RESEARCH ARTICLE SUMMARY

PLANETARY SCIENCE

The small satellites of Pluto as observed by New Horizons

H. A. Weaver,* M. W. Buie, B. J. Buratti, W. M. Grundy, T. R. Lauer, C. B. Olkin, A. H. Parker, S. B. Porter, M. R. Showalter, J. R. Spencer, S. A. Stern, A. J. Verbiscer, W. B. McKinnon, J. M. Moore, S. J. Robbins, P. Schenk, K. N. Singer, O. S. Barnouin, A. F. Cheng, C. M. Ernst, C. M. Lisse, D. E. Jennings, A. W. Lunsford, D. C. Reuter, D. P. Hamilton, D. E. Kaufmann, K. Ennico, L. A. Young, R. A. Beyer, R. P. Binzel, V. J. Bray, A. L. Chaikin, J. C. Cook, D. P. Cruikshank, C. M. Dalle Ore, A. M. Earle, G. R. Gladstone, C. J. A. Howett, I. R. Linscott, F. Nimmo, J. Wm. Parker, S. Philippe, S. Protopapa, H. J. Reitsema, B. Schmitt, T. Stryk, M. E. Summers, C. C. C. Tsang, H. H. B. Throop, O. L. White, A. M. Zangari

INTRODUCTION: The Pluto system is surprisingly complex, comprising six objects that orbit their common center of mass in approximately a single plane and in nearly circular orbits. When the New Horizons mission was selected for flight by NASA in 2001, only the two largest objects were known: the binary dwarf planets Pluto and Charon. Two much smaller moons, Nix and Hydra, were discovered in May 2005, just 8 months before the launch of the New Horizons spacecraft, and two even smaller moons, Kerberos and Styx, were discovered in 2011 and 2012, respectively. The entire Pluto system was likely produced in the aftermath of a giant impact between two Pluto-sized bodies approximately 4 to 4.5 billion years ago, with the small moons forming within the resulting debris disk. But many details remain unconfirmed, and the New Horizons results on Pluto's small moons help to elucidate the conditions under which the Pluto system formed and evolved.

RATIONALE: Pluto's small moons are difficult to observe from Earth-based facilities, with only the most basic visible and near-infrared photometric measurements possible to date. The New Horizons flyby enabled a whole new category of measurements of Pluto's small moons. The Long Range Reconnaissance Imager (LORRI) provided high–spatial resolution panchromatic imaging, with thousands of pixels across the surfaces of Nix and Hydra and the first resolved images of Kerberos and Styx. In addition, LORRI was used to conduct systematic monitoring of the brightness of all four small moons over several months, from which the detailed rotational properties could be deduced. The Multispectral Visible Imaging Camera (MVIC) provided resolved color measurements of the surfaces of Nix and Hydra. The Linear Etalon Imaging Spectral Array (LEISA) captured near-infrared spectra (in the wavelength range 1.25 to 2.5 μm) of all the small moons for compositional studies, but those data have not yet been sent to Earth.

RESULTS: All four of Pluto's small moons are highly elongated objects with surprisingly high surface reflectances (albedos) suggestive of a water-ice surface composition. Kerberos appears to have a double-lobed shape, possibly formed by the merger of two smaller bodies. Crater counts for Nix and Hydra imply surface ages of at least 4 billion years. Nix and Hydra have mostly neutral (i.e., gray) colors, but an apparent crater on Nix's surface is redder than the rest of the surface; this finding suggests either that the impacting body had a different composition or that material with a different composition was excavated from below Nix's surface. All four small moons have rotational periods much shorter than their orbital periods, and their rotational poles are clustered nearly orthogonal to the direction of the common rotational poles of Pluto and Charon.

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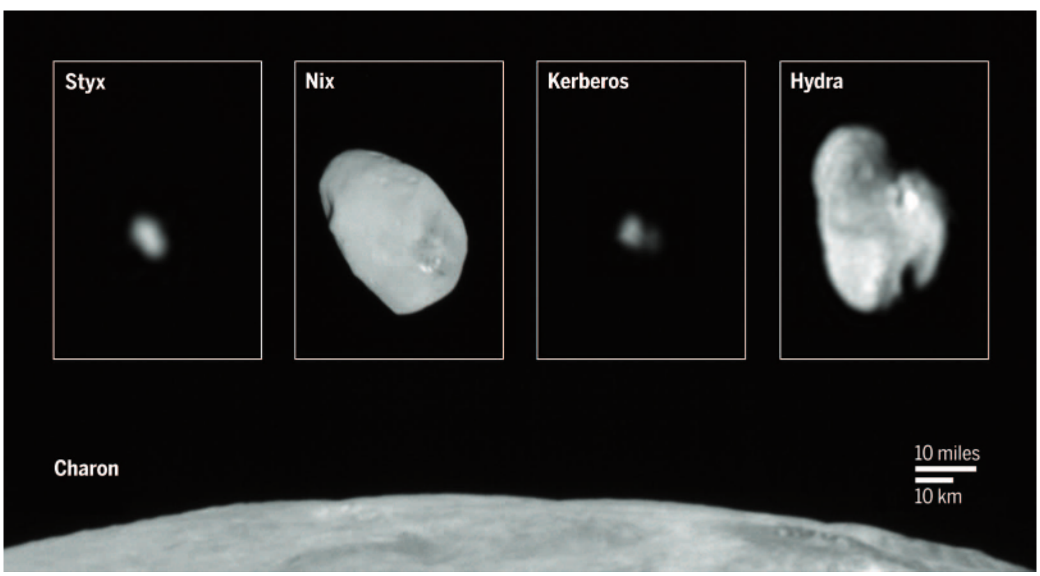
CONCLUSION: Pluto's small moons exhibit rapid rotation and large rotational obliquities, indicating that tidal despinning has not played the dominant role in their rotational evolution. Collisional processes are implicated in determining the shapes of the small moons, but collisional evolution was probably limited to the first several hundred million years after the system's formation. The bright surfaces of Pluto's small moons suggest that if the Pluto-Charon binary was produced during a giant collision, the two precursor bodies were at least partially differentiated with icy surface layers. ■



Pluto's family of satellites. NASA's New Horizons mission has resolved Pluto's four small moons, shown in order of their orbital distance from Pluto (from left to right). Nix and Hydra have comparable sizes (with equivalent spherical diameters of ~40 km) and are much larger than Styx and Kerberos (both of which have equivalent spherical diameters of ~10 km). All four of these moons are highly elongated and are dwarfed in size by Charon, which is nearly spherical with a diameter of 1210 km. The scale bars apply to all images.

The list of author affiliations is available in the full article online.
*Corresponding author. E-mail: hal.weaver@jhuapl.edu
Cite this article as H. A. Weaver *et al.*, *Science* 351, aae0030 (2016). DOI: 10.1126/science.aae0030

RESEARCH ARTICLE

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The small satellites of Pluto as observed by New Horizons

H. A. Weaver,[1]* M. W. Buie,[2] B. J. Buratti,[3] W. M. Grundy,[4] T. R. Lauer,[5] C. B. Olkin,[2] A. H. Parker,[2] S. B. Porter,[2] M. R. Showalter,[6] J. R. Spencer,[2] S. A. Stern,[2] A. J. Verbiscer,[7] W. B. McKinnon,[8] J. M. Moore,[9] S. J. Robbins,[2] P. Schenk,[10] K. N. Singer,[2] O. S. Barnouin,[1] A. F. Cheng,[1] C. M. Ernst,[1] C. M. Lisse,[1] D. E. Jennings,[11] A. W. Lunsford,[11] D. C. Reuter,[11] D. P. Hamilton,[12] D. E. Kaufmann,[2] K. Ennico,[9] L. A. Young,[2] R. A. Beyer,[6,9] R. P. Binzel,[13] V. J. Bray,[14] A. L. Chaikin,[15] J. C. Cook,[2] D. P. Cruikshank,[9] C. M. Dalle Ore,[9] A. M. Earle,[14] G. R. Gladstone,[16] C. J. A. Howett,[2] I. R. Linscott,[17] F. Nimmo,[18] J. Wm. Parker,[2] S. Philippe,[19] S. Protopapa,[12] H. J. Reitsema,[2] B. Schmitt,[19] T. Stryk,[20] M. E. Summers,[21] C. C. C. Tsang,[2] H. H. B. Throop,[22] O. L. White,[9] A. M. Zangari[2]

The New Horizons mission has provided resolved measurements of Pluto's moons Styx, Nix, Kerberos, and Hydra. All four are small, with equivalent spherical diameters of ~40 kilometers for Nix and Hydra and ~10 kilometers for Styx and Kerberos. They are also highly elongated, with maximum to minimum axis ratios of ~2. All four moons have high albedos (~50 to 90%) suggestive of a water-ice surface composition. Crater densities on Nix and Hydra imply surface ages of at least 4 billion years. The small moons rotate much faster than synchronous, with rotational poles clustered nearly orthogonal to the common pole directions of Pluto and Charon. These results reinforce the hypothesis that the small moons formed in the aftermath of a collision that produced the Pluto-Charon binary.

Pluto's four small moons Styx, Nix, Kerberos, and Hydra (in order of increasing distance from Pluto; hereafter we refer to this sequence as SNKH) were discovered using the Hubble Space Telescope (HST): Nix and Hydra in 2005 (*1*), Kerberos in 2011 (*2*), and Styx in 2012 (*3*). SNKH orbit the Pluto system barycenter in essentially the same plane (coincident with the Pluto-Charon orbital plane) and in nearly circular orbits with orbital semimajor axes of 42,656, 48,694, 57,783, and 64,738 km, and orbital periods of 20.2, 24.9, 32.2, and 38.2 days, respectively (*4*, *5*). These orbital periods are nearly integer multiples of Charon's 6.4-day orbital period, with ratios of 3:4:5:6 for SNKH, respectively (*4*, *5*). Sensitive searches for other moons with New Horizons were unsuccessful (*6*), demonstrating that no other moons larger than ~1.7 km in diameter (assuming the geometric albedo is ~0.5) are present at orbital radii between 5000 and 80,000 km, with less stringent limits at larger radii.

The long-term dynamical stability of Kerberos places severe constraints on the allowable masses and surface reflectances (i.e., albedos) of Nix and Hydra (*7*). These latter constraints, together with the disk-integrated brightness measurements of Nix and Hydra (brightness is proportional to the product of the object's cross-sectional area and its albedo), suggested that Nix and Hydra are relatively small, icy satellites (*7*). Adopting the hypothesis that impact-generated debris from the small moons produced a regolith covering Charon's surface (*8*, *9*), so that all of Pluto's moons would have similar visible-light albedos (the visible-light albedo of Charon is ~0.38), the average spherical-equivalent spherical diameters of Styx, Nix, Kerberos, and Hydra would be approximately 7, 40, 10, and 45 km, respectively. However, the observed brightness of Kerberos, together with dynamical constraints on its mass (*4*), suggested (*5*) that it has a much lower albedo and a much larger size (e.g., diameter of 25 km for an albedo of 0.06). On the basis of an extensive set of HST brightness measurements over time, it was argued that Nix is highly elongated, with a maximum to minimum axial ratio of ~2 (*5*). Similar measurements suggested that Hydra was also elongated, but less so than Nix (*5*). No stable rotational period could be found for either Nix or Hydra, perhaps suggesting that both bodies were tumbling chaotically as a result of the large and regular torques exerted on them by the Pluto-Charon binary (*5*).

The New Horizons mission provided an opportunity to make spatially resolved observations of Pluto's small moons, thereby testing the findings from Earth-based observations (*4*, *5*) and various theoretical predictions (*7*–*9*) by giving direct measurements of their sizes, shapes, surface albedo, and color variations, along with snapshots of their rotational states. In addition, an extensive and systematic set of unresolved panchromatic brightness measurements of the small moons over several months (early April to early July 2015) was obtained by New Horizons during the approach to Pluto, which provides further information on their shapes and more precise information on their rotational states. Here, we report on the results from the New Horizons observations of Pluto's small moons using data received on Earth by mid-December 2015. All the data discussed here were obtained by either the Long Range Reconnaissance Imager (LORRI), a panchromatic camera (*10*), or the Multispectral Visible Imaging Camera (MVIC), a color camera (*11*). Infrared spectral measurements from the Linear Etalon Imaging Spectral Array (LEISA) (*11*) will provide detailed compositional information, but those data will not be sent to Earth until March or April 2016.

Physical properties

Table 1 presents a log of all the resolved measurements of Pluto's small moons. Some examples of the resolved images are shown in Fig. 1 (see also fig. S1 and figs. S7 to S14). Systematic measurements of the brightness variations of Pluto's moons between May and early July 2015 were used together with the resolved measurements to constrain the sizes, shapes, rotation periods, and rotation poles of all four moons (*12*) (Table 2). Figure 2 shows the observed brightness variations after phasing by the best-fit rotational periods (see also figs. S2 and S3). Unlike the case for Pluto and Charon—each of which synchronously rotates with a period of 6.3872 days, equal to their mutual orbital period around their common barycenter—Pluto's small moons rotate surprisingly rapidly (Hydra has the fastest rotational period, ~10 hours) and all are far from synchronous. The rotational poles (Table 2 and table S4) are clustered nearly orthogonal to the direction of the common rotational poles of Pluto and Charon: The inclination angles relative to the Pluto-Charon pole direction are 91°, 123°, 96°, and 110° for SNKH, respectively. Nominally, all the small moons have retrograde rotation, but Nix is the only one significantly so (i.e., retrograde with greater than 1σ confidence). This collection of inclinations is inconsistent

[1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA. [2]Southwest Research Institute, Boulder, CO 80302, USA. [3]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. [4]Lowell Observatory, Flagstaff, AZ 86001, USA. [5]National Optical Astronomy Observatory, Tucson, AZ 26732, USA. [6]SETI Institute, Mountain View, CA 94043, USA. [7]Department of Astronomy, University of Virginia, Charlottesville, VA 22904, USA. [8]Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, USA. [9]Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035, USA. [10]Lunar and Planetary Institute, Houston, TX 77058, USA. [11]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. [12]Department of Astronomy, University of Maryland, College Park, MD 20742, USA. [13]Massachusetts Institute of Technology, Cambridge, MA 02139, USA. [14]University of Arizona, Tucson, AZ 85721, USA. [15]Independent science writer, Arlington, VT, USA. [16]Southwest Research Institute, San Antonio, TX 78238, USA. [17]Stanford University, Stanford, CA 94305, USA. [18]University of California, Santa Cruz, CA 95064, USA. [19]Université Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France. [20]Roane State Community College, Oak Ridge, TN 37830, USA. [21]George Mason University, Fairfax, VA 22030, USA. [22]Planetary Science Institute, Tucson, AZ 85719, USA.
*Corresponding author. E-mail: hal.weaver@jhuapl.edu

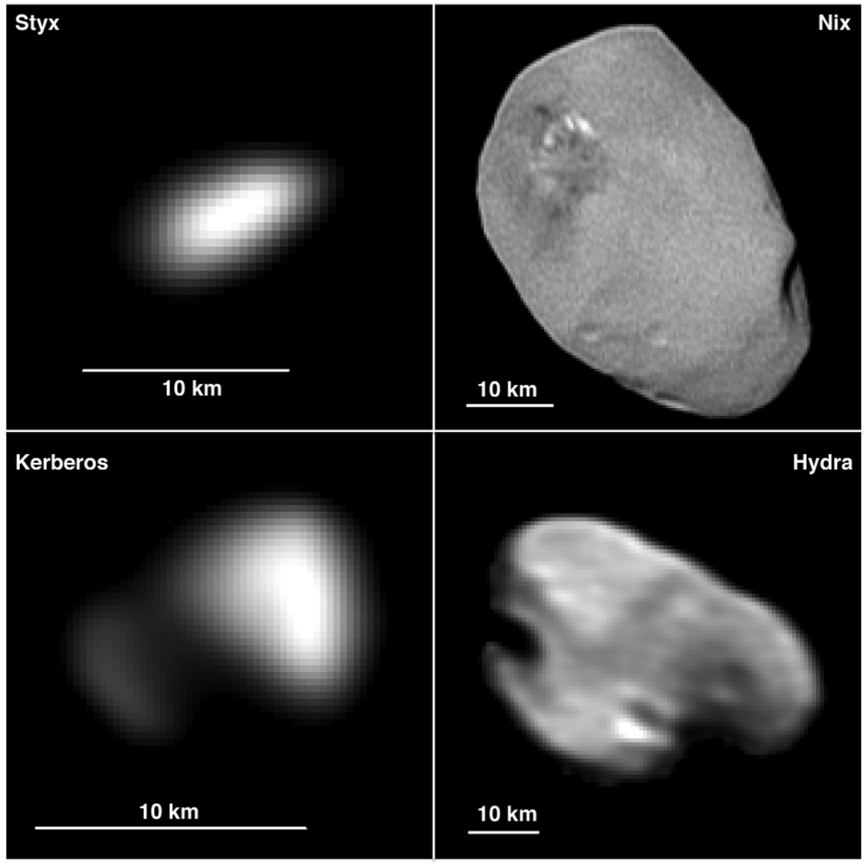

Fig. 1. Best-resolved images of Pluto’s four small moons. Celestial north is up; east is to the left. The Styx image is a deconvolved (12) composite of six images from U_TBD_1_02 (Table 1) that has been resampled with pixels one-eighth of the native pixel scale for cosmetic purposes. The Nix image is a deconvolved single image from N_LEISA_LORRI_BEST and is displayed with the native pixels. The Kerberos image is a deconvolved composite of four images from U_TBD_2 and has been resampled with pixels one-eighth of the native pixel scale for cosmetic purposes (12) (fig. S1). The Hydra image is a deconvolved composite of two images from H_LORRI_BEST with pixels one-half of the native scale. Some surface features on Nix and Hydra appear to be impact craters (12).

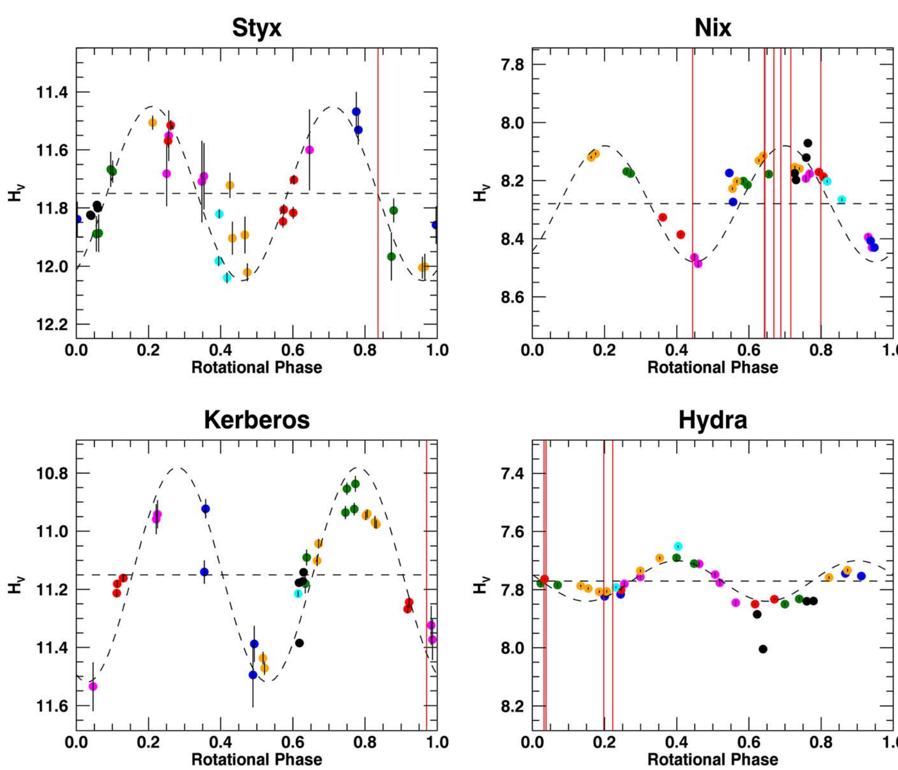

Fig. 2. Rotational light curves for Pluto’s small moons. Systematic measurements of the brightnesses of Pluto’s small satellites were obtained by LORRI during the approach to Pluto from May through early July 2015. H_V refers to the total (i.e., integrated over the entire target) visible magnitude (V band) referenced to a heliocentric distance of 1 AU, a spacecraft-to-target distance of 1 AU, and a solar phase angle of 0° (using a phase law of 0.04 mag/deg). Different colors are used for the seven different observing epochs (12) (table S4); $\pm 1\sigma$ error bars are shown for each measurement (some error bars are smaller than the symbols). Three different algorithms were used to search for periodic variations in the data (12). The rotational periods derived from that analysis (Table 2) were then used to phase the brightness data, producing the light curves displayed above. These double-peaked light curves presumably result from the rotation of elongated bodies, with the light-curve amplitude determined by the variation in the cross-sectional area presented to the observer, which depends on the body’s shape and the angle between the rotational pole and the line of sight to the body. The rotational phases for all the resolved observations of the small satellites (Table 1) are indicated by the vertical red lines, although the angle between the observer and the rotational pole may be different for these observations relative to the earlier ones. The dashed curves are sinusoids with the best-matched periods. The amplitudes for Styx, Nix, Kerberos, and Hydra, respectively, are 0.30, 0.20, 0.37, and 0.07 mag. The dashed horizontal lines are the mean H_V values, which are 11.75, 8.28, 11.15, and 7.77 mag for Styx, Nix, Kerberos, and Hydra, respectively.

with an isotropic distribution; even with only four points, a Kolmogorov-Smirnov test shows a less than 1% probability that this is a uniform distribution in inclination (i.e., the pole inclinations are nonuniform to a 2σ to 3σ confidence level). These results on the rotational properties have not been seen in other regular satellite systems in the solar system. Rapid rotations and large obliquities imply that tidal despinning has not played a major role in the moons' rotational histories. The moons have probably never reached the state of near synchronicity where chaotic perturbations by Charon have been predicted to dominate (*5*); determining whether chaos plays a role in the moons' current rotational dynamics is deferred to a future study.

Pluto's small moons have highly elongated shapes with maximum to minimum axial ratios of ~1.5 to 2 (Table 2). Highly asymmetrical shapes are typical of many other small bodies in the solar system and presumably reflect a growth process by agglomeration of small objects into loosely bound, macroporous bodies whose gravity was insufficient to pull them into more spherical shapes. Kerberos, in particular, has a double-lobed shape, suggesting the merger of two smaller bodies. Hydra also has a highly asymmetrical shape that may also indicate the merger of smaller bodies, but the divots in Hydra's surface may plausibly have been produced by impacts from the local Kuiper Belt population. The nonspherical shapes of Pluto's small satellites are consistent with their formation in the remnant disk produced by the collision of two large Kuiper Belt objects (KBOs) that formed the Pluto-Charon binary (*13*–*15*).

Large uncertainties in the masses of the small moons (up to ~100%), as well as large uncertainties in their volumes, preclude determining accurate values for their densities at this time (densities of 0 are within the current error estimates). However, the New Horizons results on Kerberos (see below) clearly demonstrate that the current dynamical estimate for its mass (*4*) is an overestimate, possibly by a factor of ~100.

Table 1. Log of available resolved observations of Pluto's small moons. All observations of Pluto's small satellites with a resolution better than 15 km per pixel and downlinked to Earth before 15 December 2015 are listed. The dates are the mid-observation times at the New Horizons spacecraft. Resolution refers to the projected distance at the object subtended by a single instrument pixel. The phase angle is the Sun–object–New Horizons angle. All observations were taken with the LORRI panchromatic camera (10), except "N_COLOR_2" and "N_MPAN_CA," which were taken with the MVIC color camera (11).

Object	Observation name	Date in 2015 (UTC)	No. of images containing object	Resolution (km/pixel)	Phase angle (degrees)
Styx	U_TBD_1_02	07-13 23:44:56	6	3.13	17.3
Nix	N_LORRI_APPR_1D2	07-13 23:19:29	2	2.92	13.4
	N_COLOR_2	07-14 08:03:29	1	3.10	8.45
	N_LORRI_BACKUP	07-14 08:06:58	4	0.76	8.34
	N_COLOR_BEST	07-14 09:12:59	1	1.99	6.13
	N_LEISA_LORRI_BEST	07-14 10:03:10	1	0.30	9.45
	N_MPAN_CA	07-14 11:16:35	1	0.45	85.9
	N_DEP_SOONEST	07-14 14:56:57	16	0.93	158
Kerberos	U_TBD_2	07-14 04:24:17	4	1.97	24.7
Hydra	H_LORRI_APPR_1D2	07-13 23:16:23	2	3.18	21.5
	H_COLOR_1	07-14 04:54:09	1	7.17	26.7
	H_COLOR_BEST	07-14 07:37:00	1	4.59	33.5
	H_LORRI_BEST	07-14 07:40:28	8	1.14	33.9

Albedos and surface features

The New Horizons spacecraft trajectory was designed to maximize the scientific return on Pluto and Charon, and observations of those bodies were given priority during the flyby. Nonetheless, Nix and Hydra were imaged with sufficient resolution to investigate brightness variations, color variations, and topographical features across their surfaces. Direct surface reflectance (I/F, the ratio of reflected intensity to incident flux from the Sun) measurements are also available for Kerberos and Styx. Contour maps of raw I/F values for the best-resolved images of SNKH are shown in figs. S8 to S11.

All four small satellites have high albedos, similar to those of some of Saturn's small, icy moons (*16*). Even at a phase angle of 34°, I/F on Hydra reaches 0.56 ± 0.03 (the quoted error is the estimated ±1σ uncertainty in the LORRI absolute calibration). Peak values of I/F for Styx, Nix, and Kerberos are 0.40 ± 0.02, 0.57 ± 0.03, and 0.45 ± 0.02 at phase angles of 17.3°, 9.5°, and 24.7°, respectively. Converting these reflectances into geometric albedos (by definition, the geometric albedo is the I/F at a phase angle of 0°) requires knowledge of the phase function, including any brightness increase that might occur near 0° as a result of coherent backscattering. We used the total light integrated over the best image of Nix to constrain its geometric albedo, and then we used the relative albedos derived from the unresolved brightness measurements of all the small moons (when the phase angle was identical for all the small moons; we also accounted for rotational light-curve variations among the small moons) to estimate the geometric albedos of Styx, Kerberos, and Hydra.

We derive a visible-band apparent magnitude $V = -0.79 \pm 0.05$ for the best image of Nix, which was taken at a moderate phase angle of 9.5°. For a phase law with a linear phase coefficient of 0.04 mag/deg, which we favor, the geometric

Table 2. Properties of Pluto's small satellites. The sizes (diameters) are three-dimensional ellipsoidal best fits to the resolved and unresolved (light curve) measurements (12). Uncertainties are ±3 km (±1σ) for Styx, Kerberos, and Nix and ±10 km (±1σ) for Hydra. Kerberos has a dual-lobed shape that is not fit well by a single ellipsoid. The orbital periods are from (5). The rotation rates are determined from analyses of light-curve data taken over several months (12). Rotational pole directions are determined from a model that attempts to match both the light-curve measurements and the resolved measurements (12). The pole positions listed below are accurate to ±10° (±1σ, see also fig. S4); the rotational poles of Pluto and Charon both point at [RA, DEC] = [132.993°, −6.163°]. The geometric albedos listed here may not fully account for any potential rapid increase in brightness near 0° phase angle (see text for further details). On the basis of a recent (November 2015) analysis of stellar calibration data, we have reduced LORRI's sensitivity by 20% relative to the preflight value, which raises the derived geometric albedo values (tabulated below) by 20% relative to the values based on the original calibration. LORRI's sensitivity has been stable at the ~1% level since launch, and a more definitive absolute calibration is expected from stellar observations planned in July 2016.

Object	Size (km)	Orbital period (days)	Rotation rate (days)	Rotation pole [RA, DEC]	Geometric albedo
Styx	16 × 9 × 8	20.16155 ± 0.00027	3.24 ± 0.07	[196°, 61°]	0.65 ± 0.07
Nix	50 × 35 × 33	24.85463 ± 0.00003	1.829 ± 0.009	[350°, 42°]	0.56 ± 0.05
Kerberos	19 × 10 × 9	32.16756 ± 0.00014	5.31 ± 0.10	[222°, 72°]	0.56 ± 0.05
Hydra	65 × 45 × 25	38.20177 ± 0.00003	0.4295 ± 0.0008	[257°, −24°]	0.83 ± 0.08

albedo is 0.61. For a phase law of 0.02 mag/deg, which is near the extreme of what is observed for asteroids and other planetary satellites, the geometric albedo would be 0.51. Thus, for Nix we adopt a geometric albedo of 0.56 ± 0.05. Using the relative albedo measurements derived from the extensive set of observations taken during May to July 2015 (Fig. 2), we derive the geometric albedos for Styx, Kerberos, and Hydra listed in Table 2. None of these geometric albedo values account for potential rapid brightness increases near 0° phase angle, where observations from New Horizons were not possible.

The vast majority of KBOs that are considered small (although most of their diameters exceed 100 km) have visible-band geometric albedos of less than 20%, with typical values of ~10% (*17*, *18*). Thus, these new measurements provide further evidence that Pluto's small moons were not captured from the general Kuiper Belt population, but instead formed by agglomeration in a disk of material produced in the aftermath of the Charon-forming collision (*13*–*15*). The geometric albedos of the small moons appear to be larger than the value for Charon (~0.38), contrary to the prediction that regolith transfer from the small moons to Charon would result in approximately equal geometric albedos for all of Pluto's moons (*8*, *9*). The high albedo and small size for Kerberos directly contradict the prediction (*5*) that Kerberos should be large and dark. However, our observational results from New Horizons support the predictions from two theoretical studies (*7*, *15*), which argued for high albedos for the small moons on the basis of dynamical considerations.

Although diagnostic compositional spectra on Pluto's small moons have not yet been received from the New Horizons spacecraft, the combination of high surface albedo and their residence at large heliocentric distances strongly suggests that all the moons are covered with icy material. By analogy with Charon, which is covered in H_2O ice but not massive enough to retain more volatile ices (e.g., N_2, CH_4, CO, etc.) over the age of the solar system (*19*, *20*), we propose that the surfaces of Pluto's small moons are likely also covered with H_2O ice. We further note that if the Pluto-Charon binary was produced by a giant collision in which both precursor bodies were at least partially differentiated with icy surface layers, any small moons formed in the resulting debris disk are predicted to be rich in water ice (*14*, *15*).

Both Nix and Hydra have surface features that we attribute to impact craters caused by bombardment from small bodies in the local Kuiper Belt population. We identify 11 craterlike features on Nix and 3 craterlike features on Hydra (*12*) (figs. S12 to S14). We calculate crater densities of 1×10^{-3} to 3×10^{-3} km^{-2} for crater diameters of ≥4 km, which match or exceed the values found (*21*) on the older regions of Pluto and Charon after accounting for the much lower gravities of Nix and Hydra (Fig. 3) (*22*). Given the resolution and phase angle limitations of the images (Table 1) and the difference in impact speeds for the small moons relative to Pluto, these cumulative counts should be considered minimum values. Assuming that our identification of craters on Nix and Hydra is correct, the high crater densities suggest (*21*, *22*) that the surfaces of Nix and Hydra date back to at least 4 billion years ago, when the population density of the Kuiper Belt was perhaps 100 times the present-day value (*23*). Catastrophic disruption since that time is not predicted for Nix and Hydra (*22*), which is consistent with their ancient surface ages.

Nix and Hydra have mostly neutral (i.e., gray) colors, but Hydra is somewhat bluer than Nix (Fig. 4). Perhaps Hydra's surface is icier than Nix's, which might explain both its higher albedo and bluer color. The largest crater on Nix's surface is redder than the rest of its surface (Fig. 5). Possible explanations are that the impacting body had a composition different from that of Nix or that the impact exposed material with a different composition from below Nix's surface. No color variation is detected for the other impact craters identified on Nix's or Hydra's surfaces.

Implications

The New Horizons observations of Pluto's small satellites have produced a number of results:

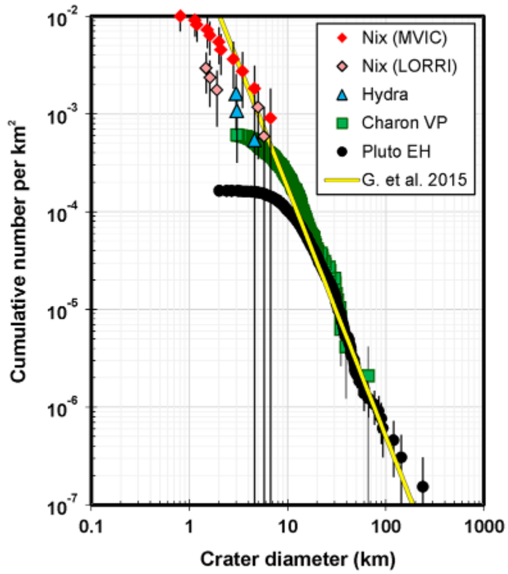

Fig. 3. Cumulative crater size-frequency distributions for Nix, Hydra, Pluto's encounter hemisphere (EH), and Charon's Vulcan Planum (VP). The curves for Pluto and Charon are from Moore et al. (21). Nix and Hydra crater sizes (table S2) are scaled downward by a factor of 2.1 (appropriate for porous regolith-type material) to account for the difference in gravity between these small moons and Pluto (12). Standard Poisson statistical errors ($\sqrt{N}$) are displayed. The phase angle for the "Nix (LORRI)" data (N_LEISA_LORRI_BEST; phase angle 9.45°) was less ideal for topographic feature identification than the phase angle for the "Nix (MVIC)" observation (N_MPAN_CA; phase angle 85.9°). Thus, the lower crater density for Nix (LORRI) versus Nix (MVIC) may be an artifact of the viewing and lighting geometry. The yellow line indicates the Greenstreet et al. (22) prediction for the cumulative density of craters on Pluto's surface over a span of 4 billion years for their "knee" model. Although not saturated in appearance, Nix and Hydra both exhibit slightly higher crater densities than Pluto and Charon, implying a surface age of at least 4 billion years (see text).

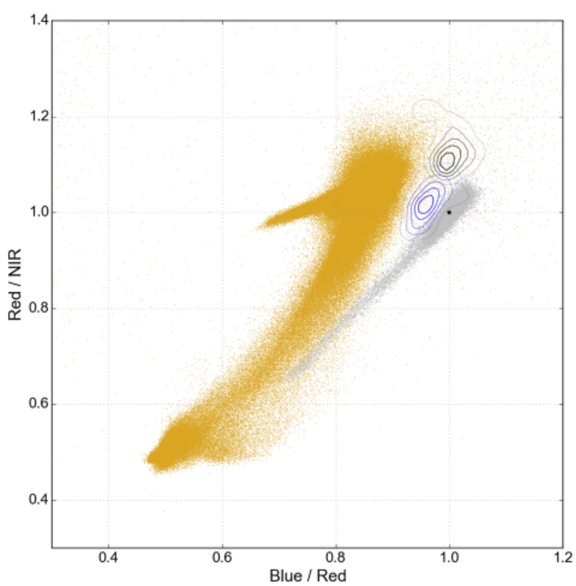

Fig. 4. Color ratios for the surfaces of Pluto, Charon, Nix, and Hydra. Blue/Red and Red/NIR color ratios derived from MVIC images are displayed (Blue = 400 to 550 nm, Red = 540 to 700 nm, NIR = 780 to 975 nm). Gold points are from Pluto's surface; silver points are from Charon's surface. Blue contours show the distribution of colors on Nix's surface; black contours show the distribution of colors on Hydra's surface. The normalized solar color is denoted by the star (at coordinate [1,1] in the plot); surfaces redder than solar are at the lower left of the star, and regions bluer than solar appear at the upper right. Pluto exhibits a diversity of colors over its surface (24). Charon has less color diversity than Pluto, and the range of its colors follows a mixing line (24). Nix and Hydra have nearly solar colors (i.e., gray color) that are distinct from either Pluto or Charon, with Hydra being slightly bluer than Nix.

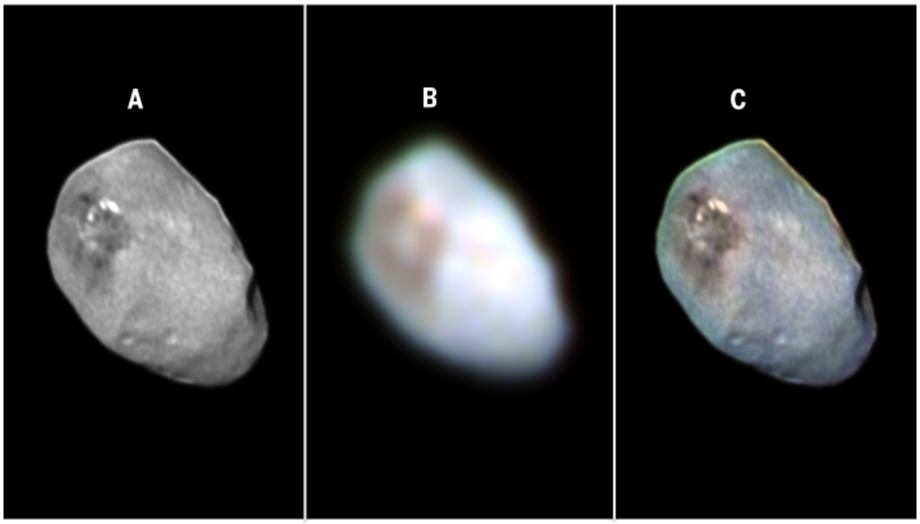

Fig. 5. Color of Nix's surface. (**A**) Panchromatic LORRI image of Nix taken from N_LEISA_LORRI_BEST (Table 1). (**B**) Enhanced MVIC color image of Nix taken from N_COLOR_BEST. (**C**) The LORRI image of Nix was colored using the data derived from the MVIC image. Most of Nix's surface is neutral (i.e., gray) in color, but the region near the largest impact crater is slightly redder than the rest of the surface. Celestial north is up and east is to the left for all images.

rapid rotation rates and unusual pole orientations; bright, icy surfaces with albedos and colors distinctly different from those of Pluto and Charon; evidence of merged bodies; and surface ages of at least 4 billion years. Perhaps the rotational properties of the small moons are affected by stochastic collisional processes, which could both spin up the moons and reorient their rotational axes, more strongly than had been appreciated. The presence of a distinctly different layer of material uncovered and/or deposited by an impact on Nix demonstrates that these bodies possess regoliths. The New Horizons measurements suggest that regolith sharing between the small moons and Charon is less extensive than previously thought (*8*, *9*). Collisions are also implicated in determining the shapes of the small moons: Kerberos appears to record the slow merger of two separate bodies, and Hydra has large surface indentations that might reflect mass loss by impacting bodies. However, the major collisional evolution of the small moons was probably limited to the first several hundred million years after the solar system's formation, because the surface crater retention ages of Nix and Hydra exceed 4 billion years.

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ACKNOWLEDGMENTS

We thank the many dedicated engineers who contributed to the success of the New Horizons mission and NASA's Deep Space Network for a decade of excellent support to New Horizons. This work was supported by NASA's New Horizons project. As contractually agreed to with NASA, fully calibrated New Horizons Pluto system data will be released via the NASA Planetary Data System at https://pds.nasa.gov/ in a series of stages in 2016 and 2017 because of the time required to fully downlink and calibrate the data set. Also supported by NASA's Origins research program (D.P.H.) and Centre National d'Etudes Spatiales, France (S. Philippe and B.S.). S.A.S. is affiliated with Florida Space Institute, Uwingu LLC, Golden Spike Co., and World View Enterprises.

SUPPLEMENTARY MATERIALS

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5 December 2015; accepted 22 February 2016
10.1126/science.aae0030

The small satellites of Pluto as observed by New Horizons

H. A. Weaver *et al.*

Science **351**, (2016);
DOI: 10.1126/science.aae0030