# The Discovery of Faint Irregular Satellites of uranus and neptune

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**Suggested Running Head:** Irregular Satellites of the Gas Giants

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## 1. Introduction

A more complete picture of the formation environment of neptune and uranus will provide many clues about the formation of these giant planets.

Irregular satellites are those planetary satellites which are on highly elliptic and/or highly inclined orbits. They are thought to have been captured into orbit around their planet during the late stages of planet formation (see Peale 1999). Until recently, theories of satellite capture lacked many constraints due to the limited number of known satellites, but additional information from the rapidly-growing number of known irregular satellites is providing strong constraints on these theories.

We are currently surveying the contents of the outer solar system to arrive at the fossil record of gas giant formation.

Since 1997 we have been systematically surveying the environs of the giant planets in order to extend the inventory their irregular satellite systems. In 1997 we discovered the first two irregular satellites of uranus. In 1999, we conducted a complete survey of the environs of uranus, finding three more satellites and thus extend the size distribution of known satellites of that planet down to about 20 km diameter (Gladman et al. 2001). On the same nights as the uranus survey we also conducted a similarly-deep ($m_R \sim 24$) search around neptune without success. In September 2000 we conducted several searches around saturn using a variety of telescopes. We discovered 12 new irregular satellites with diameters from 3 to 50 km. In November 2000 Sheppard et al. (2001) conducted a preliminary search around jupiter that revealed 10 new irregulars satellites of that planet.

The inter-comparison of these satellite systems has yielded valuable new insights into their capture (see Gladman et al. 2001). In particular, the fact that the smallest satellites in these systems are *not* on systematically smaller or more circular orbits implies that they were not captured by gas drag, which would cause the orbits of the smallest moons to spiral towards the planet and circularize.

Figure 1 shows the eccentricity, inclination and semimajor axis for all irregular satellites with well determined orbits. The strong grouping in inclination of the “families” of irregulars is made quite obvious in this sketch as is the uniformity of the semimajor-axis distribution. The groups have relative velocities of a few $km/s$, typical of ejecta velocities from the largest member of the group (Gladman et al. 2001). The groupings appear to support the hypothesis that the irregulars are the result of the disruption of a larger parent body.

In light of this, our previous null-detection around neptune becomes a window to new understanding. A good case has been made by Goldreich et al. (1989) that massive Triton was captured from heliocentric orbit, and its initially eccentric orbit subsequently was circularized by tidal dissipation (McKinnon 1984; Goldreich et al. 1989; McKinnon, Lunune, & Banfield 1994). In the process, a retrograde Triton would have ejected or accreted any pre-existing irregular neptunian satellites within about 200 neptunian radii ($R_N$). More distant irregular satellites should have survived due to their much longer collisional time scales (Goldreich et al. 1989). Nereid, with $a = 219R_N$ and aphelion at 400 $R_N$, may be such a survivor, or may have been captured after Triton; its unusually large eccentricity of 0.75 may reflect near-ejection by gravitational interaction with Triton.

However, a comparison with the irregular satellite systems of the other giant planets suggests another interpretation. In all of the other systems there are just 1 or 2 large irregulars followed by a suite of smaller moons. Moving those satellite systems to neptune’s distance would drop the reflexed solar flux from the smaller moons below the limit of our previous survey. Thus, Nereid may simply be the only large moon around neptune, accompanied by a retinue of other satellites which are just below the previous limit.

Additionally, the large numbers of irregular satellites found orbiting jupiter and saturn appears to indicate that the formation mechanism has some dependence on planet mass. However, the smaller members of the saturn population would be undetected if place in orbit around uranus.

These findings provided strong motivation for a search for faint irregular satellites of neptune and uranus.

## 2. Observations

Detecting the population small irregular satellites orbiting a distant planet provides a number of observational challenges. The luminosity of a object which is seen only via reflected Sun light goes as

$$m_r \simeq 25.0 + 2.5 * \log{(\frac{\Delta_{AU}}{30})^4 (\frac{45}{D_{km}})^2 (\frac{6}{\mathsf{p}_{\%}})}$$

The smaller members of each of the families of irregulars orbiting saturn have sizes of a few 10s of km diameter (for an assumed albedo of 6%). When placed at the distance of neptune, the flux from these objects drops to below $m_R = 25$.

The preferred orbital inclination of irregular satellites is not well constrained (outside a given family). Thus, a complete search of for irregular satellites must encompass the region surrounding each planet which is likely to posses long-lived stable orbits. Our saturn search and previous neptune and uranus searches suggests that region is the inner half of the planet's Hill sphere. The angular extent of the Hill sphere is given as;

$$R_{Hill}(radians) = (\frac{M_{planet}}{3M_{\odot}})^{1/3}$$

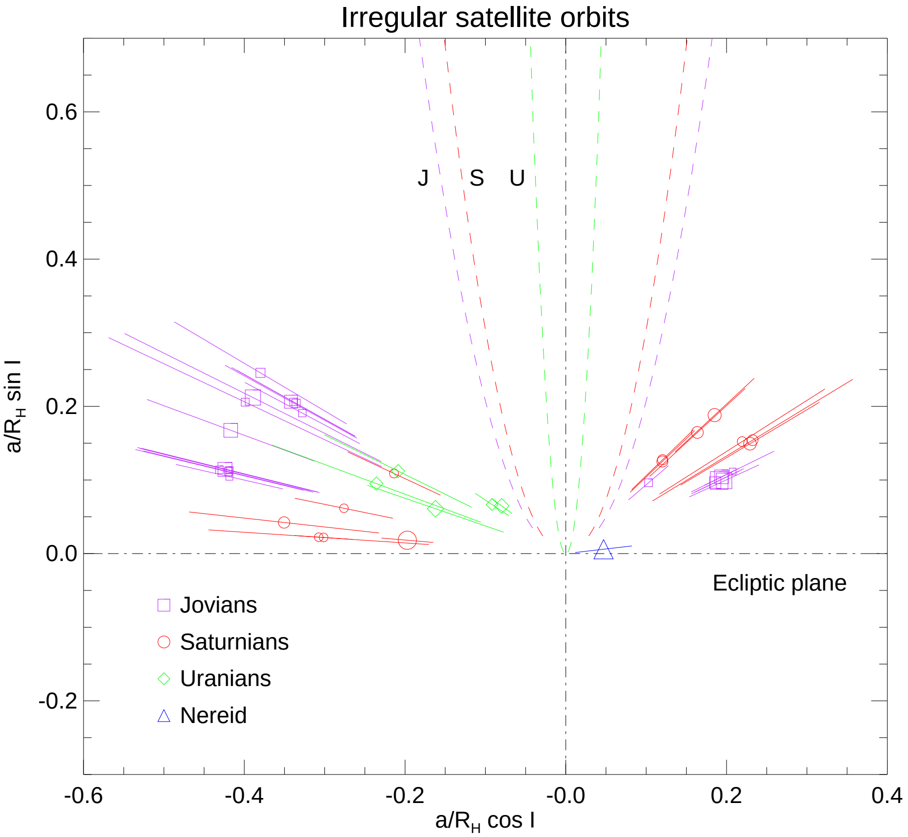

Fig. 1.— A sketch comparing the orbital properties of the irregular satellites. Each orbit's inclination $I$ relative to the J2000 ecliptic is illustrated by the angle from the horizontal; moons in the right quadrant move in the same (direct) sense as their planets orbit the Sun while those in the left quadrant are retrograde. The radial distance from the origin to the symbol represents the orbital semimajor axis $a$ (in units of Hill sphere radius $R_H$). Symbol sizes are proportional to the log of the satellite's radius, for albedos of 6%. Line lengths illustrate the pericenter-to-apocenter variation due to the orbital eccentricity $e$. The region within which the Kozai mechanism removes nearly polar orbits is indicated by the dashed lines for each planet. Triton's orbit is at the origin at this scale.

In projection on the sky neptune's Hill Sphere covers 6.8 square degrees and uranus' covers 6.5 square degrees.

In addition to the areal coverage required and the faintness of the candidates is the complication of the objects motion. To reach the desired faintness requires many hours of observing per night and this is best done when the planet is near opposition. However, this is exactly the time when the largest reflex motion will occur. For objects in a circular orbit the apparent sky motion, caused almost entirely by the earth's orbital motion, is approximately

$$\Theta \simeq \frac{137''}{\Delta_{AU}}$$

The precise rate of motion is determined by the orbit of the remote object and the distance to that object. To prevent losses due to trailing the object should not move more than one seeing disk in a single exposure. Thus, for objects $\sim 30AU$ from the sun the exposure times must be limited to 8 minutes or less to prevent losses (for seeing of $\sim 1''$).

To meet our observing requirements we used the CFH12k Mosaic camera mounted on the Canada-France-Hawaii Telescope (CFHT) and the 8k Mosaic mounted on the Blanco 4m, operated by Cero Telolo Inter-American Observatory (CTIO).

The CTIO 4-meter and CFHT 3.6-meter telescopes are very well suited to this project. The large field of view of the available mosaic cameras (36'x36' and 28'x42') permitted us to search the entire region within which distant, irregular satellites of neptune are expected to be dynamically long-lived.

We searched a 'rosette' of 4 mosaic pointings around each planet (Figures 2 and 3). On each night of the observing we repeatedly imaged one or two fields over the course of hours using a continuos series of 8 minute exposures (see Table 1).

### 2.1. CTIO

The image quality (seeing), as measure by the full-width at half-maximum for point sources, was somewhat variable during our CTIO observations. The seeing range from 0.9 to 2.1 arcseconds over the course the 4 nights of observations and with the majority of the data acquired in seeing of 1.1”.

We imaged using a $VR$ filter (Allen et al. 2001) which is centered between the $V$ and $R$ bands and approximately 100nm wide. During the course of the night we acquired images of the standard field SA92 (Landolt 1992). These observations were used to tie the the $VR$ observations to the Kron $R$ photometric system. Using these standard star observations we determined a photometric transform of

$$m_R = -2.5 \log f_{15pix}/t(s) + 26.1 - 0.1 * X \pm 0.1$$

where $f_{15pix}$ is the flux in a 15 pixel aperture, $t$ is the exposure time in seconds and $X$ is the airmass.

### 2.2. CFHT

The CFHT image quality was somewhat better but neptune and uranus only above airmass of 2.0 for a few hours per night. All imaging was done through the CFHT12k Kron R filter.

The first set of images were acquired in late July 2001, while neptune was approaching opposition. The first night was clear and photometric with seeing of about 0.8”. However, only one field was image and the remainder of the time was lost to weather.

During a second CFHT allocation in late August we imaged a rosette of fields around uranus, again in the Kron R filter. During the two weeks between the CTIO

Table 1. Search Fields

| Field name | $\alpha$ | $\delta$ | Exposure | Image | Date |
|---|---|---|---|---|---|
| | 2000 | | Time ($s$) | Quality | |
| CFHT neptune | | | | | |
| NW | 20:38:00 | -18:05:50 | 26x480s | 0.8” | 2001 07 23 |
| CTIO neptune | | | | | |
| N10032W3 (NE) | 20:38:34 | -18:01:02 | 39x480s | 1.0 – 1.3” | 2001 08 10 |
| N11033 (SE) | 20:39:05 | -18:37:33 | 33x480s | 1.0 – 1.2” | 2001 08 11 |
| N12034 (SW) | 20:36:29 | -18:43:59 | 42x480s | 1.3 – 2.0” | 2001 08 12 |
| CTIO uranus | | | | | |
| U13051 (NW) | 21:40:32 | -14:22:17 | 19x480s | 1.0 – 1.4” | 2001 08 13 |
| U13034 (SW) | 21:41:06 | -14:56:19 | 20x480s | 1.0 – 1.3” | 2001 08 13 |
| CFHT uranus | | | | | |
| NE | 21:41:05 | -14:28:07 | 16x480s | 0.6” | 2001 08 24 |
| SE | 21:42:06 | -14:54:28 | 17x480s | 0.7” | 2001 08 24 |
| SW | 21:39:31 | -15:01:26 | 14x480s | 0.7” | 2001 08 25 |
| NW | 21:38:33 | -14:37:16 | 17x480s | 0.8” | 2001 08 25 |

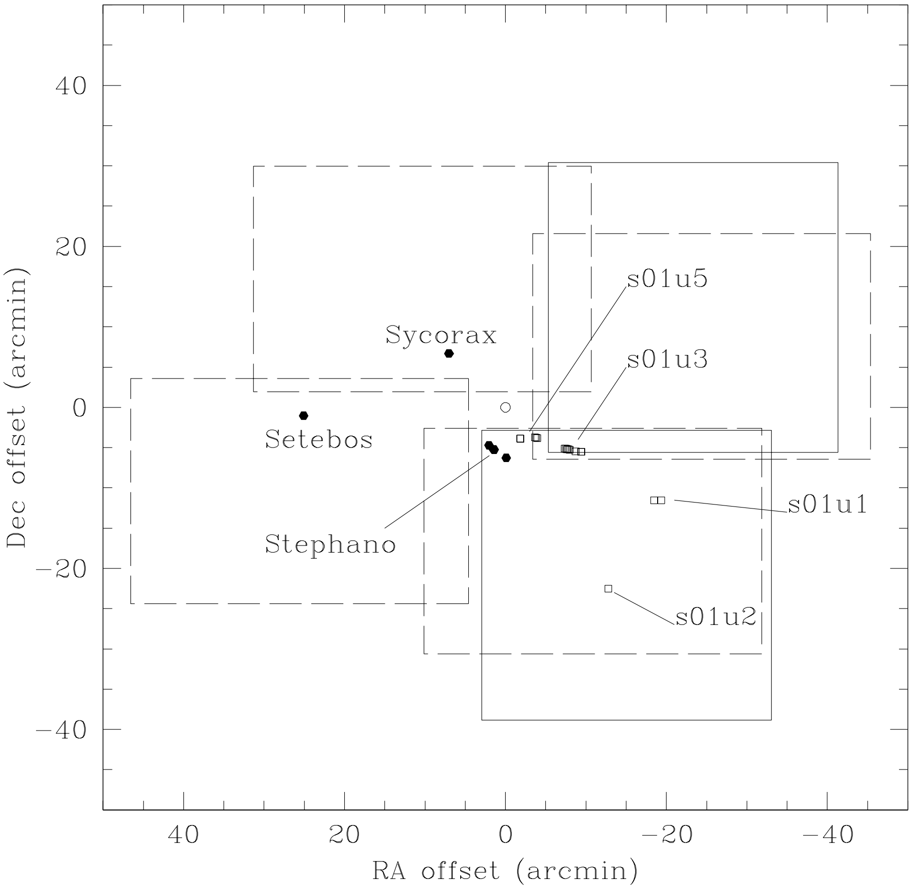

Fig. 2.— Layout of the search fields surrounding uranus (open circle at the origin). The solid-line boxes show the positions of the fields searched from CTIO. The dashed-line boxes show the fields searched from CFHT. The four faint uranian irregular satellites found here (s01u1, s01u2, s01u3, and s01u5) are indicated with open squares. The positions of the known uranian irregular satellites Sycorax, Setebos, and Stephano at the dates of the search are indicated with solid hexagons. The other two known uranian irregulars, Caliban and Prospero, were in the central hole at the time of the search.

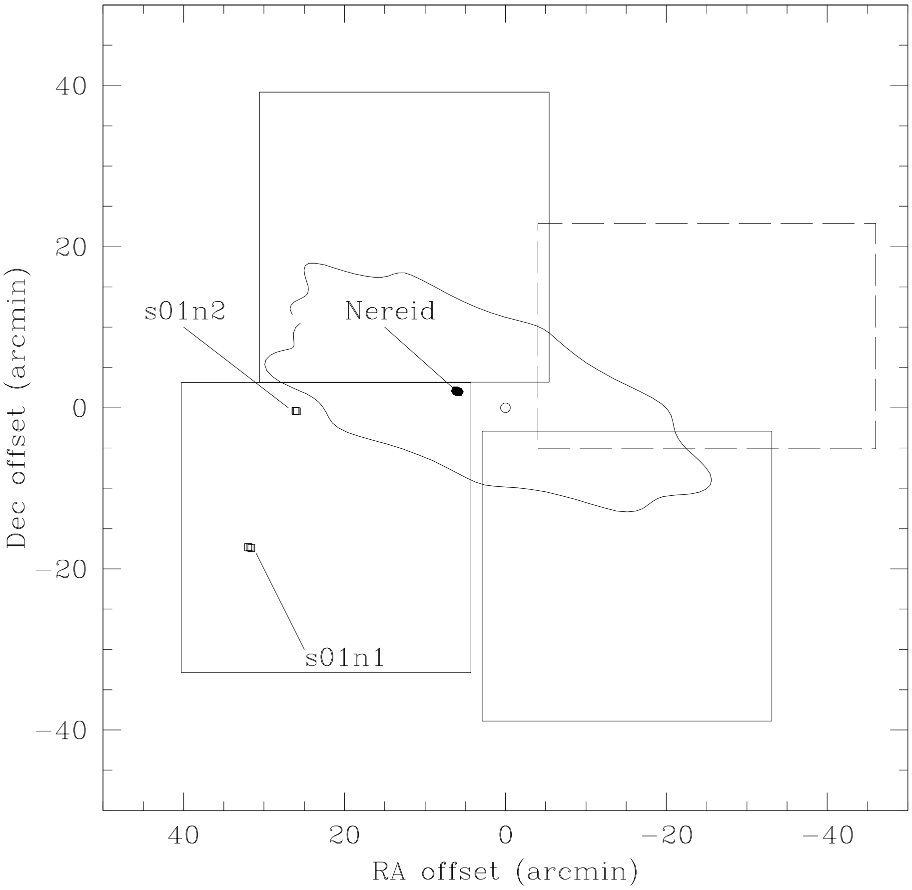

Fig. 3.— Layout of the search fields surrounding neptune (open circle at the origin). The solid-line boxes show the positions of the fields searched from CTIO. The dashed-line boxes show the fields searched from CFHT. The two faint neptunian irregular satellite candidates found here (s01n1 and s01n2) are indicated with open squares. The positions of the known neptunian irregular satellite Nereid at the dates of the search is indicated with a solid hexagon. The orbit of the uranian irregular satellites Setebos is shown, scaled correctly to neptune's distance and Hill sphere; a neptunian irregular satellite system will likely occupy a similar volume of space.

and CFHT observing runs we searched the CTIO data and found three of the candidate satellites orbiting uranus. Those fields which contained satellites at CTIO were re-image at CFHT.

During both CFHT observing sessions we observed Landolt standard fields and determined the photometric transformation

$$m_R = -2.5 \log f_{15}/t(s) + 26.0 - 0.1X \pm 0.02$$

.

### 2.3. Data Analysis

To combine the exposures and compensate for the reflex motion of the satellites orbiting the target planet we have developed a suite of scripts written in the IRAF/CL scripting language (Tody 1993). These scripts recombine a series of short exposures after shifting them to compensate for the expected rate of motion for the objects orbiting around the target planet. Essentially this recombination is done at rates that are within a few pixels per hour of the motion of planet. The technique for combining images was developed for searches of objects in the Kuiper belt and is fully described in Gladman et al. (1998).

For the CTIO data we eliminated images with seeing worse that 1.2” from our final analysis as the poorer quality images tended to “blur-out” stars resulting in an increasing in crowding and reducing the overall efficiency of the detection process.

In order to determine the detection efficiency we planeted artificle satellite candidates into the images and measured the fraction of planeted objects recovered. By combining the best available data we where able to obtain detection limits (50% of planeted objects found) of $m_R = 25.8$ for our neptune search fields and $m_R = 25.4$ for our uranus search.

Once a candidate was found we then split the dataset into 3 groups, the first half, middle half and last half. Each set was then combined separately and the object was looked for on each of the 3 combined images. Each of the candidates was found on each of the 3 groups and the astrometric and photometric measurements are from those 3 groups of images.

Although the image quality at CFHT was much better than at CTIO the shortened total exposure time significantly reduced our detection limit. From the efficiency of our planeted object detections we determine the limit for the CFHT data to be $m_R = 24.9$.

## 3. Satellite Candidates

### 3.1. Uranus

In our search of the CTIO uranus data we discovered 4 objects moving at rates consistent with a satellite orbiting uranus. The intention of this work was to probe the luminosity function of satellites of the gas giants and not to determine the orbits of the satellites. Thus, we did not schedule multiple follow-up observations using the discover platform. However, we did repeat our search of 2 of the CTIO uranus fields at CFHT. Only the candidate s01u03 was contained in the CFHT pointings (see Figure 2) and bright enough to be seen.

Given that we have only observed these objects for very short arcs there is the possibility that they are passing centaurs. However, our previous searches for brighter satellites of uranus (also conducted near opposition) did not reveal any “false” candidates and we feel it unlikely that these objects are chance objects passing near uranus at rates consistent with an irregular satellite orbiting that planet.

The astrometric positions of the newly discovered uranian satellites are given in

Table 2 and an example of a detection image set is given in Figure 4.

Table 2. Uranian candidates; astrometric and photometric measurements

| Date (UT) | $\alpha$ (2000) | $\delta$ | $m_R$ | Observatory Code |
|---|---|---|---|---|
| s01u1 | | | | |
| 2001 08 13.23319 | 21:40:52.96 | -14:46:58.9 | 25.0 | 807 |
| 2001 08 13.29446 | 21:40:52.36 | -14:47:01.8 | 24.9 | 807 |
| 2001 08 13.35711 | 21:40:51.75 | -14:47:04.6 | 25.1 | 807 |
| 2001 09 21.17200 | 21:35:14.43 | -15:14:26.4 | 25 | 675 |
| 2001 09 21.22091 | 21:35:14.10 | -15:14:28.0 | 25.1 | 675 |
| 2001 09 21.24238 | 21:35:13.94 | -15:14:29.0 | ··· | 675 |
| s01u2 | | | | |
| 2001 08 13.23319 | 21:41:15.72 | -14:57:57.9 | 25.6 | 807 |
| 2001 08 13.29446 | 21:41:15.18 | -14:58:00.9 | ··· | 807 |
| 2001 08 13.35711 | 21:41:14.59 | -14:58:04.0 | ··· | 807 |
| s01u3 | | | | |
| 2001 08 13.22537 | 21:41:35.65 | -14:40:38.7 | 25.5 | 807 |
| 2001 08 13.23319 | 21:41:35.55 | -14:40:39.4 | 24.9 | 807 |
| 2001 08 13.29446 | 21:41:34.96 | -14:40:42.3 | 25.3 | 807 |
| 2001 08 13.35711 | 21:41:34.36 | -14:40:45.2 | 25.2 | 807 |
| 2001 08 25.32061 | 21:39:40.47 | -14:50:14.4 | 25.1 | 568 |
| 2001 08 25.35899 | 21:39:40.12 | -14:50:16.3 | ··· | 568 |
| 2001 08 25.40381 | 21:39:39.70 | -14:50:18.2 | ··· | 568 |
| 2001 08 25.41067 | 21:39:39.63 | -14:50:18.9 | ··· | 568 |

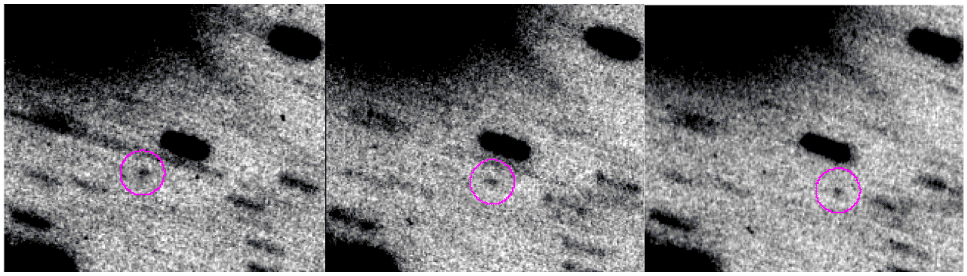

Fig. 4.— Three images showing the uranian satellite candidate s01u3. Here we have subdivided the full data set into three batches which were shifted at the rate and direction of the motion of uranus and then recombined. The satellite is indicated by the circle in each image and can be seen moving from left to right. The elongated features in the images are stars that have been smeared out by the shifting process.

### 3.2. Neptune

Our search around neptune revealed two satellite candidates orbiting that planet. As with the Uranian candidates, the possibility of chance passage of centaurs can not be eliminated using only the discovery observations. The location, at discovery, of these two candidates is show in Figure 3. The astrometric and photometric discovery measurements are listed in Table 3.

### 3.3. Recovery

In order to determine the orbital elements of the satellite candidates, and confirm them as satellites, we obtained followup time at on the Magellan, Hale and VLT telescopes. Unfortunately weather and other events worked against our attempts and we were only able to recover 3 of the uranian candidates using the Hale 5m. The successful astrometric measurements of the uranian candidates are given in Table 2.

The length of the measured orbital arcs are insufficient for any orbital solutions to be determined. However, the level of false candidates in our other searches has been 0 and we feel confident that the detections reported here are bona-fide satellites of uranus and neptune.

## 4. Discussion

Given the inclination grouping of irregular satellites they are most likely the result of a collisional formation mechanism. The velocity distribution within the inclination groups also appears to be consistent with a collisional formation process with the observed velocity spread within the groups being approximately the escape velocity of the large member of the group.

Table 2—Continued

| Date<br>(UT) | $\alpha$<br>(2000) | $\delta$ | $m_R$ | Observatory<br>Code |
|---|---|---|---|---|
| 2001 08 25.46677 | 21:39:39.15 | -14:50:21.3 | ··· | 568 |
| 2001 08 25.51790 | 21:39:38.71 | -14:50:23.5 | ··· | 568 |
| 2001 09 21.17887 | 21:35:53.96 | -15:08:25.0 | ··· | 675 |
| 2001 09 21.22091 | 21:35:53.65 | -15:08:26.4 | ··· | 675 |
| s01u5 | | | | |
| 2001 08 13.23319 | 21:41:51.63 | -14:39:12.5 | 25.1 | 807 |
| 2001 08 13.29446 | 21:41:51.05 | -14:39:15.7 | 25.3 | 807 |
| 2001 08 13.35711 | 21:41:50.46 | -14:39:18.7 | 25.5 | 807 |
| 2001 08 25.41067 | 21:39:59.66 | -14:49:03.4 | ··· | 568 |
| 2001 09 21.17887 | 21:36:24.32 | -15:06:48.1 | ··· | 675 |
| 2001 09 21.21562 | 21:36:24.07 | -15:06:49.2 | ··· | 675 |

Note. — Observatory codes: 807 - Blanco 4m, 568 - CFHT 3.6m, 675 - Hale 5m

Table 3. Neptune candidates; astrometric and photometric measurements

| Date<br>(UT) | $\alpha$<br>(2000) | $\delta$ | $m_R$ | Observatory<br>Code |
|---|---|---|---|---|
| s01n1 | | | | |
| 2001 08 11.04727 | 20:39:43.76 | -18:39:59.9 | 25.1 | 807 |
| 2001 08 11.15269 | 20:39:43.07 | -18:40:02.5 | 24.9 | 807 |
| 2001 08 11.29134 | 20:39:42.17 | -18:40:05.9 | 25.2 | 807 |
| s01n2 | | | | |
| 2001 08 11.05005 | 20:39:20.34 | -18:23:04.1 | 25.4 | 807 |
| 2001 08 11.08372 | 20:39:20.13 | -18:23:04.9 | 25.4 | 807 |
| 2001 08 11.17850 | 20:39:19.51 | -18:23:07.2 | 25.4 | 807 |

Note. — Observatory codes: 807 - Blanco 4m, 568 - CFHT 3.6m, 675 - Hale 5m

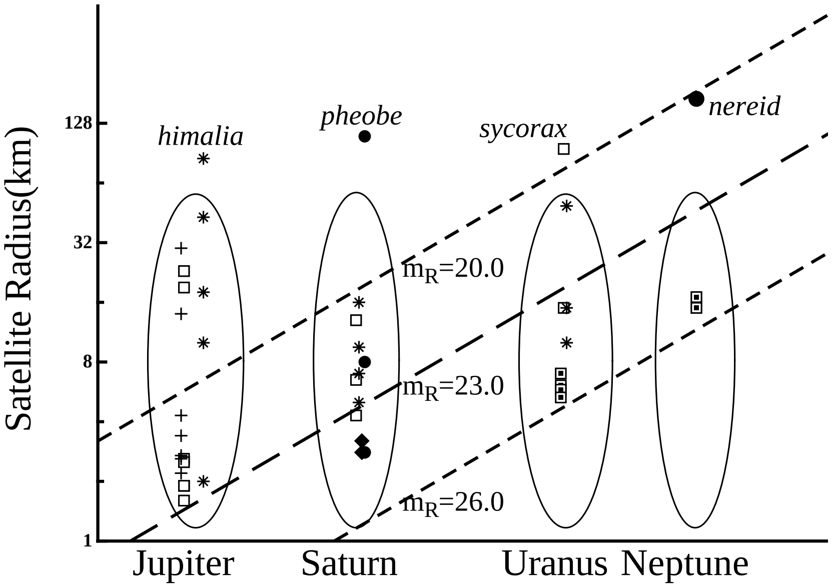

Fig. 5.— The diameters of the known irregular satellites and satellite candidates (box within a box) are shown versus heliocentric distance. Symbol type indicates the orbital grouping at jupiter, saturn, uranus, and neptune. The dashed lines are detection limits for the given $m_R$ magnitudes for objects of a given size and distance assuming a geometric albedo of 6%.

If, however, the capture process also involves a significant contribution from gas drag then the expectation is for some amount of segregation with smaller satellites concentrated towards the planet and on more circular orbits. This segregation is not observed in among the small satellites of saturn. Our new satellite candidates of uranus and neptune are not concentrated towards the planet center. These new detections combined with our previous ones cast serious doubt on the role of gas drag in satellite capture.

If the irregular satellites truly are the result of collisional processes then we would expect them to follow a collisional size distribution. The first indication that this is the case comes from our very successful search around saturn which revealed 12 new satellites of that planet. We have now conducted a search around neptune and uranus and find that the distribution is weighted towards fainter, ie smaller, satellites.

Each of the giant planets has one very large irregular satellite (Himalia for jupiter; Phoebe for saturn; Sycorax for uranus, and Nereid for neptune) followed by a retinue of smaller irregulars. The largest members of each smaller retinue is consistently 30-40 km with a growing population of smaller objects (see Figure 4). Indeed, our candidates around uranus appear to be members of this "fragmen" class and the candidate satellites of neptune appear to be the largest members of that planets retinue.

Although we cannot determine the pericentric distance for these new irregulars we do note that at discovery the candidates satellites of netune were outside the 200AU zone which may have been cleared during Triton's catpure. The lack of satellites interior to the 200 AU zone is a telling feature. However, this may still be due to the small numbers of known irregulars satellites of neptune.

## 5. Conclusion

We have conducted a search for irregular satellites orbiting the planets neptune and uranus reaching 50% detection limits of $m_R = 25.8$ and $m_R = 25.4$ and covered the entire inner half of each planet's Hill sphere. During this search we found 2 new candidate satellites of the planet neptune and 4 new candidate satellites of the planet uranus.

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