

Supplementary Materials for

The Pluto system: Initial results from its exploration by New Horizons

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Materials and Methods

Method for Estimating Sensitivity of New Satellite Searches

To estimate the sensitivity of our searches for new satellites and dust in the Pluto system, we seeded LORRI images made on approach for satellite search purposes with synthetic objects: unresolved sources, simulated satellites, and dust ring structures of various intensities. Typically, we added ~ 30 synthetic satellites, randomly scattered throughout a satellite search image, with intensities ranging from brighter than the expected sensitivity limit to much fainter than the predicted limit. The synthetic objects were placed in the search images with motions consistent with Keplerian motion centered on the barycenter (for objects exterior to Charon) or on Pluto (for objects interior to Charon) and small eccentricities and inclinations.

After these synthetic images were produced, they were distributed to seven team members (including the person who generated the synthetic images) expert in this kind of analysis. Each person independently developed their own method of analyzing the images and practiced and refined the methodology on both real and simulated images.

The analysis techniques described above were applied to images sent to Earth at each of seven satellite/ring search observations conducted during the approach to Pluto in 2015: May 11 (144 images), May 29 (144 images), June 5 (216 images), June 15 (384 images), June 23 (72 images), June 26 (48 images), July 1 (48 images). The sensitivity limit for new satellites improved monotonically with time owing to the decrease in the spacecraft's range to the Pluto system.

After seeding the observed images with synthetic objects, the results from each of the data analyzers were compiled and compared. We defined the sensitivity limit as the faintest intensity for which at least two independent detections were made for all synthetic objects of that brightness or brighter.

The results of our analysis are summarized in Figure S6. The sensitivity limit is larger close to Pluto because scattered light and ghosts from Pluto and Charon (which are $\sim 10^5$ times brighter than Styx, the faintest known satellite in the Pluto system) severely limits the sensitivity in their vicinity. Sensitivity is also larger more than 50,000 km from Pluto because more distant radii were only covered by earlier observations, which had a larger absolute field of view but lower

sensitivity (the angular field of view was essentially the same for all observations). The quoted diameter limits scale inversely with the square root of the adopted geometric albedo.

We determined ring density upper limits by measuring the median or robust mean of the brightness of the sky background as a function of radius from the barycenter, and avoiding image azimuths with elevated background due to ghosts. We repeated the analysis after adding synthetic ring-like structures of known I/F, centered on the barycenter, with a brightness near the predicted sensitivity limit, to determine the faintest rings that could be detected by observers searching for implanted structures. The most constraining limits came from the earliest observations on May 11th, because ghosts from Pluto and Charon limited sensitivity in later observations.

Supplementary Text

Measuring the Size and Oblateness of Pluto and Charon

New Horizons returned a sequence of LORRI optical navigation (NAV) images on approach to the Pluto system designed to provide trajectory information. With continually improving resolution, these images also provided the opportunity to definitely determine Pluto's size and shape. In detail each NAV sequence was a multiple image set, with two or three images taken at each pointing for Pluto. Also used was P_LORRI_Fullframe, a 4-image set, of which 2 were returned to the ground on 13 July 2015. Each image was deconvolved to mitigate the broadening effects of the LORRI point-spread-function, and subsequently each image in a given pointing was Nyquist sub-sampled and coadded. Illuminated limbs were determined by a variety of methods, from threshold image brightness to maximum brightness gradient. The size and shape data in Table 1 (main text) were determined by taking limb profiles from P_LORRI_Fullframe (3.82 km/pix), as well as the highest resolution NAV sequences: NAV_C4_L1_Crit_37_01 (3 images, 12.6 km/pix), NAV_C4_L1_Crit_36_01 (3 images, 15.1 km/pix), and NAV_C4_L1_Crit_35_02 (2 images, 19.6 km/pix). These profiles were combined in a joint, weighted fit for the best polar (a) and equatorial (c) axis for Pluto. Errors were driven by the best-resolved limb profile (P_LORRI_Fullframe).

The technique for Charon is quantitatively similar, except that the best image for size and shape determination was a single frame of a 4-frame pointing (C_LORRI_Fullframe, 2.3 km/pix).

Additional Pluto Radio Occultation Details

Radio occultation results on the neutral atmosphere of Pluto were derived from preliminary analysis of a subset of measurements at occultation entry (193°E, 17°S) that extend from the surface to an altitude of about 300 km. The method of analysis (36) includes a correction for diffraction from Pluto's limb.

The full radio occultation datasets at Pluto extend to an altitude of more than 6000 km at both ingress and egress. However, most of these data, as well as all Charon radio occultation data) have not been sent to Earth yet and so are not yet available, including in the altitude range where an appreciable ionosphere is expected to be present.

Figures and Legends

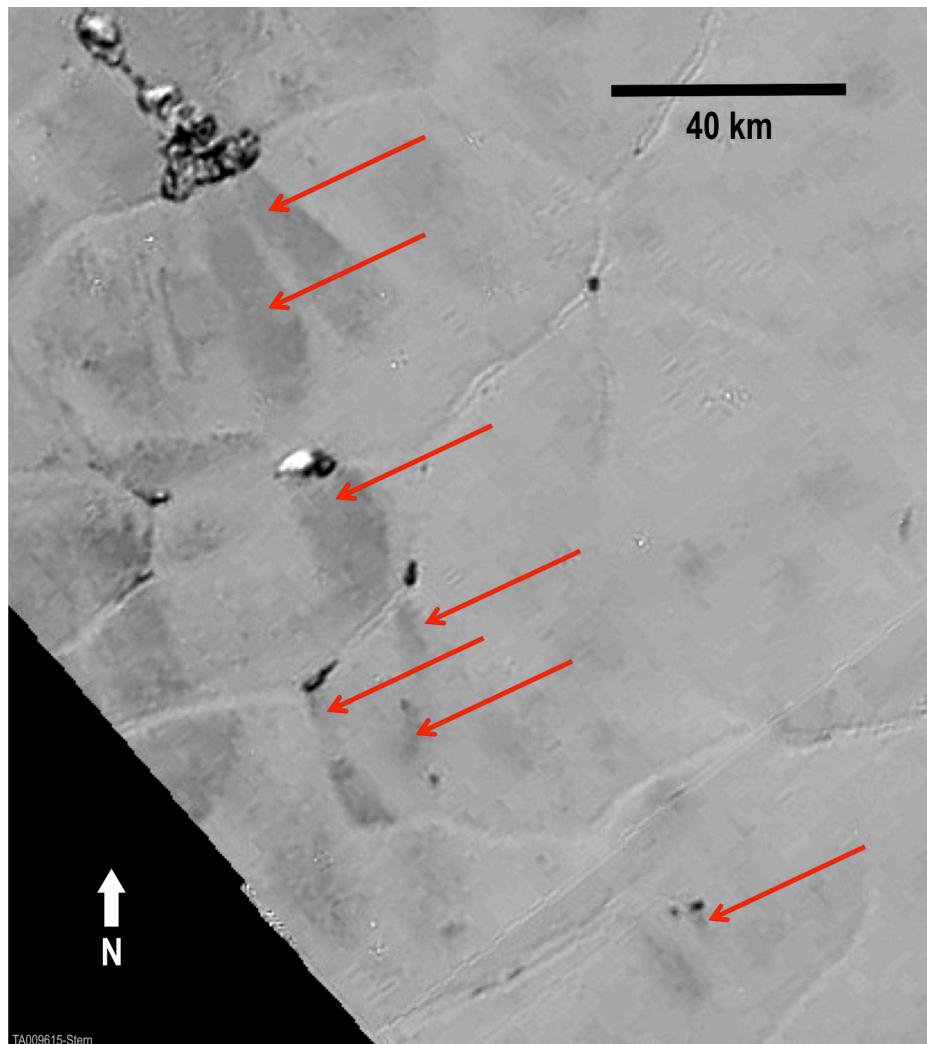


Figure S1. Possible wind streaks on western Sputnik Planum. A number of diffuse streaks appear parallel (roughly 140° clockwise from north) and are associated with dark spots or hills. The spots and hills are plausible upwind sources of dark material; alternately, the hills may even induce downwind turbulence that removes bright material.

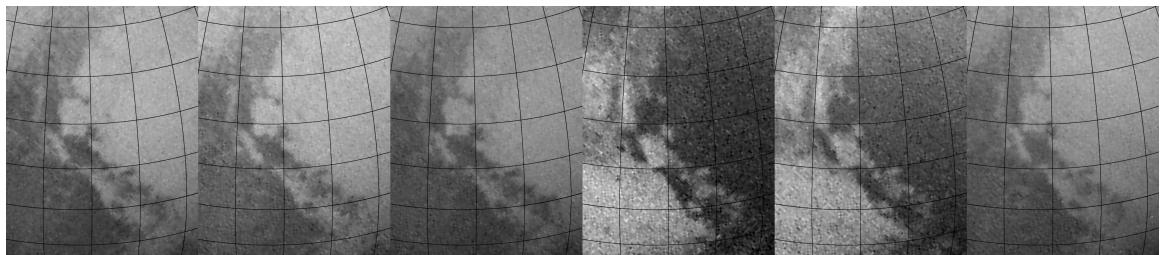


Figure S2. Pluto spectral maps. Six wavelengths from the New Horizons Ralph spectral mapping observation of Pluto obtained at a range of 147,000 km, on 2015 July 14 8:42 UT. From left to right, the wavelengths are 1.57, 1.58, 1.59, 1.66, 1.79, and 1.89 μm .



Figure S3. Deep chasma on Charon. A deep chasm, informally named Argo Chasma, is apparent centered near the 1 o'clock position near the top of the image.

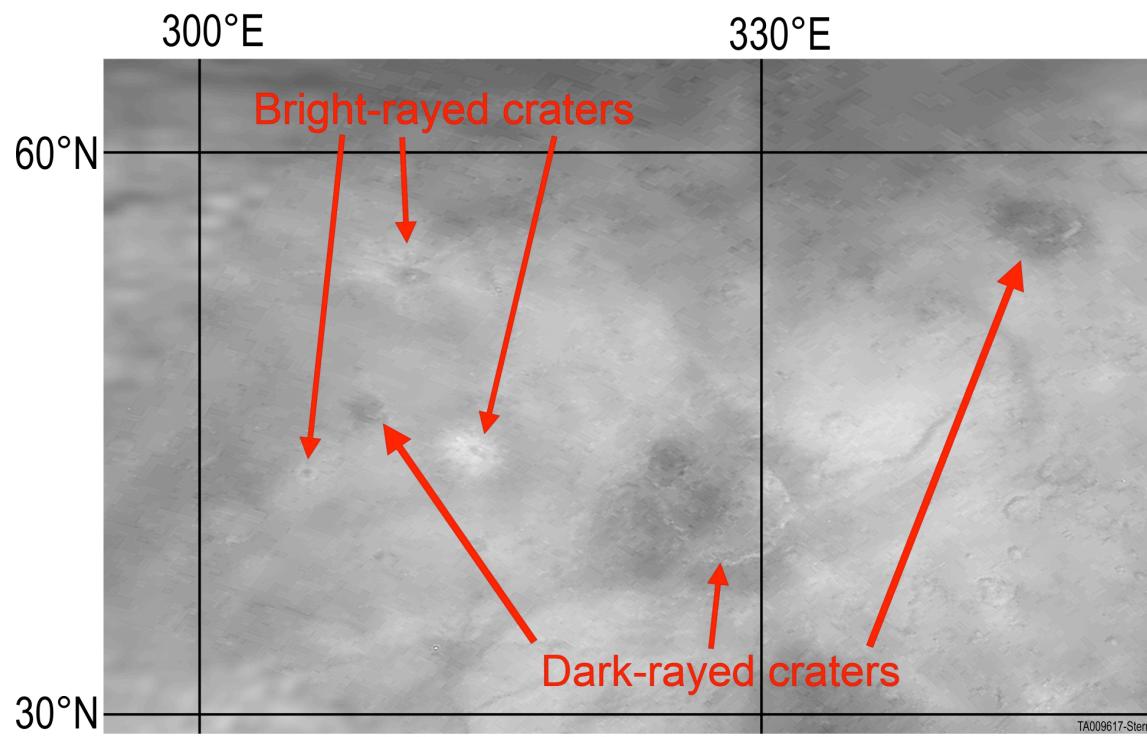
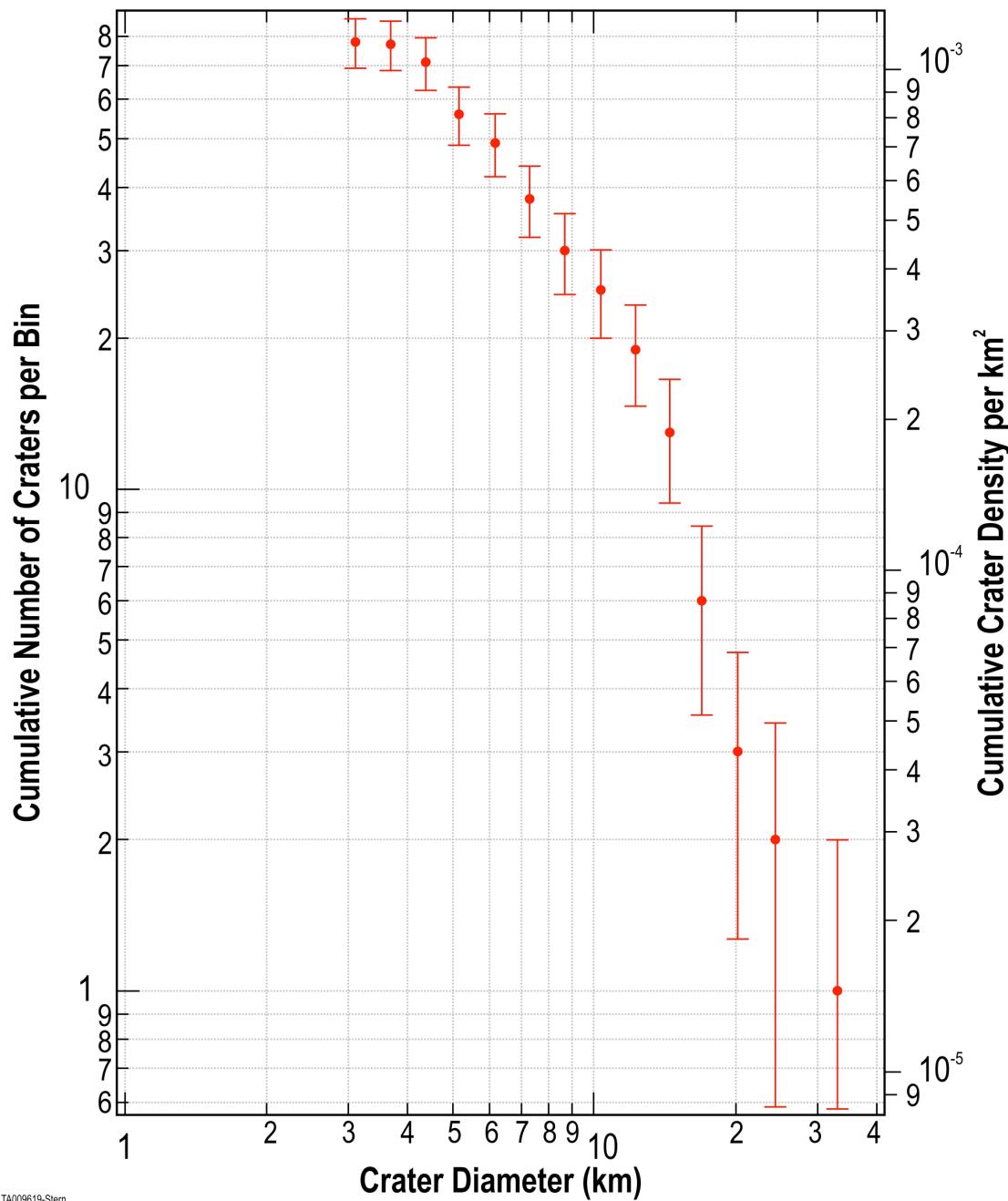


Figure S4. Crater rays and ejecta on Charon. Both bright and dark crater ejecta are seen on Charon's surface.



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Figure S5. Measured cumulative crater density of Vulcan Planum on Charon. Craters were identified within a 68,850 km² region of consistent low sun angle and good topographic discrimination. Cumulative counts were binned in standard logarithmic intervals of 2^{1/4}, except when the number of craters (N) was only a few. Poisson statistical errors (\sqrt{N}) were assumed. See main text for other details.

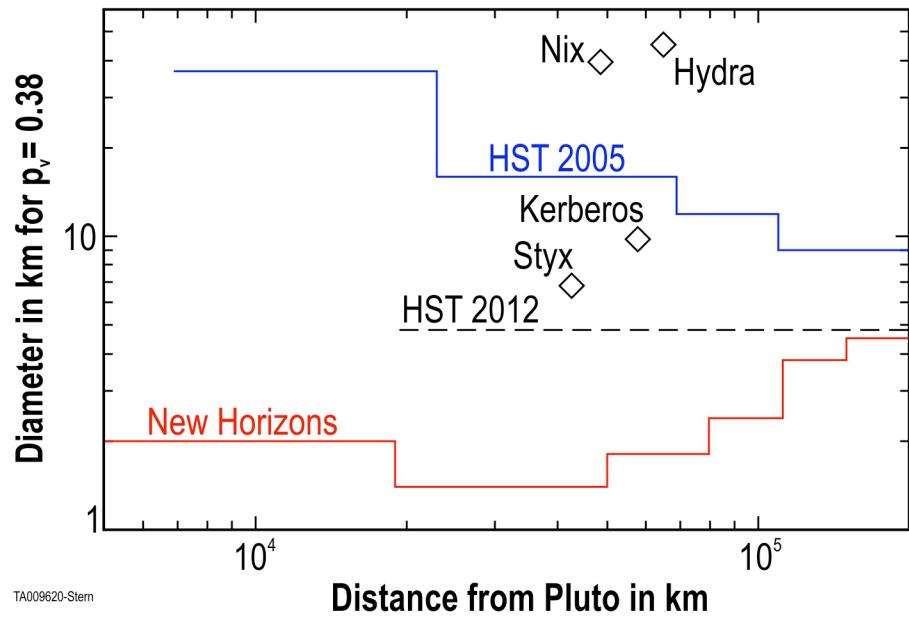


Figure S6. Satellite search limits. Upper limit to the diameter of undiscovered satellites of Pluto for an assumed geometric albedo p_v of 0.38, based on *New Horizons* approach images (red line), compared to previous published limits from 2005 HST observations (31) (blue line) and from 2012 HST observations (32) (black dashed line). The diameters and orbital distances of Pluto's four known small satellites the same albedo assumption, are also shown.

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