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On the roles of escape erosion and the viscous relaxation of craters on Pluto

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ABSTRACT

Pluto and its satellites will be the most distant objects ever reconnoitered when NASA's New Horizons spacecraft conducts its intensive flyby of this system in 2015. The size-frequency distribution (SFD) of craters on the surfaces in the Pluto system have long been expected to provide a useful measure of the size distribution of Kuiper Belt Objects (KBOs) down to much smaller size scales than presently observed. However, currently predicted escape rates of Pluto's atmosphere suggest that of order one-half to several kilometers of nitrogen ice has been removed from Pluto's surface over geologic time. Because this range of depths is comparable to or greater than most expected crater depths on Pluto, one might expect that many craters on Pluto's surface may have been removed or degraded by this process, biasing the observed crater SFD relative to the production–function crater SFD. Further, if Pluto's surface volatile layer is comparable to or deeper than crater depths, and if the viscosity of this layer surface ice is low like the viscosity of pure N_2 ice at Pluto's measured 35 K surface temperature (or as low as the viscosity of CH_4 ice at warmer but plausible temperatures on isolated pure-CH_4 surfaces on Pluto), then craters on Pluto may also have significantly viscously relaxed, also potentially biasing the observed crater SFD and surface crater retention age. Here we make a first exploration of how these processes can affect the displayed cratering record on Pluto. We find that Pluto's surface may appear to be younger owing to these effects than it actually is. We also find that by comparing Pluto's cratering record to Charon's, it may be possible to estimate the total loss depth of material from Pluto's surface over geologic time, and therefore to estimate Pluto's time-averaged escape rate.

1. Introduction

The reconnaissance of the Pluto system by New Horizons in 2015 will shed light on many aspects of this planet and its satellites (e.g., Stern, 2008).

Of relevance to our work here, New Horizons imagery of the Pluto system is expected to provide valuable insight into the population distribution of impacting Kuiper Belt Objects (KBOs) via the study of crater size frequency distributions on Pluto and its satellites. Much of this work will be carried out using data from the LOng Range Reconnaissance Imager (LORRI) on New Horizons, which will achieve maximum resolutions of 0.07 km/pixel on Pluto and 0.15 km/pixel at Charon, respectively, with characteristic hemispherical resolutions of 0.46 km and 0.61 km/pixel respectively[1] (Weaver, personal communication, 2014).

At such resolutions, craters of diameter greater than about 1 km should be resolved across large expanses of both Pluto and Charon.[2] The parent bodies of such 1 km craters likely correspond to impactor diameters near 100 m (estimated from Eq. (1)), much smaller than the smallest KBOs currently detectable from Earth. Still smaller craters from still smaller impactors down to several tens meters in diameter may be recognized via their ejecta blankets or in the highest resolution planned New Horizons images. As a result, New Horizons should provide valuable and otherwise unobtainable insights into the KBO size frequency distribution (SFD) at scales from tens of meters up to tens of kilometers in diameter.

However, Pluto has an ~10 microbar-class atmosphere (e.g., Elliot et al., 2007). Owing to a combination of Pluto's low gravity and an ~100 K upper atmospheric temperature, Pluto's atmosphere is predicted to be escaping at rates between 10^{27} and 10^{28} molecules s^{-1} (e.g., Zhu et al., 2014; Tucker et al., 2012; Strobel, 2008; Krasnopolsky, 1999). Such escape rates, unless only recent

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[1] Owing to the general lack of craters on Triton's surface, it proved to be a poor probe of the Kuiper Belt's population structure (e.g., Stern and McKinnon, 2000). Moreover, many craters imaged there were likely from impactors with a planetocentric origin (Schenk and Zahnle, 2007).

[2] Imagery of Nix and Hydra will achieve somewhat lower resolutions; this, and their smaller surface areas make them less suitable than Charon for crater size frequency comparison to Pluto, and so these satellites will not be further discussed in this paper.

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or sporadic, imply of order one-half to several kilometers of volatile nitrogen, CO, and CH_4 ice have likely been removed from Pluto's surface over geologic time.[3] In what follows we assume that these 10^{27-28} s^{-1} escape rates, quoted widely in the literature, are correct, but note that significantly lower escape rates—even as time averages—would largely negate the effects of escape erosion that we discuss here.

Because this range of depths of surface N_2 loss is comparable to or greater than most expected crater depths on Pluto, it is possible that many craters on Pluto's surface may have been largely erased by the loss of surface material to escape. Such an effect would bias the observed crater SFD relative to the native or production–function crater SFD, in turn biasing KBO SFDs. Further, owing to N_2's weak viscosity at the 35 K surface temperature characteristic of Pluto, craters there may also have viscously relaxed, creating geomorphological changes that also affect the observed crater SFD and apparent surface crater retention age (CRE), also biasing the KBO SFD.

As a guide to the interpretation of New Horizons imagery, we explore how these two evolutionary processes—crater escape erosion and crater viscous relaxation–may have an affect Pluto's observed cratering record. In what follows, all references to surface age refer to the apparent CRE.

2. Methods

In order to simulate the expected crater production population on Pluto and Charon, one needs to define both an expected impactor size distribution and the resulting crater sizes. There is considerable uncertainty in the literature as to the small-end size distribution of Kuiper Belt impactors, so we selected a variety of plausible distributions in the recent literature to represent various possibilities. Like impactor SFDs, crater scaling laws are also not very well defined for low velocity impacts on icy surfaces, so we again selected multiple examples and modeled the resulting crater diameters and depth to diameter ratios. We then modeled the effects of crater erosion and relaxation on our derived impactor SFDs to evaluate the degree to which erosion and relaxation change the observable crater SFDs over time.

2.1. Impactor size distributions

Ground-based surveys of KBOs (e.g. Millis et al., 2002; Petit et al., 2011) have shown that KBOs can be grouped into several major dynamical groups. The major such groups are the classical low inclination, low eccentricity KBOs, resonant objects (like Pluto) which have mean motion resonances with Neptune and are more dynamically excited than the classical belt, and the scattered disk of KBOs (like Eris) which are in inclined and eccentric orbits not associated with a mean motion resonance with Neptune. Pluto's orbit is immersed in and has been bombarded by all three populations to varying degrees over time (e.g., Dell'Oro et al., 2013).

The impactor flux on Pluto and Charon will naturally be dominated by smaller KBOs which are too faint to observe from Earth.[4] As a result, the SFD of KBOs smaller than about 10 km can presently only be extrapolated from the SFD of larger KBOs. This is particularly problematic for a range of reasons, including that collisions between KBOs are expected to typically be disruptive, eroding away small KBOs and potentially creating a break in the KB's size frequency distribution (e.g. Stern, 1996; Leinhardt et al., 2008, and references therein). Several different predictions have been made of the location of this size break in the KBO population and its effect on the distribution of impactors on Pluto and Charon. Durda and Stern (2000) used the model of Weissman and Levison (1997) with the break at 10 km to derive a total of 8900 impactors larger than 1 km on Pluto over the past 3.5 Gyr. Later, Zahnle et al. (2003) derived a more complex size distribution with multiple breaks at 1.5 km, 5 km, and 30 km, which produced 5250 impactors on Pluto for their Case A and 18,300 impactors larger than 1 km for their Case B. Even more recently, using a numerical collision code with an initial size break at 60 km, de Elía et al. (2010) estimated that over the past 3.5 Gyr Pluto has collided with 1271–5552 impactors larger than 1 km. And more recently, Bierhaus and Dones (2015) combined Fraser et al.'s (2014) KBO population model with size a break at 145 km for "cold" low-inclination KBOs and 130 km for "hot" high-inclination KBOs with Pluto collision probabilities from Dell'Oro et al. (2013) to estimate that 350–1750 impactors larger than 1 km have hit Pluto over the past 3.5 Gyr. The various estimates in the number of 1 km craters expected on Pluto just reviewed differ by over an order of magnitude, reflecting the significant extant uncertainty in the number of small KBOs.

Fig. 1 displays predicted Pluto cratering relative size-frequency distributions (called *R*-plots) for the different Kuiper Belt impact populations discussed just above. The results, shown in Fig. 1, assume an impactor density of 500 kg m^{-3}, as may be typical of most smaller KBOs (Vilenius et al., 2014, and references therein). With this density, the craters in most cases reach geometric saturation ($R = 0.2$) at around 1 km diameter. If the impactors were all higher density, near 2000–2500 kg m^{-3} (a plausible near-bounding case in the Kuiper Belt; e.g., Vilenius et al., 2014), then the cratering distributions in Fig. 1 would shift upward, but keep the same slopes. In this higher impactor density case, craters would reach saturation at closer to 10 km diameter. In either case there are a sufficient number of smaller primary craters to make identification of secondary craters difficult (Bierhaus and Dones, 2015).

Of the nine Kuiper Belt impactor models from the literature plotted in Fig. 1, four were adopted to go forward with in this work, so as to reduce unnecessary plot complexity in what follows. These four were chosen on the basis of both their plausibility and representativeness. For example, the three populations of de Elía et al. (2010) ("ESB10") are essentially one main prediction (Population 2), with Populations 1 and 3 representing larger and smaller initial power law indices respectively; hence, their intermediate prediction was chosen. Models "BD14 $q = 2.00$" (Bierhaus and Dones, 2015; here and later, q is used to denote the exponent of the population power law size distribution) and "ZSLD03 A" (Zahnle et al., 2003) were chosen because they represent bounding scenarios that do not resemble other predictions in the model set. Although "DS00" Durda and Stern (2000), "ZSLD03 B" (Zahnle et al., 2003) and "BD14 $q = 2.95$" (Bierhaus and Dones, 2015) were each based upon different initial KBO populations, they produce quite similar crater populations on Pluto and Charon. We chose the BD14 $q = 2.95$ model as representative, since it better reflects the current knowledge of KBO populations.

2.2. Crater scaling from impactor size

Owing to the predominance of impactors from the classical Kuiper Belt, Dell'Oro et al. (2013) estimates a mean impactor approach speed to the Pluto system is near 1.9 km s^{-1}. Accounting for gravitational focusing (Krivov et al., 2003), this leads to average impact speeds of 2.3 km s^{-1} and 2.0 km s^{-1} on Pluto and Charon, respectively. By comparison, Zahnle et al. (2003) give average impact speeds of 20 km s^{-1} for Ganymede, 16 km s^{-1} for Rhea, 10.3 km s^{-1} for Ariel, and 8.2 km s^{-1} for Triton. Clearly, impacts on Pluto and Charon occur at much lower velocities than most icy bodies that

[3] This in turn implies either internal resupply or a very pure volatile layer. A detailed discussion of these possibilities was first made in Stern et al. (1988).

[4] For example, a 10 km KBO even with a high albedo of 0.5 at 40 AU has a visual magnitude of only about 27, while a 1 km KBO at this albedo and distance would have a visual magnitude of 32.