The seventh inner moon of Neptune

M. R. Showalter1*, I. de Pater2, J. J. Lissauer3 & R. S. French1

During its 1989 flyby, the Voyager 2 spacecraft imaged six small moons of Neptune, all with orbits well interior to that of the large, retrograde moon Triton1. Along with a set of nearby rings, these moons are probably younger than Neptune itself; they formed shortly after the capture of Triton and most of them have probably been fragmented multiple times by cometary impacts1–3. Here we report Hubble Space Telescope observations of a seventh inner moon, Hippocamp. It is smaller than the other six, with a mean radius of about 17 kilometres. We also observe Naiad, Neptune’s innermost moon, which was last seen in 1989, and provide astrometry, orbit determinations and size estimates for all the inner moons, using an analysis technique that involves distorting consecutive images to compensate for each moon’s orbital motion and that is potentially applicable to searches for other moons and exoplanets. Hippocamp orbits close to Proteus, the outermost and largest of these moons, and the orbital semimajor axes of the two moons differ by only ten per cent. Proteus has migrated outwards because of tidal interactions with Neptune. Our results suggest that Hippocamp is probably an ancient fragment of Proteus, providing further support for the hypothesis that the inner Neptune system has been shaped by numerous impacts.

We have devoted three Hubble Space Telescope (HST) observing programmes to studies of the rings, ring arcs and small inner moons of Neptune. We used the High Resolution Channel (HRC) of the Advanced Camera for Surveys (ACS) in 2004–2005 and the Ultraviolet/Visible Imager (UVIS) of Wide Field Channel 3 (WFC3) in 2009 and 2016. Hippocamp, also designated5 as S/2004 N 1 and Neptune XIV, was discovered during a reanalysis of the first two datasets (Fig. 1a–c) and confirmed in the third (Fig. 1d).

The long delay between the first image acquisition and the discovery of Hippocamp arose because of the specialized image processing techniques required. To detect a small moon in an image, motion smear should be limited to the scale of the point-spread function. For Neptune’s inner system, this limits exposure times to 200–300 s before smear dominates and the signal-to-noise ratio (SNR) ceases to grow. We have developed an image processing technique to push integration times well beyond this limit. Although the moons of Neptune move rapidly across the detector, that motion is predictable and can be described by a distortion model. Our procedure involves deriving a pair of functions r(x) and θ(x) that return the orbital radius and inertial longitude, respectively, as a function of the two-dimensional (2D) pixel coordinate x. The inverse function x(r, θ) can also be readily defined. We derive the mean motion function n(r) from Neptune’s gravity field, including its higher moments5 J₂ and J₄. One can use these functions to transform an image taken at time t₀ to match the appearance of another image obtained at time t₁ by relocating each pixel x₀ in the original image to a new location x₁:

\[ x₁ = x (r (x₀), θ (x₀) + n (r (x₀)) (t₁ - t₀)) \]  

(1)

After the transformation, any moon on a prograde, circular, equatorial orbit will appear at fixed pixel coordinates. Transformed images can be co-added so that much longer effective exposure times are obtained (Fig. 2). The transformation creates a spiral pattern that becomes tighter with decreasing r (Fig. 2c) and fails when adjacent pixels shear to the point that individual point-spread functions (PSFs) are severely distorted. For the inner Neptune system, this limits the co-adding of images to those that have been obtained within a single HST orbit of Earth, which typically allows 50 min of Neptune observation.

We have obtained 20 detections of Hippocamp (Extended Data Table 1). Most detections required co-adding of all the long-exposure images (typically 8–11) taken during each HST orbit. In 2016, by timing our orbits carefully relative to Hippocamp’s orbit and by using the broadest filter (F350LP), we were consistently able to detect the moon in half-orbits comprising only about 15 min of integration. The detections varied in SNR from 2.3 to 13.2. Hippocamp is most detectable at maximum elongation, where sky motion is slower, background noise is reduced and, if the body is irregular, it presents a larger cross-section. A combination of favourable circumstances provided us with one visit in which Hippocamp was visible without co-adding; see Supplementary Videos 1 and 2.

This same procedure has also revealed Naiad (Extended Data Fig. 1; Extended Data Table 2). Identifying Naiad was challenging because its orbit differed substantially from that predicted by the latest ephemerides6; in 2016, Naiad fell nearly 180° away from its predicted location. Nevertheless, astrometry from HST and Voyager is consistent with uniform, near-circular motion if one allows for a 1° increase in Naiad’s Voyager-derived mean motion7; see Extended Data Table 3. The large ephemeris error implies that reported detections8 of Naiad with the W. M. Keck Telescope in 2002 were misidentifications. A 19° error in the predicted orbit of Thalassa8 suggests that it may also have been misidentified in the same dataset.

Determining the orbits of Hippocamp and Naiad entailed solving for the best-fit orbits of all of Neptune’s inner moons simultaneously. Table 1 lists our derived orbital elements. Each orbit is defined relative to its local Laplace plane; this plane nearly aligns with Neptune’s equator to the point that individual point-spread functions (PSFs) are severely distorted. For the inner Neptune system, this limits the co-adding of images to those that have been obtained within a single HST orbit of Earth, which typically allows 50 min of Neptune observation.

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Fig. 1 | Detections of Hippocamp in 2004–2016. a, View from Visit 04 of programme GO-10398, showing the earliest detection of Hippocamp, on 2004 December 9. Neptune is behind the HRC occulting mask. b, Visit 08 of programme GO-10398, on 2005 May 12. c, View from the first orbit during Visit 01 of programme GO-11656, on 2009 August 19. The grey vertical band is due to Neptune’s saturation bloom, in which the heavily saturated pixels of the charge-coupled device tend to saturate adjacent pixels above and below. d, Visit 03 of programme GO-14217, on 2016 September 2. Panels a and b have been rotated 90° anticlockwise. In each panel a small square locates Hippocamp, and a close-up is shown in the inset. Other moons and the outline of Neptune are indicated.

Fig. 2 | Image processing steps leading to the discovery of Hippocamp. a, Image ib2e02zq_flt, the first in a sequence of eight long-exposure images from the second HST orbit of Visit 02 in programme GO-11656 (2009 August 19). b, Image ib2e02zmq_flt, taken 21 min later. Despina, Galatea and Larissa have shifted noticeably in position. c, Image from a, transformed to match the geometry of the image in b. d, The result of co-adding all eight images, revealing Hippocamp and Thalassa. The outline of Neptune’s disk, as distorted by the camera, is shown in each panel.
Neptune’s other inner moons. All of the candidate images either were badly smeared or definitively missed Hippocamp on the basis of its predicted position relative to the observed locations of other moons. The Voyager images established an upper limit of about 5 km on the radius of any undiscovered moons\(^1\) (assuming \( k = 0.09 \)). That search was complete inside \( r = 65,000 \) km and partially complete inside \( 90,000 \) km. Between the limits of the Voyager search and the orbit of Proteus, we can now rule out any moons that are half as bright as Hippocamp, which corresponds to \( R \approx 12 \) km. Beyond Proteus, our images are freer from Neptune’s glare and orbital motion is slower, making it possible to co-add larger sets of images (Extended Data Fig. 3). Implant tests within these images indicate that a moon with about 30% of Hippocamp’s brightness (\( R \approx 10 \) km) would generally be visible beyond Proteus. Our orbital coverage is complete out to \( r \approx 200,000 \) km and about two-thirds complete out to \( r \approx 300,000 \) km. However, moons on modestly inclined or eccentric orbits would be much harder to detect.

Using the orbital elements of Table 1 and methods previously applied to the Pluto system\(^2\), we conducted an exhaustive search for resonances between these moons. No plausible Lindblad, corotation or three-body resonances up to second order in eccentricity and inclination were found. The search was complete for numeric coefficients up to 200.

The discovery of tiny Hippocamp contributes to our understanding of the history of Neptune’s inner system. Extended Data Fig. 4 shows Hippocamp in context. It orbits just 12,000 km interior to Proteus, a body with 4,000 times its volume. Proteus and Hippocamp were even closer in the past because Proteus is migrating outwards owing to tidal interactions with Neptune. Hippocamp, with its much lower mass, migrates very slowly and remains close to its point of origin. It is therefore worth exploring the possible connection between these moons.

Cometary impacts are thought to have disrupted Neptune’s smallest moons multiple times; only Proteus is likely to have survived intact since shortly after the capture of Triton\(^3\). The Pharos crater on Proteus is unusually large relative to the moons, suggesting that Proteus may have also come close to disruption. We hypothesize that a large impact, perhaps the Pharos event itself, released debris from Proteus into orbit around Neptune. Some of this debris settled into a stable orbit, perhaps 1,000–2,000 km (a few Hill radii) interior to Proteus\(^14\), and accreted into Hippocamp. Notably, the volume of Hippocamp is only about 2% of the missing volume associated with the Pharos impact basin\(^13\)—merely a rounding error.

This scenario has several complications. First, Proteus would probably have increased Hippocamp’s eccentricity and inclination when their orbits were still very close, or perhaps later, as it crossed a strong Hippocamp resonance\(^8\). It might therefore be surprising that Hippocamp’s eccentricity and inclination are very small, statistically indistinguishable from zero (Table 1). A later orbital disruption may have also come close to disruption. We hypothesize that a large impact, perhaps the Pharos event itself, released debris from Proteus into orbit around Neptune. Some of this debris settled into a stable orbit, perhaps 1,000–2,000 km (a few Hill radii) interior to Proteus, and accreted into Hippocamp. Notably, the volume of Hippocamp is only about 2% of the missing volume associated with the Pharos impact basin—merely a rounding error.

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For this scenario to work, Proteus must have migrated by more than about 11,000 km in its lifetime. The migration rate is inversely proportional to Neptune’s ‘quality factor’, Q. For Proteus to migrate by this distance in 4 billion years, Q must be ≲15,000 for Neptune. This is compatible with the inferred range of Q for Neptune (12,000–330,000) and also for Uranus (11,000–39,000). A smaller Q would imply that Proteus migrated farther and therefore Hippocamp is somewhat younger. However, because the impactor flux was higher early in the Solar System’s history, Hippocamp is probably at least a few billion years old.

However, one line of argument suggests an upper limit of 10,000 km on the migration of Proteus. As Proteus crossed $r \approx 107,000$ km, it entered a 2:1 resonance with Despina, where simulations indicate that Despina’s inclination should have grown to a value much larger than that currently observed. However, because Despina is thought to have been disrupted 3–6 times in the last 4 billion years, this constraint on the migration of Proteus may not apply.

We cannot rule out the possibility that Hippocamp formed in situ and has no connection to Proteus. However, its tiny size and peculiar location lead us to favour the proposed formation scenario, which illustrates the roles that collisions and orbital migration have played in shaping the Neptune system that we see today.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41586-019-0909-9.

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Additional information
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Methods. Our dataset encompasses most of HST images of the Neptune system taken in 2004–2016. Only our observing programmes (GO-10398, -11565 and -14217) were capable of detecting Hippocamp, Naiad and Thalassa, but other programmes provided detections of the larger moons, which contributed to the precision of our orbit solutions and photometry. Three programmes that focused exclusively on imaging the planet through narrowband filters (GO-10423, 14044 and 14334) were omitted because of low sensitivity to the small satellites. We performed most of our analysis using calibrated (‘FLT’) image files. For the three smallest satellites, we used alternative calibrated images (‘FLC’), where available; these account for the charge-transfer efficiency of the charge-coupled device (CCD) and are expected to be more accurate for very faint targets. However, for our purposes, the difference was negligible.

Observing techniques. For our own observing programmes, we employed broad visual–band filters, primarily CLEAR in ACS/HRC and F606W and F350LP in WFC3/UVIS. Neptune is typically observable for about 50 min of HST’s orbit around the Earth, which is sufficient to obtain 8–11 very long exposures (175–320 s). Most visits also included a few short exposures for geometric and photometric reference.

All images were targeted at the centre of Neptune. On some occasions, we performed dithering steps part-way through an orbit of HST to prevent hot pixels from remaining at fixed locations. However, this was not strictly necessary; the moons move by many pixels within a single HST orbit, so no moon is ever affected by a particular hot pixel more than once. In 2016 (programme GO-14217), we scheduled most of our visits to be split across two orbits to improve coverage in orbital longitude: each half-orbit contained 5 or 6 long exposures.

Most observations were scheduled to keep Triton outside the field of view. However, this was not always possible and observations of Triton contributed to our analysis, in particular because the orbit of Triton defines the orientation of the Laplace planes.

During 2004 (programme GO-10398; see Fig. 1a), we used the occulting mask on the HRC to suppress excess light from Neptune. Although the mask was designed to obscure point targets, we found it to be successful at suppressing the glare from Neptune. The 3″ mask barely covered Neptune’s 2.4″ disk, requiring us to centre Neptune with fine precision. The process of positioning the coronagraph was automated; the camera took an image and then shifted the pointing to place the brightest pixel at the centre of the mask. We found that Neptune is a featureless disk in ultraviolet light, so we used filter F330W (with passband 0.33 ± 0.03 μm) for the initial pointing. This procedure worked every time.

We also developed other techniques to suppress the light from Neptune in the absence of a coronagraph. The CCDs on HST ‘bloom’ along the y axis when saturation occurs, but this generally does not corrupt pixels that are offset along the x axis. During 2005 (Fig. 1b) we simply shortened our exposure times to limit the distance the image would move when it bloomed (Fig. 1c). d). We chose observing periods around opposition, when we could orient the camera so that the rings and satellites extended outwards to the right and left, parallel to the x axis. In these cases, overexposing Neptune is essentially harmless.

Image processing. Although we were able to control Neptune’s saturation using the methods described above, glare from Neptune was ever-present and, with all long exposures on HST, cosmic rays created a smattering of ‘snow’ atop most images (Extended Data Fig. 5a). Hot pixels fall at known locations in each image and are catalogued for each detector. Cosmic-ray hits were recognized as clusters of pixels in one image that differ by more than three standard deviations from the median of identical exposures from the same HST orbit. For cosmetic purposes, we overwrote these pixels with the median of the adjacent pixels (Extended Data Fig. 5b). However, we also kept track of overwritten pixels using a boolean mask and ensured that masked pixels were ignored in the subsequent data analysis (Extended Data Fig. 5c). We suppressed the glare and diffraction spikes by aligning the centre of Neptune in all the images from each HST visit that shared a common filter. We constructed a background image from the median value of all the identical exposures from the same HST orbit. For cosmetic purposes, we overwrote these pixels with the median of the adjacent pixels (Extended Data Tables 1, 2).

Small-moon detections. The three smallest moons, Naiad, Thalassa and Hippocamp, required additional effort to detect. We performed a procedure akin to ‘unsharp masking’, in which we subtracted the median of the nearby pixels (in a box ranging in size from 7 × 7 to 13 × 13, depending on the circumstances) from each pixel in a given image. Normally, unsharp masking uses the mean, not the median, but the median suppresses most of the artefacts produced by the mean, such as dark circles around bright features. This step removed the last remaining background gradients from the images (Extended Data Fig. 5e).

We customized the image distortion and co-adding procedure for each moon on the basis of the number of images required to obtain a usable detection. Hippocamp was mostly targeted with the wide-field camera (WFC3) and could often be detected in half-orbits of co-added data; this allowed us to obtain two measurements per HST orbit rather than one. Thalassa could sometimes be seen in individual images, but in other cases it was necessary to co-add two or more images. We have described our co-adding procedure above (Fig. 2). Once we detected a body, we adopted a slightly different image processing procedure to optimize the images for our analysis. We transformed each set of images using the fixed mean motion n_0 for each moon, as determined during the discovery/recovery process:

$$x = x_0 / (t-t_0)$$

This transform is preferred because it does not create a spiral pattern that arises when n is treated as a function of r, so it is less disruptive to the PSFs. When searching for moons outside the orbit of Proteus (Extended Data Fig. 3), the motion was slow enough to co-add images spanning a few adjacent orbits. In these cases, we transformed the images using polar coordinates, so that the longitude at an epoch varies from 0° to 360° along the x axis and the radius increases along the y axis:

$$x = r \cos \theta (x_0) + n \sin \theta (x_0)$$

$$y = r \sin \theta (x_0)$$

Astrometry. Because Neptune is large and often saturated, it was unusable as a pointing reference. Background stars could have also provided pointing references, but these were generally absent. As a result, we performed an initial navigation (pointing correction) for each image by searching for the brightest moons by eye. We could easily obtain initial precision of 1–2 pixels, at which point it became practical to search for the known moons using an automated procedure. Here, the best directions were inspected visually and rejected if the moon could not be clearly seen or if something nearby could have corrupted the measurement. Naiad, Thalassa and Hippocamp were too small to be detected in this way and were handled by an entirely manual process, as discussed further below.

For each measurement, we fitted a model PSF to a small square of the image surrounding each detectable body. Model PSFs were generated using the Tiny Tim software maintained by the Space Telescope Science Institute (STScI). The parameters to be fitted included the centre position (x, y), the scaling factor to match the brightness of the body, and parameters required to define an underlying 2D ramp of background light. The background ramp was needed to account for Neptune’s glare. Nearest the planet, we used a 2D quadratic requiring six additional free parameters; elsewhere, we used a 2D linear function requiring just three.

For the faintest moons, we adopted a slightly different procedure. Many of these images had been distorted and co-added, so the PSF was no longer accurately described by the Tiny Tim model. Instead we used a uniform 2D Gaussian for the PSF. Given how faint these objects are in our data, this simpler PSF model was adequate for our needs. To handle the possibility of a bias between the centre of the model PSF and the Gaussian, we performed the same Gaussian fits on Despina, Galatea and Larissa, and then calculated the mean offset between the centres of the PSF and the Gaussian. We applied these corrections—typically a few hundredths of a pixel—to the centre location of each Gaussian fit.

We solved for the best-fit values of (x, y) via straightforward nonlinear least-squares fitting (Extended Data Tables 1, 2; Table 1 Source Data). We estimated the uncertainties by linearizing the model around the best-fit solution and then solving for the covariance matrix. This procedure generally provided a reliable estimate of the uncertainties—typically, a few tenths of a pixel. However, some error-bar estimates were clearly too small; this created difficulties when fitting orbits because the measurements, although extremely accurate, produced anomalously large residuals in units of the standard deviation, σ. We solved this problem by setting 0.1 pixels as the absolute floor for σ.

Orbit models. We describe the orbit of each moon using nine orbital elements (Table 1). However, we reduce the number of free parameters to six by using Neptune’s known gravity field to derive the values of the semimajor axis (a), the apsidal precession rate (ω) and the nodal regression rate (Ω) from the extended data tables (Tables 1, 2). The relationship that we use is accurate to second order in (e, i).

$$L_1 = 3.408 \times 10^{-6} \text{ and } L_2 = -33.40 \times 10^{-6}$$

Assuming Neptune’s radius to be 25,225 km. Our reference epoch is midnight 2009 January 1 UTC, chosen because
it falls near the mid-time of all our observations. In barycentric dynamical time (TDB), this is 284,040,066.184 after the J2000 epoch (2000 January 1.5 TDB).

Triton’s orbital inclination is 157.4°, which means that it is both retrograde and tilted away from Neptune’s equator by 22.6°. Its nodal regression period is about 600 years. Over that interval, the pole of Triton’s orbit sweeps out a cone with a half-width of 22.2° while Neptune’s rotation pole sweeps out a cone of 0.3°. This polar wander is rapid enough that it must be accounted for when describing the orbits of the inner moons. Furthermore, Triton tilts the Laplace planes of the moons from Neptune’s equator and towards its own orbital plane. We follow methods described elsewhere 7 to determine the tilt of each moon’s Laplace plane (Table 1).

For Triton’s orbit we describe the shape and orientation using prograde angles but reverse the signs of α, γ, and Δ. Furthermore, we hold n, a, and Δ fixed in our analysis but use our own astrometry to define the remaining elements. We choose this approach because 1) our time baseline for Triton is short compared to that of previous studies 6, 2) these quantities describe the orientation of the Laplace plane, which affects all the remaining moons, but 3) because of vagaries in the definition of the longitude of reference (discussed below), we prefer to avoid depending entirely on published orbital elements. However, our results are compatible with previous results; see Extended Data Table 3.

Defining an appropriate reference longitude in the context of misaligned planes and precessing poles is challenging. Ideally, we seek an inertially fixed definition that is independent of epoch. Notably, previous studies on the orbits of Neptune’s inner moons adopted many different references, none of which meet these requirements. The common node of all the Laplace planes is a tempting reference point, but it is not well determined and, of course, it rotates every 600 years. For this investigation, all longitudes were measured from the ascending node of the Neptune system’s invariable plane on the International Celestial Reference Frame equator, which is a fixed direction in space. The pole of this plane has right ascension RA = 299.46° ± 0.14° and declination dec. = 43.40° ± 0.03°. The uncertainties are small; any future change in the best-fit invariable pole will merely introduce a small, constant offset to the orbital elements λ0, γ0, and Ω0. From this reference direction, all longitudes are measured as broken angles along the invariable plane to the common ascending node of all the Laplace planes, thence along each moon’s Laplace plane to its orbital ascending node, and thence along the orbit plane. Using this frame definition, we can update all published orbital elements to a common epoch (Extended Data Table 3). All orbits are in good agreement for Despina, Galatea, Larissa and Proteus. Naiad’s orbit agrees with the Voyager-era solution 7; if one increases its mean motion by 1σ, the 2004 solution 8 disagrees with this work because it includes an erroneous measurement. We also note that the orbit solutions for Thalassa appear to be diverging, although all solutions agree at the Voyager epoch.

Orbit fitting. We converted our astrometry from (x, y) coordinates to right ascension and declination using published distortion models for the HST cameras 15. In the case of Neptune, we filtered at a rate of 1 Hz and performed a box analysis showed persistent, large residuals. By experimentation, we determined that this was caused by a plate-scale error; a scale correction factor of 0.9987 made the problem go away.

The fitting process requires a simultaneous solution for the orbital elements of every moon, plus precise navigation of every image. As in previous analyses of HST images 16,17, we assumed that HST does a perfect job of tracking the position of Neptune within each HST orbit. Thus, one need not determine a unique pointing correction for every image; instead, images obtained through the same filter during the same HST orbit.

For Triton, orbit fits were solved for the orbital elements of all the moons while holding the navigations fixed. Second, we held the orbits fixed and solved for improved navigations. Repeating the process quickly led to convergence for both sets of parameters. Most navigations were precise; the median uncertainty was 0.01 pixels and the mean was 0.05 pixels. At each iteration, we used the best-fit determination of Triton’s descending node to define the Laplace planes for the other moons. After this process was completed, we held the navigations fixed while solving for the orbits of the smaller moons.

Not unexpectedly, this analysis revealed that a small number of our measurements were erroneous. This is related to the fact that astrometric errors do not obey a normal distribution; the distribution has an extended tail due to the small, but not negligible, fraction of the population beyond the 3σ level. The fitting process is a powerful tool for detecting these outliers. Investigating the distribution revealed that the break between the Gaussian behaviour and the extended tail occurred near 3σ. We therefore categorized each measurement with residuals below 3σ as valid and those with residuals >3σ as clearly invalid. Invalid measurements were rejected outright, whereas measurements between 3σ and 5σ were regarded as probably erroneous. Including them in the fit could bias our answers, but excluding them would artificially reduce our assessed uncertainties. Our solution was to exclude them from the fit, but then to apply an enhancement factor to the overall goodness of fit (GOF = χ² per DOF) following a procedure to compensate for the possible bias. This method involves a Monte Carlo simulation of what the enhancement factor would need to be if the distribution of the residuals were truly Gaussian-distributed and we omitted the 3σ outliers; details are discussed elsewhere 12.

Photometry. We obtained photometry from images taken through the filters CLEAR, F606W and F350LP, all having passbands comparable to a very wide V filter. We measured the ‘ensquared energy’ of Despina, Galatea, Larissa and Proteus by summing the pixel values inside square boxes centred on the known location of each moon. Each sum was corrected for an estimate of the mean local background by averaging the pixels in a surrounding border 1–3 pixels wide. However, each of these measurements undercounts the photons from a point source because the PSFs have extended tails. We determined the correction factor for each box size based on tabulations of the ensquared energy correction factor for UVIS 21 and adapted a table of encircled energy for HRC 22.

The optimal box size for a given moon depends on circumstances: smaller boxes provide lower precision because of small-number statistics and the large correction factor, whereas large boxes are more likely to be corrupted by background variations or bad pixels. To handle this in an automated manner, we calculated the sums for each moon in each image using up to 18 combinations of box size and border width. Each measurement was corrected for the PSF as described above, and then we derived a robust mean and the standard deviation from all the measurements of each moon acquired through the same filter during the same HST orbit.

For Naiad, Thalassa and Hippocamp, we used co-added images with distorted PSFs, so the above procedure was inappropriate. Instead, we obtained results simultaneously with our astrometry by recording the volume under the fitted Gaussian. To correct for the undercount, we performed the same analysis on the four larger moons and used that to derive a correction factor for each instrument, filter and box size. We then applied this factor, which was typically in the range 2–3, to each measurement.

We converted from raw-image values to the calibrated, disk-integrated reflectivity D as follows. The file header of every calibrated Hubble data product contains the parameter PHOTFLAM, the image’s ‘inverse sensitivity’ in units of erg cm−2 Å−1 s−1. PHOTFLAM, multiplied by the exposure time, converts the pixel values to intensity, I, in units of erg cm−2 Å−1 s−1. Reflectivity is the dimensionless ratio of I to F, where F is the incoming solar flux density. We calculated F by averaging the solar spectrum (as defined by the STScI data product ‘sun_reference_stis_001.fits’) over the throughput of each instrument and filter. The resulting value is what would be expected from an unperturbed astronomical unit, so we divided F by the square of the Sun–Neptune separation distance in astronomical units for the time of each visit. The resulting factor would be appropriate for determining the reflectivity of an extended source. For an unresolved point source, we also multiplied by the projected area of a pixel in units of square kilometres. The resulting quantity, multiplied by the sum of the pixel values within the PSF of a point source, is D. Individual values are listed in the Source Data for Table 1.

We normalized all measurements to compensate for the irregular shapes of the moons, modelling them as triaxial ellipsoids using published values for the three radii 11 (a, b, c). Owing to tidal locking, the long axis (a) points towards Neptune and the short axis (c) is normal to the orbit plane. The projected cross-section A of a moon depends on the sub-Earth longitude θ (measured from the long axis) and latitude φ as follows:

$$A = \pi \left( a \cos \theta \cos \phi + (a \sin \theta \cos \phi)^2 + (a \sin \phi)^2 \right)^{1/2}$$

Using this formula, we re-scaled all measurements to (θ, φ) = (90°, −27°), because our best photometry was obtained near this geometry. Shape corrections were typically less than 5%.

Extended Data Fig. 2 shows the phase curves for all of the inner moons. Measurements span phase angles α = 0.03°–1.92°. The moons all show a marked opposition effect, typically with a slope of 0.2 magnitudes per degree. We note that this surge is much steeper than the phase function slope measured from Voyager images 0.11 at α > 12°. The moons’ phase curves and colour properties warrant further study but that topic is beyond the scope of this paper.

Because we have many measurements in which α < 0.1, a linear fit to the data provided an accurate measure of each moon’s visual, disk-integrated photometry in pseudo phase (D in Table 1). The effective radius R is [D(α) / α] 1/2, where 11

$$\dot L = 0.09 \pm 0.01$$

Code availability. The Python 2.7 source code that implements all the key image processing steps is permanently archived at http://dmp.seti.org/mshowell/neptune_
xiv/software. For orbit fitting and image geometry calculations, we used widely used procedures for which many implementations exist; we have documented all of our procedures in detail but have not distributed our own custom source code.

Data availability
All source data used in this study are in the public domain and may be obtained from the STScI archive at http://archive.stsci.edu/hat/search.php. The Voyager images referenced in this paper can be retrieved from NASA’s Planetary Data System at https://pds-rings.seti.org/viewmaster/volumes/VGISS_8xxx/VGISS_8207. Data files for every image analysed in this investigation, at nearly every intermediate step in the analysis, are permanently archived at http://dmp.seti.org/mshowalter/neptune_xiv.

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Extended Data Fig. 1 | Recovery of Naiad. a, b. Portions of an HST image after processing and co-adding as described in the text. The location of Naiad in each panel is indicated by a small square; close-ups are shown in the upper-right insets. The outline of Neptune's disk is indicated by a blue ellipse. a, View from Visit 01, orbit 1 of HST programme GO-11656, obtained on 2009 August 19. The image shows the first unambiguous detection of Naiad since the 1989 Voyager flyby of Neptune. b, View from Visit 08, orbit 2 of programme GO-14217, taken on 2016 September 2.
Extended Data Fig. 2 | Phase curves of Neptune’s inner moons.

a–g, Measurements of disk-integrated reflectance $D = I/F$ versus phase angle for each of Neptune’s inner moons, obtained through broad visual filters. Error bars are $\pm 1\sigma$. Colours indicate the instrument, filter and observing mode, as defined in the legend. Solid lines are least-squares linear fits to the data; dotted lines indicate the range of the uncertainty in the model, $\pm 1\sigma$, as derived from the covariance matrix of each fit. The values in Table 1 correspond to the mean and uncertainty extrapolated to phase angle $\alpha = 0$. 
Extended Data Fig. 3 | Deep searches for small moons. 

**a**, **b**, Multiple HST images co-added into a ‘map’ in which longitude increases from 0° to 360° along the horizontal axis and radial position is 0–400,000 km along the vertical axis. **a**, View derived from the five HST orbits of programme GO-11656, obtained on 2009 August 19. **b**, View from the two orbits of Visit 03 in HST programme GO-14217, taken on 2016 September 2.
Extended Data Fig. 4 | Diagram of the Neptune system. All of the known features of the Neptune system interior to Triton are shown to scale. (Triton orbits about three times farther out than Proteus.) Rings and arcs are shown in green. Moon shapes are indicated by red ellipses indicating their dimensions $a \times c$, enlarged relative to their orbits by a factor of 20.
Extended Data Fig. 5 | Image processing steps. a, Image icwp01n7q_flt.fits, taken on 2016 August 31. b, The same image after hot pixels and cosmic-ray hits have been removed. c, The boolean mask, where white indicates pixels ignored in further analysis. d, The image after the mean of other images from the same HST visit have been averaged and subtracted. This step removes most of the glare. e, The image after an unsharp-masking process involving the subtraction of a median-filtered version of the same image. The outline of Neptune’s disk is indicated by a blue ellipse in each panel.
Extended Data Table 1 | Measurements of Hippocamp obtained in this study

| Target Image | Coadded Images | Integration (min) | Filter | Exposure Midtime | X | Y | ΔRA (arcsec) | Δdec (arcsec) | D (km²) | SNR |
|--------------|----------------|------------------|--------|-----------------|---|---|-------------|--------------|---------|-----|
| j95m01evqflt_h.fits | 3 | 5.8 | CLEAR | 2004-11-06T10:26:48 | 419.847 | 983.368 | -4.71005 | -0.52841 | 68.6 | 4.3 |
| j95m03fqlflt_h.fits | 8 | 29.6 | CLEAR | 2004-12-08T07:18:46 | 442.524 | 606.458 | 4.61184 | 1.11939 | 28.3 | 2.4 |
| j95m04o7qflt_h.fits | 8 | 29.6 | CLEAR | 2004-12-09T07:18:56 | 415.280 | 613.995 | 4.18700 | 1.76485 | 26.2 | 2.4 |
| j95m06c7qflt_h.fits | 10 | 7.5 | CLEAR | 2005-04-01T20:14:51 | 476.950 | 366.555 | -4.18766 | -1.90511 | 43.3 | 15.2 |
| j95m07zaqflt_h.fits | 10 | 7.5 | CLEAR | 2005-05-06T23:01:47 | 529.614 | 331.725 | -4.9666 | -1.49335 | 96.2 | 7.5 |
| j95m08s6qflt_h.fits | 10 | 7.5 | CLEAR | 2005-05-12T05:21:29 | 537.735 | 271.063 | 4.23993 | 2.00512 | 99.2 | 6.7 |
| j95m10dwqflt_h.fits | 10 | 7.5 | CLEAR | 2005-05-17T00:28:38 | 559.740 | 331.725 | -4.59666 | -1.49335 | 96.2 | 7.5 |
| ib2e01vqyqlc_h.fits | 8 | 36.7 | F606W | 2009-08-19T09:49:25 | 225.504 | 204.913 | 1.94315 | 2.89369 | 92.4 | 6.5 |
| ib2e02z5qlc_h.fits | 8 | 36.7 | F606W | 2009-08-19T14:37:13 | 159.100 | 213.065 | -3.66390 | 0.42630 | 98.6 | 8.0 |
| ib2e02zmqlc_h.fits | 8 | 36.7 | F606W | 2009-08-19T16:08:47 | 122.376 | 220.431 | -4.54516 | -0.79672 | 82.3 | 10.6 |
| icwp01n9qlc_h.fits | 6 | 17.5 | F350LP | 2016-08-31T09:54:26 | 386.764 | 257.339 | 3.94639 | 3.01685 | 137.0 | 12.1 |
| icwp02blqlc_h.fits | 5 | 14.6 | F350LP | 2016-09-02T08:11:09 | 370.531 | 210.993 | 3.53758 | 3.22970 | 91.9 | 6.7 |
| icwp02bqqlc_h.fits | 6 | 17.5 | F350LP | 2016-09-02T09:35:53 | 348.195 | 203.966 | 2.32684 | 3.28363 | 130.6 | 12.4 |
| icwp03dqqlc_h.fits | 5 | 14.6 | F350LP | 2016-09-02T17:37:15 | 130.693 | 259.309 | -4.33879 | -2.33913 | 109.3 | 13.2 |
| icwp03dqqlc_h.fits | 6 | 17.5 | F350LP | 2016-09-02T17:56:53 | 134.089 | 269.453 | -4.29093 | -2.54418 | 130.6 | 12.4 |
| icwp03djqlc_h.fits | 5 | 14.6 | F350LP | 2016-09-02T19:11:40 | 132.450 | 282.777 | -3.79933 | -3.11553 | 109.3 | 12.4 |
| icwp03dqqlc_h.fits | 6 | 17.5 | F350LP | 2016-09-02T19:31:18 | 140.841 | 292.191 | -3.59005 | -3.20677 | 83.0 | 8.3 |
| icwp03ijqlc_h.fits | 5 | 14.6 | F350LP | 2016-09-03T09:37:18 | 320.212 | 207.023 | 0.99358 | 2.94761 | 225.0 | 11.2 |

*Target Image* defines the geometry of each measurement after the images have been distorted and co-added. The column 'Coadded Images' lists the number of images coadded, followed by the range of two-letter codes that identify these images; all coadded files have the same name except that these codes replace the seventh and eighth characters. The locations (X, Y) are in absolute pixel coordinates, where (0, 0) refers to the centre of the lower left pixel in the image. ΔRA and Δdec are measured offsets from the centre of Neptune. Associated uncertainties (1σ) are given directly below each value. Uncertainties in the right ascension and declination are treated as equal. Disk-integrated photometry D is only listed for the first row of each HST orbit because it is derived from every image of that orbit, even when multiple astrometric measurements were obtained. ‘SNR’ shows the statistical significance of the detection.

1σ Target Image defines the geometry of each measurement after the images have been distorted and co-added. The column 'Coadded Images' lists the number of images coadded, followed by the range of two-letter codes that identify these images; all coadded files have the same name except that these codes replace the seventh and eighth characters. The locations (X, Y) are in absolute pixel coordinates, where (0, 0) refers to the centre of the lower left pixel in the image. ΔRA and Δdec are measured offsets from the centre of Neptune. Associated uncertainties (1σ) are given directly below each value. Uncertainties in the right ascension and declination are treated as equal. Disk-integrated photometry D is only listed for the first row of each HST orbit because it is derived from every image of that orbit, even when multiple astrometric measurements were obtained. ‘SNR’ shows the statistical significance of the detection.
## Extended Data Table 2 | Measurements of Naiad obtained in this study

| Target Image | Coadded Images | Integration (min) | Filter | Exposure Midtime | \(X\) | \(Y\) | \(\Delta RA\) (arcsec) | \(\Delta dec\) (arcsec) | \(D\) (km²) | SNR |
|--------------|----------------|------------------|--------|-----------------|------|------|------------------------|------------------------|----------------|-----|
| j95m03lfq_flc_n.fits | 3 | 11.1 | CLEAR | 2004-12-08T07:18:46 | 447.764 | 882.189 | -2.06041 | -0.61781 | 181.2 | 5.7 |
| id-if | \(\pm 0.223\) | 0.242 | 0.00651 | 0.00651 | 32.0 |
| ib2e01vvq_flc_n.fits | 4 | 18.3 | F606W | 2009-08-19T09:33:10 | 123.819 | 282.561 | -2.01216 | -0.03538 | 365.9 | 10.8 |
| vu-vx | \(\pm 0.199\) | 0.158 | 0.00736 | 0.00736 | 33.9 |
| ib2e01vzq_flc_n.fits | 4 | 18.3 | F606W | 2009-08-19T09:54:50 | 118.458 | 292.112 | -2.21316 | -0.40442 | 98.0 | 3.0 |
| vy-w1 | \(\pm 0.276\) | 0.266 | 0.01110 | 0.01110 | 32.0 |
| ib2e01ycq_flc_n.fits | 4 | 18.3 | F606W | 2009-08-19T12:41:10 | 211.801 | 289.305 | 1.51768 | -0.41238 | 256.5 | 4.1 |
| vy-ye | \(\pm 0.406\) | 0.405 | 0.01660 | 0.01660 | 62.8 |
| ib2e01ygq_flc_n.fits | 4 | 18.3 | F606W | 2009-08-19T13:02:50 | 223.523 | 278.360 | 1.97107 | 0.00364 | 98.0 | 3.0 |
| yf-y1 | \(\pm 0.263\) | 0.257 | 0.01065 | 0.01065 | 33.9 |
| ib2e02z2q_flc_n.fits | 4 | 18.3 | F606W | 2009-08-19T14:20:58 | 273.630 | 277.791 | 1.67568 | 1.11004 | 264.8 | 3.6 |
| z1-z4 | \(\pm 0.438\) | 0.438 | 0.01794 | 0.01794 | 73.2 |
| icwp02bkq_flc_n.fits | 2 | 5.8 | F350LP | 2016-09-02T08:07:20 | 205.526 | 248.834 | -1.93850 | -0.45324 | 529.6 | 7.8 |
| bj-bk | \(\pm 0.469\) | 0.459 | 0.01901 | 0.01901 | 67.9 |
| icwp02bmq_flc_n.fits | 3 | 8.8 | F350LP | 2016-09-02T08:14:58 | 202.733 | 251.872 | -1.99146 | -0.60242 | 336.8 | 4.7 |
| bl-bn | \(\pm 0.205\) | 0.206 | 0.00842 | 0.00842 | 67.9 |
| icwp02bpq_flc_n.fits | 3 | 8.8 | F350LP | 2016-09-02T09:32:04 | 215.269 | 287.926 | -1.19946 | -1.62137 | 568.8 | 7.2 |
| bo-bq | \(\pm 0.357\) | 0.365 | 0.01479 | 0.01479 | 79.3 |
| icwp02bsq_flc_n.fits | 3 | 8.8 | F350LP | 2016-09-02T09:43:31 | 222.884 | 289.936 | -0.88472 | -1.58766 | 168.7 | 2.9 |
| br-bt | \(\pm 0.301\) | 0.275 | 0.01181 | 0.01181 | 79.3 |
| icwp03diq_flc_n.fits | 2 | 5.8 | F350LP | 2016-09-02T19:07:51 | 312.340 | 257.061 | 2.03039 | 0.96539 | 449.3 | 12.8 |
| dh-di | \(\pm 0.307\) | 0.280 | 0.01204 | 0.01204 | 35.1 |
| icwp03dkq_flc_n.fits | 3 | 8.8 | F350LP | 2016-09-02T19:15:29 | 312.982 | 253.043 | 1.97173 | 1.1473 | 114.7 | 3.2 |
| dj-dl | \(\pm 0.300\) | 0.301 | 0.01232 | 0.01232 | 35.1 |
| icwp03dpq_flc_n.fits | 3 | 8.8 | F350LP | 2016-09-02T19:27:29 | 318.702 | 252.912 | 1.89372 | 1.30350 | 114.7 | 3.2 |
| do-dq | \(\pm 0.181\) | 0.164 | 0.00708 | 0.00708 | 35.1 |
| icwp03dsq_flc_n.fits | 3 | 8.8 | F350LP | 2016-09-02T19:38:56 | 317.252 | 248.502 | 1.75323 | 1.42909 | 114.7 | 3.2 |
| dr-dt | \(\pm 0.290\) | 0.279 | 0.01166 | 0.01166 | 35.1 |
| icwp04liq_flc_n.fits | 2 | 5.8 | F350LP | 2016-09-03T09:33:29 | 313.127 | 255.198 | 1.90079 | 1.25313 | 406.4 | 5.6 |
| ih-ii | \(\pm 0.161\) | 0.157 | 0.00652 | 0.00652 | 72.6 |
| icwp04ikq_flc_n.fits | 3 | 8.8 | F350LP | 2016-09-03T09:41:07 | 313.536 | 251.923 | 1.83671 | 1.36675 | 114.7 | 3.2 |
| ij-il | \(\pm 0.159\) | 0.162 | 0.00658 | 0.00658 | 35.1 |

*Target Image* defines the geometry of each measurement after the images have been distorted and co-added. The column ‘Coadded Images’ lists the number of images coadded, followed by the range of two-letter codes that identify these images; all coadded files have the same name except that these codes replace the seventh and eighth characters. The locations \((X, Y)\) are in absolute pixel coordinates, where \((0, 0)\) refers to the centre of the lower left pixel in the image. \(\Delta RA\) and \(\Delta dec\) are measured offsets from the centre of Neptune. Associated uncertainties (1σ) are given directly below each value. Uncertainties in the right ascension and declination are treated as equal. Disk-integrated photometry \(D\) is only listed for the first row of each HST orbit because it is derived from every image of that orbit, even when multiple astrometric measurements were obtained. ‘SNR’ shows the statistical significance of the detection.
Extended Data Table 3 | Comparison of projected mean longitudes at three epochs

| Orbit & Reference | Epoch         | Origin (°) | λ (°)     | n (°/day) | As Published | 1989-08-18.5 TDB | 2000-01-01.5 TDB | 2009-01-01.0 TDB | UTC λ (°) |
|-------------------|---------------|------------|-----------|-----------|--------------|-----------------|-----------------|----------------|-----------|
| Naiad             | O 1991 [6]    | 0.202      | 60.260    | 1222.844100 | 60.463        | 73.913          | 54.829          |
|                   | ± 0.042       | ± 0.013800 | ± 0.042   | ± 52.274   | ± 97.642      |
| JO 2004 [5]       | 1989-08-18.5 TDB | 352.424   | 68.103    | 1222.843579 | 60.528        | 72.005          | 51.207          |
|                   | ± 0.035       | ± 0.00804  | ± 0.035   | ± 3.046    | ± 5.689       |
| This work         | 2009-01-01.0 UTC | 156.354   | 1222.858303 | 61.493     | 128.746       | 156.354         |
|                   | ± 0.248       | ± 0.000133 | ± 0.977   | ± 0.504    | ± 0.248       |
| Thalassa          | O 1991 [6]    | 0.202      | 239.737   | 1115.755600 | 239.939       | 322.152         | 329.542         |
|                   | ± 0.028       | ± 0.010100 | ± 0.028   | ± 38.259   | ± 71.463      |
| JO 2004 [5]       | 1989-08-18.5 TDB | 352.424   | 247.581   | 1155.755977 | 240.005       | 283.646         | 32.306          |
|                   | ± 0.025       | ± 0.00236  | ± 0.025   | ± 0.894    | ± 1.670       |
| This work         | 2009-01-01.0 UTC | 50.874    | 1155.758516 | 240.608    | 293.867       | 50.874          |
|                   | ± 0.077       | ± 0.000033 | ± 0.248   | ± 0.134    | ± 0.077       |
| Despina           | O 1991 [6]    | 0.202      | 85.272    | 1075.734200 | 85.474        | 126.623         | 323.630         |
|                   | ± 0.014       | ± 0.002800 | ± 0.014   | ± 10.606   | ± 19.811      |
| JO 2004 [5]       | 1989-08-18.5 TDB | 352.424   | 93.113    | 1075.733061 | 85.538        | 122.373         | 315.635         |
|                   | ± 0.014       | ± 0.00031  | ± 0.014   | ± 0.118    | ± 0.220       |
| This work         | 2009-01-01.0 UTC | 315.642   | 1075.733079 | 85.420     | 122.322       | 315.642         |
|                   | ± 0.014       | ± 0.000011 | ± 0.081   | ± 0.040    | ± 0.014       |
| Galatea           | O 1991 [6]    | 0.200      | 46.644    | 839.659800  | 46.845        | 78.167          | 340.403         |
|                   | ± 0.011       | ± 0.002500 | ± 0.011   | ± 9.470    | ± 17.689      |
| JO 2004 [5]       | 1989-08-18.5 TDB | 352.424   | 54.488    | 839.661288  | 46.912        | 83.871          | 350.999         |
|                   | ± 0.010       | ± 0.000022 | ± 0.010   | ± 0.084    | ± 0.156       |
| This work         | 2009-01-01.0 UTC | 351.114   | 839.661311 | 46.865     | 83.911        | 351.114         |
|                   | ± 0.008       | ± 0.000005 | ± 0.035   | ± 0.018    | ± 0.008       |
| Larissa           | O 1991 [6]    | 0.197      | 184.828   | 649.053400  | 185.025       | 359.304         | 42.854          |
|                   | ± 0.009       | ± 0.001600 | ± 0.009   | ± 6.611    | ± 11.321      |
| JO 2004 [5]       | 1989-08-18.5 TDB | 352.424   | 192.665   | 649.054076  | 185.090       | 1.929           | 47.701          |
|                   | ± 0.008       | ± 0.000013 | ± 0.008   | ± 0.050    | ± 0.092       |
| This work         | 2009-01-01.0 UTC | 47.807    | 649.054085 | 185.133    | 2.066         | 47.807          |
|                   | ± 0.006       | ± 0.000004 | ± 0.026   | ± 0.013    | ± 0.006       |
| Proteus           | O 1991 [6]    | 0.136      | 213.669   | 320.765400  | 213.805       | 273.140         | 349.639         |
|                   | ± 0.007       | ± 0.000900 | ± 0.007   | ± 3.409    | ± 6.368       |
| JO 2004 [5]       | 1989-08-18.5 TDB | 352.424   | 221.446   | 320.765626  | 213.870       | 274.061         | 351.303         |
|                   | ± 0.006       | ± 0.000005 | ± 0.006   | ± 0.020    | ± 0.036       |
| J 2009 [4]        | 2000-01-01.5 TDB | -0.037    | 274.037   | 320.765625  | 213.814       | 274.000         | 351.236         |
| This work         | 2009-01-01.0 UTC | 351.307   | 320.765625 | 213.880    | 274.068       | 351.307         |
|                   | ± 0.002       | ± 0.000001 | ± 0.009   | ± 0.005    | ± 0.002       |

The mean longitude of each moon discovered by Voyager is projected to the epoch of each published solution in the three rightmost columns. All are referenced to zero longitude, as defined in Methods. ‘Origin’ indicates the location in the frame of the published reference longitude used for that orbit; it must be added to the published solution to match the frame defined herein. Quoted uncertainties are ±1σ.
Extended Data Table 4 | Candidate Voyager images of Hippocamp

| Image             | X (sample) | Y (line) | Inside? | Exposure Time (s) | Phase Angle (°) | Range (km) |
|-------------------|------------|----------|---------|-------------------|-----------------|------------|
| C1120426.IMG      | 996        | -120     | no      | 2.88              | 14.875          | 8,994,200  |
| C1121132.IMG      | 970        | 242      | no      | 61.44             | 14.382          | 8,772,700  |
| C1121139.IMG      | 955        | 255      | no      | 61.44             | 14.386          | 8,769,200  |
| C1121214.IMG      | 925        | 823      | no      | 61.44             | 14.412          | 8,751,400  |
| C1121221.IMG      | 906        | 835      | no      | 61.44             | 14.419          | 8,747,700  |
| C1121346.IMG      | 570        | 434      | yes     | 61.44             | 14.530          | 8,700,300  |
| C1121353.IMG      | 543        | 441      | yes     | 61.44             | 14.541          | 8,696,100  |
| C1121428.IMG      | 458        | 985      | no      | 61.44             | 14.603          | 8,674,400  |
| C1121435.IMG      | 428        | 990      | no      | 61.44             | 14.617          | 8,669,900  |
| C1121741.IMG      | 672        | 403      | yes     | 61.44             | 15.045          | 8,529,400  |
| C1121744.IMG      | 658        | 400      | yes     | 61.44             | 15.053          | 8,526,800  |
| C1121747.IMG      | 57         | 394      | yes     | 61.44             | 15.060          | 8,524,200  |
| C1121750.IMG      | 43         | 391      | yes     | 61.44             | 15.068          | 8,521,600  |
| C1121802.IMG      | 536        | 999      | no      | 61.44             | 15.098          | 8,510,900  |
| C1121805.IMG      | -27        | 992      | no      | 15.36             | 15.106          | 8,507,800  |
| C1121808.IMG      | -40        | 989      | no      | 15.36             | 15.114          | 8,505,100  |
| C1131016.IMG      | -176       | -94      | no      | 15.36             | 16.292          | 3,940,700  |
| C1133210.IMG      | 957        | 372      | no      | 3.84              | 15.039          | 2,981,700  |
| C1133624.IMG      | 813        | 101      | no      | 3.84              | 16.589          | 2,719,300  |
| C1133630.IMG      | 781        | 59       | yes     | 3.84              | 16.613          | 2,712,500  |

*X (sample)* and *Y (line)* are pixel coordinates, where (1, 1) refers to the middle of the upper left pixel and Y is measured downwards; this is the convention for the Voyager camera. Predicted coordinates do not account for the innate distortion or the pointing uncertainties of the Voyager images. *Inside?* is ‘yes’ if both of Hippocamp’s coordinates fall inside the range 1–800, which indicates that Hippocamp is more likely to fall inside the field of view.