FORMATION OF PLUTO AND CHARON FROM TWO PARTIALLY DIFFERENTIATED IMPACTORS. **S. J. Desch**[1]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287. (steve.desch@asu.edu).

The Pluto system is unique in many ways. Pluto has 5 satellites: Charon, Nix, Hydra, Styx and Kerberos. Aside from the gas giants, no solar system bodies are known to possess as many. (Who's a planet now?!) Charon has 12% the mass of Pluto, exceeding even the Moon-Earth mass ratio. Like the Earth and Moon, the Pluto-Charon system has been modeled as arising from the impact of two bodies, in this case large Kuiper Belt Objects (KBOs) [1]. But currently *two* scenarios are considered. In the first ("intact moon") scenario, an impactor with relatively low mass (30% of the Pluto-Charon total mass) collides with the larger body; after losing substantial mass, the impactor separates from the larger body and enters into orbit around it. The second ("disk") scenario more closely resembles the model for the Moon's formation. In it, the impactor and the target have essentially identical mass (50% of the Pluto-Charon total mass). The collision sends material into orbit around the pair as their cores merge to form Pluto. Charon forms from some of the material in the disk, the rest of which is reaccreted by Pluto, except for some which escapes. The intact moon scenario was considered by [1] to be somewhat more probable with regard to the resultant angular momentum, but both scenarios were considered viable. Here I discuss how predictions of the thermal evolution and internal structures of the impactors can be used to distinguish between these scenarios and to constrain the origin of Pluto and Charon.

According to [1], the collision of the two objects had to happen with low relative velocity ($\leq 0.9\,\mathrm{km\,s^{-1}}$). For this to occur with high probability, [1] considered it likely that the collision took place after the two bodies were caught in the 3:2 resonance with Neptune. This requires the collision to take place after Neptune started its outward migration, which [2] have associated with the Late Heavy Bombardment 3.9 Gyr ago. Accordingly, we consider it likely the collision took place ≈ 1 Gyr after solar system formation. This is sufficiently long that heating by long-lived radionuclides should have caused the separation of a rocky core from an ice mantle, even for an impactor as small as 30% of the Pluto-Charon mass [3]. An object with this mass and a mean density $2\,\mathrm{g\,cm^{-3}}$ would have radius 800 km, a mass almost triple that of Charon, and would have been large enough to differentiate.

The fact that the impactors should have both differentiated immediately calls into question the intact moon scenario. This scenario requires the impactor to lose $\approx 70\%$ of its mass before emerging as Charon. Because its outer icy layers would have been preferentially lost, Charon would have a density *greater* than that of the impactor. This is difficult to reconcile with the low density of Charon, $\approx 1.63\,\mathrm{g\,cm^{-3}}$, lower than that of Pluto, $\approx 2.03\,\mathrm{g\,cm^{-3}}$, which is itself comparable to other KBOs. We consider the formation of Charon from a disk to be more likely.

In the disk scenario, Charon forms from some fraction of the disk material that is ejected from the outer layers of the two impactors. Allowing both objects to have masses of 53% of the Pluto-Charon total mass, and mean densities $2.00\,\mathrm{g\,cm^{-3}}$, they would each have radii 972 km, again, large enough to differentiate and form rocky cores [3]. Now the question is why Charon has as *high* a density as it does, since it should form preferentially from the outer layers of the bodies, presumably pure ice, with density $\approx 1\,\mathrm{g\,cm^{-3}}$. This conundrum, pointed out by [1], is resolved by the recognition that for the surface temperatures characteristic of the Kuiper Belt, the viscosity of the ice is too high to allow for complete differentiation; an undifferentiated crust is predicted to remain [3-5]. This is *despite* the gravitationally unstable nature of the resultant structure, with a rock/ice layer atop an ice mantle, although formally unstable to Rayleigh-Taylor instabilities, it is nonetheless stable on geologic timescales [4,5]. Because of this undifferentiated crust, the resultant disk will contain some rocky material as well as ice.

To estimate the fraction of rock in the disk, we must determine the structure of the two impactors. We have run the thermal evolution code of [3] for a KBO with radius 972 km and mean density $2.00\,\mathrm{g\,cm^{-3}}$. We calculate the evolution of the KBO to proceed as follows. First, long-lived radionuclides decay, heating the interior above the melting point of ice; rock and ice separate within the interior, forming a rocky core and icy mantle, surrounded by a thick, undifferentiated crust of rock and ice. Then, because the density of this rock/ice crust exceeds the density of the ice mantle, Rayleigh-Taylor (RT) instabilities will initiate, seeking to overturn these two layers. The rock/ice crust sinks (eventually adding rock to the core) while the ice mantle grows, at the expense of the crust. Eventually the RT instabilities reach a layer close enough to the surface (with temperature $T_{\rm surf} =$ 50 K) that the temperature is so low, and the ice viscosity so high, that the timescale of the RT instability exceeds the age of the solar system. For all practical purposes, differentiation ceases when a layer with this low temperature, which we call $T_{\rm diff}$, is reached. We calculate $T_{\rm diff}$ by using the growth rate calculated by [6] for RT instabilities when the viscosity varies exponentially with temperature and therefore with height, over a lengthscale L. The critical viscosity for the RT instability to grow from an initial perturbation Z_0 to an amplitude L, in a timescale τ, is

$$\eta_{\rm crit} = \left[(n-1)^{1/n} \frac{C_{L\,\Delta\rho}}{2n} \right] \left(\frac{Z_0}{L} \right)^{(n-1)/n} \Delta\rho\, g\, L\, \tau,$$

where $\Delta\rho = 1.065\,{\rm g\,cm^{-3}}$ is the density contrast between the ice mantle and rock/ice crust and $g = 0.54\,{\rm m\,s^{-2}}$ is the gravitational acceleration for these impactors, and $C_{L\,\Delta\rho} = 0.76$ [5,6]. We used the ice rheology of [7] to determine that basal slip dominates the viscosity, so $n = 1.8$ (and $L \approx 3.6$ km). Asssuming $Z_0 = 1$ km, we find that RT instabilities propagate the differentiation to the surface until temperatures below $T_{\rm diff} = 145\,{\rm K}$ are reached. In our thermal evolution modeling, we find that differentiation proceeds outward to a radius of 927 km, leaving a crust 45 km thick that does not differentiate. The structure of the body then includes: a rocky core of radius 716 km and mass 5.00×10^{24} g at the center (assuming olivine rock with density $3.25\,{\rm g\,cm^{-3}}$); a liquid layer from 716 km to 729 km, with mass $\sim 10^{23}$ g; an ice mantle extending from 729 km to 927 km, with mass 1.60×10^{24} g (with density $0.935\,{\rm g\,cm^{-3}}$); and an undifferentiated ice/rock layer 45 km thick, with mass 1.02×10^{24} g, of which 0.77×10^{24} g is rock and 0.25×10^{24} g is ice. This is the structure of each of the two bodies when they collide.

Following the collision, we assume that Pluto forms from the merger of the two rocky cores, plus whatever ice is needed to accrete to yield Pluto's mass and density. Exactly one half of Pluto's mass is found within a radius of 910 km within each impactor. Forming Pluto from this material in each impactor ensures it has the required mass and a rock fraction ≈ 0.77, yielding a mean density only slightly higher than the mean densities of the impactors. As for Charon, it must form from whatever material does not escape and does not form Pluto. If we assume that a fraction 6.0% of the total mass escapes the system, all from the outermost layers beyond 953 km in both impactors, then the shells between 909 km and 953 km have combined mass exactly equal to that of Charon. Charon would accrete from ice shells between 909 km and 927 km, having combined mass 0.36×10^{24} g, and rock/ice crust shells between 927 km and 953 km, having mass 1.16×10^{24} g. Charon's mass would be then be 1.52×10^{24} g. Given a rock fraction in the crust of 0.749, Charon would accrete 0.87×10^{24} g of rock, yielding a final rock fraction within Charon of 0.57. We calculate Charon's density would be $1.60\,{\rm g\,cm^{-3}}$, very close to its observed density. The final density is sensitive to the assumed escape fraction, among other parameters, but an escape fraction of 6.0% is very much within the range of escape fractions found by [1] in her numerical simulations of equal sized impactors.

Based on our thermal models, both the impactor and target objects that formed Pluto and Charon must have been large enough to differentiate before the impact. Because the mean density of Charon would be greater than the starting bodies in the intact moon scenario, yet Charon is less dense than Pluto and most KBOs, we consider this scenario unlikely. The alternative scenario, formation of Charon from a disk, was considered by [1] to be less likely because Charon was predicted to form mostly from ice, but this conclusion was based on the impactor and target being *fully* differentiated. Our thermal evolution models [3,4] indicate that KBOs will retain undifferentiated crusts of thickness ≈ 45 km. In the disk scenario, Charon would form from a mix of ice and this undifferentiated crust material, explaining very neatly why its density is somewhat lower than Pluto's but still much higher than that of ice alone.

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