LETTERS

Discovery of two new satellites of Pluto

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Pluto's first known satellite, Charon, was discovered[1] in 1978. It has a diameter (~1,200 km) about half that of Pluto[2–4,17], which makes it larger, relative to its primary, than any other moon in the Solar System. Previous searches for other satellites around Pluto have been unsuccessful[5–7], but they were not sensitive to objects ≲ 150 km in diameter and there are no fundamental reasons why Pluto should not have more satellites[6]. Here we report the discovery of two additional moons around Pluto, provisionally designated S/2005 P 1 (hereafter P1) and S/2005 P 2 (hereafter P2), which makes Pluto the first Kuiper belt object known to have multiple satellites. These new satellites are much smaller than Charon, with estimates of P1's diameter ranging from 60 km to 165 km, depending on the surface reflectivity; P2 is about 20 per cent smaller than P1. Although definitive orbits cannot be derived, both new satellites appear to be moving in circular orbits in the same orbital plane as Charon, with orbital periods of ~38 days (P1) and ~25 days (P2).

We observed Pluto with the Hubble Space Telescope using the Wide-Field Channel (WFC) mode of the Advanced Camera for Surveys (ACS) on UT 2005 May 15 and May 18 (Fig. 1). The ACS/WFC consists of two 4,096 × 2,048 pixel CCDs (WFC1 and WFC2) butted together, effectively forming a single 4,096 × 4,096 pixel camera with a gap of ~50 pixels between the two CCDs. The F606W ('Broad V') filter, which has a centre wavelength of 591.8 nm and a width of 67.2 nm, was used for all images. At the time of the observations, Pluto was 31.0 astronomical units (AU) from the Sun, 30.1 AU from the Earth, and had a solar phase angle of 0.96° on 15 May and 0.88° on 18 May. Identical strategies were employed on each observing date. First, a single short exposure (0.5 s) was taken to enable accurate positions of Pluto and Charon to be measured on unsaturated images. Then, two identical, long exposures (475 s) were taken at the same pointing to provide high sensitivity to faint objects. Finally, the telescope was moved by ~5 pixels in one dimension and ~60 pixels in the other dimension, and two identical, long exposures

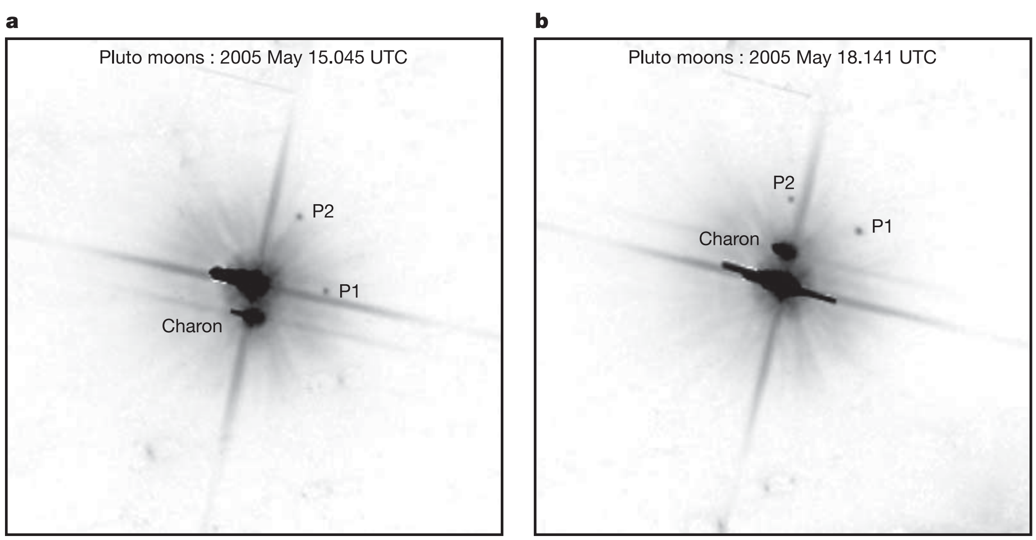

Figure 1 | Images of the Pluto–Charon system, showing the new satellites, S/2005 P 1 (P1) and S/2005 P 2 (P2). a, Data taken on 2005 May 15.045 UTC; **b**, Data taken 3.1 days later on 2005 May 18.141 UTC. Each frame is a small section (256 pixel × 256 pixel) of the full image that is centred on Pluto and subtends 12.8 arcsec × 12.8 arcsec, which projects to 280,000 km × 280,000 km at Pluto. Celestial north is up and east is to the left. A logarithmic intensity stretch is used to enhance the visibility of the two new satellites in the presence of the much brighter, saturated images of Pluto and Charon. P1 is near the 3 o'clock position on 15 May and moves to the 2 o'clock position 3.1 days later, while P2 moves from the 1 o'clock position to the 12 o'clock position over the same time interval. Charon has moved (also anticlockwise) from one side of Pluto to the other between the two epochs, as expected, owing to its orbital period of 6.4 days. We used the individual, bias-subtracted, flat-fielded files from the ACS calibration pipeline as the starting point for our data reduction. We coaligned the four long-exposure images taken on each date and combined them using a sigma-clipping procedure that filters out anomalous features not present (to within the noise level) in all images. Thus, the many camera artefacts present in the flat-fielded images (cosmic ray events, hot pixels, dead pixels, and so on), as well as most of the star trails, are removed in the composite image. The few remaining faint blotches are artefacts caused by incomplete subtraction of star-trails in the field, and their spatial distributions are very different from the PSF-like distributions of P1 and P2. The geometric distortion in the composite image was removed using the same remapping algorithm employed by the standard ACS/WFC calibration process.

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Table 1 | **Astrometry and photometry of Pluto satellites**

	Pluto		Charon		S/2005 P1		S/2005 P2	
Date (UT May 2005)	[r, θ]	V	[r, θ]	V	[r, θ]	V	[r, θ]	V
15.045	[0, 0]	14.12 ± 0.08	[0.834, 176.77]	16.22 ± 0.10	[1.85, 264.21]	NA	[2.09, 326.94]	23.38 ± 0.17
18.141	[0, 0]	14.28 ± 0.08	[0.855, 355.04]	16.28 ± 0.10	[2.36, 305.76]	22.93 ± 0.12	[2.22, 355.51]	NA

'Date' refers to the mid-point of the observing period. r is the distance in arcsec, and θ is the celestial position angle in degrees (measured eastward from north) in the J2000 reference frame from the centre-of-light of the specified object to the centre-of-light of Pluto. The 1σ errors in r and θ are 0.035 arcsec and 0.7°, respectively, and are mainly due to the uncertainty in locating Pluto in the long-duration exposures. The centre-of-light is offset from the centre-of-body by ~100 km for Pluto and by ≤20 km for Charon[2], but these offsets were ignored in our orbital analyses. V is the observed visual magnitude of the object, when available, and was calculated using a 5-pixel-radius (0.25 arcsec) aperture. We used the information and procedures described in ref. 15 to convert the observed signal in this small aperture to a V-magnitude in the standard Johnson-Landolt system. Adopting a $B - V$ colour of 0.7 (that is, similar to Charon-like[12] and solar-like[16] colours), we derive $V = -2.5 \log S/t + (26.38 \pm 0.07)$, where V is the V-band magnitude in the Johnson-Landolt system, S is the net signal in electrons in the 5-pixel-radius aperture, and t is the exposure time in seconds. We calculated the magnitudes of Pluto and Charon in the same way, although both objects (especially Pluto) are slightly resolved, which introduces an additional systematic error in those cases. NA, not available.

(475 s) were taken to provide data in the region of the sky falling in the inter-chip gap during the first two long exposures. The telescope was programmed to track the apparent motion of Pluto (~3 arcsec h^{-1}) for all exposures.

The two new satellites are detected with high signal-to-noise ratio ($S/N \geq 35$) and have a spatial morphology consistent with the ACS point spread function (PSF; this is the spatial brightness distribution expected for unresolved objects). Unlike virtually all of the spurious features in the individual ACS images, the two new objects were observed in two consecutive images on two different dates. Furthermore, the objects do not appear in the images where they are not expected, namely when the telescope pointing placed the objects in the inter-chip gap. Although P1 and P2 are several thousand times fainter than Pluto, their images look nothing like the well-documented[8] ghosts and scattered-light artefacts produced near bright, highly saturated objects. In short, all the available evidence supports the claim that the objects observed near Pluto–Charon are real astronomical objects, and none of the data suggest that these objects are observational artefacts.

Next we address the issue of whether P1 and P2 are associated with the Pluto–Charon system. Only astronomical bodies moving at approximately the same non-sidereal rate as Pluto will have PSF-like spatial distributions, and asteroids and stars are easily recognized by their trailed images. We estimate that foreground or background objects must have a heliocentric distance within ~0.25 AU of Pluto's to remain within 2 arcsec of Pluto over the 3.1 days between the two sets of ACS observations. On the basis of the known sky-projected density of Kuiper belt objects (KBOs) as a function of magnitude[9], the probability of finding any similarly bright KBO within 2.5 arcsec of Pluto is $\sim 4 \times 10^{-6}$, which means that the probability of finding two KBOs in this same region is $\sim 1.6 \times 10^{-11}$. These statistical arguments are not strictly applicable to the plutino KBO population (that is, objects that share Pluto's 3:2 orbital resonance with Neptune), for which resonances and other gravitational perturbations might keep objects relatively close to Pluto. Nevertheless, there must be only a vanishingly small chance that the two observed objects are random KBOs that happen to be aligned with Pluto during the course of our observations.

Orbital analysis based on the astrometry of P1 and P2 (Table 1) provides even stronger evidence that the two objects are indeed associated with Pluto. Although the astrometric data from two observations alone are not enough to compute definitive orbits, we investigated the hypothesis that the objects have circular orbits in the same plane as Charon's orbit. Adding these two constraints (that is, zero eccentricity and the same orbital plane as Charon) allows us to solve for the orbital radii that best match the observations. We find that the orbital radii are 64,700 ± 850 km for P1 and 49,400 ± 600 km for P2, both measured relative to the system barycentre. The results are depicted in Fig. 2. The excellent agreement between the observed and model orbits (reduced $\chi^2_\nu \approx 1$ for the fits) supports our assumption that the orbits are circular and coplanar with Charon's orbit, and also reinforces the conclusion that P1 and P2 are associated with the Pluto system. Using the known mass of the Pluto system and Kepler's third law, we derive orbital periods of 38.2 ± 0.8 days for P1 and 25.5 ± 0.5 days for P2. The ratios of the orbital periods to the orbital period of Charon (6.387245 ± 0.000012 days)[2] are 5.98 ± 0.12 for P1 and 3.99 ± 0.07 for P2. This suggests that P1 may be in a 6:1, and P2 may be in a 4:1, mean motion orbital resonance with Charon, and that P1 and P2 may be in a 3:2 resonance with each other. Further investigation of these possible resonances, or slight deviations from these resonances, will undoubtedly provide significant insights into the dynamical evolution of the Pluto system.

After finding the orbital solutions described above, we re-examined

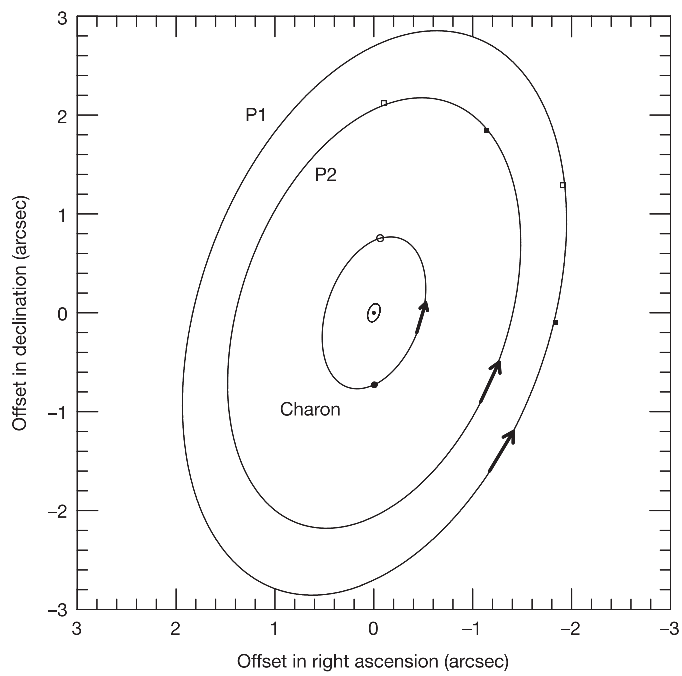

Figure 2 | **Preliminary orbits for P1 and P2, assuming that they are circular and in the same plane as Charon's orbit.** The barycentre of the system is the dot in the centre, Pluto's orbit is the smallest ellipse, Charon's orbit is the next ellipse (its positions on 15 May and 18 May are indicated by the filled and open circles, respectively), an orbit that is consistent with P2's measured positions is next, followed by an orbit that is consistent with P1's measured positions. For the last two cases, the filled squares are the observed positions on 15 May, and the open squares are the observed positions on 18 May. The uncertainties (1σ) in the measured positions are approximately the size of the symbols. At Pluto's distance, 1 arcsec projects to 21,800 km. Charon's orbital plane is inclined by ~36° relative to the line-of-sight, which means that the circular orbits of the satellites appear elliptical when projected on the plane of the sky. All four objects orbit the barycentre in an anticlockwise direction in this view, and all positions are displayed in the J2000 reference frame with celestial north up and east to the left.

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some Hubble Space Telescope data of Pluto taken in 2002 under another programme (M.W.B., unpublished work). That programme was optimized to study the surfaces of Pluto and Charon and used much shorter exposure times (6 s for a V-band filter and 12 s for a B-band-filter) than employed in our programme. Nevertheless, by combining all the images obtained on a given date in the same filter, a limiting sensitivity could be achieved that is very close to the observed magnitudes of P1 and P2 (see Table 1). On the observation date (UT 2002 June 14) with the best geometry (lowest phase angle and smallest geocentric distance), two objects are weakly detected ($S/N \approx 4$) along the predicted orbital paths of P1 and P2 in both the V-band and B-band images, providing independent evidence that P1 and P2 are indeed satellites of Pluto.

Our photometry results are summarized in Table 1. On 15 May P2 has a visual magnitude (V) of 23.38 ± 0.17, and on 18 May P1 has $V = 22.93 \pm 0.12$. P1 is too close to a diffraction spike for accurate photometry on 15 May, but the brightness then seems consistent with the value observed on 18 May. P2 is too close to a diffraction spike for accurate photometry on 18 May, but the brightness then seems consistent with the value observed on 15 May. Small bodies are often highly irregular in shape, which results in significant temporal variation in brightness as the object rotates. Whether this is true for P1 and P2 must await future investigations.

If the geometric albedo is known, the size of an object can be calculated from its magnitude using a standard relation[10]. For a geometric albedo of 0.04 (that is, comet-like[11]), P1 has a diameter of 167 ± 10 km, and P2 has a diameter of 137 ± 11 km. If the albedo is 0.35 (that is, Charon-like[12]), the diameters are 61 ± 4 km for P1 and 46 ± 4 km for P2. Both satellites are tiny compared to Pluto and Charon, which have diameters of $2,328 \pm 42$ km (refs 2, 3) and $1,207.2 \pm 2.8$ km (ref. 4), respectively. (Using other data from the Charon occultation, Gulbis *et al.*[17] derive a diameter of $1,212 \pm 16$ km.) The masses of P1 and P2 account for less than 5×10^{-4} of the mass of the Pluto system, assuming that the densities of P1 and P2 are similar to, or smaller than, Pluto's density.

We also searched the entire ACS/WFC field-of-view (202 arcsec × 202 arcsec) for other satellites, but none were found down to a limiting magnitude of $V \leq 26.2$ (90% confidence limit) for the region between 5 and 100 arcsec from Pluto[13]. Thus, the Pluto system of satellites appears to be very compact.

The implications of the discovery of P1 and P2 for the origin and evolution of the Pluto system, and for the satellite formation process in the Kuiper belt, are discussed in a companion paper[14].

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