nature Vol 439|23 February 2006|doi:10.1038/nature04548

LETTERS

A giant impact origin for Pluto's small moons and satellite multiplicity in the Kuiper belt

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The two newly discovered[1] satellites of Pluto (P1 and P2) have masses that are small compared to both Pluto and Charon—that is, 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. This discovery, 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. These facts naturally raise the question of how this puzzling satellite system came to be. Here we show that P1 and P2's proximity to Pluto and Charon, the fact that P1 and P2 are on near-circular orbits in the same plane as Pluto's large satellite Charon[1], along with their apparent locations in or near high-order mean-motion resonances, all probably result from their being constructed from collisional ejecta that originated from the Pluto–Charon formation event. We also argue that dust–ice rings of variable optical depths form sporadically in the Pluto system, and that rich satellite systems may be found—perhaps frequently—around other large Kuiper belt objects.

The orbits of P1 and P2 reveal that Pluto's satellite system is both largely empty and highly compact (Fig. 1). 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 the three satellite orbits, the system appears to be devoid of other bodies[2].

We calculated the characteristic tidal e-folding spin-down time[4], $T^{\text{spin-down}}$, for these bodies, to evaluate whether they should be expected to have rotational periods similar to their weeks-long orbital periods. We assumed standard values for the mass and radius of Pluto[5], and minimal masses of P1 and P2. For P1, assuming a rigidity like H_2O-ice and a dissipation factor $Q = 100$, we found $T_1^{\text{spin-down}} \approx 10^{11}$ yr in its current orbit. Making the same assumptions for P2, we found $T_2^{\text{spin-down}} \approx 10^{12}$ yr in its current orbit. It is therefore clear that the characteristic spin-down times for both P1 and P2 are expected to significantly exceed the 4.5 Gyr age of the Solar System. As a result, P1 and P2 are not expected to be in synchronous rotation with Pluto unless they previously orbited much closer to Pluto, where the spin-down time is decreased by orders of magnitude. If P1 or P2 are discovered to be spin–orbit synchronized, it would therefore suggest that these satellites formerly spent some considerable time closer to Pluto and then subsequently migrated outward as Charon and Pluto exchanged orbital and spin angular momentum to reach their current tidal equilibrium state. We return to this point later when discussing the origin of the system.

First, however, we develop some collisional considerations. Studies of the collisional environment of the present-day Kuiper belt acting on Pluto–Charon and Kuiper belt bodies of smaller sizes revealed[6,7] that the critical size boundary for catastrophic breakup over the past 4 Gyr occurs at diameters of ~4 km. P1 and P2 are large compared to this critical size scale for catastrophic disruption in the Kuiper belt. P1 and P2 are thus likely to be ancient bodies originally formed during the same era as Pluto and Charon, and are unlikely to have been subsequently disrupted and re-accreted in the past few Gyr.

Collisional studies have also revealed[6] that in the present day Kuiper belt, the cumulative fraction of the surface cratered by all 8 m diameter and larger Kuiper belt object (KBO) impactors ranges from ~7% to ~32% for bodies on orbits approximately like Pluto's. This does not include the additional surface area covered by ejecta blankets, which would increase this by a factor of 2 to 4, nor does it take into account higher cratering rates in the ancient Kuiper belt, before its mass depletion. Even for these conservative assumptions, we can predict that the surfaces of P1 and P2 will be significantly cratered.

Characteristic collisional velocities for Kuiper belt impactors onto these satellites are in the range 1–2 km s^{-1}. It has been demonstrated[6] that objects of the size class of P1 and P2 in the Kuiper belt have probably lost some 10–20% of their mass to impact erosion. We conclude from this that the present day sizes and mass of P1 and P2 are unlikely to be very different from their sizes and masses at the time of their formation.

The characteristic ejecta velocity resulting from collisions onto these satellites should be of order 1–10% of the speed of Kuiper belt debris impactors, or 10–100 m s^{-1}. At these speeds, collisional ejecta fragments will escape the satellites themselves but generally remain trapped in orbit about Pluto. This is in contrast to the situation obtaining at Charon (with its ~500 m s^{-1} escape velocity) because most collisional ejecta falls back onto Charon's surface, and does not reach orbit about Pluto. As such, the bombardment of P1 and P2 by small Kuiper belt debris almost certainly generates faint, dusty ice particle rings around Pluto, with time-variable optical depth.

A crude estimate of the approximate optical depth of these rings can be derived by assuming that 10% of the mass of these satellites may have been eroded from them over time[6]. If we then adopt the conservative assumptions of (1) minimum estimated satellite masses[1] for P1 and P2, (2) a mean lifetime for ejected particles of 10^5 yr (that is, an order of magnitude shorter than the estimated lifetime against erosion and sublimation of Kuiper belt dust particles[8]), (3) that only 10^{-4} of the debris is in micrometre-sized particles, (4) that the ring particles have 1 g cm^{-3} density, and (5) a (conservative) characteristic width spanning the entire separation between P1 and P2, we derive a characteristic ring optical depth estimate of $\tau = 5 \times 10^{-6}$. This is comparable to the optical depth of Jupiter's tenuous ring system. This estimate is only very approximate,

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but from it we conclude that Pluto can transiently possess dust rings as a result of the stochastic bombardment of P1 and P2 by small Kuiper belt debris.

Now consider how P1 and P2 may have formed. 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[9–12]. But what is the origin of P1 and P2, two remarkably smaller satellites exterior to Charon?

P1 and P2's proximity to Pluto and to Charon, their apparent locations in or near high-order mean-motion resonances, and in the plane of Charon's orbit[1], together present strong challenges to any assumed capture origin, but naturally suggest a formation in association with the giant impact origin of Charon. We therefore suggest that P1 and P2 are, like Charon, likely to be constructed of material ejected into orbit about Pluto as a result of the Charon-forming impact event.

This hypothesis is further 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[4]:

$$\tau = e/(\mathrm{d}e/\mathrm{d}t) = 2Q_\mathrm{s}/[21\mu n(R_\mathrm{s}/a_\mathrm{s})^5 k_2]$$

Here e is eccentricity, Q_s is the dissipation coefficient for the satellite, μ is the satellite mass ratio relative to its primary (Pluto in this case), 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 second degree potential Love number of the satellite.

Adopting the P1 and P2 orbits we reported elsewhere[1], $Q_\mathrm{s} = 100$ (considered typical of icy satellites), $k_2 = 0.055$ (appropriate for rigid ice[4]), densities of $2\,\mathrm{g\,cm^{-3}}$ (that is, similar to Pluto and Charon), and assuming that P1 and P2 have their maximum permissible radii[1], we find tidal circularization timescales 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 values are <1 (strengthless rubble piles) and/or unless gas drag assisted any putative eccentricity decay. In contrast, Charon's orbital eccentricity decay timescale is short, $\sim 3 \times 10^6$ yr, and the tidal decay timescale for eccentricity near Pluto's Roche lobe is only of order 10^5 yr. This suggests to us that the circular orbits of P1 and P2 imply that (1) they most probably formed much closer to Pluto, rather than farther out or by capture from heliocentric orbit, and (2) they subsequently evolved outward to their present-day positions during the tidal evolution of Charon to its current orbit.

This said, we note that the very small masses of P1 and P2 relative to Charon beg the question of why so little material would have escaped accumulation into orbiting bodies other than Charon, and therefore, why there are not more small satellites of Pluto. Perhaps other satellites did form, but eventually became dynamically

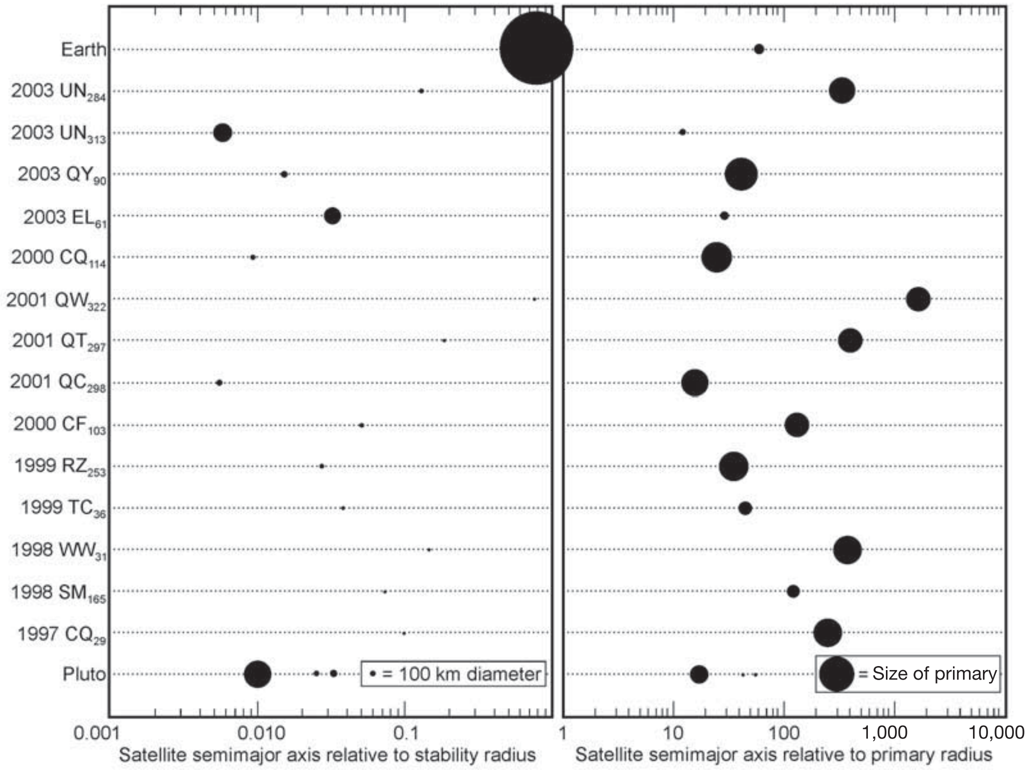

Figure 1 | The architecture of the Pluto system compared to other KBOs with known satellites and to the Earth–Moon system. The orbital distances and sizes of all three satellites in the Pluto system are shown here in comparison to other relatively well characterized KBO–satellite systems, and the Earth–Moon pair. P1 and P2 orbit relatively close to Pluto at distances of 64,700 ± 850 km and 49,400 ± 600 km, respectively[1]. Photometry of these two bodies[1] indicates that their visual magnitudes were $V = 22.93 \pm 0.12$ and 23.38 ± 0.17, respectively, in mid-May 2005. For an assumed (that is, comet-like) 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 (that is, like Charon[5], 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. For this figure, all satellites are assumed to lie at their discovery distance if a formal semi-major axis has not yet been established. The left-hand panel shows satellite sizes on an absolute scale, with orbital distances normalized to the orbital stability zone within which the primary body can retain satellites over long timescales. Masses were computed from sizes assuming a density of $\rho = 2\,\mathrm{g\,cm^{-3}}$, like Pluto and Charon[5]. The right-hand panel shows the systems with satellite sizes normalized to the radius of the primary in each system (for example, Charon appears larger than the Moon), and their orbital distances in units of the primary's radius; object sizes were computed assuming 4% albedos.

destabilized, resulting in accumulation onto Charon or Pluto; or perhaps there are other, still fainter, satellites that escaped detection below the new Hubble Space Telescope observation[2] threshold near a visual magnitude of $V = 26.2$.

Finally, it has been estimated that 20%, or more, of the known KBOs have satellites[13]. This suggests that there must be tens of thousands of KBOs with satellites. Given this, and the presence of P1 and P2 orbiting Pluto, we consider it likely that many KBO satellite systems will be revealed to be multiples when examined closely. Figure 1 further illustrates this point, showing the ample space available for minor satellites in the known KBO systems.

We suggest that a natural place to expect multiple satellite systems (and associated rings) would be around those KBOs that possess tightly bound, large satellites reminiscent of binary formation events like the Pluto–Charon pair. Such objects include 1997 CQ_{29}, 1998 SM_{165}, 1999 TC_{36}, 2003 UB_{313} and 2003 EL_{61}. It will also be useful to search for more distant, irregular satellites orbiting KBOs to determine whether less-compact (for example, capture-related) architectures also exist among KBOs with satellite systems.

Received 17 November; accepted 20 December 2005.

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Acknowledgements We thank W. McKinnon, R. Canup and W. Ward for reading and commenting on this manuscript.

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