FORMATION, COMPOSITION, AND HISTORY OF THE PLUTO SYSTEM: A POST-*NEW-HORIZONS* SYNTHESIS. William B. McKinnon[1], Christopher R. Glein[2], and Alyssa R. Rhoden[3], [1]Dept. Earth and Planetary Sci. and McDonnell Center for the Space Sci., Washington University in St. Louis, Saint Louis, MO 63130 (mckinnon@wustl.edu), [2]Southwest Research Institute, San Antonio, TX 78238, [3]Southwest Research Institute, Boulder, CO 80302.

Introduction: The *New Horizons* encounter with Pluto revealed not just a remarkable dwarf planet, but a complex, scientifically rich planetary system far out in the Kuiper belt [1]. This talk will draw on encounter results, and together with other talks at this *PANH* conference, synthesize and summarize what we have learned from *New Horizons*, highlighting some of the less understood or appreciated aspects.

Formation: As now understood, the Pluto system was emplaced into its 3:2 mean motion resonance with Neptune as part of the overall dynamical rearrangement of the outer solar system attendant upon a compact, but ultimately unstable, arrangement of 4 or more giant planets emerging from the protosolar nebula [2]. The Kuiper belt as a whole is almost entirely derived from a ~15–20 M_{Earth} remnant planetesimal disk originally orbiting exterior to Neptune, a disk whose main mass extended not much further than 30 AU (Neptune's present semimajor axis) [3]. The most natural time scale for this instability is *early*, within a few 10s of Myr of dissipation of the gaseous protosolar nebula, and not 100s of Myr later [3]. Implantation into the Kuiper belt is not particularly efficient, of order 10^{-3}. This implies many Pluto-scale dwarf planets were lost, ejected to the scattered/scattering disk, Oort cloud, or accreted by the giant planets, or in the case of Triton, captured.

The origin of the Pluto-Charon binary is widely regarded as due to a relatively giant (for the Kuiper belt) impact [4]. Other mechanisms for binary formation have been proposed for Kuiper belt objects, but the large masses of Pluto and Charon, the great specific angular momentum of the pair, and coplanar system of smaller satellites, all argue for an impact origin similar to that of the Earth-Moon [1].

Numerical simulations of the Charon-forming impact to date favor a relatively slow collision (i.e., an impact speed ≈ υ_{esc}), and partially differentiated precursors [4]. Completely differentiated precursors (i.e., bodies with ice mantles and rock cores) yield, post-impact, a very icy Charon in orbit about Pluto, contrary to Charon's mean density, whereas totally undifferentiated precursors yield very rock- and organic-rich small satellites, in apparent contradiction to their extremely icy nature [2]. More specific constraints await higher resolution impact simulations.

The inference of a relatively slow moon-forming collision is consistent with late oligarchic growth in the ancestral planetesimal disk; that the precursors were only partially differentiated could be a signature of earlier growth by pebble accretion in the presence of nebular gas, i.e., by collisions so small that accretional heat was not deeply buried. Once the dynamical instability initiates, however, impact speeds would have necessarily climbed to several km/s, arguably inconsistent with forming Charon, though not with violent collisions generally (e.g., Sputnik basin, which we note is far too small to be the impact scar of the Charon-forming impact, though it must also have formed prior to Pluto's emplacement into the 3:2 resonance).

Composition: Pluto's composition provides a key constraint on formation conditions, as well as interior and atmospheric evolution. With regards to the diagnostic volatiles, the surface is dominated by molecular nitrogen and methane [5,6]. The nitrogen is concentrated in Sputnik Planitia, while the methane is more widely distributed. It has been estimated that there are 10^{20} moles of N_2 in Sputnik Planitia [7]. Carbon monoxide is also concentrated in Sputnik Planitia, but it appears to be substantially less abundant, at least in the surface. The global abundance of methane has not yet been estimated, but the integrated loss with time, using the present observed escape rate, could have exceeded 10^{19} moles [1]. Spectral signatures of NH_3 have been found, whereas there is no evidence of CO_2. The atmospheric composition reflects the surface, with fractionation driven by different vapor pressures and temperatures of the dominant volatile sources. The most abundant atmospheric volatile is nitrogen, followed by methane, and then CO [8,9].

The available data allow us to develop and constrain different hypotheses of volatile origin and evolution, but the data are insufficient to deduce a uniquely favored scenario. One possibility is that the volatiles were accreted in the same chemical forms in which they now exist. In a primordial scenario, cold building blocks of Pluto would have contained CO, CH_4, and N_2, as in the most thoroughly characterized comet, 67P/Churyumov-Gerasimenko. The abundance of N_2 in comet 67P can yield the inventory in Sputnik Planitia, if the cometary abundance is scaled up to the mass of Pluto [7]. Comets, however, appear to contain too much CO to be consistent with that observed at Pluto, unless most of Pluto's accreted inventory of

CO is buried in deeper layers of glacial ices, or the CO could have been destroyed by aqueous chemistry in a subsurface ocean [7].

An alternative scenario that requires further consideration involves the formation of N_2 and CH_4 by the thermal decomposition of organic materials in a rocky core. This type of model was recently proposed for Titan [10]. Abundant CHON organic solids should have been present in rocks accreted by Pluto, as in cometary and interplanetary dust particles. These organic-rich rocks could have undergone substantial heating if incorporated into a core on Pluto. Heating favors the formation of the small, stable molecules CH_4, CO_2, NH_3, and N_2 in addition to graphite. Qualitatively, the surface assemblage of volatiles suggests relatively high temperatures (to form N_2) and somewhat reduced conditions (to inhibit CO_2 formation). It is, however, unclear if a metamorphic process can account for the presence of CO, or if an exogenic source of CO might need to be considered. The more refractory, insoluble organic fraction could also form an important, internal structural layer within Pluto, especially if the bulk organic fraction is anywhere close to that observed at 67P [11].

History: The post-formation tidal evolution of Pluto-Charon should have followed a path familiar from studies of the Earth-Moon system. Following relatively rapid circularization of their mutual orbits and spin down of Charon to spin-orbit synchronism, Charon should have slowly been driven outward until Pluto itself reached the 1:1 spin-orbit resonance [12]. Only by fine-tuning tidal parameters it is possible for Charon to maintain a finite orbital eccentricity as it retreats from Pluto [13]. If Pluto remains relatively non-dissipative then the orbital expansion time scale could in principle be quite long [14], but evidence for active geology, including circumstantial evidence for an internal ocean, argues against this being the case. Nevertheless, the orbital expansion could easily have lasted long enough to complete post-emplacement of the binary in the 3:2 resonance with Neptune. The four exterior small satellites, or their precursors, were nominally also being tidally driven out, but a self-consistent story for how this was accomplished has proved elusive [1].

Some clues to Charon's evolution may be contained in the tectonic features visible on its surface. Charon exhibits a large canyon system as well as many, more dispersed fractures in Oz Terra [15], which have been interpreted as evidence of global expansion. If Charon once had a subsurface ocean, freezing of the ocean would have resulted in a net volume increase, perhaps causing the expansion. If, however, Charon possessed an ocean during its orbital circularization and recession, it may have been responsive enough to tides to induce stresses that fractured the surface [16]. Even if the stress magnitudes are low, the presence of a freezing ocean can add a large, uniform background stress that can combine with tidal stresses to achieve failure [e.g., 17]. More detailed comparison between observed fractures and tidal stress patterns is warranted and may provide the best test of a past ocean as well as constraints on Charon's orbital evolution. In deep time, other processes could have contributed to global volume change on Pluto and Charon as well, such as differentiation and de/serpentinization [15].

During the tidal expansion of Charon's orbit, Pluto's tidal bulge (bulges in the case of Charon) should have collapsed, but there is no evidence in the spherical shapes of Pluto and Charon (to the limits of measurement [18]) for fossil bulges, nor obvious tectonic evidence of the predicted degree-2 shape changes [14]. The former sets important limits on the early thickness, rigidity, and brittle strength of the lithospheres of both bodies, whereas the latter has not been tested for in detail.

On Pluto, younger tectonic features are (almost) exclusively extensional (normal faults and graben). Although plausibly also driven by ocean freezing and global expansion [15], their predominant orientation perpendicular to Sputnik Planitia matches the extensional stress pattern predicted for an angularly broad positive load (mascon) on a spherical shell (in the manner of Tharsis) [19], and is part of the circumstantial evidence for a dense oceanic upwelling beneath Sputnik [20]. Ammonia has also been detected on both Pluto and Charon [e.g., 21], supporting the possibility and/or preservation of putative oceans through freezing point depression.

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