A Survey for “Normal” Irregular Satellites Around Neptune: Limits to Completeness

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ABSTRACT

We surveyed 1.75 square degrees of sky near Neptune to an R-band 50% detection efficiency of 25.8 mags (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 and having a distant retrograde orbit and moderate eccentricity. Until 2003 Neptune was only known to have two satellites which 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. (2004) 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 semi-major axes, inclinations and eccentricities. They may be fragments of a once larger satellite.

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

2The observations for this work were acquired while the author was at the Institute for Astronomy at the University of Hawaii.
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, Burns & Tauber 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, Jewitt and Kleyna 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 ten 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 1995; Thommes et al. 2002; Boss 2002). 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 which 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 is 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 semi-major 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 (Figure 1) it has the least well-characterized outer irregular satellite system. We wish to determine if 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 will 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 square degrees 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 August 29 and 30, 2003 using the Suprime-Cam camera on the Subaru 8.2 meter diameter telescope atop Mauna Kea. The Suprime-Cam imager uses 10 MIT/LL 2048 × 4096 CCDs arranged in a $5 \times 2$ pattern (Miyazaki et al. 2002) and with 15$\mu$m 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 second exposures. Landolt (1992) standards were used for calibration on both photometric nights.

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

\[
r_H = a_p \left[ \frac{m_p}{3M_\odot} \right]^{1/3}
\]

where \( a_p \) and \( m_p \) are the orbital semi-major axis and mass of the planet 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 3 times each on one night and 2 times each on the second night for a total of 5 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 square degrees 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 which appeared in all three images from one night and had a motion consistent with being beyond the orbit of Jupiter (motion of 18 to 1 arcsecond per hour). 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 (\( \sim 3.5 \) arcseconds per hour). 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 magnitudes, which we take as the limiting magnitude of this survey.

There was virtually no scattered light beyond about 45 arcseconds from Neptune. Scattered light did not significantly affect our detection efficiency until about 20 arcseconds from Neptune at which point the background was only 30% higher than the nominal sky background. The region within \( \sim 10 \) arcseconds 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 on the IAU Circular Number 8193 (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 and thus 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 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

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

in which $r$ is in km, $R$ is the heliocentric distance in AU, $\Delta$ is the geocentric distance in AU, $m_\odot$ is the apparent red magnitude of the sun ($-27.1$), $p_R$ is the red geometric albedo, and $\phi(\alpha)$ is the phase function in which the phase angle $\alpha = 0$ deg at opposition. We assume $\phi(\alpha) = 10^{-0.4 \beta \alpha}$, where $\beta$ 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 magnitudes corresponds to a satellite with radius of $17(0.04 p_R)^{1/2}$ km.

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 degrees with respect to the ecliptic and an eccentricity of 0.45. The semi-major axis of Psamathe is about $46 \times 10^6$ km which corresponds to $0.4 r_H$. The relatively large eccentricity allows Psamathe to reach almost $0.6 r_H$ from Neptune (Figure 4), near the theoretical stable limit of $0.7 r_H$ 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 semi-major axes with inclinations and eccentricities, respectively, of the irregular satellites of all the planets. Both Nereid and Triton standout 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 semi-major 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 over an order of magnitude smaller semi-major axis than other irregular satellites and also has a circular orbit, likely significantly modified by tidal interactions with Neptune (Goldreich et
The Neptune satellites discovered by Holman et al. (2004) and in this work are “normal” irregular satellites as judged by their large semi-major axes and orbital eccentricities and inclinations. The Neptune irregular satellites Psamathe (S/2003 N1) and S/2002 N4 have similar large semi-major axes, inclinations and eccentricities 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 which share similar semi-major axes and inclinations as part of a dynamical family like those observed at Jupiter (Sheppard and Jewitt 2003). Families have also been reported at Saturn (Gladman et al. 2001) but these appear significant only in inclination space, unlike the satellites of Jupiter which are grouped in both inclination and semi-major axis. No other obvious groupings are apparent. The inclination region $60 < i < 140$ degrees is void of known satellites consistent with the action of the Kozai instability (Kozai 1962; Carruba et al. 2002; Nesvorny 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

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

where $\Sigma(m_R)$ is the number of objects per unit area brighter than $m_R$, $m_o$ is the magnitude zero point, and $10^\alpha$ describes the slope of the luminosity function. Figure 7 shows the CLF using all seven known Neptune satellites which have orbits indicative of capture. We believe that the outer satellites of Neptune are complete to near 25.5 mags ($r > 20$ 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 which 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 $10 < r < 100$ 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 $10 < r < 100$ 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 $\Gamma$ 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 ($\alpha$) 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 $10 < r < 100$ km of Jupiter, Saturn and Uranus (Sheppard & Jewitt 2003; Kavelaars et al. 2004; Sheppard et al. 2005). Jupiter’s smallest satellites ($r < 5$ 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 $r < 5$ km. Uranus’ 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 ($r > 50$ 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 if 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 ultra deep survey of 1.75 deg$^2$ around Neptune reaching 50% detection efficiency at a red limiting magnitude of 25.8 mags. This corresponds to objects with $r > 17$ 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 $100 > r > 10$ km around Jupiter, Saturn and Uranus ($q \sim 2$) while steeper power laws ($q \sim 3.5$) appear for satellites with $r < 5$ km which may be a sign of collisional evolution.

Acknowledgments

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Table 1. Geometrical Circumstances of Neptune

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<tr>
<th>UT Date</th>
<th>R (AU)</th>
<th>$\Delta$ (AU)</th>
<th>$\alpha$ (deg)</th>
<th>RA ($''$/hr)</th>
<th>Dec ($''$/hr)</th>
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<tr>
<td>2003 Aug 29</td>
<td>30.078</td>
<td>29.156</td>
<td>0.79</td>
<td>-3.5</td>
<td>-1.0</td>
</tr>
<tr>
<td>2003 Aug 30</td>
<td>30.078</td>
<td>29.163</td>
<td>0.82</td>
<td>-3.5</td>
<td>-1.0</td>
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Table 2. Outer Irregular Satellites of the Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Irr$^a$</th>
<th>R-Mag$^b$</th>
<th>$r_{\text{min}}$$^c$</th>
<th>Hill$^d$</th>
<th>Hill$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(#)</td>
<td>(mag)</td>
<td>(km)</td>
<td>Radii</td>
<td>Radii</td>
</tr>
<tr>
<td>Mars$^e$</td>
<td>0</td>
<td>23.5</td>
<td>0.1</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Jupiter</td>
<td>55</td>
<td>23.5</td>
<td>1</td>
<td>4.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Saturn</td>
<td>26</td>
<td>24.5</td>
<td>3</td>
<td>3.0</td>
<td>6.9</td>
</tr>
<tr>
<td>Uranus</td>
<td>9</td>
<td>26</td>
<td>7</td>
<td>1.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Neptune$^f$</td>
<td>5(7)</td>
<td>25.5</td>
<td>20</td>
<td>1.5</td>
<td>11.6</td>
</tr>
</tbody>
</table>

$^a$Number of known outer irregular satellites as of December 1, 2005.

$^b$Approximate limiting magnitude in the R-band of completeness for 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' two inner satellites may have been captured in a similar way as the outer irregular satellites of the giant planets.

$^f$Neptune only has 5 “normal” irregular satellites if the “unusual” Triton and Nereid are not included.
Table 3. Physical and Orbital Properties of Neptune’s Irregular Satellites*  

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


\(^a\)Mean semi-major axis with respect to Neptune.

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

\(^c\)Mean eccentricity.

\(^d\)The argument of Pariaphis.

\(^e\)The longitude of the ascending node.

\(^f\)The mean anomaly.

\(^g\)Orbital period of satellite around Neptune.

\(^h\)Apparent red (0.65 \(\mu\)m wavelength) magnitude. Uncertainties are around 0.2 mags.

\(^i\)Radius of 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
semi-major axis and large eccentricity. It may be a perturbed regular satellite.
Fig. 1.— The distances of the planets versus 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. Though 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.
Fig. 2.— The survey area around Neptune searched for satellites using the Suprime-Cam on the 8.2m 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 0.7 $r_H$).
Fig. 3.— Detection efficiency of the Neptune survey versus the apparent red magnitude. The 50\% detection efficiency is at about 25.8 mags as determined from visual blinking and 25.7 mags 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 (PSF) of the images with motions similar to Neptune in the survey fields. Effective radii of the apparent magnitude was calculated assuming the object would have an albedo of 0.04. The efficiency does not account for objects which would have been undetected because of the chip gaps. Scattered light was not a significant problem in the survey.
Fig. 4.— A plan view of Neptune’s satellite orbits. The three small outer retrograde irregular orbits are shown in red, 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 dashed circle shows the theoretical outer limit of stability for Neptune satellites at 0.7 $r_H$. The orbits are projected into the ecliptic, centered on Neptune with axes in kilometers with zero degrees longitude on the left side of the x-axis.
Fig. 5.— An inclination comparison between the currently known 97 irregular satellites of the giant planets. The horizontal axis is the fraction of the satellite’s mean semi-major 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 symbol represents the radius of the object: Large symbol $r > 25$ km, medium symbol $25 > r > 10$ 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.
Fig. 6.— Same as Figure 5 except eccentricity is plotted on the vertical axis. Both Triton and Nereid standout 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.
Fig. 7.— The cumulative luminosity function (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.— The cumulative luminosity function (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 Figure 7. The slopes for irregular satellites with $100 > r > 10$ km are plotted for Jupiter, Saturn and Uranus. They all are shallow and very similar ($\alpha \sim 0.20$) but because of the different distances the further planets CLF’s 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.
Fig. 9.— The 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 $100 > r > 10$ km. Neptune’s limited number of known small outer irregular satellites with $100 > r > 10$ 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 $q \sim 1.5$. Both Jupiter and Saturn appear to show a steeper size distribution for irregular satellites with $r < 5$ km which may be a sign of collisional processing. To date neither Uranus’ or 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.