IMPACTS AND CRATERING ON PLUTO: IMPLICATIONS FOR THE SOURCE OF PLUTO'S NITROGEN (N_2). Kelsi N. Singer and S. Alan Stern. Southwest Research Institute, 1050 Walnut Street, Boulder, CO 80302, United States (ksinger@boulder.swri.edu, astern@swri.edu).

Introduction: What will Pluto and Charon's craters tell us? In preparation for the closest approach of NASA's New Horizons spacecraft on July 14th, 2015, we consider models that will relate the observed craters to Kuiper belt object (KBO) impactor populations, surface properties, subsurface structure, cratering physics/scaling, and surface-atmosphere interactions. Craters on Pluto and Charon occur under unique conditions: low impact speeds (average ~ 2 km s^{-1} [e.g., 1,2] an icy surface with a combination of N_2, CH_4, and/or H_2O ices, and gravity and escapes speeds intermediate to those of the smaller and larger icy satellites. Thus craters on Pluto and Charon will provide a key comparative study to those on other worlds. Additionally, constraints derived from Pluto system craters on the size distribution of small KBOs will improve our estimates of cratering rates and refine age estimates on other solar system bodies [e.g., 3-5].

Predicted Impactor Populations Using observations of current KBO densities [6], typical KBO impact velocities onto Pluto of ~1-2 km s^{-1} [e.g., 2], and Pluto's cross section, Stern et al [7] estimate ~14,000 comets 1 km in diameter or larger would impact Pluto over 4 billion years. Bierhaus and Dones [2] considered different KBO subpopulations and estimated 1840 impactors > 1 km in diameter (nominal case, 5600 for maximum case). The largest impactor predicted to hit Pluto in the last ~4 billion years is ~60 km in diameter, and on Charon ~25 km [2].

We note however that that there is uncertainty in the slope of the size distribution for KBOs smaller than 100 km in diameter, which New Horizons crater data from Pluto and Charon will help constrain [see discussion in 2,5,8,9]. Additionally a correction factor of ~2-10 may be needed [5,8] to account for collisional and dynamical erosion of the Kuiper Belt leading to a smaller number of current KBOs compared with early in Solar System history [e.g., 10-12].

What craters will New Horizons be able to observe? Table 1 lists the highest resolutions achieved by the New Horizons LOng Range Reconnaissance Imager (LORRI) for Pluto and Charon. The absolute best resolutions will occur over two narrow strips of terrains, thus we show in Table 1 a second number that is given for the highest resolution covering the majority of the lit hemisphere. Using a practical four-pixel minimum for crater identification, the size of the smallest craters that could be observed and other quantities are estimated in Table 1.

Cometary Impactors, Cratering, and Pluto's N_2

Atmospheric Loss: In addition to Pluto's surface ice composition being dominated by molecular nitrogen [16-17], Pluto's atmosphere consists of a >90% mole fraction N_2 [18] with surface pressures estimated on the of order ~10 μbars [19]. Models predict the N_2 escape rate is 10^{27}–10^{28} molecules s^{-1}, varying by an order of magnitude over the course of Pluto's year [e.g., 20]. For reference, this leads to ~1-2x$10^{12\text{-}13}$ g of N_2 lost per year; for reference, the estimated current global atmospheric mass of Pluto, based on pure N_2 of 10 μbars and 35 K is ~5x10^{17} g [7].

Using the range of escape rates stated above, a simple linear extrapolation of the escape rate yields a total mass of N_2 lost over four billion years of 6x$10^{21\text{-}22}$ g. This is equivalent to a condensed N_2 surface layer on Pluto of depth 0.4-4 km [7].

N_2 Delivery by Comets: Stern et al. [7] estimate an N_2 mass of 5x$10^{10\text{-}11}$ g in a 1 km comet with a 50:50

Resolutions (best overall and hemispheric coverage)	4-Pixel Final Crater Diameter	Excavation Depth[a]	Transient Crater Diameter[b]	Impactor Diameter[c]	Number of Impacts this Size or Greater in 4 Gyr[d]	Min Size of Primary needed to create Secondary[e]
Pluto						
Best: ~70 m px^{-1}	~300 m	30 m	250 m	20 m	2.4*10^6	6 km
Hemi: ~300 m px^{-1}	~1.2 km	120 m	1 km	110 m	1.1*10^5	24 km
Charon						
Best: ~150 m px^{-1}	~600 m	60 m	500 m	35 m	1.8*10^5	12 km
Hemi ~600 m px^{-1}	~2.4 km	240 m	2 km	200 m	7.5*10^3	48 km

Table 1: [a]Excavation depth taken as ~1/10th the transient crater diameter [13]. [b]For simple craters (D_{final} < 4 km in diameter [4]), we used the apparent diameter as an approximation for the transient, taken as 0.83*D_{final} based on lunar data [14]. [c]Scaling from Holsapple [15] with updated parameters from http://keith.aa.washington.edu/craterdata/scaling/theory.pdf. Scaling for ice-on-ice impacts, 2 km s^{-1} impact speeds, 45° impactor, d/D = 0.2 for simplicity, Pluto's gravity is 0.66 m s^{-2}, Charon's is 0.23 m s^{-2}. [d]Bierhaus and Dones [2] nominal rates from their Table 8. [e]Size of primary crater necessary to produce a secondary crater at the 4-pixel final crater diameter (based on the largest secondaries being ~5% the size of the primary [13]).

ratio of H_2O to refractories and typical cometary nitrogen abundances [21,22]. Using the ~14,000 comets > 1 km in diameter estimate cited above and calculating based purely on 1 km-diameter comets, this number of impacts would deliver ~$7 \times 10^{14-15}$ g of N_2 over 4 Ga, far, far less than the anticipated N_2 inventory lost over time to escape.

Thus, even given uncertainties in the impactor flux, it does not appear that comets could deliver enough N_2 to supply Pluto's atmosphere. This is a key conclusion of our work. We note that our 14,000 impactor estimate is comparable to, but on the higher end of other predictions in the literature [1-3,7,8]. Except in the extremely unlikely scenario that a recent, relatively large impact is supplying the current atmosphere, these calculations imply endogenic sources must dominate replenishment of Pluto's N_2.

N_2 Excavation by Impacts: Impacts could punch through any lag deposits of the more refractory but considerably less abundant CH_4 (or water-ice/other involatile materials) that one expects to build up during Pluto's history as N_2 escapes to space; this would allow excavated N_2 to resupply Pluto's atmosphere, defeating the involatile lag deposit's tendency to choke off N_2. A simple estimate of N_2 excavated based on ½ the transient crater's volume is presented in Table 2 (examples per impactor size). Dividing by the mean time between impacts of a given size yields a rough approximation for the mass of N_2 available to resupply the atmosphere per year, per impact size. Integrating these values over impactors ranging from 0-60 km in diameter, we arrive at a total mass of 1×10^{15} g yr^{-1}. This order of magnitude estimate is larger than the predicted escape rate ($1.4 \times 10^{12-13}$ g yr^{-1}), and thus it is possible that the cratering process can resupply Pluto's atmosphere without need for deep-seated cryovolcanism or another tectonic or geodynamic means to resupply the atmosphere against involatile lag deposit build up from the escape process.

Conclusions: Comets deliver six-to-eight orders of magnitude less N_2 than is necessary to support the current atmospheric escape rates over Pluto's history. However, N_2 excavated during these impacts, might be able to resupply Pluto's atmosphere if the surface N_2 layer is relatively thick.

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Impactor Diameter [km]	Transient Crater Diameter[a] [km]	~Final Crater Diameter[b] [km]	Excavated N_2 Mass[c] [g]	τ_{impact} (mean time between impacts)[d] [yr]	N_2 Avail. / yr (Column 4/ τ_{impact}) [g N_2 / yr]	$\tau_{N2\ Loss}$ (Column 4/ N_2 escape rate) [yr]
0.01	0.15	0.18	1.4*10^11	461	3.0*10^8	0.1
0.05	0.54	0.65	6.0*10^12	8,860	6.8*10^8	4.3
0.5	3.3	3.9	1.4*10^15	608,600	2.2*10^9	967
1	5.6	6.8	6.9*10^15	2.2*10^6	3.2*10^9	4,938
5	20	32	3.1*10^17	4.2*10^7	7.3*10^9	217,866
10	34	59	1.6*10^18	1.5*10^8	1.0*10^10	1.1*10^6
20	59	108	8.0*10^18	5.3*10^8	1.5*10^10	5.7*10^6
40	102	197	4.1*10^19	1.9*10^9	2.1*10^10	2.9*10^7
60	140	280	1.1*10^20	4.0*10^9	2.6*10^10	7.5*10^7

Table 2: [a]Scaling as in Table 1, footnote d, for Pluto. [b]Simple crater conversion from transient to final as described in Table 1, complex craters (D > 4 k) use McKinnon and Schenk [23; their eqn 1]. Although the latter was derived for the higher gravity bodies Ganymede and Callisto, there is currently no equivalent for lower gravity icy bodies. [c]Half of the volume of the transient crater, using a thick, 99% N_2 surface layer. [d]Bierhaus and Dones [2], nominal rates from their Table 8.