The Origin of the Quadruple System at Pluto. S.A. Stern[1], H.A. Weaver[2], A.J. Steffl[1], M.J. Mutchler[3], W.J. Merline[1], M.W. Buie[4], E.F.Young[1], L.A. Young[1], & J.R. Spencer[1]. [1]Southweest Research Institute. [2]Johns Hopkins Applied Physics Laboratory. [3]Space Telescope Science Institute. [4]Lowell Observatory.

Introduction: Our discovery of two new satellites of Pluto [1], designated S/2005 P 1 and S/2005 P 2 (henceforth, "P1 and "P2"), combined with the constraints on the absence of more distant satellites of Pluto[2], reveal that Pluto and its moons comprise an unusual, highly compact, quadruple system. The two newly discovered satellites of Pluto have masses that are small compared to both Pluto and Charon, i.e., between 5×10^{-4} and 1×10^{-5} of Pluto's mass, and between 5×10^{-3} and 1×10^{-4} of Charon's mass.

Discussio:. P1 and P2 orbit relatively close to Pluto at distances of 64,700±850 km and 49,400±600 km, respectively[1]. Their orbits [1] appear to be nearly circular, and in the plane of Charon's orbit. Photometry [1], indicates that their visual magnitudes were V=22.93±0.12 and 23.38±0.17, respectively, in mid-May 2005. For an assumed lower limit albedo of 0.04 (as shown), one derives upper limit diameters of 167±10 km for P1 and 137±11 km for P2. If their albedos are as high as 0.35 (i.e., like Charon, a reasonable upper limit), then their diameters are only ~61±4 km and ~46±4 km, respectively. Pluto apparently has no undiscovered satellites farther out in the system down to objects 40 times fainter than P1 or P2.

The orbits of P1 and P2 reveal that Pluto's satellite system is both largely empty and highly compact. All three of Pluto's known satellites orbit in the inner ~3% of Pluto's satellite prograde orbit stability radius[3], which extends outward to 2.2×10^6 km from Pluto. Outside of the three satellite orbits, the system appears devoid of other bodies [2].

Pluto's satellite Charon is half of Pluto's diameter, and has a specific angular momentum so high that there is broad agreement that the pair was generated via a giant collision with an ancient impactor [3,4,5,6].

How did the quadruple system come to be? We argue that P1 and P2's proximity to Pluto and Charon, their orbits coincident with the plane of Charon's orbit, and their apparent locations in or near high-order mean-motion resonances with Charon, all result from their formation with Charon.

This hypothesis is supported by the circular or near-circular orbits of P1 and P2. We elaborate on this case by estimating the characteristic e-folding eccentricity decay time: following Dobrovolskis, i.e., $\tau = e/[de/dt] = 2Q_s/[21\mu n(R_s/a_s)^5 k_2]$. Here Q_s is the dissipation coefficient for the satellite, μ is the satellite mass ratio relative to Pluto, n is the orbital mean motion of the satellite, R_s is the satellite's radius, a_s is the satellite's orbital semi-major axis, and k_2 is the satellites' second degree potential Love number.

Adopting the satellite orbits we reported elsewhere [1], Q_s=100 (considered typical of icy satellites), k_{2s}=0.055 (appropriate for rigid ice [4]), densities of 2 g cm^{-3} (i.e., similar to Pluto and Charon), and assuming that P1 and P2 have their maximum permissible radii [1], we find tidal circularization time scales of 65 Gyr and 500 Gyr, respectively. Thus, it is seen that near their current orbits, or farther out, the eccentricity decay times for P1 and P2 are far too long to damp from high eccentricity capture values to circular orbits in the age of the solar system unless either the satellite Q's are <1 (strengthless rubble piles) and/or unless gas drag assisted any putative eccentricity decay. In contrast, Charon's orbital eccentricity decay time scale is short, $\sim 3 \times 10^6$ yr, and the tidal decay time scale for eccentricity near Pluto's Roche lobe is only of order 10^5 years.

Occam's razor thus suggests that the circular orbits of P1 and P2 directly imply that (i) they most likely formed nearer Pluto, rather than farther out or by capture from heliocentric orbit, and (ii) they subsequently evolved outward to their present-day positions during the tidal evolution of Charon to its current orbit. Such a scenario is consistent with state of the art simulations of the formation of the Pluto-Charon binary[6].

Implications for Other KBOs With Satellites: Finally, it has been estimated that 20%, or more, of the known KBOs have satellites [7]. This result and our work suggest that there must be tens of thousands of KBOs with satellites. A natural place to expect multiple satellite systems (and associated rings) would be around those KBOs which possess tightly bound, large satellites reminiscent of binary formation events like the Pluto-Charon pair. Such objects include 1997 CQ29, 1998 SM165, 1999 TC36, 2003 UB313, and 2003 EL61. It will also be useful to search for more distant, irregular satellites orbiting KBOs to determine whether less compact, e.g. capture-related architectures also exist among KBOs with satellite systems.

References

[1] Weaver, H.A., Stern, S.A., Mutchler, M.J., Steffl, A.J., Merline, W.J., Spencer, J.R,, Buie, M.W., Young, E.F., & Young, L.A., *Nature*, in press (2006). [2] Steffl, A.J., Mutchler, M.J., Weaver, H.A., Stern, S.A., Young, E.F., Durda, D.D., Terrell, D., Buie, M.W., Young, L.A., Spencer, J.R., & Merline, W.J. *Astron. J.*, submitted (2006). [3] McKinnon, W.B. *Nature*, **311**, 355 (1984). [4] McKinnon, W.B. *Astrophs. J.*, **344**, L41 (1989).[5] Stern, S.A., McKinnon, W.B., & Lunine, J.I., 1997. In *Pluto and Charon* (eds., S.A. Stern and D.J. Tholen, eds.), 605 (U. Ariz. Press, Tucson, 1997). [6] Canup, R.M. *Science*, 307, 546 (2005). [7] Stephens, D.C., and Noll. K.S. *Astron J.*, in press (2006).