New Horizons Ring Collision Hazard: Constraints from Earth-based Observations

A White Paper for the New Horizons Mission

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Abstract

The New Horizons spacecraft's nominal trajectory crosses the planet's satellite plane at $\sim 10,000$ km from the barycenter, between the orbits of Pluto and Charon. I have investigated the risk to the spacecraft based on observational limits of rings and dust within this region, assuming various particle size distributions. The best limits are placed by 2011 HST observations, which significantly improve on the limits from stellar occultations, although they do not go as close to the planet. From the HST data and assuming a 'reasonable worst case' for the size distribution, we place a limit of $N < 10$ damaging impacts by grains of radius < 0.2 μm onto the spacecraft during the encounter. The number of hits is $\approx 100\times$ above the NH mission requirement, and $\approx 1000\times$ above the mission's desired level. Continued studies with HST may improve our limit on N by a factor of a few. Stellar occultations remain valuable because they are able to measure N closer to the Pluto surface than direct imaging, although with a sensitivity limit several orders of magnitude higher than that from HST imaging. Neither HST nor occultations are sensitive enough to place limits on N at or below the mission requirements.

1 Background and Motivation

On November 3-4, 2011, the "New Horizons Encounter Hazards Workshop" workshop was held at Southwest Research Institute, Boulder, CO. The purpose of the workshop was to discuss possible collisional hazards to New Horizons (NH) during its upcoming 2015 trajectory through the Pluto system. Discussion topics included a variety of theoretical modeling and observations, each of which placed limits on a range of particle sizes at different locations within the system. Based on these inputs and followup work, the NH mission will decide on a final trajectory at some point prior to the 2015 encounter. This paper summarizes work I presented at the workshop.

2 Mission Requirements

The New Horizons spacecraft incorporates a multi-layer flexible shield, which in part protects the spacecraft against damage from high-speed micrometeoroid dust impacts. The shield is designed to protect NH against impacts of 3×10^{-4} g at relevant speeds. The New Horizons mission itself has defined a slightly lower critical mass of $m_c = 1 \times 10^{-4}$ g. The mission has a requirement of $N < 0.1$ impacts of size m_c or greater during the encounter, and a 'desirement' of $N < 0.01$ impacts of mass m_c. For the purpose of this paper, I assume a density of 4 g cm^{-3}, corresponding to a critical radius $r_c = 0.2$ mm.

3 Observational Limits

Rings in reflected light. Observations by HST and ground-based telescopes can be used to search directly for rings and dust orbiting in the region near Pluto. Assuming a non-resolved uniform ring of optical depth $\tau < 1$, the observed brightness in reflected light is

$$\frac{I}{F} = \frac{\tau a}{\mu} \frac{P(\alpha)}{P(0^\circ)} \tag{1}$$

In this expression, I is the measured ring intensity and πF is the incident solar flux. The ring's optical depth is τ, and albedo is a. μ is the cosine of the angle B, which is the tilt angle of the rings (from normal) as seen by the observer. $P(\alpha)$ is the particle's phase function at scattering angle α. For Earth-based observations of Pluto α is always less than 1.5°, so we assume $\alpha = 0^\circ$ and have

$$\frac{I}{F} = \frac{\tau a}{\mu} \ . \tag{2}$$

The normal optical depth for a ring seen in reflected light is

$$\tau(\lambda) = \int n(r)\, \pi r^2\, Q_{sca}(r, \lambda)\, dr, \tag{3}$$

where $n(r)$ is the size distribution of the dust grains. The scattering efficiency Q_{sca} is usually computed using Mie scattering, and approaches the value of 1 for $r \gg \lambda$ and moderately absorbing particles. For small dust grains, the albedo a is is usually calculated from Mie scattering as well. In this case we use

$$a = \frac{Q_{sca}(r, \lambda)}{Q_{ext}(r, \lambda)} - 0.5 \tag{4}$$

where the 0.5 is to account for the diffraction spike, which is formally part of the phase function but not seen in our particular observations. Q_{ext} is the extinction efficiency.

Finally, the number of damaging hits to the spacecraft during its passage through the system can be written as

$$N = n(r > r_c)\,\frac{A}{\mu_{sc}} \tag{5}$$

where $A \approx 5$ m^2 is the cross-sectional area of the spacecraft (Chris Hersman, personal communication), and μ_{sc} is the cosine of the sub-spacecraft latitude B_{sc} at closest approach. A trajectory directly through the plane will encounter fewer particles than one on a shallow slant angle; for the nominal NH encounter geometry, GeoViz[1] shows that $B_{sc} \approx 49°$. Combining Eqs. 2–5, N can be calculated exactly from I/F and the size distribution $n(r)$.

Rings in extincted light. In the case of extincted light (*e.g.*, a stellar occultation), the ring's brightness is calculated slightly differently. Here, the observed intensity I is

$$I = I_0\, e^{-\tau/\mu}\ , \tag{6}$$

where I_0 is the unocculted stellar intensity. The optical depth is given by

$$\tau(\lambda) = \int n(r)\,\pi r^2\, Q_{ext}(r,\lambda)\ dr. \tag{7}$$

Eqs. 5–7 can then be used to calculate N from τ and $n(r)$. Note that in extinction, the particle albedo is not relevant.

4 Ring Upper Limits from Stellar Occultations

Stellar occultations have two distinct advantages over direct imaging. First, they offer a higher resolution δR, defined by the Fresnel limit

$$\delta R = \sqrt{(30\ \text{AU}\,\lambda/2)} \approx 2\ \text{km}, \tag{8}$$

rather than the diffraction limit, which in the case of HST is

$$\delta R = (30\ \text{AU})\ 1.22\,\lambda/(2.4\ \text{m}) \approx 1500\ \text{km}. \tag{9}$$

Second, the occultation observations are immune to the effects of stray light. This allows for measurements to continue with no loss in sensitivity even as the star and occulting body approach each other on the detector. Imaging experiments (like on HST) are often limited by stray light, in particular when searching for faint features such as rings at sub-arcsecond separations from a bright extended object such as Pluto.

2006 AAT occultation. Pluto passed in front of the magnitude 15.5 star P384.2 on 2006 Jun 12. This occultation was observed by R. French and K. Shoemaker using the 3.9-meter Anglo-Australian Telescope (AAT). This observation coupled a large aperture with a low-noise, fast-readout CCD (10 fps) to study the system at unprecedented resolution. The data achieved a SNR of 333 per scale-height (~ 60 km). The shadow path traveled at 26.7 km/sec across Earth, giving a linear resolution of 2.67 km/sample. The 50-second central occultation measured Pluto's atmospheric structure (Young *et al.*, 2008). However, the dataset also

[1] `http://soc.boulder.swri.edu/nhgv`

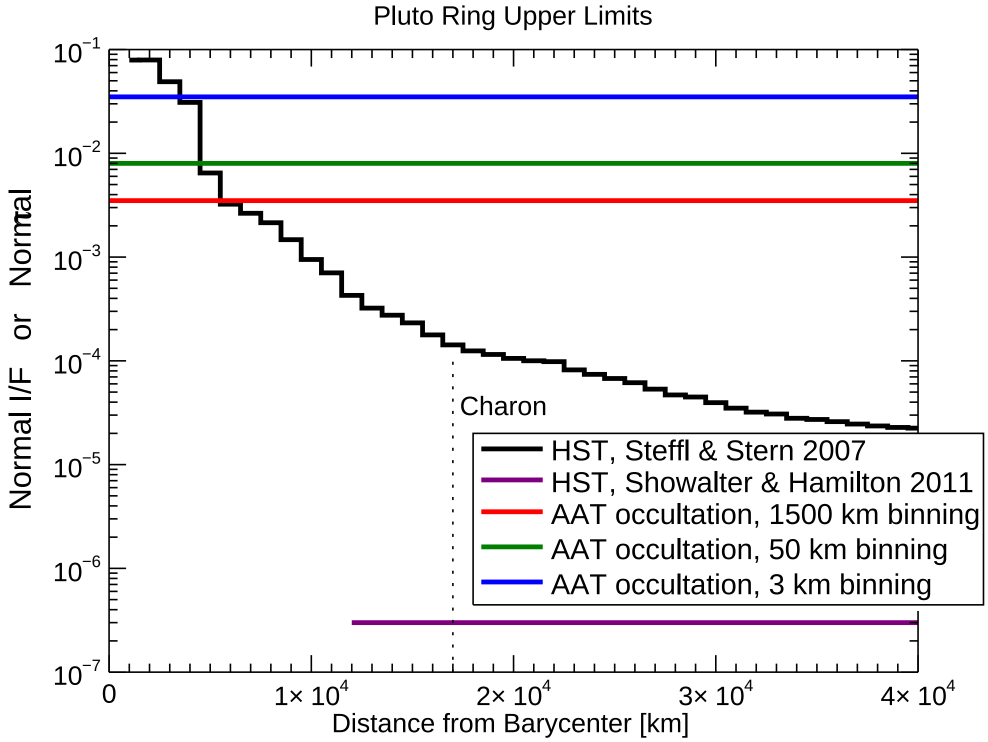

Figure 1: Observational upper limits for rings in the Pluto system. The 2007 HST observations were affected by stray light which increased moving closer to Pluto. The 2011 HST observations reduced stray light significantly but were saturated inward of 12,000 km. HST's spatial resolution was 1500 km. The 2006 AAT stellar occultation is unaffected by stray light, and provides the best limit near the system barycenter. 2007 HST data provided by A. Steffl and adapted from Steffl and Stern (2007).

included close to three hours of additional data, from two hours before the central event to one hour after. We recently re-analyzed the entire dataset to search for occultations by as-yet unknown rings, orbital debris, or satellites (Throop *et al.*, 2011). Results are shown in Table 1 and Fig. 1.

Other occultations. Additional ring occultation results have been reported by several groups. McKay (2008) and Pasachoff *et al.* (2006) report on one additional dataset taken in Australia during the 2006 Jun 12 occultation. Their limits are similar to ours. Boissel *et al.* (2008, also Boissel in preparation 2011) reports limits from four occultations in 2006-2008. Their limits are also similar to ours. Neither of these studies found any dips attributable to unknown satellites or orbital debris.

Search	Upper Limit (no detections)
Rings, 1500 km width	$\tau < 0.0035$
Rings, 50 km width	$\tau < 0.08$
Rings, 3 km width	$\tau < 0.035$
Satellites along occultation path	$r < 100$ m

Table 1: Results of search for rings in 2006 Jun 12 AAT stellar occultation, from Throop *et al.* (2011).

5 Ring Upper Limits from HST Imaging

The Hubble Space Telescope was used in June 2011 to search directly for rings around Pluto (program DD-12436, Showalter & Hamilton). These observations placed Charon and Pluto in such a way as to facilitate subtraction of stray light. The reduced stray light allowed for a much-improved lower limit to I/F compared to previous results (*e.g.* Steffl and Stern, 2007), where it was difficult to distinguish between stray light and reflected ring light.

Detailed analysis is forthcoming, but M. Showalter has presented preliminary results that showed a limit on the normal $I/F < 3 \times 10^{-7}$ outward of 12,000 km from Pluto. Inward of this distance the detectors were saturated, so no limit could be calculated.

This new limit is 3-4 orders of magnitude better than the AAT occultation data, depending on the value of particle albedo assumed. The AAT data is able to measure closer to the planet than HST, but for practical purposes the HST limit is superior. Future HST observations could be designed that would allow imaging all the way to the Pluto surface; the 12,000 km limit is due to saturation of the detectors, not stray light (M. Showalter, personal communication).

6 Impact Limits for New Horizons

In this section I use the measured constraints on ring abundance to infer the population of mm-sized grains and thus the risk to New Horizons on its path through the Pluto system.

An 'absolute worst case' scenario can be examined if we assume that 100% of the rings' optical depth is due to grains of radius exactly r_c. In this case, Eqs. 2 – 5 give us

$$N = \frac{I}{F} \frac{A}{\mu_{sc}\, a\, \pi r^2 Q_{sca}} \tag{10}$$

Plugging in the HST I/F limit and assuming an albedo $a = 0.05$, we find $N \approx 500$. This shows that observations alone, when interpreted most conservatively, cannot technically rule out a danger to the spacecraft. However, in this case our input assumptions are truly extreme enough that the computed value of N is not really a useful statement about the actual danger.

In order to make a 'plausible worst case' scenario, I make the more reasonable assumption that the grains are distributed not unimodally but in a power law, where

$$n(r)\,dr = r^{-q}\,dr \;. \tag{11}$$

The exponent q indicates the slope of the distribution. Values of $q < 3$ have most of their surface area in small grains, while $q > 3$ indicates a dominance of large grains. Power laws are believed to be common in collisional systems such as rings. The actual distribution in rings across many orders of magnitude may well be much more complex, but it has not been well measured. Also, by choosing a wide range of power laws, we are likely to bound the actual distribution.

I computed the I/F for rings with q in the range of 2–7. For each distribution, I used Mie scattering to calculate $Q_{sca}(r, \lambda)$ explicitly for every particle size. I assumed $\lambda = 0.5$ μm, and the particle composition to be a silicate-ice mixture with index of refraction $1.33 + 0.001i$. The size range extended from $r = 0.01$ μm to $r = 0.8$ mm across 100 logarithmically spaced bins. Neither the size limits nor the composition strongly affect the results. I normalized n such that I/F (Eq. 2) matched that from HST. It was then straightforward to calculate N from Eq. 5.

Results are shown in Fig. 2. The plot shows that for steep size distributions where $q \geq 4$, NH is out of the 'Danger' zone, receiving $N < 0.1$ dangerous hits. However, for $q < 3.5$, the mission's safety cannot be assured. Values of q in the range $2 - 3$ yield $N \approx 1 - 10$ dangerous hits through the encounter. Smaller values of q result in larger N, because these distributions are dominated by larger grains.

The actual value for q at Pluto is of course unknown. However, typical collisional ejecta has a $q_{ej} \approx 3.5$ upon initial creation (Durda *et al.*, 2007). Size-dependent processes in planetary rings almost always reduce q: Poynting-Robertson drag and radiation pressure are both proportional to radius, reducing q by 1. Recent simulations of dust processes at Pluto support $q = q_{ej} - 1$ (Doug Hamilton, this workshop), suggesting that $q = 2.5$ would not be unexpected for dust at Pluto. Because the curves for $q = 2 - 3$ are similar near near r_c, the inferred value for N turns out to be only weakly sensitive to changes to q. These low values of q are the most dangerous ones and the most likely, and thus *the best observational limits cannot rule out a substantial impact hazard to the spacecraft during encounter.*

I have assumed dark particles for these calculations ($a \approx 0.05$, but calculated by Mie scattering). This is consistent with the visual albedo of Uranus ring particles (Cuzzi, 1985). Icy particles with a higher albedo are also prevalent in the outer solar system, but lacking any other constraints, I use the most conservative value available. The albedo of Pluto and Charon are in the range 0.3–0.5, suggesting that ring particles could be much brighter. Brighter particles would decrease N.

Future observations. 2007 HST observations of the Pluto system (Steffl and Stern, 2007) placed limits of $I/F < 10^{-3}$ at 10,000 km. The limit was unable to go lower because of incomplete removal of stray light from Pluto-Charon in the telescope optics. The recent 2011 HST observations improved the I/F limit by some 3000× by rolling the spacecraft with Charon's orbital motion to allow for improved stray light removal. It is likely that further HST observations could improve this limit by a factor of a few, and also search closer to Pluto (Mark Showalter, personal communication). Such results would make substantial (but not

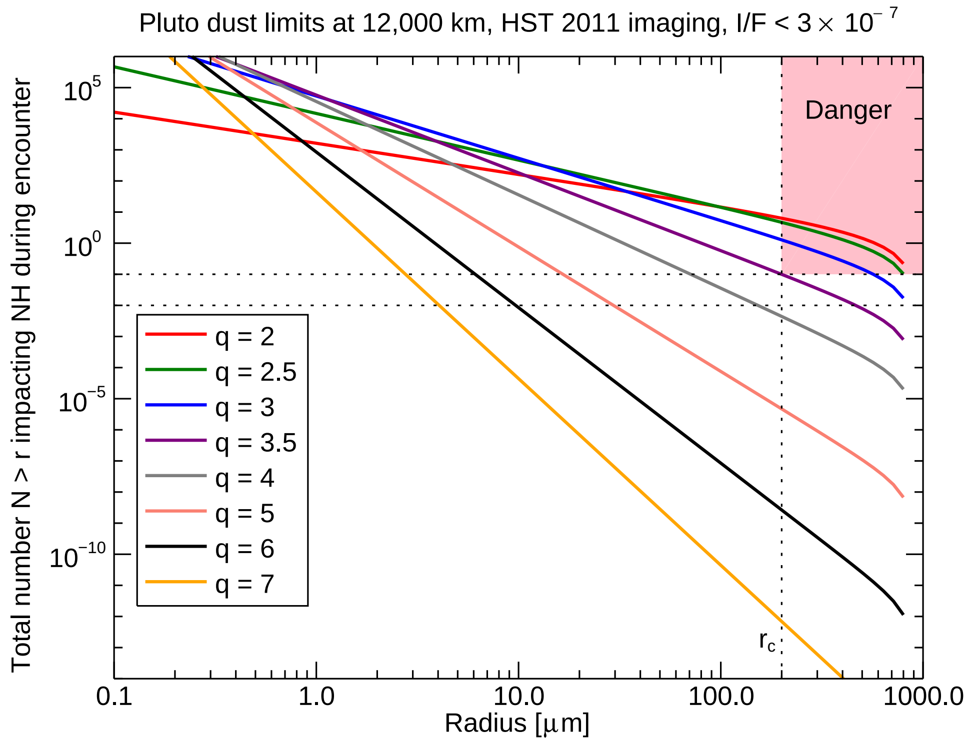

Figure 2: Constraints on dust population from 2011 HST observations. The lines indicate the different populations of grains with different size distributions. The visible I/F of all of the lines is identical and matches the HST-derived upper limit. The red quadrant indicates a population of particles that exceed the NH mission requirement of $N(r > r_c) < 0.1$. Models can place a limit of $N \lesssim 10$ particles of size r_c (red curve).

complete) progress toward placing all curves for N out of the Danger region.

The τ limit from the occultation could be improved with additional observations using brighter stars and/or larger telescopes. For instance, observing an occultation of an 11th magnitude star from a 10-m telescope would yield a signal 250× brighter the dataset used here, and an SNR some 15× better. However, such an increase in sensitivity would not be nearly sufficient to beat HST. Occultations will always be superior to HST for searching for small ring arcs and isolated 100 m objects, and in the closest region toward the planet. In particular, appulses (where the shadow path passes near the Earth but not over it) are more frequent than occultations, and would be quite valuable because they often occur with brighter stars.

7 Acknowledgments

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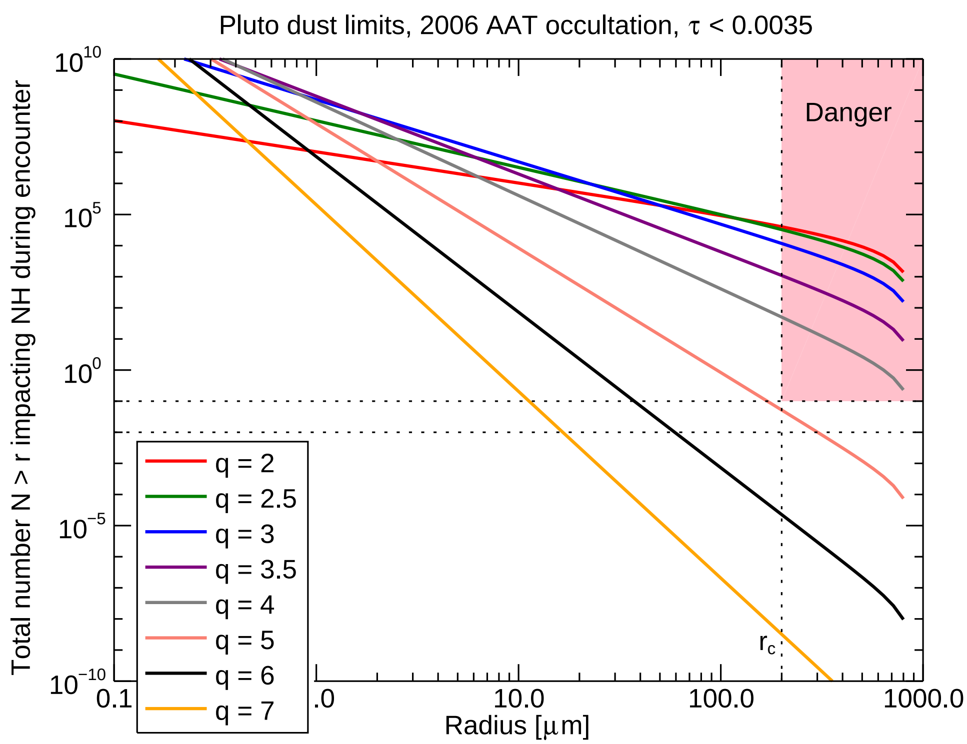

Figure 3: Same as Fig. 2, but using the limit on τ from the 2006 Jun 12 AAT stellar occultation. N is significantly higher here than with the HST figure, because of the weaker constraint on τ.

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