

A SURVEY FOR “NORMAL” IRREGULAR SATELLITES AROUND NEPTUNE: LIMITS TO COMPLETENESS¹

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Received 2005 December 13; accepted 2006 March 28

ABSTRACT

We surveyed 1.75 deg² of sky near Neptune to an *R*-band 50% detection efficiency of 25.8 mag (corresponding to radii of about 17 km for an assumed albedo of 0.04). We discovered one new outer satellite, Psamathe (S/2003 N1), about 20 km in radius with a distant retrograde orbit and moderate eccentricity. Until 2003 Neptune was only known to have two satellites that exhibited orbital signatures indicative of capture. Both of these, Triton and Nereid, are unusual when compared to the irregular satellites of other giant planets. With recent discoveries of four additional satellites by Holman et al. it is now apparent that Neptune has a distant “normal” irregular satellite system in which the satellites have radii and orbital properties similar to those of the satellites of other giant planets. We find that the satellite size distribution at Neptune is not well determined given the few objects known to date, being especially sensitive to the inclusion of Triton and Nereid in the sample. Finally, we note that Psamathe and S/2002 N4 have similar semimajor axes, inclinations, and eccentricities. They may be fragments of a once-larger satellite.

Key words: planets and satellites: general — solar system: general

1. INTRODUCTION

The irregular satellites of the giant planets have moderate-to-high orbital eccentricities and inclinations with distant prograde or retrograde orbits. Because of their extreme orbits they are believed to have been captured (Kuiper 1956). This is unlike the regular satellites, which are close to their respective planets with circular, low-inclination, prograde orbits that probably formed within circumplanetary disks of gas and dust as part of the planet formation process.

Energy must be dissipated for initially unbound satellites to become captured by a planet (Everhart 1973). With no energy dissipation, a temporarily captured satellite will either be ejected from the system or impact the planet within a few centuries (the best recent example of this was provided by D/Shoemaker-Levy 9). Three possible capture mechanisms have been discussed, but none operate efficiently in the modern solar system: (1) drag due to gas around the forming planet (Pollack et al. 1979; McKinnon & Leith 1995), (2) pull-down capture as the planet’s mass grows (Heppenheimer & Porco 1977), and (3) collisional or gravitational interactions between asteroids and/or satellites moving within the planet’s Hill sphere (Colombo & Franklin 1971; Tsui 2000; Astakhov et al. 2003; Agnor & Hamilton 2004).

The irregular satellite systems of Jupiter, Saturn, and Uranus show remarkable similarities in their populations, size distributions, and orbital properties (Sheppard & Jewitt 2003; Sheppard et al. 2005; Jewitt & Sheppard 2005). These similarities are hard to understand in view of the vast differences between the formation of the gas and ice giant planets. Gas giants Jupiter and Saturn most

likely formed by core accretion (Pollack et al. 1996) or disk instabilities (Boss 2001). Ice giants Uranus and Neptune have about 10 times less mass, are deficient in H and He compared to the gas giants, and must have formed differently from the gas giants (e.g., Lissauer et al. 1995; Thommes et al. 2002; Boss 2003). Gas drag is unlikely to have been effective at Uranus and Neptune because these planets have little gas. Pull-down capture likewise is unlikely because the ice giants had no runaway growth in mass caused by hydrodynamic inflow of nebular H and He. Instead, the preferred capture mechanism is through collisional or gravitational interactions between small bodies within the Hill spheres of the planets. Such three-body interactions are independent of the planet formation scenario and mass and could have operated around both gas and ice giants (Jewitt & Sheppard 2005).

Neptune’s satellite system is unusual compared to those of the other giant planets because it has no massive regular satellites. The current regular satellites of Neptune are less than 5 Neptune radii away from the planet, and the largest (Proteus) is only about 200 km in radius, almost an order of magnitude smaller than the largest regular satellites of the other giant planets. A possible reason is that the very massive retrograde satellite Triton, probably a captured Kuiper Belt object, ejected any regular satellites that were beyond about 5 Neptune radii (Goldreich et al. 1989). In fact, even the regular satellites currently observed may have been disrupted by Triton in the past, and what we observe today may be the reaccumulation of those fractured bodies (Banfield & Murray 1992). In addition, Triton may have scattered Nereid into its highly eccentric orbit. Because of Nereid’s small semimajor axis and low inclination compared to other irregular satellites, it is suspected to have once been a regular satellite of Neptune (Goldreich et al. 1989).

Because of Neptune’s extreme distance (Fig. 1) it has the least well characterized outer irregular satellite system. We wish to

¹ Based largely on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

² The observations for this work were acquired while the author was at the Institute for Astronomy at the University of Hawaii.

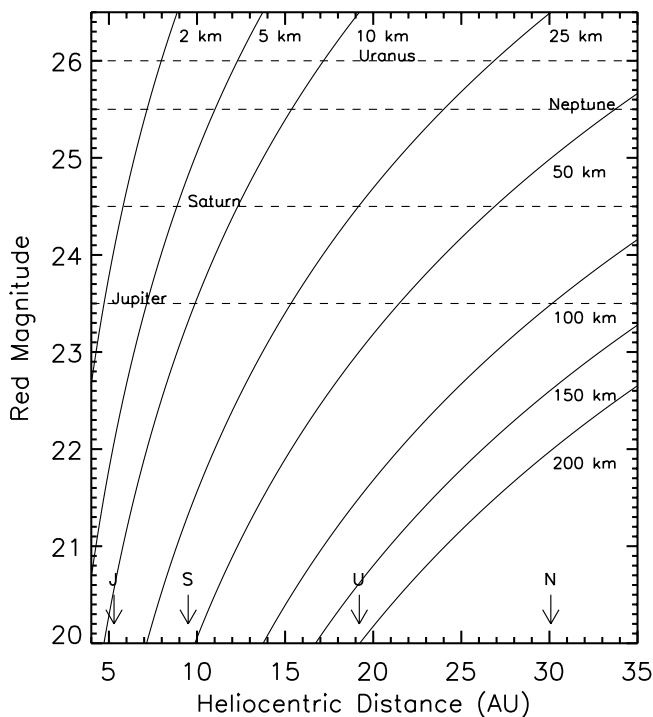


FIG. 1.—Distances of the planets vs. the observable small-body population diameter (solid lines) for a given red magnitude, assuming an albedo of 0.04. Dashed lines show the approximate survey magnitude completeness limits for satellites of each planet to date. Although Jupiter satellite surveys are the shallowest of the four planets, they have been the most sensitive to small satellites because of Jupiter’s closer proximity to Earth.

determine whether the ice giant Neptune has a population of small outer irregular satellites similar to those of gas giants Jupiter and Saturn and fellow ice giant Uranus. Until recently, Neptune was not known to have any of what we call “normal” outer irregular satellites. Only the “unusual” Nereid was known and has a relatively close-in, very eccentric, low-inclination orbit. Nereid also happens to be the largest known outer satellite of any planet. Holman et al. (2004) recently surveyed 1.4 deg² around Neptune to a 50% detection efficiency of $m_R \sim 25.5$ and announced four small outer irregular satellites of Neptune: S/2002 N1–N4 (Holman et al. 2003a, 2003b). Here we discuss an independent survey to slightly fainter magnitudes and covering a slightly larger area.

2. OBSERVATIONS AND ANALYSIS

We surveyed the space around Neptune when it was near opposition. The geometry of Neptune in the survey is shown in Table 1. The observations were obtained near new Moon on UT 2003 August 29 and 30 using the Suprime-Cam camera on the Subaru 8.2 m diameter telescope atop Mauna Kea. The Suprime-Cam imager uses 10 MIT Lincoln Laboratory 2048 × 4096 CCDs arranged in a 5 × 2 pattern (Miyazaki et al. 2002) with 15 μm pixels that give a scale of 0″20 pixel⁻¹. The field of view is about 34′ × 27′ with the north-south direction along the long axis. Gaps between the chips are about 16″ in the north-south direction and only 3″ in the east-west direction.

The images were obtained through a Kron-Cousins *R*-band filter with the telescope autoguided sidereally. Image reduction was performed by first bias-subtracting and then flat-fielding with twilight flats. Seeing during the two nights varied from 0″45 to 0″7 FWHM. Objects at Neptune’s distance trailed about 0″45 during the 500 s exposures. Landolt (1992) standards were used for calibration on both photometric nights.

TABLE 1
GEOMETRIC CIRCUMSTANCES OF NEPTUNE

UT Date	<i>R</i> (AU)	Δ (AU)	α (deg)	R.A. (arcsec hr ⁻¹)	Decl. (arcsec hr ⁻¹)
2003 Aug 29	30.078	29.156	0.79	−3.5	−1.0
2003 Aug 30	30.078	29.163	0.82	−3.5	−1.0

The region where planetary satellites may be stable is known as the Hill sphere, where the radius, r_H , depends on the planet’s mass and distance from the Sun as

$$r_H = a_p \left(\frac{m_p}{3 M_\odot} \right)^{1/3}, \quad (1)$$

where a_p and m_p are the orbital semimajor axis and mass of the planet, respectively, and M_\odot is the mass of the Sun. Table 2 shows the Hill radii for the outer planets.

The area of the Hill sphere searched for satellites is shown in Figure 2. Seven fields were imaged three times each on one night and two times each on the second night for a total of five images per field, or 35 images for the survey. The second night’s fields were at the same angular distance from Neptune as those from the first night, but the background star fields were slightly different because of Neptune’s movement between the two nights. Images of each field were spaced by about 33 minutes on a given night. Approximately 1.75 deg² around Neptune were observed, not accounting for chip gaps and bright stars. The image of Neptune was positioned in a gap between the CCD chips to prevent saturation of the detectors.

We searched for Neptune satellites in two complementary ways. A computer algorithm was used to detect objects that appeared in all three images from one night and had a motion consistent with being beyond the orbit of Jupiter (motion of 18″–1″ hr⁻¹). Second, all fields were searched a second time by displaying them on a computer screen and visually blinking them for any slow-moving objects. The limiting magnitude of the survey was determined by placing artificial objects in the fields matched to the point-spread function of the images with motions mimicking that of Neptune ($\sim 3″5$ hr⁻¹). Results are shown in Figure 3 for both the visual blinking and computer algorithm. The visual blinking was slightly more efficient, with a 50% detection efficiency at an *R*-band limiting magnitude of about 25.8 mag, which we take as the limiting magnitude of this survey.

There was virtually no scattered light beyond about 45″ from Neptune. Scattered light did not significantly affect our detection efficiency until about 20″ from Neptune, at which point the background was only 30% higher than the nominal sky background. The region within $\sim 10″$ of Neptune fell in a chip gap and was unobservable.

3. RESULTS AND DISCUSSION

Through this survey we discovered one new Neptune satellite, Psamathe (S/2003 N1), which was reported in Sheppard et al. (2003). Holman et al. (2004) detected Psamathe on only one night in their 2001 survey but did not originally obtain a second night; thus, they were unable to confirm this object as a satellite of Neptune. We also recovered, without prior knowledge of their locations, S/2002 N1, S/2002 N2, and S/2002 N3, as well as Nereid. The only other known outer satellite of Neptune, S/2002 N4, was not in our fields. All five new outer satellites of Neptune now have well-determined orbits as a result of observations of

TABLE 2
OUTER IRREGULAR SATELLITES OF THE PLANETS

Planet	Irregulars ^a	<i>R</i> -Magnitude Limit ^b (mag)	<i>r</i> _{min} Limit ^c (km)	Hill Radius ^d (deg)	Hill Radius (10 ⁷ km)
Mars ^e	0	23.5	0.1	0.7	0.1
Jupiter.....	55	23.5	1	4.7	5.1
Saturn	26	24.5	3	3.0	6.9
Uranus	9	26	7	1.4	7.3
Neptune ^f	5 (7)	25.5	20	1.5	11.6

^a Number of known outer irregular satellites as of 2005 December 1.
^b Approximate limiting magnitude in the *R* band of completeness for the respective planet’s outer satellites.
^c Approximate limiting radii of satellite searches to date.
^d The apparent angular Hill sphere radius of the planet at opposition.
^e Mars’s two inner satellites may have been captured in a way similar to that for the outer irregular satellites of the giant planets.
^f Neptune only has five “normal” irregular satellites if the “unusual” Triton and Nereid are not included.

each taken over several years by Holman et al. (2004) and our group.

We relate the apparent red magnitude of an object, *m_R*, to its radius, *r*, through

$$r = \left[\frac{2.25 \times 10^{16} R^2 \Delta^2}{p_R \phi(\alpha)} \right]^{1/2} 10^{0.2(m_\odot - m_R)}, \quad (2)$$

where *r* is in kilometers, *R* is the heliocentric distance in AU, Δ is the geocentric distance in AU, *m_⊙* is the apparent red magnitude of the Sun (−27.1), *p_R* is the red geometric albedo, and $\phi(\alpha)$ is the phase function, where the phase angle $\alpha = 0^\circ$ at opposition. We assume $\phi(\alpha) = 10^{-0.4\beta\alpha}$, where β is the “linear” phase coefficient. Using equation (2), data from Table 1, and an albedo of 0.04 we find that our 50% detection limit at 25.8 mag corresponds to a satellite with a radius of $17(0.04/p_R)^{1/2}$ km.

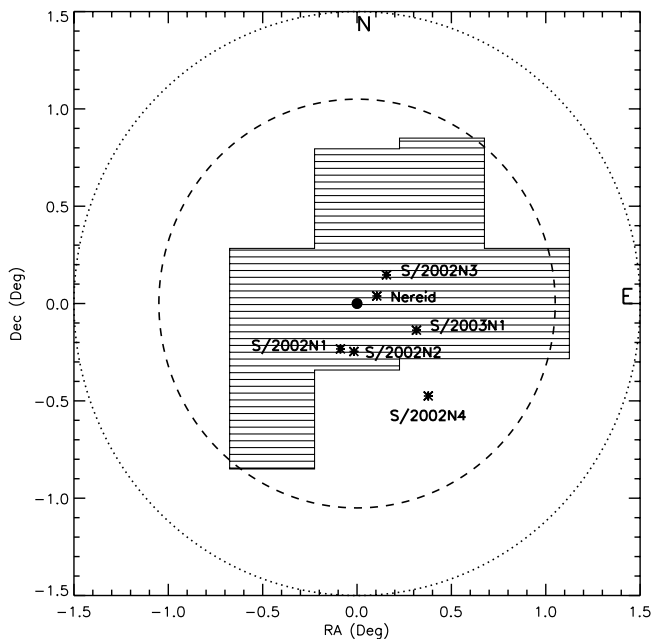


FIG. 2.—Survey area around Neptune searched for satellites using the Suprime-Cam on the 8.2 m Subaru Telescope. The black dot at the center represents Neptune’s position. Stars represent the positions at the time of observations of the outer satellites of Neptune. The dotted circle shows the projected Hill sphere of Neptune, while the dashed circle shows the theoretical outer limits of stability for Neptune satellites (at $0.7r_H$).

The radius of Psamathe is about 20 km if we assume an albedo of 0.04. Psamathe is in a retrograde orbit with an inclination of 137° with respect to the ecliptic and an eccentricity of 0.45. The semimajor axis of Psamathe is about 46×10^6 km, which corresponds to $0.4r_H$. The relatively large eccentricity allows Psamathe to reach almost $0.6r_H$ from Neptune (Fig. 4), near the theoretical stable limit of $0.7r_H$ for retrograde satellites (Hamilton & Krivov 1997).

We list the properties of all the known outer satellites of Neptune in Table 3. Figures 5 and 6 compare the semimajor axes with inclinations and eccentricities, respectively, of the irregular satellites of all the planets. Nereid and Triton stand out in these figures, leading us to label them as “unusual” irregular satellites. Nereid is quite large relative to other irregular satellites and has the lowest inclination, as well as one of the smallest semimajor axes and largest eccentricities, compared to the rest of the known outer irregular satellites of the giant planets. Triton is almost an order of magnitude larger and has a semimajor axis more than an order of magnitude smaller than those of other irregular

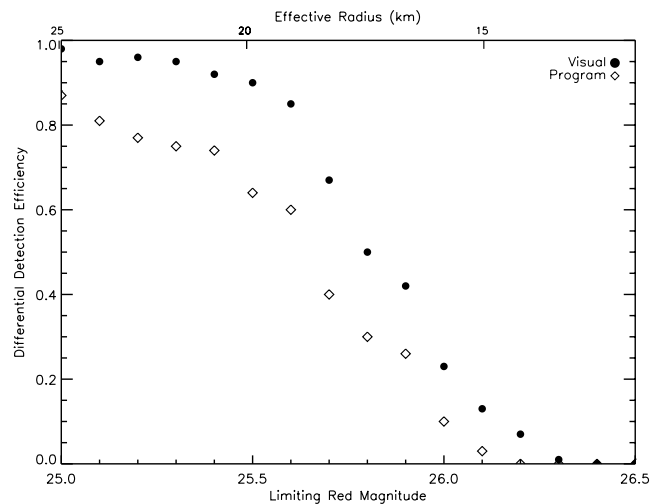


FIG. 3.—Detection efficiency of the Neptune survey vs. the apparent red magnitude. The 50% detection efficiency is at about 25.8 mag as determined from visual blinking and 25.7 mag as determined from a computer program. All fields were searched with both techniques. The efficiency was determined by placing artificial objects matched to the point-spread function of the images with motions similar to Neptune in the survey fields. Effective radii of the apparent magnitude were calculated assuming the object has an albedo of 0.04. The efficiency does not account for objects that are undetected because of the chip gaps. Scattered light was not a significant problem in the survey.

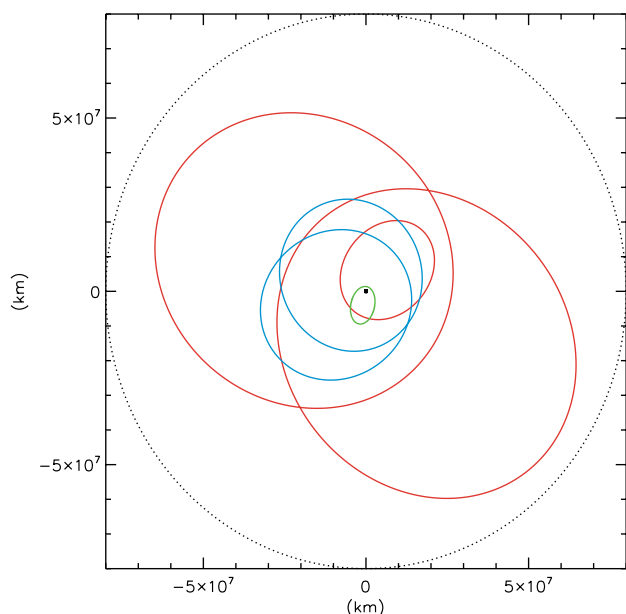


FIG. 4.—Plan view of Neptune’s satellite orbits. The three small outer retrograde irregular orbits are shown in red, and the two small outer prograde irregular orbits are shown in blue. Nereid’s orbit is shown in green. Triton’s orbit is barely visible on this scale and is represented by the black dot at the center. The dotted circle shows the theoretical outer limit of stability for Neptune satellites at $0.7r_H$. The orbits are projected into the ecliptic, centered on Neptune with axes in kilometers with 0° longitude on the left side of the x -axis.

satellites, and it has a circular orbit, likely significantly modified by tidal interactions with Neptune (Goldreich et al. 1989; Chyba et al. 1989).

The Neptune satellites discovered by Holman et al. (2004) and in this work are “normal” irregular satellites, as judged by their large semimajor axes and orbital eccentricities and inclinations. The Neptune irregular satellites Psamathe (S/2003 N1) and S/2002 N4 have similar large semimajor axes, inclinations, and eccentric-

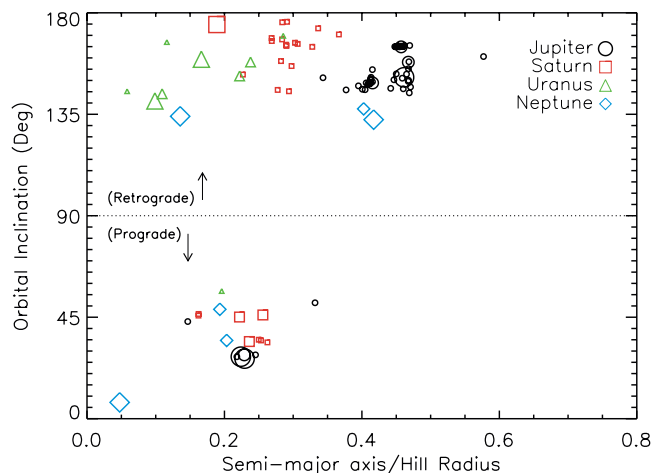


FIG. 5.—Inclination comparison of the currently known 97 irregular satellites of the giant planets. The horizontal axis is the fraction of the satellite’s mean semimajor axis compared to its respective planet’s Hill radius. The vertical axis is the mean inclination of the satellite to the ecliptic. The size of the symbols represents the radius of the object: large symbol, $r > 25$ km; medium symbol, $25 \text{ km} > r > 10$ km; and small symbol, $r < 10$ km. All giant planets independent of their mass or formation scenario appear to have similar irregular satellite systems. The “unusual” irregular Nereid is seen in the lower left. Triton has been omitted, since its inclination is only defined with respect to Neptune’s equator, since tidal evolution has probably modified its inclination. The new irregular satellites discovered in the past few years around Neptune, including Psamathe (S/2003 N1), are similar to the other known irregular satellites of the giant planets. All regular satellites would fall near the origin of this plot.

ities and thus may be daughter satellites of a once-larger parent, as also mentioned by Holman et al. (2004), but further refinement of the orbits is needed before anything definitive can be said. Further discoveries may reveal more small satellites that share similar semimajor axes and inclinations as part of a dynamical family like those observed at Jupiter (Sheppard & Jewitt 2003). Families have also been reported at Saturn (Gladman et al. 2001), but these appear significant only in inclination space,

TABLE 3
PHYSICAL AND ORBITAL PROPERTIES OF NEPTUNE’S IRREGULAR SATELLITES

Name	a^a (10^3 km)	i^b (deg)	e^c	Periapsis ^d (deg)	Node ^e (deg)	M^f (deg)	Period ^g (days)	Magnitude ^h (m_R)	r^i (km)
I Triton ^j	355	157	0.00	344.0	172.4	264.8	5.88	13.0	1353
II Nereid ^k	5513	7.2	0.75	280.8	334.8	359.3	360.1	19.2	170
S/2002 N1.....	15728	134	0.57	159.7	203.0	96.4	1879.7	24.5	31
S/2002 N2.....	22422	48	0.29	79.3	55.5	207.1	2914.1	25.5	22
S/2002 N3.....	23571	35	0.42	142.4	60.7	328.6	3167.9	25.5	21
S/2003 N1.....	46695	137	0.45	145.9	301.0	206.2	9115.9	25.5	20
S/2002 N4.....	48387	133	0.49	89.3	50.0	269.8	9374.0	24.6	30

NOTE.—Orbital data are from R. Jacobson at JPL (http://ssd.jpl.nasa.gov/?sat_elem); fits are over a 1000 yr time span. Epochs are 2003 June 10 TT for the Neptune satellites discovered in 2002 and 2003 and 1989 August 25 TT for Triton and Nereid.

^a Mean semimajor axis with respect to Neptune.

^b Mean inclination of orbit with respect to the ecliptic.

^c Mean eccentricity.

^d The argument of periapsis.

^e The longitude of the ascending node.

^f The mean anomaly.

^g Orbital period of the satellite around Neptune.

^h Apparent red ($0.65 \mu\text{m}$ wavelength) magnitude. Uncertainties are around 0.2 mag.

ⁱ Radius of the satellite assuming a geometric albedo of 0.04.

^j Triton is an “unusual” retrograde satellite and not classified as an irregular satellite under the definition of Burns (1986). Triton likely has had significant modification of its orbit from tidal interactions with Neptune (Goldreich et al. 1989; Chyba et al. 1989). Triton’s mean inclination as shown here is with respect to Neptune’s equator.

^k Nereid is an “unusual” irregular satellite because of its relatively low inclination, small semimajor axis, and large eccentricity. It may be a perturbed regular satellite.

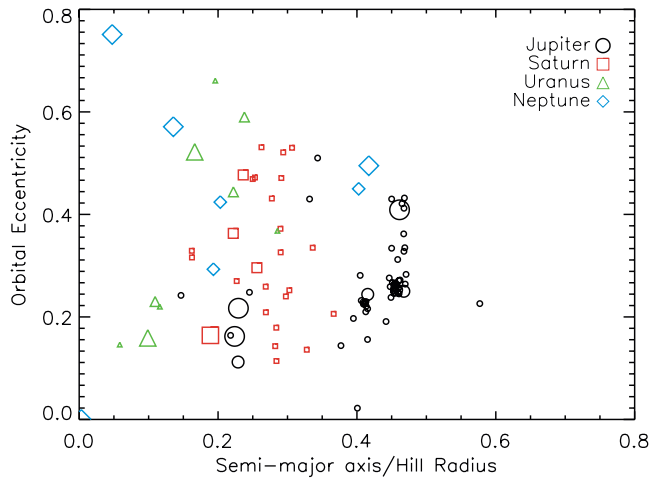


FIG. 6.—Same as Fig. 5, but with eccentricity plotted on the vertical axis. Both Triton and Nereid stand out in this plot. Nereid is in the upper left, while Triton is located at the origin of the plot. The five newly discovered outer satellites of Neptune are very similar to the known irregulars around the other giant planets. All regular satellites would fall near the origin of this plot.

unlike the satellites of Jupiter, which are grouped in *both* inclination and semimajor axis. No other obvious groupings are apparent. The inclination region $60^\circ < i < 140^\circ$ is void of known satellites consistent with the action of the Kozai instability (Kozai 1962; Carruba et al. 2002; Nesvorný et al. 2003).

3.1. Size Distribution

We represent the cumulative luminosity function (CLF), which describes the sky-plane number density of objects brighter than a given magnitude, by

$$\log [\Sigma(m_R)] = \alpha(m_R - m_o), \quad (3)$$

where $\Sigma(m_R)$ is the number of objects per unit area brighter than m_R , m_o is the magnitude zero point, and 10^α describes the slope of the luminosity function. Figure 7 shows the CLF using all

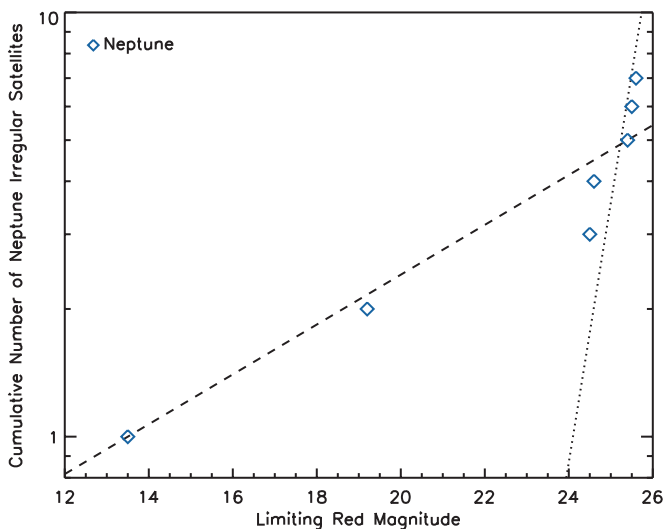


FIG. 7.—CLF for satellites of Neptune with orbits indicative of capture. The dashed line shows the best fit of the CLF using all seven satellites ($\alpha \sim 0.06$). The dotted line shows the best fit using only the five small outer irregular satellites with $r < 100$ km ($\alpha \sim 0.6$). Further data are needed, since the CLF is very sensitive to the few bright objects.

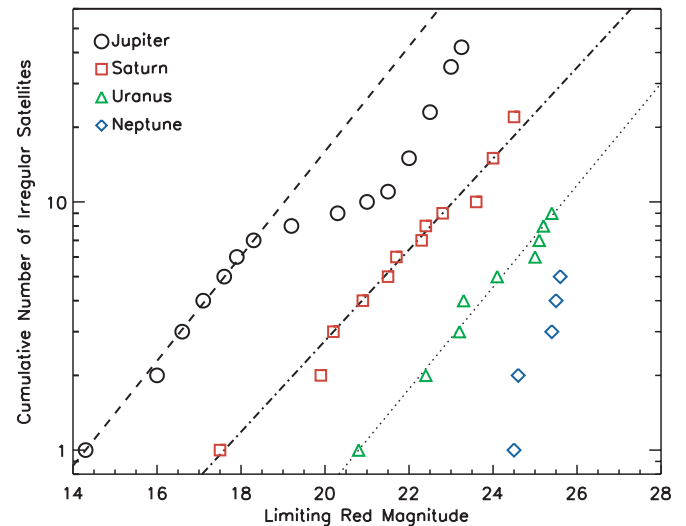


FIG. 8.—CLF for the outer irregular satellites with $r < 100$ km around Jupiter, Saturn, Uranus, and Neptune. For clarity and in order to compare similar-sized outer irregular satellites, we have omitted Neptune’s Triton and Nereid, which are plotted in Fig. 7. The slopes for irregular satellites with $100 \text{ km} > r > 10 \text{ km}$ are plotted for Jupiter, Saturn, and Uranus. They are all shallow and very similar ($\alpha \sim 0.20$), but because of the different distances the farther planets’ CLFs are shifted to the right. Neptune’s irregulars with $r < 100$ km appear to have a steeper slope, but if Nereid ($r \sim 170$ km) and/or Triton ($r \sim 1350$ km) are added the slope becomes much shallower. See the text for details.

seven known Neptune satellites that have orbits indicative of capture. We believe that the outer satellites of Neptune are complete to near 25.5 mag ($r > 20$ km) through our survey, the Holman et al. (2004) survey, and additional null-result surveys (Gladman et al. 2000). See Table 2 for the expected completeness limits for the outer irregular satellites of the planets.

Including all seven satellites around Neptune that have orbits indicative of capture, we find $\alpha \sim 0.06$, but this result is not significant in the sense that it is extremely sensitive to the inclusion of the “unusual” irregulars Triton and Nereid. We directly compare similarly sized irregular satellites ($r < 100$ km) of all the giant planets in Figure 8. Neptune’s irregular satellites with $10 \text{ km} < r < 100$ km (which excludes Triton and Nereid) show $\alpha = 0.6 \pm 0.1$ and $m_o = 24.5 \pm 0.4$, while including Nereid gives $\alpha \sim 0.1$. The sensitivity of the slope to the inclusion or exclusion of Nereid shows that further discoveries are needed in order to obtain a reliable CLF for Neptune’s outer irregular satellites. To date, the results are broadly consistent with the $\alpha \sim 0.2$ found for the irregular satellites with $10 \text{ km} < r < 100$ km around the other giant planets Jupiter, Saturn, and Uranus (Sheppard & Jewitt 2003; Kavelaars et al. 2004; Sheppard et al. 2005).

We model the irregular satellite size distribution through a differential power-law radius distribution of the form $n(r)dr = \Gamma r^{-q}dr$, where Γ and q are constants, r is the radius of the satellite, and $n(r)dr$ is the number of satellites with radii in the range r to $r + dr$. The slope of the CLF (α) and exponent of the size distribution (q) are simply related by $q = 5\alpha + 1$ when assuming similar heliocentric distance and albedos for all satellites. We show the size distribution of outer irregular satellites with $r < 100$ km in Figure 9. Using $\alpha = 0.6$ for Neptune’s outer satellites with $r < 100$ km we find $q \sim 4$, but if we include Nereid and/or Triton, in which $\alpha \sim 0.06$, we find $q \sim 1.3$. Because of the large sensitivity on Nereid, these results are still consistent with the shallow $q \sim 2$ found for the irregular satellites with $10 \text{ km} < r < 100$ km of Jupiter, Saturn, and Uranus (Sheppard

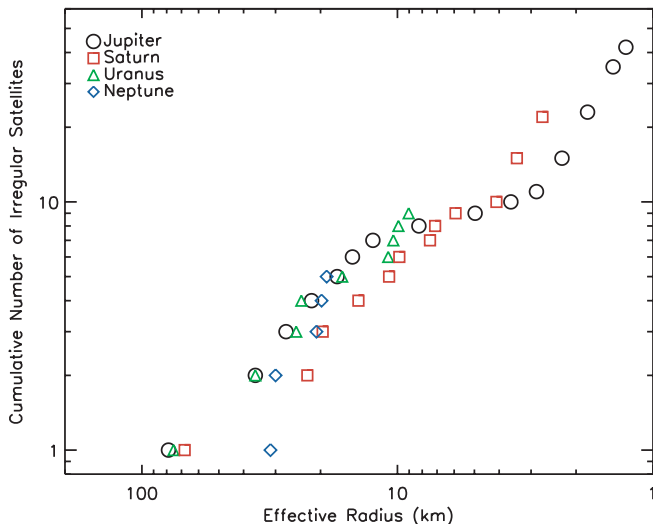


FIG. 9.—Cumulative radius function for the irregular satellites with $r < 100$ km of Jupiter, Saturn, Uranus, and Neptune. This figure directly compares the sizes of the satellites of all the giant planets, assuming all satellite populations have albedos of about 0.04. Jupiter, Saturn, and Uranus all have shallow irregular satellite size distributions of $q \sim 2$ for satellites with $100\text{ km} > r > 10\text{ km}$. Neptune's limited number of known small outer irregular satellites with $100\text{ km} > r > 10\text{ km}$ show a steeper size distribution of $q \sim 4$, but if Nereid and/or Triton are included we find a much shallower size distribution of $q \sim 1.3$. Both Jupiter and Saturn appear to show a steeper size distribution for irregular satellites with $r < 5\text{ km}$, which may be a sign of collisional processing. To date, neither Uranus's nor Neptune's Hill spheres have been surveyed to these smaller sizes. Further discoveries of irregular satellites around Neptune are needed to obtain a reliable size distribution.

& Jewitt 2003; Kavelaars et al. 2004; Sheppard et al. 2005). Jupiter's smallest satellites ($r < 5\text{ km}$) follow a steeper power law of $q \sim 3.5$, while Saturn's small irregulars also show a steepening in the size distribution for $r < 5\text{ km}$. Uranus's known irregulars do not yet extend down to these small sizes (see Table 2). These “bumps” in the size distribution are probably caused by the collisional evolution of the irregular satellites and may be similar to what has been observed in the main belt of asteroids (Davis et al. 2002; Bottke et al. 2005). The large ($r > 50\text{ km}$) Kuiper Belt objects and Centaurs both have similar size distributions of $q \sim 4$ (Trujillo et al. 2001; Sheppard et al. 2000),

while the smaller Kuiper Belt objects may have a shallower slope (Bernstein et al. 2004). Smaller Neptune satellites probably await discovery and will allow us to determine whether the steep size distribution power law continues to these smaller objects. If the slope is significantly different than that found for the other giant planets, it may be a disruption signature from the capture of Triton and the scattering of Nereid from the regular satellite population.

4. SUMMARY

1. We have conducted an ultradeep survey of 1.75 deg^2 around Neptune reaching 50% detection efficiency at a red limiting magnitude of 25.8 mag. This corresponds to objects with $r > 17\text{ km}$ (for an assumed albedo of 0.04).

2. We discovered one new satellite, Psamathe (S/2003 N1), and detected four of five previously known small irregular satellites in our survey. Psamathe is about 20 km in radius (assuming an albedo of 0.04) and has a distant, eccentric retrograde orbit similar to those of other irregular satellites thought to have been acquired by capture.

3. Neptune has a distant irregular satellite population with sizes and orbital properties like those of the irregular satellites found around Jupiter, Saturn, and Uranus.

4. The size distribution of Neptune's irregular satellites is poorly determined by the existing data. Larger samples of the small outer irregular satellites of Neptune are needed to determine the size distribution with more confidence. Shallow power-law size distributions have been found for the irregular satellites with $100\text{ km} > r > 10\text{ km}$ around Jupiter, Saturn, and Uranus ($q \sim 2$), while steeper power laws ($q \sim 3.5$) appear for satellites with $r < 5\text{ km}$, which may be a sign of collisional evolution.

We thank Brian Marsden and Bob Jacobson for orbit determinations of the satellites. This work was partially supported by a NASA grant to D. J. Additional support for this work was provided by NASA through Hubble Fellowship grant HF-01178.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555.

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