ON THE ORIGIN OF THE PLUTO SYSTEM. M. Neveu[1,2], R. M. Canup[3], and K. M. Kratter[4], [1]U. of Maryland, College Park, MD, USA. [2]NASA Goddard Space Flight Center, Greenbelt, MD, USA (marc.f.neveu@nasa.gov). [3]Southwest Research Institute, Boulder, CO, USA (robin@boulder.swri.edu). [4]Astronomy Department / Steward Observatory, U. of Arizona, Tucson, AZ, USA (kkratter@email.arizona.edu).

Introduction: We describe constraints and review models for the origin of the Pluto-Charon binary and the small moons Styx, Nix, Kerberos and Hydra. We also highlight open issues and discuss implications.

Observational Constraints: The heliocentric orbit of the Pluto system at ≈40 AU is triply resonant with Neptune's orbit, involving mean motions (3:2), arguments of perihelion, and longitudes of ascending node. Therefore, Neptune likely shaped the Pluto system's eccentric and inclined heliocentric orbit [1,2].

System dynamics. The plane of the Pluto system is highly oblique to its heliocentric orbit. The Pluto-Charon mass ratio, 8.2 [3], is low. Their close (distance 16.5 Pluto radii), tidally locked, circular mutual orbit coplanar with both equators implies that the binary is in tidal equilibrium. Circularization timescales, which increase dramatically in wider orbits, imply that the binary has always been close together [4]. The small moons, of combined mass $\approx 6\times10^{-6}$ times that of the binary [3], orbit it with high obliquity on circular, coplanar orbits close to (but not exactly in) 3:4:5:6 mean motion resonance with Charon. This could result from a stable resonant configuration perturbed by the binary [5,6]. The small moons are not tidally locked, likely because Pluto's small mass cannot synchronize their spins in <1 Gyr, longer than the timescale of perturbation by impacts [7]. More distant Kerberos/Styx-sized regular moons ($\sim10^{16}$ kg) are unlikely on dynamical grounds and based on searches with *New Horizons* [8-10].

Compositions. Charon's bulk density (1700 kg m^{-3} [11]), lower than Pluto (1854 kg m^{-3}), implies that Charon is icier [12,13]. The densities of the small moons are not tightly constrained [3]. Pluto displays surface CH_4, N_2, and CO frosts in addition to H_2O and sparse NH_3. In contrast, H_2O and NH_3 make up much of Charon and the puzzlingly brighter surfaces [14] of Nix, Hydra, and (for H_2O) Kerberos [15,16]. Styx's composition is unknown.

Formation Models: The influence of Neptune over the system's orbit makes it very likely that Pluto and Charon accreted closer to the Sun (<30 AU) than today, with orbital expansion and excitation caused by a rearrangement of the giant planets including the outward migration of Neptune [2,17]. Pluto's moon system could have survived this migration [18], so whether the heliocentric migration predated the system-forming event is an open question.

Giant impact. The Pluto-Charon binary's low mass ratio, high angular momentum, and close separation makes an impact on Pluto from a like-sized impactor its prime origin scenario [19-21 and references therein]. This impact must predate Charon's ≈4 Gyr old surface [22]. At ≈40 AU, binary-forming impacts could have occurred every 100-300 Myr [23], and likely more often closer in. The mass ratio is reproduced with an impact velocity only slightly higher than proto-Pluto's escape velocity [20]. Two scenarios yield the observed mass and angular momentum distribution [20]: collision between differentiated (or partially so [24,25]) progenitors forming a disk from which Charon accretes, or quasi-intact formation of Charon from un- or partially-differentiated progenitors [20,24]. If the small moons originate as collisional debris [20,26,27], they would likely be icier in the disk scenario [25], or icier or with the same ice/rock ratio as the progenitors in intact Charon models [24]. The disk scenario would yield an icier Charon [12], but it is difficult to explain Charon's large mass in this case [20]. The disk density and debris size distribution, an open issue, might be inferred from crater populations on Charon [28].

Orbital expansion of the small moons out to today's tens of Pluto radii must have been much faster than expansion driven by the feeble solid tides raised by these moons on Pluto. Resonant interactions with Charon could have sped up their migration on Charon's orbital expansion timescale [27]. This scenario reproduces the moons' high obliquity [7], but also yields eccentric orbits incompatible with observations [29]. Alternatively, the small moons might have formed in an extended debris ring, requiring less migration [23]. This issue remains open.

Identifying a Pluto collisional family, as found for Haumea [30], would validate the impact scenario. Members of such a family should have survived, but are dynamically difficult to spot [28].

Alternatives. Fission of a fast-spinning Pluto could also explain a high-angular-momentum binary [31,32], but the amount of spin up needed to launch material into a ring from which Charon accretes [33] is only achievable with a giant impact [21]. Co-accretion as a binary cannot supply Pluto's high obliquity or the system's high angular momentum [21]. With accretion by streaming instability, the high angular momentum may have prevented accretion into a single body [34], but this demands an instability of unduly high (~Pluto) mass [35]. Capture could be enabled by dynamical friction from surrounding small bodies [36] or pebbles, but this requires an excessively dense disk [14]. These alternatives must also explain the system's high obliquity and form small moons near orbital resonances with Charon from smaller impacts onto Pluto or Charon, the breakup of prior satellite(s), collisional capture [37], or co-accretion, all of which are unlikely [14,24,28,38,39].

Implications: *Physical state of proto-Pluto and giant impactor.* Pluto and Charon's relative masses and densities can be reproduced with several partially differentiated structures for the progenitors: an icy mantle overlying a rock-ice core [24], undifferentiated crust surrounding an ice mantle and rock core [25], and a 'mud' mantle of fine-grained rock and ice above a rock core [40]. This degeneracy prevents pinpointing their time of formation. In all cases, the progenitors (radius ≈1000 km) could maintain a thin global H_2O-NH_3 ocean just above the core.

Thermal processing and loss of volatiles. Pluto's N_2 abundance is consistent with a primordial supply [41], but could also result from the oxidation of NH_3 and/or organic nitrogen. The lack of N_2 on lower-gravity Charon suggests loss during the giant impact, later degassing and escape [42] during resurfacing [22], or (if N was supplied in reduced form) a lack of oxidation. The latter case would imply that oxidation kinetics were only fast enough on post-impact Pluto, presumably warmed by a greater supply of radionuclides and/or the impact itself. Likewise, the presence of CH_4 on Pluto but not Charon suggests either a primordial supply that escaped from Charon [43], or a product of the reduction of CO_2, CO, or organic C that did not occur on Charon. In the latter case, carbon reactions were partial even on Pluto, whose surface CO would otherwise have been converted to more stable species [41,44]. Pluto and Charon may be two archetypes of the bimodal volatile inventories detected on other large Kuiper belt objects [45].

Other binary dwarf planets. Differences in impact angle and velocity between two like-sized dwarf planets can lead to larger ice/rock fractionations [46], e.g. possibly for Eris-Dysnomia [47,48] and Orcus-Vanth [49]; or outcomes other than a binary [24,47], such as Haumea which only has small moons [50]. Although the orbit and compositions of Pluto-Charon suggest an impact origin, those of other binary systems may be compatible with alternative origins such as capture [36], e.g. for Eris and much darker Dysnomia [48,51], Orcus-Vanth [49], or the eccentric moon of 2007 OR_{10} [52]; or co-accretion [34,53], e.g. for G!kún‖'hòmdímà-G!ò'é!hú [53]. Possible origins may depend on formation location (dynamical class).

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