THE PLUTO-CHARON SYSTEM REVEALED: GEOPHYSICS, ACTIVITY, AND ORIGINS.

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Introduction: The New Horizons encounter with the Pluto-Charon (PC) system in July, 2015, provided many scientific surprises [1]. Foremost was the diversity, complexity, and ongoing vigor of Pluto's geology. This includes evidence for present and past glacial activity, major young cryovolcanic constructs, and a most unusual solid state tectonic regime in a thick layer of volatile ices trapped within major structural basin [2,3]. Even Charon, half the size of Pluto, revealed itself to have had a spectacular geologic past [2]. On a more technical level, no new satellites were discovered on approach, despite 4 having been found in deep HST searches after the mission received its formal start [4]. More surprising was the discovery that Pluto's atmosphere is thinner and less distended, with an escape rate 2 orders of magnitude less, than had been assumed for decades – yet it is an atmosphere with extensive haze layers [5]. And despite Pluto-Charon's presumed "giant impact" origin, no hint of a fossil oblateness from Pluto's post-impact spindown was detected [1].

The orbital architecture of the Kuiper belt all but demands an epoch of planetary migration. The most developed version, the Nice instability model, posits a compact giant planet configuration and a massive outer disk of remnant planetesimals [e.g., 6,7]. The instability implants Neptune within the disk, where its orbit circularizes as the planet migrates outward. In doing so, Neptune scatters planetesimals from the disk into the present range of the Kuiper belt and beyond, and the surviving planetesimals (both resonant and non-resonant) are trapped. Pluto is one of these (resonant) bodies, and the Nice model predicts it originally accreted well inside its present position, somewhere in the 20-to-34 AU range [6,7]. So, do New Horizons results inform or constrain such models, or the timing of the dynamical instability? Is the Nice model consistent with the formation of the Pluto-Charon binary? And is a giant impact still implicated, or could the PC-system have formed by a different mechanism?

Bulk Properties: Whole disk imaging from New Horizons, and determination of the system barycenter from HST-based astrometry [8], have provided firm size and density constraints for Pluto and Charon (Fig. 1). Pluto and Charon have rather similar bulk densities, more similar to each other than to other large bodies in the Kuiper belt. Their rock/ice ratios are similar as well (Fig. 2), though Charon is nominally icier (at the 10%

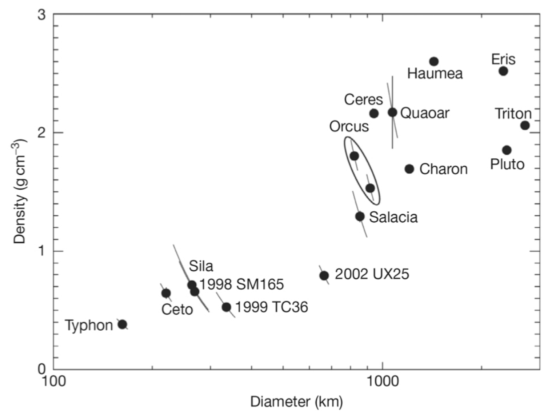

Figure 1. Densities of large and midsize KBOs and related bodies (after [9]).

level). The models in Fig. 2 are designed to constrain bulk ice/rock ratios taking into account temperature and pressure effects, but they do not incorporate such details as internal oceans [11], carbonaceous layers [12], or crustal porosity [13]. Such details are important, e.g., if Pluto has an ocean while Charon does not, then the rock/ice ratios of both bodies would be even more similar. This is important because Charon's iciness compared with that of Pluto is a major constraint on Charon-forming impact models [14,15].

Calculations suggest that despite possible differences in internal structures, Charon is truly icier than Pluto [16]. The small satellites appear icier still [4]: if the satellites are rubble piles, impacts with small Kuiper belt objects will occur in the gravity regime, and most ejecta will be local. A somewhat icier Charon and ice-dominated small satellites are consistent with the collision of partly differentiated precursor bodies, bodies that approach each other with a relatively low v_∞ [15]. This is in turn consistent with conditions in the ancestral Kuiper belt (the remnant planetesimal disk referred to above), but implies that the impact precursors themselves accreted relatively late and slowly (to limit $^{26}Al/^{60}Fe$ and accretional heating). Such satellite iciness is, in contrast, not consistent with direct formation of PC-system from a steaming instability in the solar nebula followed by direct collapse of gravitationally bound clumps of "pebbles," a proposed formation mechanism for Kuiper belt binaries, including PC [17]; a straightforward reading of the pebble scenario predicts a primordial, or at least uniform, composition for

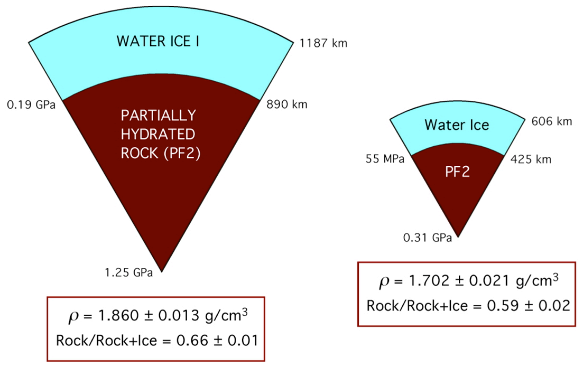

Figure 2. Simple structural models of Pluto and Charon. Densities are based on [1] and solar-composition rock (updated from [10]); mass fractions are calculated on an anhydrous basis.

all bodies in the system (not observed).

Differentiation State and the Possibility of Oceans: If Pluto or Charon are undifferentiated, their internal temperatures would have to have remained below water-ice melting (at least) throughout their histories, possibly due to solid state convection [12]. Long-term cooling would, in this case, inexorably lead to the growth of dense, rock-rich ice II at the expense of rock-rich ice I, resulting in strong surface compression for both bodies. Compressive tectonics are not observed on Pluto or Charon; rather, the opposite is seen [2]. This indicates that Pluto and Charon are both differentiated to some degree, which is consistent with the extensive volatile ices (N_2, CO, CH_4) seen on Pluto and the ammonia-water ice detected on Charon [3]. Moreover, the freezing of internal oceans, always a theoretical possibility [11,18,19], offers a plausible driver for the extensional tectonics seen (though not a unique one). Extensional disruption of Charon's surface is particularly thorough (albeit ancient [1,2]), which would seem to imply a substantial amount of ice melting early in that moon's history. This raises the question of the heat source responsible, especially as post-impact tidal heating, as Charon evolves outwards, nominally concentrates within Pluto [20].

Oblateness and its Discontents: Pluto should have been rapidly spinning and quite oblate post-giant-impact [15,20]. Yet no oblateness, much less triaxiality, has been detected for Pluto, to within a flattening of 0.6%, or 7 km (2σ) [1,21]. This implies a warm and deformable interior during or subsequent to spindown [1]. On one level this is understandable, as Pluto's icy lithosphere was likely thin enough in early epochs (perhaps ~50 km) that it would have been unable to offer sufficient brittle strength against what would have been profound spindown stresses. A fossil flattening of 2-3 km was predicted based on strength support in such an icy lithosphere [22], but this was stated as a lower limit because strength support in an internal rocky core lithosphere was seen as more important. This is obviously not the case (and note that Pluto's hydrostatic flattening today is <1 km). Perhaps Pluto did not have a core during spindown, or at least a fully formed one, or perhaps soft rock cores are just that, soft. There are also no obvious tectonic signatures of the collapse of Pluto's putative oblateness [23]. In all, no concrete evidence that Pluto ever spun rapidly. Apparently, such events are extremely early in Pluto's history, and have been erased by subsequent activity.

Activity Yesterday and Today. Some combination of N_2, CO, and CH_4 ices is undergoing convective overturn in Sputnik Planum (informally named), which is itself contained within a very broad basin several km deep. The rheologies of these ices are sufficiently soft that they can be mobilized for nominal Pluto radiogenic heat flows of a few mW/m^2 [2]. Pluto's glacial cycle is dominated by N_2, the most volatile of the ices, and is insolation driven (N_2 sublimates, condenses on upland terrains, builds up, and flows back into the basin, eroding and modifying the landscape as it does [2]). Convection within Sputnik Planum may nonetheless be critical to maintaining this glacial cycle, by continuously refreshing the planum surface and preventing build up of a choking, tholin-rich lag [24]. Glacial activity (erosion) was much more extensive in the past [2]. Was there a greater amount of N_2 earlier, despite the lack of evidence for substantial atmospheric escape? Or are we seeing back to a warmer epoch, when Pluto was closer to the Sun? Even accounting for the faint young Sun, Pluto could have enjoyed twice its present insolation, which for the same N_2-ice albedo would imply surface pressures approaching 1 mb (and all that follows). A deeper question is the source of Pluto's N_2, and whether there is enough to fill the basin. If not, does CO ice make up the difference?

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