On an impact origin of Pluto-Charon. R. M. Canup[1] and E. Asphaug[2], [1]Southwest Research Institute; 1050 Walnut Street, Suite 400, Boulder, CO 80302 robin@boulder.swri.edu, [2]Earth Sciences Department, University of California; Santa Cruz, CA 95064.

Introduction: The Pluto-Charon system shares key commonalities with the Earth-Moon system, *e.g.*, its large satellite-to-planet mass ratio, high system angular momentum and a potentially reduced satellite density relative to that of the planet. In both cases an impact origin is favored (*e.g.*, [1-2]). However until recently [3] no quantitative simulations of potential Pluto-Charon forming impacts had been performed. Unlike the relatively well-constrained situation for the formation of Earth's Moon, key properties of Pluto and Charon - their rock/ice fractions, mass ratio, and total system angular momentum - are somewhat uncertain. However, a primary challenge to an impact origin is obtaining a sufficient yield of material in bound orbit: Charon likely contains ~10% of Pluto's mass, whereas the Moon has only ~ 1% of the Earth's mass. Previous impact simulations involving rocky objects have found a maximum yield of material placed in orbit of only ~ 3 to 4% of the total colliding mass (e.g., [4-5]) Here we report on simulations of potential Pluto-Charon forming impacts using smoothed-particle hydrodynamics and a variety of rock-ice compositions.

Results: Charon contains 8 to 15% of the mass of Pluto [6]. The angular momentum of the Pluto-Charon system is not known precisely, but is estimated in the range $L_{P\text{-}C}$ = 6 to 8 x 10^{37} g-cm^2/s [7]. This implies a system angular momentum that likely exceeds the critical angular momentum for rotational stability, L^*, for a single object containing the total system mass. For an impact between initially non-rotating objects with an impact velocity equal to the mutual escape velocity ($v_{imp} = v_{esc}$), the resulting system (L/L^*) is just a function of K (the moment of inertia factor of the colliding objects), g (the ratio of the impactor mass to the total colliding mass), and the normalized impact parameter, b (where $b = \sin x$ and x is the impact angle),

$$\frac{L}{L^*} = \frac{\sqrt{2}}{K} b g (1-g)\sqrt{g^{1/3} + (1-g)^{1/3}} \qquad (1)$$

where L^* is defined by equating the centrifugal to the gravitational force for a spherical body (e.g., [5]). For a Pluto-Charon system mass and mean density $M_{P\text{-}C}$ = 1.47 x 10^{25} g and $\langle \rho_{P\text{-}C} \rangle$ ~ 1.9 g/cm^3,

$$0.929\left(\frac{0.4}{K}\right) \le \left(\frac{L_{P-C}}{L^*}\right) \le 1.238\left(\frac{0.4}{K}\right) \qquad (2).$$

From Eq. (1), (L/L^*) is maximized for the $v_{imp} = v_{esc}$ case for a grazing impact (b = 1) between like-sized objects (g = 0.5), and for this case, the resulting (L/L^*) = 1.11(0.4/K). Since K = 0.4 for a uniform density object, a smaller value of K would be expected given that, e.g., Pluto is likely differentiated (*e.g.* [8]). Thus for the low impact velocity, no-spin case, an oblique collsion between objects close in size is needed to account for $L_{P\text{-}C}$. Previous simulations of lunar-forming impacts [4, 9] suggest that the fractional yield of orbiting material generally increases as the impact parameter or g is increased, implying that an oblique collision of like-sized objects would also be the impact condition predicted to produce the maximum yield of orbiting material.

Method: The SPH code we utilize [9] employs a tree code for gravitational interactions and variable smoothing lengths. Internal strength is ignored, a valid assumption for the sizes of interest here. The energy budget is determined by shock heating, ($P\ dV$) work, and the equation of state. We utilize a semi-analytical equation of state, ANEOS [10]. In ANEOS, thermodynamic quantities necessary to describe the material state and pressure for a given input temperature and density are derived fom the Helmholtz free energy, an approach that maintains thermodynamic consistency even across phase changes and with mixed phase states. We use an upgraded ANEOS [11] that allows for a more realistic description of molecular vapor phases, and consider a variety of compositions whose material constants were provided to us by H.J. Melosh and E. Pierazzo. Each impact simulation involved N = 20,000 SPH particles tracked for a time ~ days.

Results: We have performed 30 SPH simulations involving a variety of target/impactor compositions and rock-ice ratios, all with g = 0.5, $L \approx L_{P\text{-}C}$ and $v_{imp} \approx v_{esc}$. The fractional yield of orbiting material is significantly greater for these types of impacts than in the lunar-forming simulations, and the highest yields are at the lower limit of those needed to form Charon.

Fig. 1 shows a collision with $v_{imp} = v_{esc}$ between like-sized objects that are 30% iron, 70% dunite and 40% water ice by mass. After an initial grazing impact the objects separate before re-colliding with a somewhat smaller impact parameter, yielding a rotating central ellipsoid. A bar mode appears and develops spiral arms trailing off its ends (*e.g*., [12]). As the cores of the objects merge, arms of lower density material expand and wrap up, finally breaking to form an orbiting disk. After 55 hours, the disk mass fraction is M_D/M_T = 0.115, with an escaping fraction M_{esc}/M_T = 0.038.

We can estimate the maximum mass of the satellite that could form, M_S, from a disk of mass M_D, by assuming the satellite forms outside the Roche limit at orbital radius a, and that all disk material not incorporated into the satellite re-impacts the planet. The Roche limit is at $a_R \equiv 2.456(\rho_P/\rho_C)^{1/3} R_P$, with $2.5 \le (a_R/R_P) \le 3.1$ for 1

$\leq (r_P/r_C) \leq 2$; satellite accretion models (*e.g.* [13]) find $a \sim 1.2a_R$. Mass and angular momentum conservation then implies the fraction of the disk that can be incorporated in a satellite is:

$$\frac{M_S}{M_D} \approx 1.9 \frac{L_D}{M_D\sqrt{GM_{\oplus}a_R}} - 1.1 \qquad (3)$$

where L_D is the disk angular momentum.

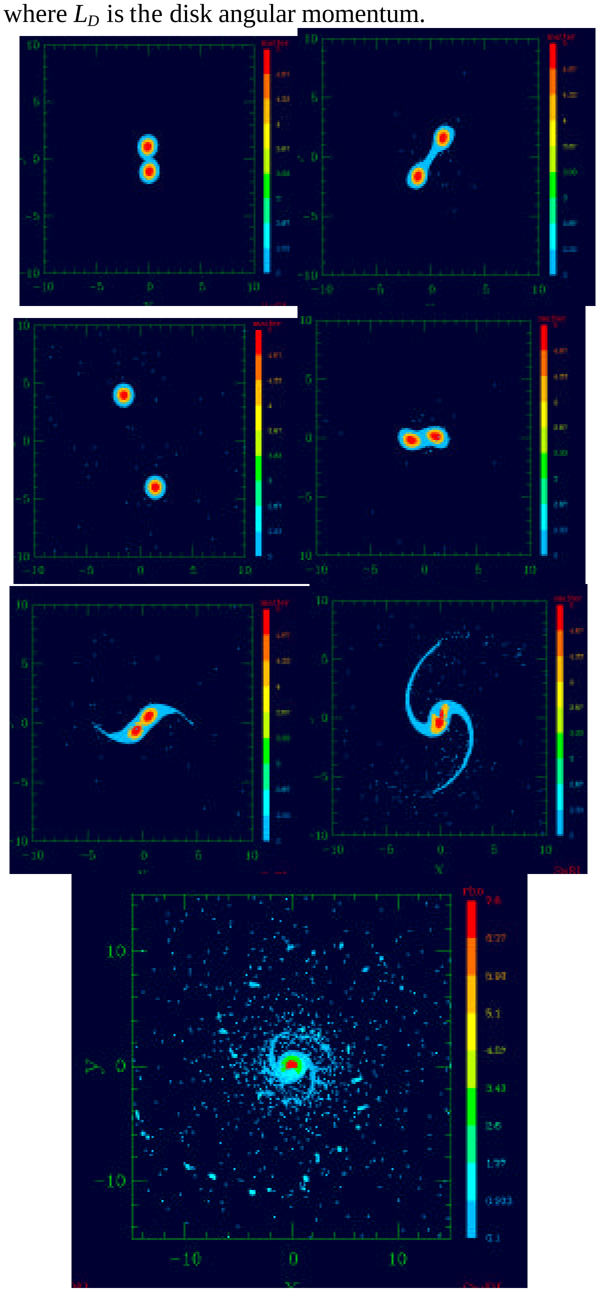

Figure 1: Simulation of a potential Pluto-Charon forming impact. In the first 6 frames color scales with material; in the last color scales with density in g/cm^3.

The estimated resulting mass ratio of satellite to the primary is then a function of the satellite-to-total mass ratio, m_S, with

$$\frac{M_S}{M_P} \approx \frac{m_S}{1-m_S}$$
$$m_S \equiv \left(\frac{M_S}{M_D}\right)\left(\frac{M_D}{M_T}\right)\left(\frac{M_T}{M_{P-C}}\right) \qquad (4)$$

where $M_{P\text{-}C}$ is the mass of the Pluto-Charon system, and M_T is the total colliding mass (typically a few percent higher than $M_{P\text{-}C}$ to account for mass escaping the system). For the simulation shown in Fig. 1, the disk angular momentum gives a predicted $M_S/M_D \sim 0.74$. With Eq. (4) this implies $M_S/M_P = 0.097$, within the range for the Pluto-Charon system. The orbiting material is composed entirely of material from the outer layers of the colliding objects, in this case, water ice.

Our initial work suggests that an impact origin requires a differentiated Pluto. Creation of a massive protocharon disk seems dependent upon the establishment of a strong central density gradient in the primary subsequent to the impact event. The simulations we have performed to date would all yield a Charon that has a significantly lower density than Pluto, since the disk is composed entirely of the low density component of the colliding objects. We expect the impact event itself will increase the rock-to-ice ratio in Pluto beyond that which might be expected through formation in situ, either by the preferential fractionation of ice into the satellite or via escape of water during the impact (*e.g.*, [14]).

We note that thus far we have focused on low velocity, oblique collisions. But an alternative means of producing $L_{P\text{-}C}$ is a higher impact velocity with a smaller impact parameter; it is not yet known whether this type of collision could also produce massive disks.

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