between the interstellar and heliospheric magnetic field. V. The Bow wave, heliospheric boundary layer, instabilities, and magnetic reconnection,” *Astrophys. J.*, vol. 845, no. 1, art. 9, 2017, https://doi.org/10.3847/1538-4357/aa7d4f.

[34] M. Opher, A. Loeb, J. Drake, and G. Toth, “A small and round heliosphere suggested by magnetohydrodynamic modelling of pick-up ions,” *Nature Astron.*, vol. 4, pp. 675–683, 2020, https://doi.org/10.1038/s41550-020-1036-0.

[35] V. Florinski and J. Heerikhuisen, “Kinetic properties of the neutral solar wind,” *Astrophys. J.*, vol. 838, no. 1, art. 50, 2017, https://doi.org/10.3847/1538-4357/aa6441.

[36] D. J. McComas, F. Allegrini, P. Bochsler, M. Bzowski, E. R. Christian, et al., “Global observations of the interstellar interaction from the Interstellar Boundary Explorer (IBEX),” *Science*, vol. 326, no. 5955, pp. 959–962, 2009, https://doi.org/10.1126/science.1180906.

[37] S. M. Krimigis, D. G. Mitchell, E. C. Roelof, K. C. Hsieh, and D. J. McComas, “Imaging the interaction of the heliosphere with the interstellar medium from Saturn with Cassini,” *Science*, vol. 326, no. 5955, pp. 971–973, 2009, https://doi.org/10.1126/science.1181079.

[38] J. S. Rankin, D. J. McComas, and N. A. Schwadron, “Galactic cosmic-ray anisotropies: Electrons observed by Voyager 1 in the very local interstellar medium,” *Astrophys. J.*, vol. 895, no. 2, art, 103, 2020, https://doi.org/10.3847/1538-4357/ab8eb2.

[39] L. F. Burlaga, N. F. Ness, D. A. Gurnett, and W. S. Kurth, “Evidence for a shock in Interstellar plasma: Voyager 1,” *Astrophys. J.*, vol. 778, no. 1, art. L3, 2013, https://doi.org/10.1088/2041-8205/778/1/l3.

[40] D. A. Gurnett, W. S. Kurth, E. C. Stone, A. C. Cummings, S. M. Krimigis, et al., “Precursors to interstellar shocks of solar origin,” *Astrophys. J.*, vol. 809, no. 2, art. 121, 2015, https://doi.org/10.1088/0004-637X/809/2/121.

[41] M. E. Hill, R. C. Allen, P. Kollmann, L. E. Brown, R. B. Decker, et al., “Influence of Solar disturbances on galactic cosmic rays in the solar wind, heliosheath, and local interstellar medium: Advanced Composition Explorer, New Horizons, and Voyager observations,” *Astrophys. J.*, vol. 905, no. 1, art. 69, 2020, https://doi.org/10.3847/1538-4357/abb408.

[42] D. J. McComas, F. Allegrini, P. Bochsler, M. Bzowski, M. Collier, et al.,. “IBEX—Interstellar Boundary Explorer,” *Space Sci. Rev.*, vol. 146, pp. 11–33, 2009, https://doi.org/10.1007/s11214-009-9499-4.

[43] D. J. McComas, E. R. Christian, N. A. Schwadron, N. Fox, J. Westlake, et al. “Interstellar Mapping and Acceleration Probe (IMAP): A new NASA mission,” *Space Sci. Rev.*, vol. 214, art. 116, 2018, https://doi.org/10.1007/s11214-018-0550-1.

[44] E. J. Zirnstein, R. Kumar, R. Bandyopadhyay, M. A. Dayeh, J. Heerikhuisen, and D. J. McComas, “Turbulent acceleration of interstellar pickup ions at the heliospheric termination shock forms the global ENA spectrum,” *Astrophys. J.*, vol. 916, no. 2, art. L21, 2021, https://doi.org/10.3847/2041-8213/ac12cc.

[45] L. A. Fisk and M. A. Lee, “Shock acceleration of energetic particles in corotating interaction regions in the solar wind,” *Astrophys. J.*, vol. 237, pp. 620–626, 1980, https://doi.org/10.1086/157907.

[46] J. Yu, L. Berger, R. Wimmer-Schweingruber, P. Bochsler, B. Klecker, et al., “Suprathermal helium in corotating interaction regions: Combined observations from SOHO/CELIAS/STOF and ACE/SWICS,” *Astron. Astrophys.*, vol. 599, art. A13, 2017, https://doi.org/10.1051/0004-6361/201628641.

[47] E. N. Parker, “The passage of energetic charged particles through interplanetary space,” *Planet. Space Sci.*, vol. 13, no. 1, pp. 9–49, 1965, https://doi.org/10.1016/0032-0633(65)90131-5.

[48] A. Shalchi, “Perpendicular transport of energetic particles in magnetic turbulence,” *Space Sci. Rev.*, vol. 216, art. 23, 2020, https://doi.org/10.1007/s11214-020-0644-4.

[49] T. G. Northrop, “Adiabatic charged-particle motion,” *Rev. Geophys. Space Phys.*, vol. 1, no. 3, pp. 283–304, 1963, https://doi.org/10.1029/RG001i003p00283.

[50] E. C. Roelof, “High latitude observations of corotating interaction regions: Remote sensing using energetic particles,” *AIP Conf. Proc.*, vol. 528, pp. 242–249, 2000, https://doi.org/10.1063/1.1324319.

[51] G. R. Gladstone, S. A. Stern, and W. R. Pryor, “New Horizons cruise observations of Lyman-α emissions from the interplanetary medium,” in *Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere*, E. Quémerais, M. Snow, R. M. Bonnet, Eds. ISSI Scientific Report Series, vol 13. Springer: New York, 2013, https://doi.org/10.1007/978-1-4614-6384-9_6.

[52] G. R. Gladstone, W. R. Pryor, S. A. Stern, K. Ennico, C. B. Olkin, et al., “The Lyman-α sky background as observed by New Horizons,” *Geophys. Res. Lett.*, vol. 45, no. 16, pp. 8022–8028, 2018, https://doi.org/10.1029/2018gl078808.

[53] G. R. Gladstone, W. R. Pryor, D. T. Hall, J. A. Kammer, D. F. Strobel, et al., “New Horizons detection of the local galactic Lyman-α background,” *Astron. J.*, vol. 162, no. 6, art. 241, 2021, https://doi.org/10.3847/1538-3881/ac23cd

[54] E. Quémerais, M. Snow, and R.-M. Bonnet, Eds. *Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere*. ISSI Scientific Report Series, vol 13. Springer: New York, 2013, https://doi.org/10.1007/978-1-4614-6384-9.

[55] G. Münch and A. Unsöld, “Interstellar gas near the sun,” *Astrophys. J.*, vol. 135, p. 711, 1962, https://doi.org/10.1086/147314.

[56] V. B. Baranov and Y. G. Malama, “Model of the solar wind interaction with the local interstellar medium numerical solution of self-consistent problem,” *J. Geophys. Res.*, vol. 98, no. A9, pp. 15157–15164, 1993, https://doi.org/10.1029/93JA01171.

[57] J. L. Linsky and B. E. Wood, “The α Centauri line of sight: D/H ratio, physical properties of local interstellar gas, and measurement of heated hydrogen (the ‘hydrogen wall’) near the heliopause,” *Astrophys. J.*, vol. 463, pp. 254–270, 1996, https://doi.org/10.1086/177238.

[58] B. E. Wood, H.-R. Müller, G. P. Zank, V. V. Izmodenov, and J. L. Linsky, “The heliospheric hydrogen wall and astrospheres,” *Adv. Space Res.*, vol. 34, no. 1, pp. 66–73, 2004, https://doi.org/10.1016/j.asr.2003.01.035.

[59] V. B. Baranov, "Gas dynamics of the solar wind interaction with the interstellar medium," *Space Sci. Rev.*, vol. 52, pp. 89–120, 1990, https://doi.org/10.1007/bf00704240.

[60] E. Quémerais, R. Lallement, J. L. Bertaux, B. R. Sandel, V. Izmodenov, and Y. Malama, "Ultraviolet glow from the hydrogen wall," *Astrophys. J.*, vol. 711, no. 2, art. 1257, 2010, https://doi.org/10.1088/0004-637x/711/2/1257.

[61] D. T. Hall, D. E. Shemansky, D. L. Judge, P. Gangopadhyay, and M. A. Gruntman, "Heliospheric hydrogen beyond 15 AU: Evidence for a termination shock," *J. Geophys. Res.*, vol. 98, no. A9, pp. 15185–15192, 1993, https://doi.org/10.1029/93ja01175.

[62] O. A. Katushkina, E. Quémerais, V. V. Izmodenov, R. Lallement, and B. R. Sandel, "Voyager 1/UVS Lyman α measurements at the distant heliosphere (90–130 AU): Unknown source of additional emission," *J. Geophy. Res. Space Phys.*, vol. 122, no. 11, pp. 10921–10937, 2017, https://doi.org/10.1002/2017ja024205.

[63] S. Redfield and J. L. Linsky, "The structure of the local interstellar medium. IV. Dynamics, morphology, physical properties, and implications of cloud-cloud interactions," *Astrophys. J.*, vol. 673, no. 1, pp. 283–314, 2008, https://doi.org/10.1086/524002.

[64] H.-R. Müller, V. Florinski, J. Heerikhuisen, V. V. Izmodenov, K. Scherer, et al., "Comparing various multi-component global heliosphere models," *Astron. Astrophys.*, vol. 491, no. 1, pp. 43, 2008, https://doi.org/10.1051/0004-6361:20078708.

[65] J. L. Linsky, S. Redfield, and D. Tilipman, "The interface between the outer heliosphere and the inner local ISM: Morphology of the Local Interstellar Cloud, its hydrogen hole, Strömgren shells, and ^{60}Fe accretion," *Astrophys. J.*, vol. 886, no. 1, art. 41, 2019, https://doi.org/10.3847/1538-4357/ab498a.

[66] P. Swaczyna, M. A. Kubiak, M. Bzowski, J. Bower, S. A. Fuselier, et al., "Very local interstellar medium revealed by a complete solar cycle of interstellar neutral helium observations with IBEX," *Astrophys. J. Suppl. Ser.*, vol. 259, art. 42, 2022, https://doi.org/10.3847/1538-4365/ac4bde.

[67] J. D. Slavin and P. C. Frisch, "The boundary conditions of the heliosphere: Photoionization models constrained by interstellar and in situ data," *Astron. Astrophys.*, vol. 491, no. 1, pp. 53–68, 2008, https://doi.org/10.1051/0004-6361:20078101.

[68] J. D. Slavin, P. C. Frisch, H.-R. Müller, J. Heerikhuisen, N. V. Pogorelov, et al., "Trajectories and distribution of interstellar dust grains in the heliosphere," *Astrophys. J.*, vol. 760, no. 1, art. 46, 2012, https://doi.org/10.1088/0004-637x/760/1/46.

[69] V. J. Sterken, N. Altobelli, S. Kempf, G. Schwehm, R. Srama, and E. Grün, "The flow of interstellar dust into the solar system," *Astron. Astrophys.*, vol. 538, art. A102, 2012, https://doi.org/10.1051/0004-6361/201117119.

[70] V. J. Sterken, N. Altobelli, S. Kempf, H. Krüger, R. Srama, et al., "The filtering of interstellar dust in the solar system," *Astron. Astrophys.*, vol. 552, art. A130, 2013, https://doi.org/10.1051/0004-6361/201219609.

[71] P. C. Frisch, S. Redfield, and J. D. Slavin, "The interstellar medium surrounding the Sun," *Annu. Rev. Astron. Astrophys.*, vol. 49, pp. 237–279, 2011, https://doi.org/10.1146/annurev-astro-081710-102613.

[72] M. Landgraf, "Modeling the motion and distribution of interstellar dust inside the heliosphere," *J. Geophys. Res.*, vol. 105, no. A5, pp. 10303–10316, 2000, https://doi.org/10.1029/1999ja900243.

[73] M. Landgraf, H. Krüger, N. Altobelli, and E. Grün. "Penetration of the heliosphere by the interstellar dust stream during solar maximum," *J. Geophys. Res. Space Phys.*, vol. 108, no. A10, art. 8030, 2003, https://doi.org/10.1029/2003ja009872.

[74] B. T. Draine, "Perspectives on interstellar dust inside and outside of the heliosphere," *Space Sci. Rev.*, vol. 143, pp. 333–345, 2009, https://doi.org/10.1007/s11214-008-9411-7.

[75] J. C. Weingartner and B. T. Draine, "Dust grain-size distributions and extinction in the Milky Way, large Magellanic Cloud, and Small Magellanic Cloud," *Astrophys. J.*, vol. 548, no. 1, art. 296, 2001, https://doi.org/10.1086/318651.

[76] V. J. Sterken, L. R. Baalmann, B. T. Draine, E. Godenko, K. Herbst, et al., "Dust in and around the heliosphere and astrospheres," *Space Sci. Rev.*, vol. 218, art. 71, 2022, https://doi.org/10.1007/s11214-022-00939-7.

[77] P. Strub, H. Krüger, and V. J. Sterken, "Sixteen years of Ulysses interstellar dust measurements in the solar system. II. Fluctuations in the dust flow from the data," *Astrophys. J.*, vol. 812, no. 2, art. 140, 2015, https://doi.org/10.1088/0004-637x/812/2/140.

[78] V. J. Sterken, A. J. Westphal, N. Altobelli, D. Malaspina, and F. Postberg, "Interstellar dust in the solar system," *Space Sci. Rev.*, vol. 215, art. 43, 2019, https://doi.org/10.1007/s11214-019-0607-9.

[79] E. A. Godenko and V. V. Izmodenov, "Effects of dispersion of the dust velocity in the LISM on the interstellar dust distribution inside the heliosphere," *Astron. Lett.*, vol. 47, pp. 50–60, 2021, https://doi.org/10.1134/S1063773721010047.

[80] W. C. Fraser, S. B. Porter, H. W. Lin, K. Napier, and J. R. Spence, "Approaches to detecting Kuiper Belt objects for NASA's New Horizons extended mission: Digging into the noise," in *Proc. 54th Lunar and Planet. Sci. Conf. 2023 (LPI)*, Contrib. No. 2806, https://www.hou.usra.edu/meetings/lpsc2023/pdf/2361.pdf.

[81] S. B. Porter, J. R. Spencer, S. Benecchi, A. J. Verbiscer, A. M. Zangari, et al., "The first high-phase observations of a KBO: New Horizons imaging of (15810) 1994 JR$_1$ from the Kuiper Belt," *Astrophys. J.*, 2016., vol. 828, no. 2, art. L15, https://doi.org/10.3847/2041-8205/828/2/l15.

[82] S. Porter, S. Benecchi, A. Verbiscer, J. Keane, J. Spencer, et al., "The poles and shapes of seven Kuiper Belt objects as measured from New Horizons," Abstract B1.2-0002-22, *44th COSPAR Scientific Assem.*, July 16–24, 2022.

[83] A. J. Verbiscer, P. Helfenstein, S. B. Porter, S. D. Benecchi, J. J. Kavelaars, et al., "The diverse shapes of dwarf planet and large KBO phase curves observed from New Horizons," *Planet. Sci. J.*, vol. 3, no. 4, art. 95, 2022, https://doi.org/10.3847/PSJ/ac63a6,

[84] H. A. Weaver, S. B. Porter, J. R. Spencer, and the New Horizons Science Team, "High-resolution search for Kuiper Belt object binaries from New Horizons," *Planet. Sci. J.*, vol. 3, no. 2, art. 46, 2022, https://doi.org/10.3847/PSJ/ac4cb7.

[85] A. J. Verbiscer, S. Porter, S. D. Benecchi, J. J. Kavelaars, H. A. Weaver, et al., "Phase curves from the Kuiper Belt: Photometric properties of distant Kuiper Belt objects observed by New Horizons," *Astronomical J.*, vol. 158, no. 3, art. 123, 2019, https://doi.org/10.3847/1538-3881/ab3211.

[86] W. B. McKinnon, D. C. Richardson, J. C. Marohnic, J. T. Keane, W. M. Grundy, et al., "The solar nebula origin of (486958) Arrokoth, a primordial contact binary in the Kuiper Belt," *Science*, vol. 367, no. 6481, art. aay6620, 2020, https://doi.org/10.1126/science.aay6620.

[87] D. Nesvorný, R. Li, J. B. Simon, A. N. Youdin, D. C. Richardson, et al., "Binary planetesimal formation from gravitationally collapsing pebble clouds," *Planet. Sci. J.*, vol. 2, art. 27, 2021, https://doi.org/10.3847/PSJ/abd858.

[88] H. F. Levison, A. Morbidelli, C. Van Laerhoven, R. Gomes, and K. Tsiganis, "Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune," *Icarus*, vol. 196, no. 1, pp. 258–273, 2008, https://doi.org/10.1016/j.icarus.2007.11.035.

[89] R. Gomes, D. Nesvorný, A. Morbidelli, R. Deienno, and E. Nogueira, "Checking the compatibility of the cold Kuiper Belt with a planetary instability migration model," *Icarus*, vol. 306, pp. 319–327, 2018, https://doi.org/10.1016/j.icarus.2017.10.018.

[90] J. L. Elliot, S. D. Kern, K. B. Clancy, A. A. S. Gulbis, R. L. Millis, et al., "The Deep Ecliptic Survey: A search for Kuiper Belt Objects and centaurs. II. Dynamical classification, the Kuiper Belt plane, and the core population," *Astronom. J.*, vol. 129, no. 2, pp. 1117–1162, 2005, https://dx.doi.org/10.1086/427395.

[91] M. Piquette, A. R. Poppe, E. Bernardoni, J. R. Szalay, D. James, et al., "Student Dust Counter: Status report at 38 AU," *Icarus*, vol. 321, pp. 116–125, 2019, https://doi.org/10.1016/j.icarus.2018.11.012.

[92] D. A. Gurnett, J. A. Ansher, W. S. Kurth, and L. J. Granroth, "Micron-sized dust particles detected in the outer solar system by the Voyager 1 and 2 plasma wave instruments," *Geophys. Res. Lett.*, vol. 24, no. 24, pp. 3125–3128, 1997, https://doi.org/10.1029/97gl03228.

[93] A. R. Poppe, C. M. Lisse, M. Piquette, M. Zemcov, M. Horányi, et al., "Constraining the solar system's debris disk with in situ New Horizons measurements from the Edgeworth–Kuiper Belt," *Astrophys. J.*, vol. 881, no. 1, art. L12, 2019, https://doi.org/10.3847/2041-8213/ab322a.

[94] M. Horányi, V. Hoxie, D. James, A. Poppe, C. Bryant, et al., "The Student Dust Counter on the New Horizons mission," *Space Sci. Rev.*, vol. 140, pp. 387–402, 2008, https://doi.org/10.1007/s11214-007-9250-y.

[95] A. Poppe, D. James, B. Jacobsmeyer, and M. Horányi, "First results from the Venetia Burney Student Dust Counter on the New Horizons mission," *Geophys. Res. Lett.*, vol. 37, no. 11, art. L11101, 2010, https://doi.org/10.1029/2010GL043300.

[96] J. R. Szalay, M. Piquette, and M. Horányi, "The Student Dust Counter: Status report at 23 AU," *Earth Planets Space*, vol. 65, pp. 1145–1149, 2013, https://doi.org/10.5047/eps.2013.02.005.

[97] E. Bernardoni, M. Horányi, A. Doner, M. Piquette, J. R. Szalay, et al., "Student Dust Counter status report: The first 50 au," *Planet. Sci. J.*, vol. 3, no. 3, art. 69, 2022, https://doi.org/10.3847/PSJ/ac5ab7.

[98] A. R. Poppe, "An improved model for interplanetary dust fluxes in the outer Solar System," *Icarus*, vol. 264, pp. 369–386, 2016, https://doi.org/10.1016/j.icarus.2015.10.001.

[99] J. I. Moses and A. R. Poppe, "Dust ablation on the giant planets: Consequences for stratospheric photochemistry," *Icarus*, vol. 297, pp. 33–58, 2017, https://doi.org/10.1016/j.icarus.2017.06.002.

[100] A. R. Poppe and M. Horányi, "Interplanetary dust delivery of water to the atmospheres of Pluto and Triton," *Astron. Astrophys.*, vol. 617, art. L5, 2018, https://doi.org/10.1051/0004-6361/201833980.

[101] S. A. Stern, "Signatures of collisions in the Kuiper Disk," *Astronom. Astrophys.*, vol. 310, pp. 999–1010, 1996.

[102] S. Yamamoto and T. Mukai, "Dust production by impacts of interstellar dust on Edgeworth-Kuiper Belt objects," *Astron. Astrophys.*, vol. 329, pp. 785–791, 1998.

[103] J.-M. Petit, J. J. Kavelaars, B. J. Gladman, R. L. Jones, J. Wm. Parker, et al., "The Canada-France Ecliptic Plane Survey—Full data release: The orbital structure of the Kuiper Belt," *Astronom. J.*, vol. 142, no. 4, art. 131, 2011, https://doi.org/10.1088/0004-6256/142/4/131.

[104] M. C. Wyatt, "Evolution of debris disks," *Annu. Rev. Astron. Astrophys.*, vol. 46, pp. 339–383, 2008, https://doi.org/10.1146/annurev.astro.45.051806.110525.

[105] C. M. Lisse, M. C. Wyatt, C. H. Chen, A. Morlok, D. M. Watson, et al., "Spitzer evidence for a late-heavy bombardment and the formation of ureilites in η Corvi at ~1 Gyr," *Astrophys. J.*, vol. 747, no. 2, art. 93, 2012, https://doi.org/10.1088/0004-637x/747/2/93.

[106] G. Bryden, C. A. Beichman, D. E. Trilling, G. H. Rieke, E. K. Holmes, et al., "Frequency of debris disks around solar-type stars: First results from a Spitzer MIPS Survey," *Astrophys. J.*, vol. 636, pp. 1098–1113, 2006, https://doi.org/10.1086/498093.

[107] G. Bryden, C. A. Beichman, J. M. Carpenter, G. H. Rieke, K. R. Stapelfeldt, et al., "Planets and debris disks: Results from a Spitzer/MIPS search for infrared excess," *Astrophys. J.*, vol. 705, no. 2, pp. 1226–1236, 2009, https://doi.org/10.1088/0004-637x/705/2/1226.

[108] C. Eiroa, J. P. Marshall, A. Mora, B. Montesinos, O. Absil, et al., "DUst around NEarby Stars. The survey observational results," *Astron. Astrophys.*, vol. 555, art. A11, 2013, https://doi.org/10.1051/0004-6361/201321050.

[109] C. H. Chen, T. Mittal, M. Kuchner, W. J. Forrest, C. M. Lisse, et al., "The Spitzer infrared spectrograph debris disk catalog. I. Continuum analysis of unresolved targets," *Astrophys. J. Suppl. Ser.*, vol. 211, art. 25, 2014, https://doi.org/10.1088/0067-0049/211/2/25.

[110] A. M. Hughes, G. Duchêne, and B. C. Matthews, "Debris disks: Structure, composition, and variability," *Annu. Rev. Astron. Astrophys.*, vol. 56, pp. 541–591, 2018, https://doi.org/10.1146/annurev-astro-081817-052035.

[111] D. C. Hines, G. Schneider, D. Hollenbach, E. E. Mamajek, L. A. Hillenbrand, et al., "The Moth: An unusual circumstellar structure associated with HD 61005," *Astrophys. J.*, vol. 671, no. 2, art. L165, 2007, https://doi.org/10.1086/525016.

[112] J. H. Debes, A. J. Weinberger, and M. J. Kuchner, "Interstellar medium sculpting of the HD 32297 debris disk," *Astrophys. J.*, vol. 702, pp. 318–326, 2009, https://doi.org/10.1088/0004-637x/702/1/318.

[113] A. Y. Abedin, J. J. Kavelaars, S. Greenstreet, J.-M. Petit, B. Gladman, et al., "OSSOS. XXI. Collision probabilities in the Edgeworth-Kuiper Belt," *Astronom. J.*, vol. 161, no. 4, art. 195, 2021, https://doi.org/10.3847/1538-3881/abe418.

[114] A. A. Penzias and R. W. Wilson, "A measurement of excess antenna temperature at 4080 Mc/s," *Astrophys. J.*, vol. 142, pp. 419–421, 1965, https://doi.org/10.1086/148307.

[115] A. Cooray, "Extragalactic background light measurements and applications," *Roy. Soc. Open Sci.*, vol. 3, no. 3, art. 150555, 2016, https://doi.org/10.1098/rsos.150555.

[116] C. C. Williams, E. Curtis-Lake, K. N. Hainline, J. Chevallard, B. E. Robertson, et al., "The JWST Extragalactic Mock Catalog: Modeling galaxy populations from the UV through the near-IR over 13 billion years of cosmic history," *Astrophys. J. Suppl. Ser.*, vol. 236, no. 2, art. 33, 2018, https://doi.org/10.3847/1538-4365/aabcbb.

[117] A. Saldana-Lopez, A. Domínguez, P. G. Pérez-González, J. Finke, M. Ajello, et al., "An observational determination of the evolving extragalactic background light from the multiwavelength HST/CANDELS survey in the Fermi and CTA era," *Monthly Notices Roy. Astronom. Soc.*, vol. 507, pp. 5144–5160, 2021, https://doi.org/10.1093/mnras/stab2393,

[118] T. R. Lauer, M. Postman, H. A. Weaver, J. R. Spencer, S. A. Stern, et al., "New Horizons observations of the cosmic optical background," *Astrophys. J.*, vol. 906, no. 2, art. 77, 2021, https://doi.org/10.3847/1538-4357/abc881.

[119] National Academies of Sciences, Engineering, and Medicine, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*. Washington, DC: National Academies Press, 2021.

[120] The Fermi-LAT Collaboration, "A gamma-ray determination of the Universe's star formation history," *Science*, vol. 362, no. 6418, pp. 1031–1034, 2018, https://doi.org/10.1126/science.aat8123.

[121] A. Ringwald and K. Saikawa, "Axion dark matter in the post-inflationary Peccei-Quinn symmetry breaking scenario," *Phys. Rev. D*, vol. 93, art. 085031, 2016, https://doi.org/10.1103/PhysRevD.93.085031. Erratum *Phys. Rev. D*. vol. 94, art. 049908, 2016.

[122] M. Zemcov, P. Immel, C. Nguyen, A. Cooray, C. M. Lisse, and A. R. Poppe, "Measurement of the cosmic optical background using the long range reconnaissance imager on New Horizons," *Nature Commun.*, vol. 8, art. 15003, 2017, https://doi.org/10.1038/ncomms15003.

[123] T. R. Lauer, M. Postman, J. R. Spencer, H. A. Weaver, S. A. Stern, et al., "Anomalous flux in the cosmic optical background detected with New Horizons observations," *Astrophys. J. Lett.*, vol. 927, no. 1, art. L8, 2022, https://doi.org/10.3847/2041-8213/ac573d.

[124] C. J. Conselice, A. Wilkinson, K. Duncan, and A. Mortlock, "The evolution of galaxy number density at $z < 8$ and its implications," *Astrophys. J.*, vol. 830, no. 2, art. 83, 2016, https://doi.org/10.3847/0004-637x/830/2/83.

[125] M. S. Akshaya, J. Murthy, S. Ravichandran, R. C. Henry, and J. Overduin, "The diffuse radiation field at high galactic latitudes," *Astrophys. J.*, vol. 858, no. 2, art. 101, 2018, https://doi.org/10.3847/1538-4357/aabcb9.

[126] M. S. Kulkarni, "Modeling the formation, evolution, and observation of first stars," PhD thesis, Columbia Univ., 2021, https://doi.org/10.7916/d8-tsa9-sv91.

[127] A. S. Stern, D. C. Slater, J. Scherrer, J. Stone, G. Dirks, et al., "ALICE: The ultraviolet imaging spectrograph aboard the New Horizons Pluto–Kuiper Belt mission," *Space Sci. Rev.*, vol. 140, pp. 155–187, 2008, https://doi.org/10.1007/s11214-008-9407-3.

[128] P. C. Brandt, E. Provornikova, S. D. Bale, A. Cocoros, R. DeMajistre, et al., "Future exploration of the outer heliosphere and Very Local Interstellar Medium by Interstellar Probe," *Space Sci. Rev.*, vol. 219, art. 18, 2023, https://doi.org/10.1007/s11214-022-00943-x.

[129] R. L. McNutt, R. F. Wimmer-Schweingruber, M. Gruntman, S. M. Krimigis, E. C. Roelof, et al., "Interstellar probe — Destination: Universe!," *Acta Astronaut.*, vol. 196, pp. 13–28, 2022, https://doi.org/10.1016/j.actaastro.2022.04.001.

Pontus C. Brandt, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Pontus C. Brandt is the deputy project scientist on the New Horizons mission and the principal investigator of the Jovian Energetic Electrons (JoEE) and the Jovian Energetic Neutrals and Ions (JENI) instruments onboard the European Space Agency's Jupiter Icy Moon Explorer (JUICE) mission. He recently served as the project scientist for the Interstellar Probe Mission Concept Study 2019–2022. He received an MS from Lund University and a PhD in space plasma physics at the Swedish Institute of Space Physics. He has been involved in the NASA IMAGE (Imager for Magnetopause-to-Aurora Global Exploration), TWINS (Two Wide-Angle Imaging Neutral-Atom Spectrometers), and Cassini missions and the European Space Agency Cluster, Mars, and Venus Express missions. In 2021, he was elected a full member of the International Academy of Astronautics. His email address is pontus.brandt@jhuapl.edu.

Heather A. Elliott, Southwest Research Institute, San Antonio, TX

Heather A. Elliott is a space plasma physicist and an adjoint professor at the Southwest Research Institute. She has a BS in physics from Clemson University, and MS in atmospheric and space science from the University of Michigan, and a PhD in physics from the University of Alabama in Huntsville. Heather is deputy principal investigator of New Horizons' Solar Wind Around Pluto (SWAP) instrument and a co-investigator on Interstellar Mapping and Acceleration Probe (IMAP) and Polarimeter to UNify the Corona and Heliosphere (PUNCH). Her research areas include analysis of large-scale structure in the solar wind; space weather impact on geophysical indices and the Global Positioning System (GPS); forecasting the solar wind at Earth; solar wind interaction with planets, objects, and interstellar material solar wind composition; and ion outflow from Earth's polar magnetosphere. In 2023, the National Oceanic and Atmospheric Administration appointed her to a three-year term on its new Space Weather Advisory Group (SWAG). Her email address is helliott@swri.edu

Matthew E. Hill, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Matthew E. Hill is a scientist in APL's Space Exploration Sector. He has a BS in physics from Rutgers University and a PhD in physics from the University of Maryland College Park. He concentrates on experimental particle physics in the space environment, and his interests range from suprathermal pickup ions to galactic cosmic rays observed from the margins of the Sun's corona to the shallows of interstellar space. Matt has been the instrument scientist for the New Horizons PEPSSI team since the 2007 Jupiter magnetotail cruise and co-investigator (Co-I) on the mission since before the 2015 Pluto encounter. He was the 2003 recipient of the American Geophysical Union's Fred L. Scarf Award for his dissertation on anomalous cosmic ray transport phenomena, primarily studied with observations he made with the Voyager 1 and 2 Low Energy Charged Particle (LECP) instruments, an APL-led experimental investigation he later joined as Co-I and for which he was named deputy principal investigator in 2023. Additional roles on other NASA missions include deputy instrument lead and Co-I on APL's EPI-Lo instrument, the low-energy component of the Princeton-led ISOIS energetic particle suite on Parker Solar Probe, a mission built, operated, and managed at APL. He also was part of the Cassini/MIMI team. His email address is matt.hill@jhuapl.edu.

Peter Kollmann, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Peter Kollmann is a staff scientist in APL's Space Exploration Sector. He has the German equivalent of a BS and an MS in physics from the University of Stuttgart and a PhD in natural sciences from the University of Braunschweig and the Max Planck Institute for Solar System Research. He studies space radiation throughout our solar system using satellite observations and theory and is deeply involved with all the recent planetary missions to Jupiter and Saturn, as well as other missions such as New Horizons and Lunar Vertex. He supports several missions through leadership roles, such as project scientist on Jupiter Icy Moon Explorer (JUICE)/Particle Environment Package (PEP)-Hi, deputy instrument scientist on New Horizons/Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI), and instrument scientist on Lunar Vertex/Magnetic Anomaly Plasma Spectrometer (MAPS). His email address is peter.kollmann@jhuapl.edu.

Parisa S. Mostafavi, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Parisa S. Mostafavi is a space scientist in APL's Space Exploration Sector. She holds an MS in plasma engineering from Shahid Beheshti University, as well as an MS and a PhD in space science from the University of Alabama in Huntsville. Her PhD thesis work focused on shock waves mediated by energetic particles and earned the American Geophysical Union (AGU) Fred L. Scarf Award in 2020, given annually to one honoree to recognize an outstanding dissertation that contributes directly to solar-planetary science. In 2019, she was the recipient of the Graduate Research Award in the University of Alabama in Huntsville College of Science. Additionally, she spent the final year of her PhD at Princeton University, where she was granted the position of visiting student research collaborator. Parisa's research interests encompass the investigation of the structure and properties of solar wind and energetic particles within both the inner and outer heliosphere. She is a science co-investigator on the SHIELD NASA Drive Center. Throughout her career, Parisa has participated in various missions and mission concepts, including Parker Solar Probe, New Horizons, InterMeso Heliophysics Mission Concept Studies (HMCS), Interstellar

Probe HMCS, and Solar Neutral Atoms Probe (SNAP) Small Explorer (SMEX). She has served on the AGU Union Medal, Award, and Prize (UMAP) Committee since 2022. Her email address is parisa.mostafavi@jhuapl.edu.

Ralph L. McNutt Jr., Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Ralph L. McNutt Jr. is a physicist in APL's Space Exploration Sector. He received a BS in physics (summa cum laude) from Texas A&M University and a PhD in physics from the Massachusetts Institute of Technology (MIT). Ralph was a member of the Ion and Neutral Mass Spectrometer Team for NASA's Cassini mission to Saturn and is a co-investigator on NASA's Voyager, New Horizons, and Parker Solar Probe operating missions and on NASA's Europa Clipper, now under development. An author on over 220 papers, he co-chaired National Academies studies on radioisotope power systems and NASA's large strategic science missions, was the principal investigator on the study of a pragmatic interstellar probe mission for NASA's Heliophysics Division (2018–2022), chaired the nuclear power assessment study for NASA (2015), and testified to Congress on radioisotope production and lessons learned from Cassini (2017). He was chief scientist for NASA's Planetary Data System and led its 2017 roadmap study. Ralph is a member and trustee of the International Academy of Astronautics (IAA) and an associate fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is a recipient of the APL Lifetime Publication Award (2020), the NASA Silver Achievement Medal (awarded to the Parker Solar Probe Team in 2019), three IAA Laurels for Team Achievement Awards (awarded to the Parker Solar Probe team in 2021, the New Horizons team in 2016, and the MESSENGER team in 2012), and 13 NASA Group Achievement Awards. Minor planet 172191 Ralphmcnutt is named for him. His email address is ralph.mcnutt@jhuapl.edu.

Fran Bagenal, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO

Fran Bagenal is a research scientist and the assistant director for planetary sciences at the Laboratory for Atmospheric and Space Physics (LASP). She studied physics and geophysics at the University of Lancaster and then, inspired by NASA's missions to Mars and the prospect of the Voyager mission, moved to the United States for graduate study at the Massachusetts Institute of Technology (MIT). She was professor of astrophysical and planetary sciences until 2015 when she chose to focus on NASA's New Horizons and Juno missions. Fran studies the magnetic fields of planets and the charged particles trapped therein. She has participated in many of NASA's planetary exploration missions, including Galileo, Deep Space 1, and the Voyager mission to Jupiter, Saturn, Uranus, and Neptune. On the Voyager mission, Fran worked on the science team for the MIT Voyager plasma instrument. She is currently co-investigator on the New Horizons missions to Pluto, as well as the chair of the magnetospheres working group for the Juno mission to Jupiter. She edited *Jupiter: Planet, Satellites and Magnetosphere* (Cambridge University Press, 2004) and is a member of the National Academy of Sciences. Her email address is bagenal@colorado.edu.

Andrew R. Poppe, Space Sciences Laboratory, University of California at Berkeley, Berkeley, CA

Andrew R. Poppe is associate research scientist at the Space Sciences Laboratory at the University of California at Berkeley. He has a PhD in physics from the University of Colorado at Boulder. Andrew works on a variety of space-related research projects. One of his main research areas is the analysis and modeling of ARTEMIS observations of lunar-plasma interactions, specifically the lunar wake, lunar exospheric pick-up ions, lunar magnetic anomalies, and the near-surface lunar photoelectron sheath. He also works in the field of interplanetary dust dynamics, specifically focusing on dust populations, dynamics, and fluxes in the outer solar system. As a graduate student, Andrew worked on the New Horizons Venetia Burney Student Dust Counter, which is an instrument that measures the density of interplanetary dust grains in the outer solar system. Using data collected both before and after the Pluto system flyby in 2015, he has compared these measurements to dynamical models of how dust grains behave in the outer solar system, where a variety of forces (e.g., gravity from the outer planets) perturbs the orbits of these dust grains. Andrew also investigates the influx of these grains into the atmospheres and onto the moons and rings of the outer planets, and how this influx might affect the outer planets. His email address is poppe@berkeley.edu.

Veerle J. Sterken, Department of Physics, ETH Zurich, Zurich, Switzerland

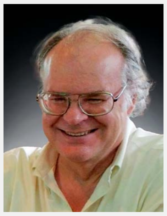
Veerle J. Sterken is a research scientist and group leader at the ETH Zürich in Switzerland. After high school in Belgium, she studied aerospace engineering at the TU Delft and obtained a PhD in geophysics at the TU Braunschweig. Her main focus of research is the dynamics of interstellar dust in the solar system, by using computer simulations and data analysis. She also performed instrument calibration experiments and led or participated in future mission studies. She worked on several projects for the European Space Agency (systems engineering), Delft University of Technology/Thales Alenia Space (spacecraft engineering), the University of Berne (precise orbit dynamics), and the International Space Sciences Institute (cosmic dust research). After working in science administration at the Swiss National Science Foundation, she returned to science with an ERC Starting Grant for research on interstellar dust and heliospheric sciences (ASTRODUST, N° 851544). She has co-edited three scientific books and (co-)authored 46 refereed publications. Veerle has received a few prizes, among them the Amelia Earhart Award in 2007 and the Christophe Plantin Prize in 2021. Her email address is vsterken@ethz.ch.

Jonathan D. Slavin, Smithsonian Astrophysical Observatory, Harvard and Smithsonian Center for Astrophysics, Cambridge, MA

Jonathan D. Slavin is an astrophysicist working in the High Energy Astrophysics Division of the Smithsonian Astrophysical Observatory. He has a PhD in physics from the University of Wisconsin-Madison. His research interests center on the diffuse interstellar medium (ISM), especially supernova remnants and dust. Supernovae inject energy into the ISM and their shock waves destroy dust. A particular interest is the nature of the local interstellar medium (LISM), the region of the ISM that is closest to us, including the gas and dust that is able to penetrate into the solar system from the surrounding Local Interstellar Cloud. Jonathan's work includes numerical hydrodynamics and modeling the dust and gas processes in shocks. His email address is jslavin@cfa.harvard.edu.

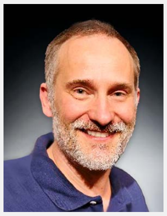
Lawrence E. Brown, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Lawrence E. Brown is a programmer/systems analyst in APL's Space Exploration Sector. He has a BS in mathematical physics from Southwestern Adventist University and a PhD in physics from the University of Chicago. Lawrence has written visualization, analysis, calibration, and modeling software and maintained science data pipelines for a number of space-based instruments observing charged particles, gamma rays, and x-rays. Current missions he supports include Jupiter Icy Moon Explorer (JUICE), Juno, Parker Solar Probe, Interstellar Mapping and Acceleration Probe (IMAP), New Horizons, and Voyager, and he also supports multiple independent research and development (IRAD) projects. His email address is lawrence.brown@jhuapl.edu.



Tod R. Lauer, National Optical Astronomy Observatory, Tucson, AZ

Tod R. Lauer is an astronomer on the research staff of the National Optical Astronomy Observatory. He holds a BS in Astronomy from the California Institute of Technology and a PhD in astronomy from the University of California, Santa Cruz. Tod was a member of the Hubble Space Telescope Wide Field and Planetary Camera team and is a founding member of the Nuker Team. His research interests include observational searches for massive black holes in the centers of galaxies, the structure of elliptical galaxies, stellar populations, large scale structure of the Universe, and astronomical image processing. He was recently the principal investigator of the Destiny JDEM concept study. Tod was awarded the NASA Exceptional Scientific Achievement Medal for his work with the Wide-Field and Planetary Camera aboard the Hubble Space Telescope, was twice awarded the AURA Outstanding Achievement Award for Outstanding Science by the Association of Universities for Research in Astronomy, and shared in the 2017 NASA Group Achievement Award presented to the New Horizons team and the 2020 Breakthrough Prize in Fundamental Physics presented to the Event Horizon Telescope collaboration. Asteroid 3135 Lauer is named for him. His email address is tod.lauer@noirlab.edu.

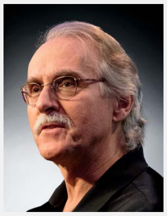


William M. Grundy, Lowell Observatory, Flagstaff, AZ

William M. Grundy is a planetary scientist at Lowell Observatory. He has a PhD from the University of Arizona. William makes spectroscopic, thermal, and imaging observations of outer solar system bodies using numerous large ground- and space-based telescopes including the Hubble Space Telescope, the James Webb Space Telescope, the Keck Observatory telescope, the Gemini Observatory telescope, the LDT, NASA's InfraRed Telescope Facility (IRTF), and the MMT Observatory telescope. Targets of these observations include icy satellites and Kuiper belt objects. Some of the larger bodies like Pluto, Triton, Eris, and Makemake have volatile surface ices that seasonally interact with their thin atmospheres, leading to a variety of complex and interesting phenomena. To support his observational work, he also studies cryogenic ices and ice mixtures in the Astrophysical Materials Laboratory at Northern Arizona University. William is involved in projects to discover Kuiper belt binaries and to determine their mutual orbits and masses, using the Hubble Space Telescope, as well as laser guide star adaptive optics techniques at the Keck and Gemini observatories. He is co-investigator on NASA's New Horizons mission that encountered the Pluto system in 2015 and the Kuiper belt object Arrokoth in 2019. He heads the mission's surface composition science theme team. His email address grundy@lowell.edu.

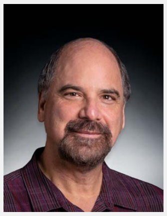
Anne J. Verbiscer, University of Virginia, Charlottesville, VA; and Southwest Research Institute, Boulder, CO

Anne J. Verbiscer is a research professor in the Department of Astronomy at the University of Virginia. She received her PhD in planetary science from Cornell University. Anne studies the icy surfaces of objects in the outer solar system using both ground-based and space-based telescopes. Using the Spitzer Space Telescope, she discovered Saturn's largest ring, the Phoebe Ring, in 2009. She is a co-investigator and deputy project scientist on New Horizons extended mission into the Kuiper Belt and was a member of the New Horizons science team for the Pluto and Arrokoth flybys. Her email address is verbiscer@boulder.swri.edu.



John R. Spencer, Southwest Research Institute, Boulder, CO

John R. Spencer is an institute scientist in Southwest Research Institute's Department of Space Studies. He obtained a BS in geology from the University of Cambridge and a PhD in planetary sciences from the University of Arizona. He specializes in studies of the moons of the outer planets, particularly the four large "Galilean" satellites of Jupiter, and other small outer solar system bodies, using theoretical models, Earth-based telescopes, close-up spacecraft observations, and the Hubble Space Telescope. John is a New Horizons science team member and a deputy project scientist for its extended mission into the Kuiper Belt. He coordinated the search for Kuiper Belt object (KBO) flyby targets beyond Pluto, which led to the discovery of New Horizons' next target, the small KBO Arrokoth. He also led New Horizons' search, during Pluto approach, for potential debris hazards in the Pluto system and led the science planning of the successful 2019 flyby of Arrokoth. In 2016 he won the American Geophysical Union (AGU) Whipple Award for "outstanding contributions in the field of planetary science," and in 2021 he was elected a fellow of the AGU. His email address is spencer@boulder.swri.edu.



Carey M. Lisse, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Carey M. Lisse is an astronomer n APL's Space Exploration Sector. He has an BA in chemistry from Princeton University, and MS in chemistry from the University of California at Berkeley, and an MS and a PhD in physics from the University of Maryland at College Park. Carey studies the formation and evolution of solar systems, including our own, from their beginnings through the formation of life, mainly through studying the clues left behind during their growth—the comets, asteroids, Kuiper Belt objects, gas, and dust left orbiting around stars as they age. He did his graduate work on the Nobel prize–winning Cosmic Background Explorer mission that characterized the radiation from the Big Bang. In 1996, he discovered x-ray emissions from Comet Hyakutake and Carbon star LSF1. He is also know for his work studying comets, exosystem detections of terrestrial planet formation, and observations of interstellar objects 1I/Oumuamua and 2I/Borisov. He was a member of the New Horizons Pluto and Arrokoth flyby science team studying how Kuiper Belt objects formed in the infant solar system. He has earned several awards, including the NASA Group Achievement Awards, NASA Special Achievement Awards, and an STScI Space Foundation Space Achievement Award. He is a fellow of American Association for the Advancement of Science. His email address is carey.lisse@jhuapl.edu.

Kelsi N. Singer, Southwest Research Institute, Boulder, CO

Kelsi N. Singer is a planetary scientist at the Southwest Research Institute. She has a BA in astronomy and anthropology from the University of Colorado and a PhD in earth and planetary science from Washington University in St. Louis. Kelsi studies the geology and geophysics of Pluto and Charon as a co-investigator and project scientist on the New Horizons mission. Her graduate research focused on the icy satellites of Jupiter, Saturn, and Neptune, and she also did postdoctoral research with the Lunar Reconnaissance Orbiter Camera (LROC), studying craters on Earth's moon. Kelsi received the American Astronomical Society (AAS) Division for Planetary Science (DPS) Harold C. Urey Prize in 2019, which recognizes outstanding achievements in planetary science by early-career researchers. Asteroid 10698 Singer was named in her honor. Her email address ksinger@boulder.swri.edu.

S. Alan Stern, Southwest Research Institute, Boulder, CO

S. Alan Stern is the associate vice president of Southwest Research Institute's space sector. He has an MS in atmospheric sciences from the University of Texas, an MS in aerospace engineering from the University of Texas, and a PhD in astrophysics and planetary science from the University of Colorado. In 2020, NASA appointed Alan to fly to space as a researcher aboard a commercial suborbital space mission. He formerly served as NASA's chief of space and Earth science programs. His career has taken him to numerous observatories, the South Pole, the Titanic, and the upper atmosphere aboard high-performance NASA aircraft. He has served on 29 space missions. He is a member of the US National Science Board and leads NASA's New Horizons mission to Pluto and the Kuiper Belt as its principal investigator. He has published over 440 technical papers and written three books. He is an associate fellow of the American Institute of Aeronautics and Astronautics (AIAA) and a fellow of the American Association for the Advancement of Science (AAAS), the Royal Astronomical Society (RAS), the American Geophysical Union (AGU), and the Explorer's Club. He was awarded the von Braun Aerospace Achievement Award, *Smithsonian Magazine*'s American Ingenuity Award, American Astronautical Society's Sagan Memorial Award, and NASA's Distinguished Public Service Medal. In both 2007 and 2016, he was named to the Time 100. His email address is astern@swri.org.