EXPLORING ICE GIANTS AT HIGH PHASE WITH NEW HORIZONS. H. B. Hammel[1], W. Grundy[2], A. Stern[3], J. Spencer[2], L.C. Mayorga[4], A.A. Simon[5], D. Wenkert[6], K. Singer[3], P. Brandt[4], A. Verbiscer[7], S. Benecchi[8] and the New Horizons Planetary Theme Team. [1]AURA, [2]Lowell, [3]SwRI, [4]APL, [5]GSFC, [6]JPL, [7]U. Virginia, [8]PSI.

Introduction: The New Horizons (NH) spacecraft has accomplished the objectives of its prime and first extended missions of exploring the Pluto system and the Kuiper Belt Object (KBO) Arrokoth. As the spacecraft embarks on its second extended "KEM 2" mission, a key theme is using the spacecraft to make unique observations across Planetary, Heliophysics, and Astrophysics disciplines. We focus here on the KEM 2 Planetary project to obtain high-phase, multi-color photometry of Uranus and Neptune. The data are of key importance not only to studies of these two ice giant planets, but also to studies of ice giant exoplanets.

Why Ice Giants: Uranus and its fraternal twin Neptune are a distinct class of giant planet dominated by heavier elements, unlike the H/He-dominated gas giant planets Jupiter and Saturn (**Fig. 1A**). The 2022 Planetary Decadal [1] identified a Uranus mission as the top flagship priority, and articulated key relevant ice giant questions, including: (1) what are the energy budgets and heat balances for the local ice giants, and what roles do H_2O and convection play; (2) what fraction of incident sunlight does each absorb, and how much thermal energy does each emit; and (3) what is the source of energy for the hot coronas and upper atmospheres of the ice giants. The NH observations are particularly relevant to the first two questions, and somewhat relevant to the third.

More broadly, because ice-giant-sized planets are common around other stars, high-phase angle observations of Uranus and Neptune are also highly valuable for exoplanet research. The 2021 Astrophysics Decadal [2] explicitly cited the need for ice giant studies (*e.g.*, pp. E-5, E-9, and E-10), noting the abundance of Neptune-class planets around other stars that can be studied with future large space telescopes (**Figs. 1A and 1B**). Stars less massive than the Sun in particular tend to host Neptune-class planets as their largest planets [3]. NH's high-phase data are important for exoplanet studies because such high phases are geometrically analogous to many future exoplanet observations.

Why NH Observations. From its vantage point deep within the Kuiper Belt, NH is uniquely able to study the atmospheres of Uranus and Neptune at high phase angles not accessible from any ground or any other space-based facilities. Earth-based observations are necessarily limited to very low phases angles (resolved data allows some study of emission angle dependencies by tracking clouds from center to limb). Voyager 2 *full-disk* encounter observations (imaging and broadband vis/NIR radiometer) were restricted to two narrow ranges of phase angle for each planet. Voyager 1 imaged Uranus and Neptune from great distances during the 1980s at 26°-107° and 15°-85° phase, respectively [4-7], but its limitations often resulted in low SNR results. Furthermore, Voyager imaging data were limited to wavelengths below about 0.6 µm. Phases accessible to NH in KEM 2, with its access to longer wavelengths, are shown in **Table 1**.

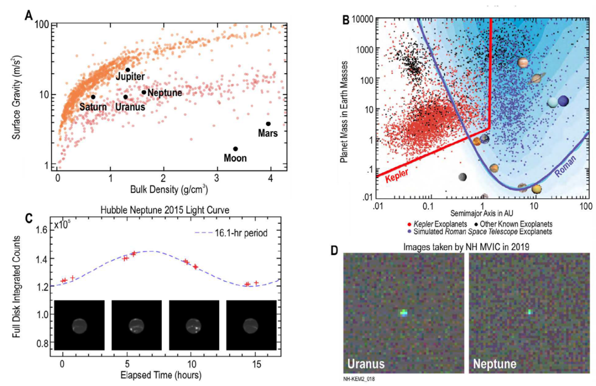

Figure 1. Uranus and Neptune in the context of known exoplanets. **A.** Density versus surface gravity for exoplanets with a low uncertainty in mass and radius: Uranus and Neptune trace a distinct branch of exoplanets (pink) that differ from gas giants (orange). **B.** Simulation of exoplanets likely to be detected with the Roman Space Telescope's microlensing survey (blue) compared with those discovered by Kepler (red) and other telescopes (black): Roman will be sensitive to those with orbits similar to the local ice giants (adapted from [8]). **C.** Neptune light curve from Hubble: cloud features affect rotational curves. **D.** Uranus and Neptune observed by MVIC in 2019 using single scans, the multicolor camera aboard NH: planned multiple scans in KEM 2 will investigate rotational modulation and permit averaging to increase overall SNR.

Table 1. Ice Giant Phase Geometry Details

Target	Previous Phases[1]	KEM 2 Phases[2]	KEM 2 Solar Elongations[2]
Uranus	26° - 107°	42° - 44°	13° - 14°
Neptune	15° - 83°	80° - 81°	30° - 32°

1 Previous high-phase observations include data from Voyager 1 as well as NH measurements in 2019.
2 KEM 2 Phases and elongations span in 2023-2024.

KEM 2's high-phase NH ice-giant data will constrain cloud and haze scattering behavior, aid interpretation of spectral studies of the atmospheres, and shed light on the physics of atmospheric aerosol particles. NH observations will also further constrain the radiative energy balance by filling in the reflected light phase curve. Radiative transfer analyses of atmospheric structure typically require high spatialresolution imaging at multiple viewing angles and wavelengths to obtain reliable results. For exoplanets, viewing geometries vary, but the planets are unresolved [9] and cannot give a unique radiative transfer solution without further analog studies ([2] p. E-5).

NH will view Uranus and Neptune as time-variable but unresolved objects at high phase angles (i.e., similar to exoplanets). But the power of these observations is they can then connect to ice-giant atmospheric characteristics gleaned from spatially-resolved Earth- and space-based imagery and spectra at low phase angles. The additional information provides much more robust quantification of the planets' distinct cloud/haze structures than the high-phase angle data alone [10, 11].

Planned KEM 2 Observations. A NH KEM 1 preliminary program in 2019 verified the ability to detect the ice giants (**Fig. 3D**). KEM 2 MVIC ice giant observations, will significantly improve on the KEM 1 and other prior ice giant data in several ways: extending the wavelength range of solar-phase-angle measurements to geometries not observable from Earth; securing higher S/N data; and obtaining high-phase observations at precisions and temporal cadences that will help disambiguate variability due to rotation.

Scaling from the KEM 1 20l9 data suggests that the 2023-24 MVIC data will yield SNRs in the Blue/Red/NIR filters of l4/34/5 and 4/6/1 per individual scan for Uranus and Neptune, respectively (Uranus and Neptune differ due to observing geometries). For both planets in 2024, scans can be combined to integrated SNR for Uranus of 34/84/13 and for Neptune of 11/17/3 in the same filters (2023 SNRs are slightly higher).

The low solar elongation of these KEM 2 observations (**Table 1**) is fine for MVIC, as it has previously observed at elongations as low as 11° without an appreciable increase in scattered light. Importantly, MVIC's color filters extend the wavelength range of high-phase Uranus and Neptune observations well beyond Voyager imaging's 0.6-μm cutoff, especially MVIC NIR filters that cover 0.78-0.98 μm. Given the decades since the Voyager flyby data, the NH observations will also sample new seasonal epochs on both ice giants, later by 46% of a Uranus orbit (~2 seasons) and 22% of a Neptune orbit (~1 season).

Uranus's rotational modulation is thought to be small, and because NH sees Uranus nearly pole-on, little diurnal variation is expected. Each year NH will make one observation set, consisting of six MVIC colors scans to build SNR (see numbers above). Neptune's well-documented temporal variability (**Fig. 1C**) drives the cadence of the KEM 2 Neptune observations. Nine MVIC color scans will be evenly spread over a single Neptune rotation in each of 2023 and 2024, providing sensitivity to both diurnal and seasonal changes.

Complementary Observations. The KEM 2 NH observations are synergistic with the Hubble Space Telescope's Outer Planet Atmosphere Legacy (OPAL) program [12, 13] which provides yearly Uranus and Neptune observations with Hubble at the low phases observable from Earth, and will continue to do so as long as Hubble can observe moving targets. OPAL includes discrete filter imaging from blue to near infrared with complete longitudinal coverage, and also resolves cloud activity (Fig. 3C), enabling better interpretation of the MVIC disk-averaged photometric results, as shown previously for interpreting Neptune data from the Kepler KEM 2 and Spitzer missions [12, 14]. JWST is also undertaking ice giant observations, but it may not be possible to get contemporaneous observations with NH. Any available ice giant data will be folded into the analysis program.

Expected Outcomes from the NH Ice Giant Observations. Contemporaneous observations from NH and Earth-based facilities will help break degeneracies in how the atmospheric aerosols scatter, better constraining their size and optical depth and reducing the number of free parameters. Uranus's phase curve was derived from Voyager 2 spatially-resolved broadband radiometer data [15]. Neptune and Uranus phase curve fits were also attempted with distant Voyager 1 and ground-based observations, but the uncertainties were large, particularly for Neptune, encompassing a broad range of possible aerosol properties [6]. The NH KEM 2 data will reduce uncertainties in the phase curve by an order of magnitude, while providing red/blue wavelength discrimination not available to either Voyager. The improvements allow accurate separation of aerosol single scattering albedo, particle size, and optical depth, reducing the number of free parameters in radiative transfer models [16].

In summary, the NH KEM 2 data of our ice giants, in combination with observations from the ground and space, will permit a comprehensive assessment of atmospheric radiation balance of Uranus and Neptune, as well as important context data for the growing population of exoplanets in the ice-giant size range.

References: [1] NRC (2022) Origins, Worlds, Life, doi: 10.17226/26522. [2] NRC (2021) Pathways to Discovery in Astronomy and Astrophysics, doi: 10.17226/26141. [3] Gould (2006) AJ 644, L37. [4] Smith (1986) Science 233, 43. [5] (1989) Science 246, 1422. [6] Pollack (1986) Icarus 65, 442. [7] Wenkert (2022) AGU Poster 32E-1865. [8] NRC (2018) Exoplanet Science Strategy, doi:10.17226/25187. [9] Carrión-González (2021) 15th EPSC 10.5194/epsc2021-694. [10] Irwin (2011) Icarus 212, 339. [11] Hueso (2020) 10.1098/rsta.2019.0476. [12] Simon (2016) ApJ 817, 162. [13] Simon (2022) Remote Sens. 14, 1518. [14] Stauffer (2016) AJ 152 142. [15] Pearl (1990) Icarus 84, 12-28. [16] Irwin (2017) Icarus 288, 99.