

Properties of the Pluto-Charon binary

The orbital period, $P = 6.38726 \pm 0.00007$ days, and semi-major axis of Charon's orbit, $a = 19636 \pm 8$ km, imply a total mass $M_{PC} = 1.471 \pm 0.002 \times 10^{25}$ g (S1). Pluto's motion relative to the system center of mass constrains the Charon-to-Pluto mass ratio, $q \equiv M_C/M_P$, with recent HST observations (S2) yielding $q = 0.122 \pm 0.008$. Radii and density estimates are $1151 \pm 6 \leq R_P$ (km) $\leq 1195 \pm 5$ and $1.83 \pm 0.09 \leq \rho_P$ (g/cm³) $\leq 2.05 \pm 0.11$ for Pluto, and $593 \pm 13 \leq R_C$ (km) $\leq 621 \pm 21$ and $1.59 \pm 0.20 \leq \rho_C$ (g/cm³) $\leq 1.83 \pm 0.18$ for Charon (e.g., S2), indicating a Charon that is comparably or less dense than Pluto.

The Pluto-Charon pair is tidally locked, so that the rotational angular velocity of both objects equals their mutual orbital velocity, $\omega \equiv (2\pi/P)$. The angular momentum of the system about its center of mass is

$$\begin{aligned} L_{PC} &= \omega \left[\frac{M_P M_C}{M_{PC}} a^2 + K_P M_P R_P^2 + K_C M_C R_C^2 \right] \\ &= \frac{\omega M_{PC}}{(1+q)} \left[\frac{q}{1+q} a^2 + K_P R_P^2 + q K_C R_C^2 \right] \approx \frac{q \omega M_{PC} a^2}{(1+q)^2}. \end{aligned} \quad (S1)$$

where K_P and K_C are the moment of inertia constants for Pluto and Charon with $K_i \equiv I_i/(M_i R_i^2)$; for K_C , $K_P > 0.3$, the sum of the two spin terms is $< 2\%$ of L_{PC} .

Disk producing impacts

Figure S1 shows the predicted q values vs. J_f for all of the disk-producing impacts. This is the most consistent scaling for these cases, and as J_f increases, the results converge to a relationship (dotted line) consistent with a planet rotating with period $\sim T_{min}$, with the rest of the angular momentum partitioned into the disk. The angular

momentum in an object rotating at its stability limit is proportional to its moment of inertia constant, K , so that as K decreases, so too does the fraction of the total angular momentum that can be accommodated by the planet. Thus for the disk-mode, forming a highly differentiated central planet with a low K (as occurs for the IDI composition) increases the yield of orbiting material for a given set of collision parameters.

Also shown on Fig. S1 (solid lines) are the limits possible for Pluto-Charon over the range of system variable estimates. Planet-disk systems closest to the Pluto-Charon region are produced by collisions with $J_{imp} > 0.4$ and $v_{imp} \sim v_{esc}$, corresponding to oblique impacts ($b' > 0.8$) of like-sized objects ($\gamma \sim 0.5$) and initial prograde spins that contribute significantly to the total impact angular momentum (10 to 25%). Somewhat higher impact speeds ($1.1 \leq (v_{imp}/v_{esc}) \leq 1.3$) between differentiated objects can produce disks, although they contain a smaller fraction of the planet's mass than their $(v_{imp}/v_{esc}) < 1.1$ counterparts. As (v_{imp}/v_{esc}) exceeds about 1.2 to 1.3 for an oblique impact, there is typically a rather abrupt transition (also seen in S3) to a non-accretionary event in which the majority of the impactor and the impact angular momentum escape.

For IDI collisions with $\gamma = 0.5$, resulting disks were composed entirely of water ice, compared to initial objects that were 40% ice and 60% rock. Disks produced by collisions of SIM objects contained at average of 80% ice and 20% serpentine, compared to initial objects that were 50% serpentine and 50% ice. However we note that compositional granularity inherent to SPH may tend to over-estimate differentiation, and this could affect the disk compositions derived from the collisions involving SIM objects.

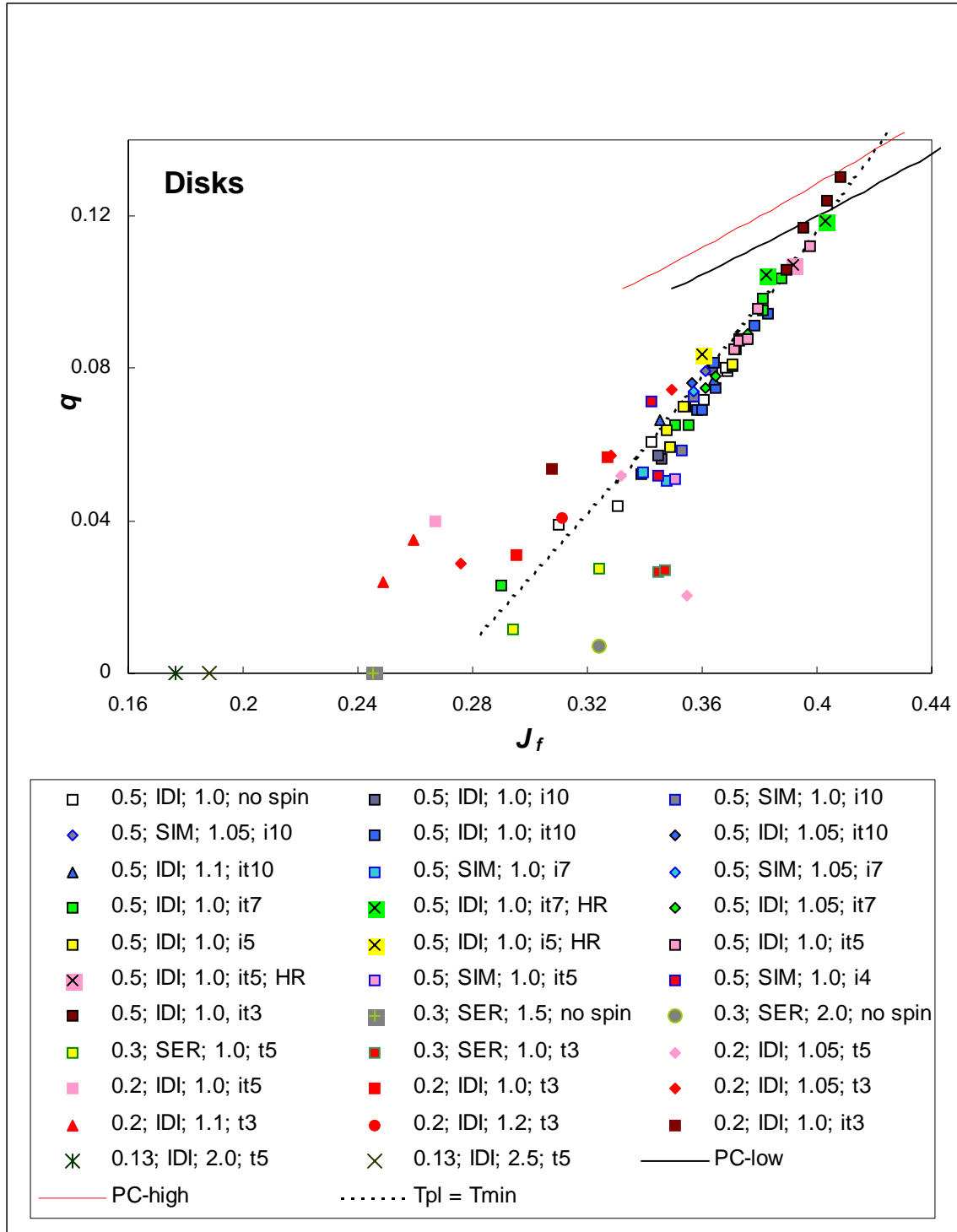


Figure S1: Results of impact simulations that produced planet-disk systems. Simulation parameters are shown in the legend where the first value is the ratio of the impactor to the total mass (γ), the second indicates the composition of the

colliding objects (see text), the third is the ratio of the impact velocity to the escape velocity, and the fourth is the pre-impact prograde spin period in hours for the impactor (“i”) and/or target (“t”). The nominal resolution is 20,000 particles; 120,000 particle simulations are indicated with “HR”. Shown is the estimated satellite-to-planet mass ratio, q , (e.g., S4) vs. the normalized angular momentum of the final bound system, J_f . The dotted line is the relationship between q and J_f for an IDI planet of mass M_p rotating with a period equal to its minimum for rotational stability, together with a moon of mass $M_s \equiv qM_p$ at $a_s = 1.2a_R$, where a_R is the Roche limit. Red and black solid lines frame the parameter regime consistent with the Pluto-Charon system.

Table S1: Parameters and results of impacts that yield disks with estimated $0.1 < q < 0.15^*$

Run	M_T / M_{PC}	γ	b'	v_{imp} / v_{esc}	J_{imp}	L_s / L_{imp}	L_{esc} / L_{imp}	M_{esc} / M_T	L_{orb} / L_{imp}	M_{orb} / M_T	J_f	q
42	1.00	0.5	0.894	1.00	0.454	0.12^{it}	0.21	0.044	0.367	0.107	0.388	0.103
71 [*]	1.06	0.5	0.876	1.00	0.447	0.13^{it}	0.19	0.032	0.385	0.111	0.383	0.104
61	1.00	0.5	0.870	1.00	0.517	0.25^{it}	0.34	0.075	0.313	0.108	0.390	0.106
73 [*]	1.06	0.5	0.863	1.00	0.465	0.18^{it}	0.20	0.035	0.376	0.107	0.392	0.107
55	1.00	0.5	0.868	1.00	0.473	0.18^{it}	0.23	0.050	0.367	0.111	0.398	0.112
62	1.00	0.5	0.841	1.00	0.505	0.26^{it}	0.30	0.069	0.334	0.106	0.396	0.117
70 [*]	1.06	0.5	0.833	1.00	0.428	0.14^{it}	0.07	0.011	0.440	0.105	0.403	0.119
60	1.00	0.5	0.900	1.00	0.530	0.25^{it}	0.33	0.076	0.337	0.116	0.404	0.124
63	1.00	0.5	0.913	1.00	0.537	0.24^{it}	0.34	0.078	0.336	0.113	0.409	0.130

*Simulations here involved differentiated objects with 40% water ice and 60% rock (with the rock composed of 30% iron and 70% dunite). The nominal resolution is $N = 2 \times 10^4$ particles; runs with $N = 1.2 \times 10^5$ particles are starred. See text for variable definitions. The pre-impact spin state of the objects is shown by the fraction $(L_s / L_{imp}) = (\vec{L}_s \cdot \vec{L}_{imp}) / |L_{imp}^2|$; superscripts i and it correspond respectively to L_s contained in the impactor or the impactor and target. Results shown are at approximately 24 hours post-impact. M_{orb} and L_{orb} are the disk mass and angular momentum, and $J_f \equiv L_f / \sqrt{GM_f^3 R_f}$ is the normalized final bound system angular momentum, where M_f is the total system mass and $R_f = (3M_f / 4\pi\rho)^{1/3}$. The final column shows the predicted mass of a moon that would accumulate from the resulting disk (e.g., S4).

- S1. D. J. Tholen, M. W. Buie, in *Pluto and Charon*, S. A. Stern, D. J. Tholen, Eds. (Univ. Arizona Press, Tucson, 1997), pp. 193-219.
- S2. C. B. Olkin, L. H. Wasserman, O. G. Franz, *Icarus* **164**, 254 (2003).
- S3. C. B. Agnor, E. Asphaug, *Astrophys. J.* **613**, L157 (2004).
- S4. S. Ida, R. M. Canup, G. R. Stewart, *Nature* **389**, 353 (1997).