Discovery of five irregular moons of Neptune

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Each giant planet of the Solar System has two main types of moons. 'Regular' moons are typically larger satellites with prograde, nearly circular orbits in the equatorial plane of their host planets at distances of several to tens of planetary radii. The 'irregular' satellites (which are typically smaller) have larger orbits with significant eccentricities and inclinations. Despite these common features, Neptune's irregular satellite system, hitherto thought to consist of Triton and Nereid, has appeared unusual. Triton is as large as Pluto and is postulated to have been captured from heliocentric orbit; it traces a circular but retrograde orbit at 14 planetary radii from Neptune. Nereid, which exhibits one of the largest satellite eccentricities, is believed to have been scattered from a regular satellite orbit to its present orbit during Triton's capture^{1,2}. Here we report the discovery of five irregular moons of Neptune, two with prograde and three with retrograde orbits. These exceedingly faint (apparent red magnitude $m_R = 24.2-25.4$) moons, with diameters of 30 to 50 km, were presumably captured by Neptune.

Recent searches for neptunian moons have employed digital techniques^{3–6}, but have revealed no new neptunian moons. The lack of discoveries has been interpreted⁶ as supporting the theory of a violent destruction of the neptunian outer satellite system when Triton was captured and tidally circularized^{1,2}. However, recent discoveries of small jovian⁷, saturnian⁸ and uranian⁹ irregular satellites suggested that previously undetected neptunian satellites might be found just beyond the earlier surveys' detection thresholds⁸.

Thus, in 2001, we searched for fainter neptunian moons, using a more sophisticated method. With the Cerro Tololo Inter-American Observatory 4-m and Canada-France-Hawaii 3.6-m telescopes, we searched 1.4 square degrees centred on Neptune (Fig. 1). The volume near a planet where satellites are dynamically stable is roughly given by the 'Hill sphere', within which the planet's gravity overcomes solar tidal perturbations ¹⁰. The radius of the Hill sphere is $R_{\rm H} = a_{\rm p} (\mu/3)^{1/3}$, where $a_{\rm p}$ is the planet's semimajor axis and μ is the ratio of the planet's mass to the Sun's. For Neptune, $R_{\rm H} = 1.15 \times 10^{11} \, {\rm km} \, (0.77 \, {\rm AU})$ or 1.5° viewed from Earth. Detailed 10-Myr numerical integrations show that prograde satellites (those orbiting in the same sense as the planet orbits the Sun) of Neptune are stable to distances of $\sim 0.4 \, R_{\rm H}$, and retrograde satellites (those orbiting in the opposite sense) are stable to $\sim 0.7 \, R_{\rm H}$, depending upon the satellite's eccentricity and inclination ¹¹. Thus, our search

was sensitive to nearly all prograde orbits. However, some retrograde satellites might lie beyond our search region (Fig. 1). We repeated our search in August 2002 and August 2003, with CTIO's Blanco telescope, in order to recover our satellites.

On each search night, we took 20–25 eight-minute exposures of one or more of our four search regions. We imaged through a "VR" filter, which is centred between the V and R bands, and is approximately 100 nm wide¹². We also acquired images of photometric standard fields¹³ to transform the VR observations to the Kron R photometric system.

For our searches we adapted a pencil-beam technique developed to detect faint Kuiper belt objects^{12,14}. The detection of faint, moving objects in a single exposure is limited by the object's motion. Long exposures spread the signal from the object in a trail; the atmospheric conditions and the quality of the telescope optics restrict the useful exposure time to the period in which the object traverses the width of the point-spread function. However, as the apparent rate and direction at which Neptune moves across the sky are known, we shift the successive images in software to compensate for that motion. We then combine the exposures to produce a single deep image. The signal from objects moving near Neptune's rate and direction collects into a point-like image. We repeat this procedure for the range of rates and directions of apparent motion that is consistent with bound satellites within our search fields. Subtraction of a template image, scaled to match the varying background and point-spread function, from each individual exposure, before it

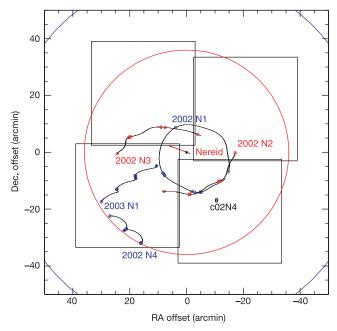


Figure 1 Search regions. The rosette of black squares indicate the $36' \times 36'$ CTIO Mosaic-II camera fields surrounding Neptune (at centre) searched in August 2002 and 2003. Our search in 2001 had a similar field pattern, but the northwest field was searched with the CFH12K camera $(28' \times 42')$. This layout covers a roughly circular region, while minimizing field overlap and avoiding significant scattered light contamination from Neptune. The open symbols mark the observed satellite positions with respect to Neptune. The traces of offset positions of the irregular satellites announced here, as well as that of Nereid, are also shown. Owing to the changing perspective from the Earth, these do not appear as segments of ellipses. The red (blue) solid circle roughly indicates the stability limit of prograde (retrograde) ecliptic satellites. The prograde and retrograde satellites are also labelled in red and blue, respectively. The labels are placed near the offset positions at the time of discovery (July or August 2001 for all but S/2002 N 4 and c02N4). In summer 2001, S/2002 N 4 was outside our search region and c02N4 was not detected. The observed positions of the unrecovered satellite candidate, c02N4, are indicated, but it is not classified as prograde or retrograde, as its orbit is undetermined.

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Table 1 The time-averaged orbital elements of Neptune's irregular satellites											
Satellite	R (mag)	Diam. (km)	a _{ave} (10 ⁶ km)	e _{ave}	e _{min}	e _{max}	i _{ave} (deg)	i _{min}	i _{max}	P (yr)	p _{coll}
Triton	13.5	2707	0.35	0.00			156.8			0.016	
Nereid	19.9	340	5.53	0.75	0.73	0.76	9.8	3.9	15.1	0.986	
S/2002 N 1	24.2	54	16.6	0.43	0.11	0.93	114.9	106.0	144.2	5.14	0.410
S/2002 N 2	25.4	31	22.3	0.27	0.06	0.63	50.4	39.2	56.3	7.98	0.015
S/2002 N 3	25.0	37	23.5	0.36	0.25	0.49	35.9	29.6	41.9	8.67	_
S/2002 N 4	24.7	43	48.6	0.39	0.11	0.76	137.4	126.6	151.0	25.77	_
S/2003 N 1	25.1	36	47.6	0.49	0.13	0.93	125.1	112.4	148.7	26.58	0.013
c02N4	25.3	33	25.1								

The apparent R-band magnitudes and diameters, along with orbital elements, current osculating orbital period (P), and probability of collision with Nereid (over 4.5 Gyr; p_{coll}) are given. The mean, minimum and maximum orbital elements, with respect to the J2000 ecliptic and equinox, are based on our numerical integrations. The diameter estimates of the newly discovered satellites assume a 6% geometric albedo. For c02N4, the projected distance between it and Neptune at the time of discovery is listed. The semimajor axes (a) of the newly discovered satellites are all significantly larger than that of Nereid but show little variation with time. However, the eccentricities (e) and inclination (i) undergo large variations. At their maximum the eccentricities of S/2002 N 1 and S/2003 N 1 exceed that of Nereid

is shifted and combined15, eliminates stars and other stationary sources of light that would otherwise appear as trails in these shifted and combined images. We apply two different detection algorithms to the shifted and combined images to identify flux sources¹⁶. These two algorithms have different false-detection characteristics; retaining only those sources detected by both algorithms eliminates a significant fraction of the spurious detections associated with cosmic-ray contamination and background fluctuations. Before applying our search algorithms to the data, we implant a large number of artificial objects, with various magnitudes, moving at different directions and rates, to calibrate our search. Our detection efficiency is found to be independent of the object's motion. Recovery observations employed both standard three image and pencil-beam techniques. Because our 12–15 August 2002 search had the most uniform conditions, we characterize our survey with it. Fitting an empirical detection efficiency function, $\epsilon = \frac{1}{2} \epsilon_{\text{max}} \{1 - \frac{1}{2} \epsilon_{\text{max}} \}$ $\tanh[(m_R - m_{50})/w]$, we find a 50% detection threshold of $m_{50} = 25.5$, a detection rate of $\epsilon_{\text{max}} = 97\%$ for objects much brighter than the detection limit, and a transition from high to low detection efficiency over roughly 2w = 0.6 mag.

Three searches yielded five new neptunian irregulars, four of which were identified in our 2001 data. All five were detected by our algorithms in the August 2002 images; however, one (S/2003 N 1) was initially overlooked during our visual inspections and was first reported by others¹⁷. Additional follow-up observations were conducted with the VLT, Magellan-II, Palomar 5-m, and Nordic Optical telescopes. These five satellites have been announced, based on recoveries in 2003, and have been re-observed in June 2004. A sixth candidate, which we designated 'c02N4', was discovered on 14 August 2002 and seen again at the VLT on 3 September 2002. Further attempts to recover this object failed. Although c02N4 is possibly a Centaur, it moved very little relative to Neptune between August and September, more consistent with it being a satellite. We also note that S/2002 N 1 was recently identified, based on our orbital solutions, in images from a 1999 search of the full Hill sphere of Neptune to a limit of $m_R = 24.3$ (ref. 6). Of the newly discovered neptunians, its orbit is now the best determined, with observations covering nearly a full orbital period. The other new neptunian satellites are much fainter than the detection threshold of that search.

Irregular satellites are widely believed to be captured from heliocentric orbits. Objects on planet-crossing orbits, with low speeds relative to the planet, can be temporarily captured into planetocentric orbit. However, apart from striking the planet, such temporarily captured bodies typically return to a heliocentric orbit in 10–100 orbits unless enough orbital energy is dissipated to make the capture permanent^{18,19}. Several dissipation mechanisms have been proposed: (1) a sudden increase in the planetary mass through accretion of nearby material¹⁸; (2) collision or gravitational interaction with an extant moon or with another temporarily captured object²⁰; (3) gas drag in an extended envelope²¹ or disk¹⁹ surrounding the still-forming planet; and (4) dynamical friction from a

background of small outer Solar System bodies^{22,23}.

Although the new satellites' orbits will undoubtedly be revised as more observations become available, we have numerically integrated their preliminary orbits for 10 Myr, including the Sun and giant planets as perturbers, to investigate their long-term dynamical stability²⁴. Table 1 lists the best-fit mean orbital elements of the satellites. We find that S/2002 N 2 is in the Kozai resonance^{11,25,26}. All of the new neptunians are stable on the timescale of the integrations. Figure 2 shows the eccentricity, inclination and semimajor axis for the neptunian irregular satellites with determined orbits, along with the results of numerical integrations to determine dynamical stability.

Neptune's irregulars are probably the remnants of a system collisionally and gravitationally altered by Triton and Nereid, as well as by the solar tidal potential. Curiously, all five new neptunian irregulars with well-determined orbits have minimum pericentre distances near the apocentre of Nereid; S/2002 N 1 crosses the orbit of Nereid most deeply at its minimum pericentre. This is consistent with an isotropic distribution of initial orbits, subsequently sculpted by gravitational perturbations. Collisions between Nereid and nearby satellites are probable¹¹. We estimate the probability of collision between the new neptunian irregulars and Nereid, assuming fixed orbital semimajor axes, eccentricities and inclinations with

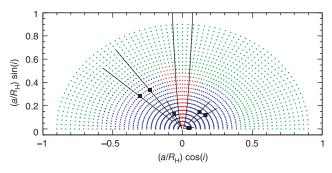


Figure 2 Dynamical stability of neptunian moons. The points indicate the initial semimajor axes and inclinations of test particles in orbit about Neptune, with the colours indicating the outcome of their numerical integration. Blue points denote particles that survived for the full 10-Myr integration. Red and green points denote the particles that moved inside the orbit of Triton ($r \approx 0.0024\,\text{Au}$) or outside 1.5 times the Hill sphere of Neptune ($r \approx 1.167\,\text{Au}$), respectively. A symplectic n-body map²⁴, modified for satellite orbits, was used. The gravitational perturbations of the Sun and giant planets were included, while those from Triton and Nereid were neglected. The test particles were started with semimajor axes of $a = 0.025-0.70\,\text{AU}$ ($\Delta a = 0.025\,\text{AU}$), inclinations $i = 0-180^\circ$ ($\Delta i = 2.5^\circ$), eccentricity e = 0.5, and argument of pericentre $\omega = 90^\circ$. The longitudes of ascending node Ω and mean anomalies M were chosen randomly. Also shown are the mean orbital elements of the new neptunian irregular satellites with secure orbits, along with that of Nereid. The lines indicate the mean pericentric and apocentric distances of these moons from Neptune. The region within which the Kozai mechanism removes nearly polar orbits is indicated by the solid, nearly parabolic line^{11,25,26}.

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random longitudes of ascending node and arguments of periapse and mean anomalies²⁷. Variations in eccentricity strongly affect the collision probability for marginally crossing orbits. We account for this by averaging the collision probability over several eccentricity oscillations induced by the solar tide. The collision probability between S/2002 N 1 and Nereid over 4.5 Gyr is 0.41. Between Nereid and S/2002 N 2 and S/2003 N 1 these are 0.016 and 0.013, respectively. For S/2002 N 3 and S/2002 N 4, the collision probabilities with Nereid are neglible. Furthermore, the probability of collisions among the new neptunians is negligible. Nereid's Hill sphere, relative to Neptune, is roughly the size of Neptune itself. The likelihood of gravitational scattering is a factor of 2×10^4 larger than that of physical collision. The high relative velocity between Nereid and the new neptunian irregulars during the encounters eliminates the possibility of direct ejection. However, it is possible that repeated gentle gravitational scattering by Nereid has shaped the orbital distribution of neptunian irregular satellites.

The jovian and saturnian irregular satellites cluster in families with similar inclination and semimajor axis^{7,8}. Photometry of the jovian and saturnian irregular satellites shows that most satellite clusters have homogeneous colours, thus intimating that irregulars are collisional fragments of larger progenitors^{28,29}. The similarities between the orbits of S/2002 N 2 and S/2002 N 3, and between those of S/2003 N 1 and S/2002 N 4, suggest that such families might exist among the neptunian irregulars as well. The remaining retrograde satellite, S/2002 N 1, has an inclination similar to that of the other retrogrades, but its semimajor axis is significantly smaller. This has been identified as a characteristic of 'chaos-assisted capture'22. Alternatively, S/2002 N 1 might be a collisional fragment of Nereid, consistent with its large probability of collision with Nereid. Photometric observations of the S/2002 N 1 show that its optical colours are similar to Nereid's³⁰. Additional photometric observations of the new neptunian satellites to compare their colours, along with further searches for additional satellites, are needed to determine whether Neptune also hosts collisional families of irregular satellites.

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Addition of nanoparticle dispersions to enhance flux pinning of the $YBa_2Cu_3O_{7-x}$ superconductor

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Following the discovery of type-II high-temperature superconductors in 1986 (refs 1, 2), work has proceeded to develop these materials for power applications. One of the problems, however, has been that magnetic flux is not completely expelled, but rather is contained within magnetic fluxons, whose motion prevents larger supercurrents. It is known that the critical current of these materials can be enhanced by incorporating a high density of extended defects to act as pinning centres for the fluxons^{3,4}. YBa₂Cu₃O₇ (YBCO or 123) is the most promising material for such applications at higher temperatures (liquid nitrogen)³⁻¹³. Pinning is optimized when the size of the defects approaches the superconducting coherence length (~2-4 nm for YBCO at temperatures ≤77 K) and when the areal number density of defects is of the order of $(H/2) \times 10^{11} \,\mathrm{cm}^{-2}$, where H is the applied magnetic field in tesla^{3,4}. Such a high density has been difficult to achieve by material-processing methods that maintain a nanosize defect, except through irradiation⁵. Here we report a method for achieving a dispersion of ~8-nm-sized nanoparticles in YBCO with a high number density, which increases the critical current (at 77 K) by a factor of two to three for high magnetic fields.

The flux pinning enhancement of type II superconductors with defects have been studied in both copper-oxide high- and low-temperature superconductor materials 3,4,14 . An areal number density of second-phase defects of over $10^{11}\,\mathrm{cm}^{-2}$ was previously