AN EXPLORATION OF CHARON'S PUTATIVE ECCENTRICITY AROUND PLUTO. W. F. Bottke, S. A. Stern, and H. F. Levison. Southwest Research Institute, 1050 Walnut St, Suite 400, Boulder, CO 80302, USA (bottke@boulder.swri.edu).

Abstract: Charon's orbital eccentricity has been reported to be in the range of 0.003-0.008 [1]. This non-zero value, if correct, indicates some significant forcing against the two-body tidal equilibrium value, which should formally be zero. We investigated whether the reported eccentricity could be a by-product of gravitational perturbations by KBO flybys through the Pluto-Charon system and KBO impacts directly onto Pluto/Charon. Our results indicate that Charon's reported eccentricity is unlikely to be caused by this effect. Although we cannot rule out some additional source of eccentricity excitation (e.g., an undiscovered satellite in the system, or a Kozai resonance), our analysis indicates it is plausible that Charon's actual orbital eccentricity is substantially smaller than the 0.003 lower limit reported previously.

Reader's Note. This LPSC abstract is based on an Astronomical Journal paper (by Stern, Bottke, and Levison) which is in press.

Introduction: HST-derived astrometry of Charon's orbit about Pluto provided evidence for a significant, non-zero orbital eccentricity of Charon, with likely values in the range 0.003-0.008 [1]. This report was somewhat of a surprise to many, and was met by some with skepticism, in that it had been expected that tidal evolution in the Pluto-Charon system would drive Charon's equilibrium eccentricity to values negligibly close to zero [2]; note that the tidal spin-down timescale of the Pluto-Charon binary (PCB) is short (~10^7 years) (e.g., [3]). Solar and planetary tides are orders of magnitude too small to induce the reported eccentricity [4]. For this reason, we investigated the possibility that physical collisions on, or flyby perturbations of, Pluto-Charon could induce the reported eccentricity, as first posited in a brief study [5].

Method: Our first step was to compute the rate at which KBOs penetrate the PCB Hill sphere. Using numerical integration, we tracked classical and resonant KBOs with multiple opposition orbits for 1 Gyr, with all passages through the PCB system recorded. To account for first-order detection biases in the Kuiper Belt population, we debiased the KBO population by weighting the data points by the sin (inclination) (e.g., [6]). We found the mean intrinsic collision probability was P_i=4.2x10^{-22} km^{-2} yr^{-1} and the mean encounter velocity between the PCB and KBOs was ~2.1 km s^{-1}.

Next, we constructed a Monte Carlo code to track the effects of KBO close encounters and collisions on Pluto and Charon. We assumed an initial Charon orbit of *a* = 19600 km, with *e, i* =0 [1]. We assumed Pluto and Charon radii of 1180 km and 600 km, respectively; we assumed Pluto and Charon masses of 1.38x10^{25} gm and 1.86x10^{24} gm, respectively, corresponding to Pluto and Charon densities of 2 gm cm^{-3}. To generate various KBO impactor populations, we assumed a power-law size-frequency distribution of KBOs with a differential power law indices of q=-4.5, -4.0, and -3.5 which bound the likely population structure of the Kuiper Belt (e.g., [7]). The number of KBOs with D>100 km and D<660 km was set to 5x10^4 and then 1.5x10^5 in successive runs for each power law. The power-law size distribution was extended down to 100 m for collisions and 5 km for close encounters. We used random deviates to select the KBO diameter and a distance of closest approach *b* of each KBO in the Monte Carlo runs. We computed KBO masses assuming spherical shapes and a bulk density of 2 gm cm^{-3}.

The mean time between encounters was computed separately, as a function of KBO size, for collisions and encounters using $T_{enc} = (P_i N_{KBO} b^2)^{-1}$, where N_{KBO} is the number of KBOs in a given size bin, and *b* is the largest separation distance capable of producing an effect of interest on Pluto-Charon. We accepted *b* up to twice the semi-major axis of Charon's orbit; tests show that larger *b* values do not produce significant differences in our results. The time between physical collisions was computed the same way, but with *b* set to the radius of the target body (Pluto or Charon).

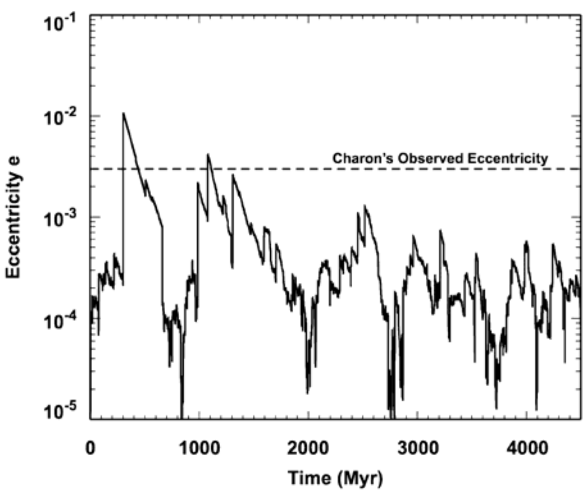
If no physical collision occurred, we used the impulse approximation and a random orientation of the encounter relative to PCB to calculate a velocity change for Charon relative to Pluto. In turn, this value was used to compute the change in orbital elements of the binary. A comparable procedure was used to determine the velocity change caused by KBO impacts.

We modeled the eccentricity of Charon as declining between excitation events due to a relaxation towards tidal equilibrium. Our procedure used the (constant time-lag) formalism developed by [8], [9]. The phase lag for the bulge raised on Pluto by Charon was arbitrarily set to 20 minutes, while the rigidity of Pluto was assumed to be water ice. To bound our results, we set Charon's rigidity to water ice and that of the Moon (6.5x10^{11} dyne cm^{-2}; [10]); these correspond to tidal damping timescales of 17 and 202 Myr, respectively.

Table 1: Run Case Descriptions

Run Case	# KBOs (D>100 km)	q	Charon's Rigidity
1W	$5x10^4$	-3.5	Water Ice
2W	$5x10^4$	-4.0	Water Ice
3W	$5x10^4$	-4.5	Water Ice
4W	$1.5x10^5$	-3.5	Water Ice
5W	$1.5x10^5$	-4.0	Water Ice
6W	$1.5x10^5$	-4.5	Water Ice
1S	$5x10^4$	-3.5	Bulk Lunar
2S	$5x10^4$	-4.0	Bulk Lunar
3S	$5x10^4$	-4.5	Bulk Lunar
4S	$1.5x10^5$	-3.5	Bulk Lunar
5S	$1.5x10^5$	-4.0	Bulk Lunar
6S	$1.5x10^5$	-4.5	Bulk Lunar

Results: Using our code, we made 12 separate model runs that consisted of two sets of 6 runs in which we varied the size distribution, total KBO population, and Charon's rigidity as described above (Table 1). Figure 1 presents the results of a sample model run (case 4S), showing Charon's eccentricity evolution as a function of time; notice the rarity with which its orbital eccentricity reaches or exceeds the nominal reported value of 0.003.



The integrated e > 0.003 value for all 12 of our model runs is given in Table 2. Median eccentricities for Charon's orbit were found to range from just below 10^{-5} to just below 10^{-3}.

Table 2: Charon's Eccentricity

Run Case	# KBOs (D>100 km)	q	Temporal Fraction e>0.003
1W	$5x10^4$	-3.5	0.003
2W	$5x10^4$	-4.0	0.002
3W	$5x10^4$	-4.5	0.001
4W	$1.5x10^5$	-3.5	0.003
5W	$1.5x10^5$	-4.0	0.001
6W	$1.5x10^5$	-4.5	0.001
1S	$5x10^4$	-3.5	0.008
2S	$5x10^4$	-4.0	0.003
3S	$5x10^4$	-4.5	<0.001
4S	$1.5x10^5$	-3.5	0.052
5S	$1.5x10^5$	-4.0	0.037
6S	$1.5x10^5$	-4.5	0.019

We found that to raise the temporal fraction in which e>0.003 to a high probability (e.g., 25%) would require that the product of Q and rigidity be higher by one or more orders of magnitude than our highest value. Note that our results give far smaller mean random eccentricities for Charon than [5] because our better constrained KBO population contains fewer large bodies.

Conclusions: We find that our chosen KBO excitation mechanism fails to produce Charon orbital eccentricities as high as those reported by [1] except rarely, and even then, only for certain Kuiper Belt models. In general, cases with greater large KBO populations and more ice-like bulk rigidities maximize the fraction of time Charon has higher orbital eccentricity.

Unexplored mechanisms that may be capable of driving Charon to a sufficiently large equilibrium eccentricity include: (i) the presence of an undetected satellite in the system, (ii) the Kozai mechanism, (iii) eccentricity resonances (perhaps related to the inclination resonance effects discussed by Rubincam 2000), and (iv) a strong libration of Pluto coupled to a significant Plutonian J_2 .

Even so, until such time as one of those routes points definitively to a resolution of the discrepancy we have discovered, we believe it is advisable that workers consider Charon eccentricities in excess of 10^{-3}, or even 10^{-4}, with a degree of skepticism.

References: [1] Tholen, D.J. and Buie, M.W. (1997) *Icarus 125*, 245. [2] Dobrovolskis, A.R., et al. (1997) In *Pluto and Charon* (U. Arizona. Press), 159. [3] Peale, S.J. (1986) In *Satellites* (U. Arizona. Press), 159. [4] Weissman, P.R. et al. (1989) *GRL 16*, 1241. [5] Levison, H. F, and Stern, S. A. (1995) *LPSC 26*, 841. [6] Brown, M., (2001) *AJ 121*, 2804. [7] Jewitt, D.C., and Luu, J.X. (2000) In *Protostars and Planets IV* (U. Arizona. Press), 1201. [8] Kaula, W.M. (1964) *Rev. Geophys. Space Phys., 2*, 661. [9] Goldreich, P, and Soter, S. (1966) *Icarus, 5*, 375. [10] Nakamura Y., Latham, G.V., and Dorman, H.J. (1976) *Lunar Sci., VII*, 602. [11] Rubincam, D.P. (2000) *JGR 105*, 26745.