PHOTOMETRY OF IRREGULAR SATELLITES OF URANUS AND NEPTUNE

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ABSTRACT

We present BVR photometric colors of six Uranian and two Neptunian irregular satellites, collected using the Magellan Observatory (Las Campanas, Chile) and the Keck Observatory (Manua Kea, Hawaii). The colors range from neutral to light red, and like the Jovian and the Saturnian irregular satellites (Grav et al.) there is an apparent lack of the extremely red objects found among the Centaurs and Kuiper Belt objects. The Uranian irregular satellites can be divided into three possible dynamical families, but the colors collected show that two of these dynamical families, the Caliban and Sycorax clusters, have heterogeneous colors. Of the third possible family, the 168° cluster containing two objects with similar average inclinations but quite different average semimajor axes, only one object (U XXI Trinculo) was observed. The heterogeneous colors and the large dispersion of the average orbital elements lead us to doubt that they are collisional families. We favor single captures as a more likely scenario. The two Neptunian satellites observed (N II Nereid and S/2002 N1) both have very similar neutral, Sun-like colors. Together with the high collisional probability between these two objects over the age of the solar system (Nesvorny et al.; Holman et al.), this suggests that S/2002 N1 is a fragment of Nereid, broken loose during a collision or cratering event with an undetermined impactor.

Subject headings: planets and satellites: formation — planets and satellites: individual (Caliban, Nereid, S/2002 N1, Sycorax, Trinculo)

1. INTRODUCTION

Irregular satellites are small bodies that orbit their parent planets in large, eccentric orbits with high inclinations relative to the planet’s equatorial plane. Irregular satellites have been discovered around all the giant planets and are thought to have been captured from heliocentric orbits during the last stages of the formation of the giant planets. While objects in heliocentric orbits may be temporarily captured in planetocentric orbits, some loss of energy is needed to make the capture permanent. Several processes have been proposed for this change of orbital energy: (1) an increase in the mass of the planet through accretion (Heppenheimer & Porco 1977); (2) gas drag through an extended envelope or disk around the still-forming planet (Pollack et al. 1979); (3) collision or close encounters with a preexisting regular moon or another temporarily captured object (Colombo & Franklin 1971); and (4) dynamical friction from a large number of small outer solar system bodies (Astakhov et al. 2003; Goldreich et al. 2002).

It was recognized by Colombo & Franklin (1971), and later by Gladman et al. (2001), that the irregular satellites cluster in groups with similar dynamical properties. This clustering is considered to be evidence that the members of a cluster are remnants of a larger progenitor that was captured and subsequently broken up (Colombo & Franklin 1971; Gladman et al. 2001). In Grav et al. (2003a) we reported optical BVRI photometry of a large number of irregular satellites of Jupiter and Saturn, showing that almost all of the known dynamical clusters have homogeneous colors, supporting the thesis suggesting the fragmentation of larger progenitors. Determining the near-infrared colors of the brightest Jovian and Saturnian irregular satellites revealed that the normalized broadband reflectance spectra are very similar to the spectra of C- and D-type outer main belt asteroids (Grav & Holman 2004).

We now turn to Uranus and Neptune. The physical knowledge of the irregular satellites of the two outer planets is extremely limited. Only two Uranian irregular satellites and one Neptunian irregular satellite have been the targets of photometrical studies and have had their colors determined. Maris et al. (2001) observed the two Uranian satellites, U XVI Caliban and U XVII Sycorax, in BVRI filters, using the 3.6 m ESO New Technology Telescope, on La Silla, Chile. They found that both have moderately red colors, with Sycorax being slightly bluer than Caliban. They compared their observations to other families of objects in the solar system and found that the two satellites were clearly redder than Uranus and its regular satellites. They also compared the V − R colors with the histogram found in Jewitt et al. (1996) and placed the satellites among the bluest Kuiper Belt objects and the reddest near-Earth objects.

Romon et al. (2001) performed a more detailed study of Sycorax, also determining the BVRI colors using the 3.5 m Telescopio Nazionale Galileo, La Palma. They, however, added photometric observations in the J band and spectroscopic observations in the near-infrared using ESO’s 8 m Very Large Telescope in Chile. They compared their results with that of other small bodies in the solar system and argued that Sycorax is more similar to trans-Neptunian objects, Centaurs, and cometary nuclei than to the Trojans and irregular satellites of Jupiter.

N II Nereid was discovered in 1949 by G. Kuiper. Due to its brightness it has been extensively studied. Colors have been determined by Schaefer & Schaefer (2000), and Brown et al. (1999) used near-infrared spectra to show that the satellite has features indicative of water ice. Voyager II observations during its flyby of Neptune were used to determine the albedo, \( p \sim 0.2 \), of Nereid (Thomas et al. 1991). It is thus believed that
Nereid is an icy body. It is either an inner satellite gravitationally scattered as N I Triton was captured or a captured ice body originating in the Kuiper Belt (McKinnon 1984; Goldreich et al. 1989).

In this Letter we report the BVR colors of six Uranian and two Neptunian irregular satellites and discuss the implications of the colors determined. In §2 we describe the observations performed and our method of data reduction. Section 3 contains the results and interpretations of the observations.

2. THE OBSERVATIONS

The observations presented here were performed at the 6.5 m Clay telescope at the Magellan Observatory using the MagIC instrument and at the 10 m Keck II telescope using the DEIMOS instrument. The observations at the Clay telescope were performed on 2003 July 27 and 28. The conditions were photometric, and observations of Caliban, Sycorax, U XX Stephano, Nereid, and S/2002 N1 were performed. The observations using the Keck were done on 2003 August 1. The first part of the night was subject to high cirrus clouds, which moved off to the horizon at about midnight. The remainder of the night was photometric, and we used it to observe the Uranian satellites U XVIII Prospero, U XIX Setebos, and U XXI Trinculo as well as the Neptunian satellites U XIX Prospero, U XXI Trinculo, and we used it to observe the Uranian satellites U XVIII Prospero, U XIX Setebos, and U XXI Trinculo as well as the Neptunian satellites U XIX Prospero, U XXI Trinculo.

A number of standard stars (Landolt 1992) were observed each night, covering the same elevation as the science targets. Transformation equations containing zero points, air-mass corrections, and color corrections were determined and thus were used to determine the $V$ magnitude and colors ($B-V$ and $V-R$) of the science targets. The DAOPHOT package under the IRAF environment was used for all the data reduction.

The MagIC instrument is a single SITe 2048 × 2048 CCD camera with a rather small field of view, 2′ × 2′. For the MagIC observations a Harris BVR filter set was used. The seeing during the observations varied from 1′′.2 to 2′′.0. We performed aperture photometry using inner and outer apertures of 1′′.725 and 4′′.14, respectively. The aperture corrections were small (0.05–0.21 mag) in all filters. Using the observed Landolt standard stars we determined the following transformation equations:

\[
B = b + 26.80 - 0.22a, \quad (1)
\]

\[
V = v + 26.94 - 0.21a, \quad (2)
\]

\[
R = r + 27.15 - 0.15a, \quad (3)
\]

where $b$, $v$, and $r$ are the instrumental magnitudes and $a$ is the air mass. Color corrections were included in the determination of the transformation equations but were negligible.

The DEep Imaging Multi-Object Spectrograph (DEIMOS) is an optical wavelength imaging spectrograph. We used the instrument in direct imaging mode. The seeing varied from 0′′.8 to 1′′.2. We again used aperture photometry, using an inner and outer aperture of 0′′.95 and 2′′.37, respectively. The aperture corrections were also small (0.05–0.29 mag) in all filters.

The filters available for the DEIMOS are rather special and do not conform to any of the usual filter systems. We therefore included color corrections in the determination of the transformation equations from instrumental to photometric magnitude. The color corrections in the $B$ and $V$ filters were non-negligible but still small given the moderate colors of our targets. For the Keck II observations we derived the following transformation equations:

\[
B = b + 27.33 - 0.24a + 0.23(B - V), \quad (4)
\]

\[
V = v + 27.90 - 0.24a - 0.15(B - V), \quad (5)
\]

\[
R = r + 28.06 - 0.15a, \quad (6)
\]

where, again, $b$, $v$, and $r$ are the instrumental magnitudes and $a$ is the air mass.

3. THE RESULTS

The data collected are presented in Table 1 and plotted in a standard $B - V$ versus $V - R$ diagram in Figure 1. The colors are similar to those found among the Jovian and Saturnian satellites, and the colors seem to be loosely separated into two groups. One is essentially neutrally colored containing Prospero, Setebos, the two Neptunian satellites observed, and possibly Trinculo. The other is slightly red and contains the two large Uranian satellites Caliban and Sycorax. The Uranian irregular satellite Stephano may, due to its large error bars, be put in either of the two groups. Interestingly, neither the Uranian nor the Neptunian irregular satellites have members with the extremely red colors found among the Kuiper Belt objects.

Caliban, Sycorax, and Nereid have had their colors determined previously (Schaefer & Schaefer 2000; Maris et al. 2001; Romon et al. 2001). The colors determined in this Letter are in excellent agreement with the results of these papers, except for the $B - V$ colors of Caliban and Sycorax determined by Maris et al. (2001). Their $B - V$ colors are higher than and inconsistent with ours even at the 3 σ level. We are unable to explain this discrepancy.

| Object               | $m_v$ (1, 1, 0) | $V$ | $B - V$ | $V - R$ | $r$ (AU) | $\Delta$ (AU) | $\alpha$ (deg) | $D$ (km) | Telescope       |
|----------------------|-----------------|-----|---------|---------|----------|--------------|--------------|--------|----------------|
| U XVI Caliban ........| 9.16 ± 0.04     | 22.58 ± 0.02 | 0.84 ± 0.03 | 0.57 ± 0.03 | 20.02 | 19.11 | 1.33 | ~74 Magellan |
| U XVII Sycorax ...... | 7.50 ± 0.04     | 20.94 ± 0.01 | 0.78 ± 0.02 | 0.62 ± 0.01 | 20.08 | 19.18 | 1.34 | ~159 Magellan |
| U XVIII Prospero .....| 10.56 ± 0.05    | 23.91 ± 0.03 | 0.80 ± 0.06 | 0.39 ± 0.04 | 20.15 | 19.20 | 1.09 | ~39 Keck II  |
| U XIX Setebos .......| 10.57 ± 0.05    | 23.88 ± 0.03 | 0.77 ± 0.06 | 0.35 ± 0.03 | 19.96 | 19.02 | 1.10 | ~39 Keck II  |
| U XX Stephano .......| 11.69 ± 0.17    | 25.12 ± 0.17 | 0.27 ± 0.24 | 0.67 ± 0.22 | 20.07 | 19.16 | 1.32 | ~23 Magellan |
| U XXI Trinculo .......| 11.92 ± 0.18    | 25.25 ± 0.18 | 1.09 ± 0.40 | 0.35 ± 0.19 | 20.07 | 19.12 | 1.08 | ~21 Keck II  |
| N II Nereid ........  | 4.44 ± 0.01     | 19.25 ± 0.01 | 0.66 ± 0.01 | 0.39 ± 0.01 | 30.07 | 29.06 | 0.26 | ~384 Magellan |
| S/2002 N1 ...........| 0.73 ± 0.13     | 0.35 ± 0.07  |         |         |         |         |         |        |                |
|                     |                 | 0.07 ± 0.06  | 0.87 ± 0.10 | 0.29 ± 0.08 | 30.12 | 29.11 | 0.25 | ~47 Magellan |
|                     |                 | 0.08 ± 0.09  | 0.51 ± 0.16 | 0.47 ± 0.12 | 30.12 | 29.10 | 0.08 | ~34 Keck II  |
Using the geometric circumstances of the observations (see Table 1) we have used the observed $V$ magnitude to derive absolute magnitudes at zero phase angle and unit heliocentric and geocentric distances. The equation used is $m_V(1, 1, 0) = V - 5 \log \Delta r - \beta \alpha$, where $V$ is the observed magnitude, $\alpha$ is the phase angle, $\beta$ is the phase-angle correction factor, and $\Delta$ and $r$ are the geocentric and heliocentric distances, respectively. While the distances and the phase angle are well-known quantities, the linear phase coefficient $\beta$ is highly uncertain. Schaefer & Tourtellotte (2001) observed Nereid at a range of phase angles and found $\beta = 0.38$ for $\alpha < 1^\circ$. This value is similar to the phase coefficients of small, inner Uranian satellites (Karkoschka 2001). We will use this value to estimate the absolute magnitudes for both the Uranian and Neptunian irregular satellites. We use the derived absolute magnitudes to determine the sizes of the satellites, by applying the equation

$$D = \frac{1329 \times 10^{(m_V/5)}}{\sqrt{p}}.$$  

where $p$ is the geometric albedo of the satellite in the visual. The geometric albedo of the irregular satellites is another highly unknown property. Of the Uranian and Neptunian satellites, only Nereid has had its albedo determined at $p = 0.2$ (Thomas et al. 1991). This value is significantly larger than that of the small inner Neptunian satellites ($p = 0.06$), the small inner Uranian satellites ($p = 0.07$), J VI Himalia ($p = 0.05$), and S IX Phoebe ($p = 0.08$). Based on this, we have chosen to use $p = 0.07$ for the Uranian irregular satellites and $p = 0.2$ for the Neptunian irregular satellites. The resulting sizes are given in Table 1.

3.1. The Uranian Irregular Satellites

Unfortunately, the colors of the Uranian irregular satellites offer little information about the satellites' origin. To check for dynamical families among the Uranian irregular satellites, we performed long-term ($t \sim 10^4$ yr) integrations of the nominal orbits of the known irregular satellites using a symplectic $n$-body integration scheme modified to handle satellite orbits. Perturbations from the Sun and the four giant planets were included, and our resulting average elements are similar to those found by Nesvorny et al. (2003; the average elements found in our integrations are plotted in Fig. 2, which includes three Uranian irregular satellites discovered after Nesvorny et al. was published).

From the average orbital elements we divide the known Uranian irregular satellites into two possible dynamical families, based on their similar mean orbital elements. The Caliban family thus includes Caliban, Stephano, and S/2001 U3, while the Sycorax family consists of Sycorax, Prospero, and Setebos. It should be noted that this separation into groups has been done by comparing the semimajor axes, eccentricities, and inclinations of the satellites. This separation leaves Trinculo, S/2001 U1, and S/2003 U3 (the only prograde Uranian irregular satellites).
ellipt known to date) as single objects. It is interesting to note that Trinculo and S/2001 U1 have very similar inclinations, similar to the two prograde Saturnian irregular satellites, and could thus be a possible third dynamical family or perhaps the results of a different capturing process than the other Uranian irregular satellites. Their separation in average semimajor axis is significantly larger, $\Delta a = 0.08$ AU, than that of the Saturnian Inuit and Galactic clusters ($\Delta a = 0.01$ AU and $\Delta a = 0.04$ AU, respectively).

It is thus clear that if the known Uranian irregular satellites are indeed clustered into dynamical families, these two families have heterogeneous colors. It should be noted that this is not necessarily hard evidence against family structure. The Hilda asteroids, for example, have an apparent spectral slope size, with the large members being P-type asteroids and the smaller members being D-type asteroids (Dahlgren & Lagerkvist 1995; Dahlgren et al. 1997). It is possible that the Uranian irregular satellites have a similar size-color correlation, but the low number of known objects available make this theory pure speculation.

3.2. Nereid and S/2002 N1

The observed colors of Nereid and S/2002 N1 are basically the same, suggesting similar surface compositions. Studies of the collisional probabilities between the irregular satellites of Neptune show that Nereid and S/2002 N1 have a high probability of colliding (0.41) over 4.5 Gyr (Holman et al. 2004). The similar colors of these two objects thus point to the possibility that S/2002 N1 is a fragment of Nereid. The low-amplitude light curve of Nereid (Grav et al. 2003b) offers no photometric evidence that Nereid was ever catastrophically disrupted; however, Voyager II images suggest a cratered body (Thomas et al. 1991). We suggest that S/2002 N1 is therefore ejecta from a cratering event on Nereid. This hypothesis would be further supported if smaller irregular satellites with similar colors and high collisional probabilities to Nereid were found. The neutral colors of Nereid and S/2002 N1 do not give any new hint to the possible origins of the two satellites. The colors, albedo, and spectra of Nereid are similar to both regular satellites, such as Oberon and Umbriel (Buratti & Mosher 1991; Brown et al. 1999), and several Kuiper Belt objects (Tegler et al. 2003). The large difference in magnitude between the two observations of S/2002 N1 indicates that the object has a significant rotational light curve, most likely due to an out-of-round shape.

4. CONCLUSIONS

We have reported $BVR$ colors of six Uranian and two Neptunian irregular satellites. The colors are similar to that of the Jovian and Saturnian irregular satellites (Grav et al. 2003a). It seems, however, unlikely that the irregular satellites of Uranus and Neptune have origins in the outer main asteroidal belt. The lack of extremely red objects among the observed Uranian and Neptunian irregular satellites makes their color distribution different from that of the Centaurs and Kuiper Belt, thus hinting at an origin among the outer planets. Note that the lack of extremely red objects could just be due to the small sample of objects studied. Further study of the irregular satellite population should settle this issue.

The heterogeneity of the possible dynamical families in the Uranian irregular system leads us to question the veracity of the apparent dynamical families. With both Uranus and Neptune possibly having undergone special events (the great collision [Brunini et al. 2002] and the capture of Triton [Farinella et al. 1980]), it seems uncertain whether one would expect any dynamical families of irregular satellites to exist around the two planets. If one chooses to invoke the hypothesis that the Caliban and Sycorax clusters are indeed real families, one has to favor the theory that the similar inclinations of Trinculo and S/2001 U1 are due to a different capturing process than the rest of the Uranian irregular satellites, due to their large separation of semimajor axes. Further study of this is necessary.

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