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Transient atmospheres on Charon and water–ice covered KBOs resulting from comet impacts

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ABSTRACT

Evidence from stellar occultation datasets and Charon's H_2O–ice dominated surface composition has long suggested a lack of any current atmosphere around this satellite planet. However, impacts from both Kuiper Belt and Oort Cloud comets must from time to time import N_2, CH_4, and other cometary super-volatiles that can create temporary atmospheres around Charon. Here we estimate the frequency of such cometary impacts on Charon and the imported mass of super-volatiles from each such impact. We then examine the characteristics of such transient atmospheric events, including their column densities, mean molecular weights, scale heights, and loss timescales. We then report on the detectability of such a transient atmosphere by New Horizons, and discuss the generalized case of cometary impact-created transient atmospheres on other satellites of Pluto and water–ice covered KBOs across the Kuiper Belt.

1. Introduction

Conventional wisdom is that Pluto's largest moon, Charon, has no atmosphere. This paradigm is supported by stellar occultation experiments (e.g., Walker, 1980; Sicardy et al., 2006), the ubiquitous presence of H_2O–ice which is not volatile on Charon's surface (Stern, 1992), the lack of any detectable ices on Charon that produce substantial vapor pressures at its ~50 K surface temperature (Cruikshank et al., 1997), and atmospheric escape modeling (e.g., Stern et al., 1988; Schaller and Brown, 2007) demonstrating that objects of Charon's size, mass, and temperature should lose surface volatiles on timescales that are short compared to the age of the Solar System.

However, as we describe here, it is possible that Charon could exhibit transient atmospheres from cometary impacts, which can deliver volatiles.[1] Charon's location, orbiting in the Kuiper Belt (KB), leads to an orders of magnitude higher impact flux than is experienced by the satellites of the giant planets, making this a possibility worthy of study. The imminent arrival of New Horizons to explore the Pluto system makes such a study particularly timely.

After reporting our findings for Charon, we generalize our findings to some other relevant bodies in the Kuiper Belt.

2. Impactor and volatile mass delivery rates

We begin with exploratory calculations regarding cometary impacts onto Charon to assess the impact frequency, mass flux of volatiles, and atmosphere of canonical $d > 1$ km diameter KB comets on Charon. Later we will briefly consider the effects of still smaller, more frequent impactors.

To begin, we adopt the observational estimate of $1.6(+2.2, -1.0) \times 10^6\ \mathrm{deg}^{-2}$ KBO impactors (comets) with diameter $d > 1$ km on the sky (Schlichting et al., 2012). Multiplying this range of sky surface density by the $\sim 10^4\ \mathrm{deg}^2$ sky area of the Kuiper Belt gives a total population estimate range of $N_{1\mathrm{km}} \sim 0.6\text{–}4 \times 10^{10}$ $d > 1$ km impactors. We adopt the geometric mean of this population estimate, $N_{1\mathrm{km}} = 1.5 \times 10^{10}$, and use it henceforth in this paper.

Next, we estimate the mean time between $d > 1$ km comet impacts on Charon as $T_{\mathrm{impact}} \sim (n\sigma v)^{-1}$, where n is the average number density of $d > 1$ km comets in the KB, σ is Charon's cross section (estimated simply as πR_{CH}^2), and v is the mean random velocity of comets in the Kuiper Belt. Adopting $v = 1\ \mathrm{km\ s}^{-1}$ (e.g., Bierhaus and Dones, submitted for publication) a Kuiper Belt spanning 30–50 AU with a half-disk wedge angle of 30 deg, and $R_{\mathrm{CH}} = 603$ km (Sicardy et al., 2006), we find a characteristic mean time between impacts of 1.3×10^6 years. This impact timescale is comparable to previous KB impact rate estimates (e.g., Bierhaus and Dones, submitted for publication; Durda and Stern, 2000).

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[1] And also potentially excavate buried volatiles beneath a H_2O–ice lag deposit.

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Therefore, we can crudely estimate there have been ~3500 impacts onto Charon of $d > 1$ km comets over time. Assuming a 1 g cm^{-3} density, each $d = 1$ km impactor imports a mass of 5×10^{14} g onto Charon. The typical speed of such impactors is only of order 1.5 km s^{-1} (e.g., Durda and Stern, 2000; Stern, 2002),[2] and the fraction of impactor kinetic energy partitioned into ejecta kinetic energy is likely only 10–20% (see the discussion of impact energy partitioning in Melosh, 1989). Although Charon's escape speed is 0.6 km s^{-1}, almost all impactor mass is expected to be retained by Charon immediately after impact.

It is important to point out that comets are known to contain significant portions of all three major super-volatiles known to exist in Pluto's atmosphere—N_2, CO, and CH_4—and Table 1 summarizes the range of typical cometary abundances of these three species and the noble gas argon. Table 2 converts these volatile fractions to masses imported in the impact of a 1 km diameter comet of density 1 g cm^{-3}.

3. Resulting post-impact atmospheric properties

Later in this paper we will show the result of post-impact simulations onto Charon. First, however, we start with a simple set of scaling calculations.

To begin, even neglecting the heat of impact, the volatiles N_2, CO, Ar, and CH_4 delivered by comet impacts onto Charon's surface will sublimate in Charon's 40–50 K surface daytime thermal environment, creating an atmosphere. Spreading the volatile impact-delivered masses shown in Table 2 over the surface of Charon produces the equivalent global average columns and pressures shown in Tables 3 and 4, respectively.

These tables demonstrate: (1) that CO is likely to dominate the immediate post-impact composition of such induced atmospheres, and (2) that the relative initial proportions of the various volatiles depends significantly on their native abundance in each particular impactor.

We further point out that the pressures shown in Table 4 are far lower than the vapor pressure equilibria of these same volatiles in Charon's 40–55 K surface thermal environment shown in Fig. 1. This is due to the fact that $d = 1$ km comets do not import sufficient volatiles to create vapor pressure equilibrium atmospheres at Charon.

Still, such impacts do create real atmospheres, with resulting mean free paths typically ranging from a few meters to a few kilometers, depending on the volatile. By comparison, at a reference gravity for Charon of 27 cm s^{-2}, the $T = 45$ K scale heights of N_2, CO, Ar, and CH_4 range between 35 and 85 km, respectively, allowing us to conclude that the initial post-impact atmosphere created by $d = 1$ km comets striking Charon are expected to be initially collisional near the surface.

However, we calculated the Jeans loss timescales at $T = 45$ for these gases at Charon and found that even the resulting atmospheric escape rate is high enough to deplete to a collisionally thin post-comet impact exosphere in about a year.

4. Post-impact simulations

Because the atmosphere is initially collisional (i.e., because the mean free path is short compared to the scale height) the atmospheric loss will initially follow a Jeans loss timescale in the exosphere until density declines sufficiently that the exobase drops to the surface; at this time the collisionless (free molecular) simulations we employ next will apply.

These simulations use a free molecular code described in Goldstein (2002) and Goldstein et al. (2007). The code makes use of the circularly restricted three-body problem in a rotating frame centered about Charon. Pluto acts as the second body, while the third bodies are the negligible mass gas particles.

Particles experience gravitational forces from Pluto and Charon, as well as Coriolis and centrifugal forces from the rotating frame. Particles continue to move about in the Pluto–Charon system until one of the following three conditions are met: (1) If a particle's distance from the center of Charon is found at any time to be less than Charon's radius, the particle is repositioned at the point where it crossed Charon's surface and reassigned a velocity sampled from a 40 K Maxwell–Boltzmann distribution characteristic of Charon's average surface temperature. This simulates a diffuse reflection off the surface with negligible residence time. A 50 K Maxwell–Boltzmann distribution run was also conducted. (2) If a particle crosses Pluto's exobase, assumed in our simulations to be 4000 km above Pluto's surface (Strobel, private communication 2013), it is assumed lost to Pluto and eliminated from the simulation. (3) Finally, particles that reach 65,000 km (i.e., just beyond the orbit of Hydra), are eliminated if they also have enough kinetic energy to reach the edge of Pluto's Hill sphere and escape the system.

At the start of each simulation, 10,000 simulation particles were placed at the chosen comet impact site on Charon's surface. Some, assumptions were made to approximate the release of gas from volatile ices during a comet impact. One was that the comet was assumed to be largely water ice with a smaller portion of volatile ices. Because the heat of vaporization for the volatile ices is small, and they are fairly low in concentration, their contribution to the heating process was assumed to be negligible.

The mass-specific energy of the impact was estimated and compared to the specific heat of ice, with an impact speed of 1.5 km s^{-1} assumed, which is broadly characteristic of impacts of KB impactors onto Charon, as discussed above. This results in a temperature rise of ~250 K to ~350 K, depending on energy partitioning fractions between heating and mechanical disintegration.

Given that the heat of fusion of ice is very high (698 kJ/kg are required to vaporize the ice), it is unlikely that much of the comet water would exceed 273 K and become vaporized. For simplicity in

Table 1
Adopted cometary volatile fraction ranges.

Supervolatile species	Adopted molar abundance (low)	Adopted molar abundance (high)
N_2	0.0002	0.002
CO	0.02	0.30
Ar	0.0	0.01
CH_4	0.005	0.02

See Crovisier (1994, 2006); fractions are normalized to H_2O.

Table 2
Adopted volatile masses per $d = 1$ km impactor.

Supervolatile species	Mass for low abundance case (g)	Mass for high abundance case (g)
N_2	5×10^{10}	5×10^{11}
CO	5×10^{12}	8×10^{13}
Ar	0	5×10^{12}
CH_4	1×10^{12}	5×10^{12}

For a 1 km diameter comet of density 1 g cm^{-3} consisting of a 50:50 mass ratio of H_2O to refractories; hence the shown volatile masses for each species are based on half the comet mass made of H_2O.

[2] This 1.5 km s^{-1} derives from combining the mean random KB orbit crossing speed of 1 km s^{-1} given above and the additional velocity impacted by impactors falling down the combined potential wells of Pluto and Charon to an impact on Charon's surface.

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