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# Craters and ejecta on Pluto and Charon: Anticipated results from the New Horizons flyby

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## ABSTRACT

We examine the flux of bodies striking Pluto and Charon, and the nature of the crater populations that will form as a result of these impacts. Assuming impact speeds of 2 km/s and an impact angle of 45°, a 1 km impactor will form a 4.2 km diameter transient crater on Pluto, and a ~5.0 km crater on Charon, as compared with 8–13 km for several mid-sized saturnian satellites and 8–10 km for the icy Galilean satellites. We predict that secondary craters will be present in the crater size–frequency distribution (SFD) for Pluto and Charon at sizes less than a few km, at spatial densities comparable to the range seen on the mid-sized saturnian satellites and distinctly less than seen on the icy Galilean satellites. Pluto should have more secondary craters formed per primary impact than Charon, so if neither crater population on these bodies is in saturation, Charon's crater SFD should be the "cleanest" reflection of the primary, impacting SFD. Ejecta from Pluto and Charon escape more efficiently from the combined system, relative to ejecta from a satellite in orbit around a giant planet, due to the absence of a large central body. We estimate that Kuiper Belt Objects (KBOs) with diameters larger than 1 km should strike Pluto and Charon on (nominal) timescales of 2.2 and 10 million years, respectively. These estimates are uncertain because the numbers of small KBOs are poorly constrained. Our estimated rates are smaller than earlier predictions of impact rates, primarily because we assume a KBO size distribution that is shallower overall than previous studies did. The impact rate, combined with the observed crater SFD, will enable estimates of relative and absolute age of different geologic units, should different geologic units exist. We explore two scenarios in regards to the crater population: (1) a shallow (differential power-law index of $p \sim 2$, i.e. for $dN/dD \propto D^{-p}$), based on the crater SFD observed on young terrains of Galilean and saturnian satellites; and (2) a slightly steeper SFD ($p \sim 3$), based on extrapolations of larger (~100 km) KBOs from ground-based surveys. If the observed primary crater SFD, at diameters less than a few tens of km, is consistent with a differential power-law index $p \sim 2$, that will confirm that KBOs are deficient in small bodies relative to extrapolations from known ~100 km KBOs, consistent with expectations derived from examination of crater populations in young terrains on the Galilean and saturnian satellites. If the crater SFD has $p \geqslant 3$ over all observed sizes, then that power-law index applies across the KBO population over at least two orders of magnitude (1 km to100 km objects), and there must be some process that erodes the small KBOs when they migrate to the Jupiter–Saturn region of the Solar System. Whatever SFD is observed, the primary crater population on Pluto and Charon will provide the strongest constraint on the SFD of small KBOs, which will be beyond the observational reach of ground- and space-based telescopes for years to come. This, in turn, will provide a fundamental constraint for further understanding of the evolution of this distant and compelling population of bodies beyond Neptune.

## 1. Introduction

The flyby of the Pluto system is our first opportunity to view surfaces that are the gateway to the deep outer Solar System. The lessons of the Voyager, Galileo, and Cassini missions tell us that the small icy worlds of the outer Solar System are determined to confound our preconceived notions of what complexity is possible in small bodies. Ongoing ground- and space-based observations of Pluto have revealed an increasingly intricate multi-body system, demonstrating that the Pluto–Charon system continues the wondrous befuddlement imparted by the icy satellites of the giant planets.

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To understand the Pluto system, we start by applying the familiar tools developed by examination of other planetary surfaces across the Solar System. A key tool is the study of impact craters, which are the most abundant landform in the Solar System. Examining crater sizes, shapes, and spatial distributions enables a host of scientific explorations that are diagnostic of the surface and near sub-surface, while comparing craters between objects enables an extensive array of comparative planetology. The crater size–frequency distribution (SFD) tells us about the impacting population, and the variation of the crater SFD tells us about the relative ages of different surface units. Crater morphology (e.g. depth-to-diameter ratios, ejecta blanket styles) probes the structure of the surface and the near-surface; comparing morphology and degradation of similar-sized craters provides information on erosional rates and/or relaxation rates (see Moore et al. (2015) in this volume for further discussion of these topics for Pluto and Charon). Ejecta from craters create secondary craters, and on low-mass, multi-body systems like Pluto and Charon, can lead to sesquinary craters (craters made by ejecta that initially escape a body but later re-impact the parent object, or another). Perhaps most importantly, comparing crater spatial densities on different geologic units provides a measure of relative age; and if one knows or assumes an impact rate, then it is possible to estimate absolute surface ages, providing a clock of Solar System time at a more distant range from the Sun than has ever been possible.

Here we focus on what we may see at Pluto and Charon in regards to their crater populations, and consequences for key areas: (i) the relative populations of different types of impact craters; (ii) the population of small bodies in the Kuiper Belt; and (iii) relative and absolute ages of the Pluto system. For (ii), New Horizons offers our best chance for the foreseeable future to estimate the size–frequency distribution of the small bodies whose orbits interact with the Pluto system; small, dark, distant objects are hard to see and will remain invisible to even the most powerful ground-based telescopes for some years,[1] but the craters they make on Pluto and Charon will be visible. Thus the primary crater populations on Pluto/Charon are the best opportunity to evaluate the SFD of small Kuiper Belt Objects (KBOs) below current detection limits of ground- and space-based telescopes.

### 1.1. Types of impact craters

All impact craters are made by projectiles striking a surface, but there are multiple sources of projectiles:

- *Primary craters* are formed by the strike of comets or asteroids from heliocentric orbits; primary craters form at all scales, from microscopic pits to enormous impact basins thousands of kilometers in diameter. Primary impact speeds are a function of the orbits of the two bodies that collide, and any gravitational focusing that may occur due to a large central body (e.g. impact speeds on the moons of Jupiter and Saturn increase for satellites orbiting closer to their parent planets because of gravitational focusing). Impact angle (here defined as zero when the impactor strikes perpendicular to the surface) can be between essentially zero and ninety degrees, although a typical value is 45°.
- *Secondary craters* are made by debris, ejected from the formation of a primary crater, moving sufficiently fast that reimpact on the surface causes a crater to form. The largest secondary crater is typically 4–5% of its primary's diameter (Melosh, 1989; McEwen and Bierhaus, 2006), so in general their effect on the crater SFD is a function of the largest primary crater on the target body. The maximum speed possible for a secondary crater is limited by the escape velocity of the body (moderated by third-body or multi-body effects; more on that below).
- *Sesquinary craters*, still a relatively new concept whose contribution to the overall cratering records is not well understood, are made by material ejected during a primary cratering event that is moving sufficiently fast that it escapes the source body, and which subsequently reimpacts that body or another object some time later (Dobrovolskis and Lissauer, 2004; Zahnle et al., 2008).

If we wish to use the crater population to derive details of Pluto's age and SFD of the impacting population, we must first understand – or at least estimate – the relative contribution of each crater type to the overall population. Even if we cannot classify, on a crater-by-crater basis, the origin of that particular impact, we can use statistical arguments derived from the analysis here to constrain the role of non-primary craters, and/or provide guidance to which portion of the population is most likely to be primary craters.

### 1.2. Craters in the outer Solar System

The Voyager, Galileo, and Cassini missions have significantly advanced our understanding of the outer Solar System, imaging the giant planets and many of their moons and resolving them into a panoply of worlds. The image data returned from these missions have revealed impact histories that at first blush appeared similar to that of the inner Solar System, but, upon further inspection, have proven to be different. While Voyager-era interpretations of the Galilean satellites initially revealed crater SFDs that were grossly similar to those on the Moon and Mars, several advances have changed that earlier interpretation, two of which we mention here: (i) dynamical modeling, and observations of small body populations, indicate that ecliptic comets (bodies thought to originate in the Kuiper Belt; see Section 1.7) are the dominant impactors in the outer Solar System, vs. the asteroids that dominate impacts in the inner Solar System (Zahnle et al., 2001, 2003; Dones et al., 2009); (ii) more extensive image data from Galileo at Jupiter (Schenk et al., 2004; Bierhaus et al., 2009) and Cassini at Saturn (Kirchoff and Schenk, 2010) have shown that the crater SFDs on the icy moons of those bodies are, in fact, different from those seen on surfaces in the inner Solar System. Models of impact rates on the giant planets and their satellites rely on calculations of dynamical transport from small-body source regions such as the Kuiper Belt. The Pluto/Charon system has the advantage that no such dynamical simulations are required to estimate impact rates, since Pluto and its moons are embedded within the Kuiper Belt. The largest uncertainty in computing impact rates for Pluto and Charon is that we need to make a large extrapolation in size from the large KBOs we can see to the small KBOs that make the craters. Furthermore, the Kuiper Belt has a number of distinct components whose size–frequency distributions differ, at least for the large bodies that can be observed telescopically from Earth (see Section 4).

We briefly review the state of knowledge for impact crater populations in the outer Solar System, as a means to set the stage for our examination of craters in the Pluto system.

### 1.3. Cratering on the Galilean satellites

Despite its failed main antenna, the Galileo spacecraft returned sufficient image data of the Galilean satellites to provide significant advances in our understanding of the crater populations on these moons. The increased areal coverage, and increased spatial resolution in certain areas, enabled global estimates of the crater

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[1] However, the population of small Kuiper Belt Objects is starting to be probed by Earth-based occultation experiments (Schlichting et al., 2012; Zhang et al., 2013).