KISS-AND-CAPTURE PRESERVES AN ANCIENT CHARON AROUND PLUTO C. A. Denton[1,2] E. Asphaug[1], A. Emsenhuber[3] and R. Melikyan[1]. [1]Lunar & Planetary Lab, University of Arizona, Tucson, AZ, [2]Southwest Research Institute, Boulder, CO, and [3]Physics Inst., NCCR PlanetS, U. Bern, Switzerland. (adeene.denton@contractor.swri.edu)

Introduction: The Pluto-Charon binary is generally assumed to be formed through a giant impact, due to the bodies' large relative masses and the large angular momentum of the system. However, the impact conditions for Charon's collisional capture, including impact angle, impact velocity, and pre-impact spin, remain poorly understood. Previous 3D smoothed-particle hydrodynamics (SPH) simulations have demonstrated the viability of collisional capture for Charon; however, both bodies were assumed to be strengthless fluids [1–3]. As material strength has been shown to influence impact outcomes at sizes of up to several lunar masses [4], it is likely that the conditions of the Charon-capturing impact are dependent on the material properties of the colliding bodies. Returning to and evaluating the outcomes of collisions between Pluto- and Charon-like bodies may also provide greater understanding of other large-mass Kuiper Belt binaries, which may share a similar origin [5, 6].

Here, we revisit the collisional capture of Charon, using impact simulations that incorporate material strength for both bodies, to determine the influence of material strength on collisional capture outcomes for Pluto, Charon, and other large-mass Kuiper Belt binaries.

Methods: We simulate the Pluto-Charon-forming collision using SPHLATCH [7–9], an SPH code that incorporates a geophysically realistic strength model that approximates objects as solids subject to friction and limited by plastic and thermal yielding [4]. Our initial simulations follow prior work and assume that the impactor, proto-Charon, is ~1/3 the total mass of the system [2]. As in previous work, both bodies are assumed to be fully differentiated and are approximated as 85% rock, 15% ice by mass, followed by simulations with bodies whose compositions are more similar in mass and size to modern Pluto and Charon [10]. We explore a range of impact velocities commensurate with prior work, $v_{\mathrm{coll}}/v_{\mathrm{esc}} \approx 1.0 - 1.3$, which encompasses relatively slow collisions at close to the escape velocity of the system to relatively rapid collisions for the Kuiper Belt. We also asses a broad suite of impact angles to encompass the full scope of impact outcomes ($\theta_{\mathrm{coll}} \sim 40{-}70^\circ$). The spin period of the target (proto-Pluto) is varied from no spin up to a period of 3 h.

Results: We find that the addition of material strength vastly alters the conditions under which Pluto captures Charon following the impact. Simulations which previously captured Charon when both bodies are assumed to be strengthless no longer do so once strength is included; instead, the grazing impact becomes a hit-and-run, and proto-Charon escapes the system entirely. This difference reflects the inclusion of strength, which prevents the bodies from experiencing the extreme deformation that characterizes fully fluid collisions. Instead, we find that collisions at more common, less oblique impact angles (around $\sim 45^\circ$)—those which lead to full merging when strength is neglected—now produce a captured satellite. The process by which capture occurs, which we call "kiss-and-capture," produces a relatively intact Charon on a circular, outwardly-expanding orbit, consistent with the state of the system today.

Figure 1 shows the time evolution of a kiss-and-capture collision for a Pluto and Charon-like system, which is characterized by an initial collision that produces an initial merger, or "kiss," before the two bodies separate intact. Proto-Pluto and proto-Charon briefly collide (1a-b), before coupling more deeply (1c) to corotate for several rotational periods (1d). Pluto and Charon then slowly decouple over a period of tens of hours (1e-f), forming a stable, outward-expanding binary pair (1g-h). Pluto and Charon separate due to the influence of Pluto's pre-impact rotation. As Charon's center of mass is outside of Pluto's corotation radius while the bodies are merged, it lags behind Pluto's slightly faster rotation period. This lag induces tidal dissipation, a process which translates torques to Charon that cause it to separate and commence an outward migration into a close, relatively circular orbit (1i). The final system at the end of the simulation possesses an angular momentum close to that observed (1j). For simulations with an initial impactor more similar to Charon's present-day mass, in addition to matching the contemporary angular momentum of the system, we find that outward migration can place Charon at an orbital radius close to its present distance [10].

Implications: In our simulations of the Pluto-Charon giant impact, both bodies remain largely intact, though globally resurfaced, following the initial collision, which has testable geologic and geophysical implications for their evolution. The thermal history of Pluto and Charon remains uncertain, particularly whether they possessed enough initial heating to produce and sustain subsurface oceans [11]. Kiss-and-capture imparts extensive heating, both through the initial impact as well as subsequent frictional heating as Charon is driven outwards by tides. Widespread, potentially long-lived heating from kiss-and-capture could induce melting and expansion of surface oceans, and help reconcile widespread geologic ac-

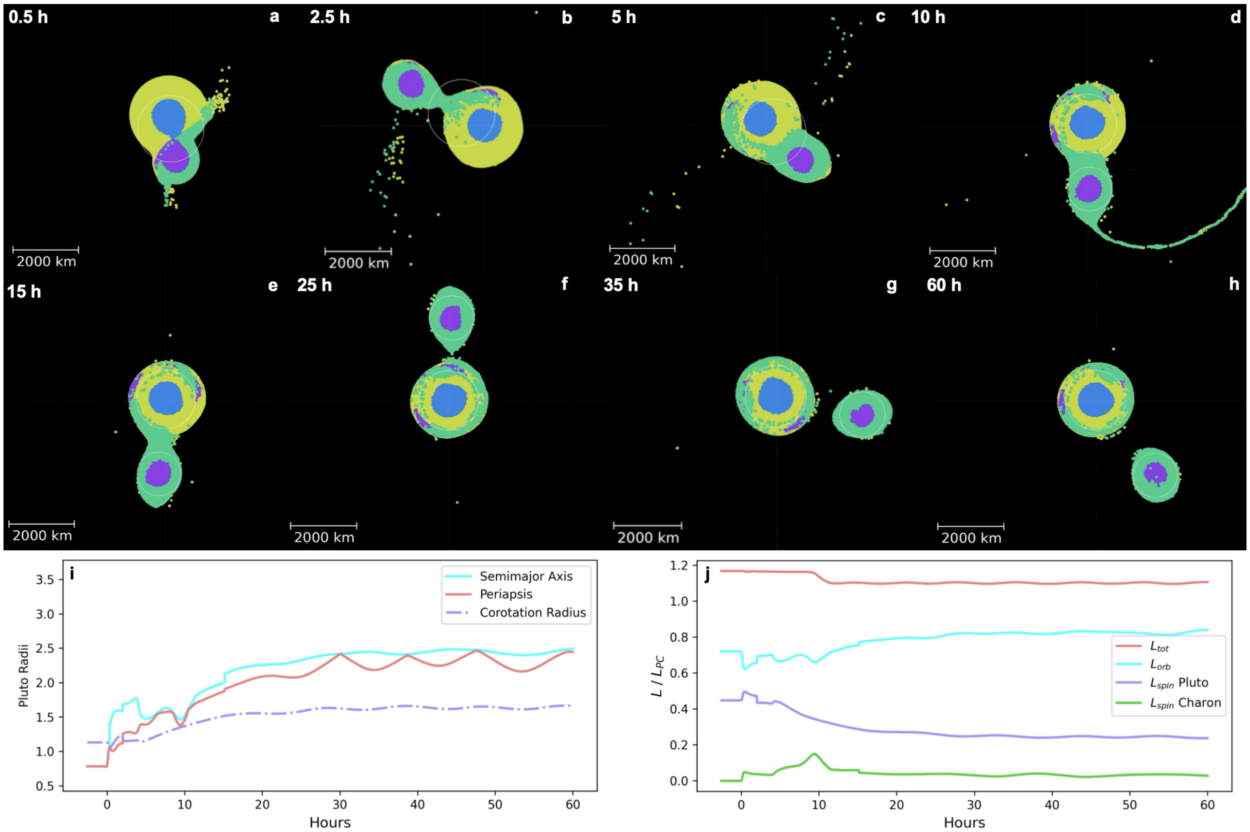

Figure 1: Time series and orbital evolution of a potential Charon–capturing collision at 45°. Colors represent composition: yellow and green for ice mantles, blue and purple for rocky cores, of target and impactor. Proto-Charon contacts (a) and then co-rotates (b-d) with proto-Pluto. The bulk of Charon, outside of corotation, is unable to orbit as fast as Pluto rotates, so the bodies decouple (e-f) and Pluto torques Charon (g-h) into a close, relatively low-eccentricity ($e = 0.2 - 0.3$) orbit from which it will migrate further. Orbital evolution includes (i) evolution of the semimajor axis (cyan) and periapsis (red) of Charon in comparison to the Pluto-Charon corotation radius (lavender), with respect to Pluto's radius, and (j) the total angular momentum of the system compared to the actual Pluto-Charon value (red), and angular momentum contributions from Pluto and Charon's orbital momentum (cyan) and from spin of each body (lavender, green).

tivity with a colder, younger origin for Pluto and Charon.

Conclusions: Our models successfully reproduce a Pluto-Charon-like system, constraining the conditions of their origin. We find that, for Pluto to capture Charon, a kiss-and-capture must occur, in which the two bodies collide and briefly co-rotate, before stabilizing into a tidally-locked binary pair as they separate. This scenario can produce a system that closely matches Pluto and Charon's present sizes, masses, and orbital separation. As the conditions under which kiss-and-capture occurs encompass common impact angles and a range of impact velocities, these simulations of Pluto and Charon may represent the first example of a new means of collisional capture in the Kuiper Belt.

References: [1] Canup, R. M. (2005). *Science* **307,** 546–550. [2] Canup, R. M. 2010. *The Astronomical Journal* **141.** [3] Arakawa, S. et al., 2019. *Nature Astronomy* **3,** 802–807. [4] Emsenhuber, A. et al., (2024). *Planetary Science Journal.* [5] Brown, M. E. et al., (2006). *The Astrophysical Journal* **639,** L43. [6] Brown M. E. Butler, B. J. (2023). *The Planetary Science Journal* **4,** 193. [7] Reufer, A. (et al., 2012). *Icarus* **221,** 296–299. [8] Asphaug, E. & Reufer, A. (2013). **223,** 544–565. [9] Emsenhuber, A. et al., (2018). *Icarus* **301,** 247–257. [10] Denton, C. A. (2025). *Nature Geoscience.* [11] Bierson, C. et al., 2020. *Nature Geoscience* **13,** 468–472.