NEAR-INFRARED PHOTOMETRY OF THE IRREGULAR SATELLITES OF JUPITER AND SATURN

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ABSTRACT

We present \( \text{JHK} \), photometry of 10 Jovian and four Saturnian irregular satellites, taken with the Near-InfraRed Imager at the 8 m Gemini North Observatory on Mauna Kea, Hawaii. The observed objects have near-infrared colors consistent with C-, P-, and D-type asteroids, although J XII Ananke and S IX Phoebe show weak indications in possible water features in the \( H \) filter. The four members of the Himalia family have similar near-infrared colors, as do the two members of the Gallic family, S XX Paaliaq and S XXIX Siarnaq. From low-resolution, normalized reflectance spectra broad on the broadband colors and covering 0.4–2.2 \( \mu \text{m} \), the irregular satellites are identified as C-type (J VII Pasiphae, J VI Himalia, and S IX Phoebe), P-type (J XII Ananke and J XVIII Themisto), and D-type (J IX Carme and J X Sinope), showing a diversity of origins for these objects.

Subject headings: \begin{itemize}
\item planets and satellites: general
\item planets and satellites: individual (Ananke, Himalia, Pasiphae, Phoebe, Sinope)
\end{itemize}

1. INTRODUCTION

The satellites of the giant planets can be divided into two classes, regular and irregular, based on their orbital characteristics. The regular satellites are thought to have been formed in a planetocentric disk with nearly circular, prograde orbits close to the equatorial plane of the planet. The irregular satellites, however, have highly inclined and eccentric orbits, both prograde and retrograde. These orbital characteristics suggest that they formed outside the circumplanetary disk and were subsequently captured. Objects in heliocentric orbits can be temporarily captured, for 10–100 orbits. Several mechanisms for making a temporary capture permanent have been proposed: (1) fragmentation during a single collision between an outer satellite and an asteroid (Colombo & Franklin 1971); (2) a rapid increase in the mass of a planet during formation; and (3) gas drag from an extended gas envelope (Pollack, Burns, & Tauber 1979) or a flattened disk (Čuk & Burns 2004) around the planet. All these theories imply different dynamical distributions, capture timescales, and satellite ages.

Determining the physical characteristics of the irregular satellites is key to understanding their origin. In Grav et al. (2003) and Grav & Holman (2003), we reported a large set of optical \( \text{BVRI} \) colors of the irregular satellites and showed that most of the dynamical clusters have homogeneous colors, indicating that the clusters are the result of the capture of larger progenitors that were subsequently disrupted (Gladman et al. 2001). The optical colors are consistent with the progenitors being outer main belt asteroids due to the lack of the extremely red colors found among the Centaur and Trans-Neptunian object population. Extending the wavelength coverage into the near-infrared significantly helps in distinguishing between the possible origins of the progenitors.

Cruikshank (1980) and Degewij, Cruikshank, & Hartmann (1980) reported near-infrared observations of the irregular satellites J VI Himalia and S IX Phoebe and found that the colors were different from those of the regular satellites, looking like low albedo carbonaceous chondritic asteroids. \( \text{IJHK} \)-band spectroscopy of J VI Himalia was collected by Dumas, Owen, & Barucci (1998), and Brown (2000) presented 1.3–2.4 \( \mu \text{m} \) near-infrared spectra of J VI Himalia, J VII Elara, J VII Pasiphae, S IX Phoebe, and N II Nereid. The three Jovian irregular satellites have flat, featureless spectra consistent with dark, carbonaceous chondrites. Both S IX Phoebe and N II Nereid had broad absorption features centered on 2 \( \mu \text{m} \), indicating the presence of water ice. They argued that the presence of water ice on S IX Phoebe demonstrated that it is a captured outer solar system body rather than an asteroid. The Two Micron All Sky Survey (2MASS) detected six of the then eight known Jovian irregular satellites in the \( \text{JHK} \), bandpasses (Sykes et al. 2000b). They found colors that were consistent with C- and D/P-type asteroids, except for J X Sinope, which had an extreme \( J—H \) color. However, their \( 1 \sigma \) errors were significant in that they were evenly distributed in the range from 0.03 (J VI Himalia) to 0.28 (J X Sinope).

This work reports near-infrared photometry of 10 Jovian and four Saturnian irregular satellites. In § 2, we discuss the observations and the routines used for image reduction, data analysis, and calibration. In § 3, we discuss our result and compare it with the results of other observations of irregular satellites in the near-infrared wavelength region. In § 4, we discuss the implications of our observations. Note that when referring to C-, P-, and D-type asteroids in the following text, we are using the taxonomical classification scheme developed by Tholen (1984).

2. THE OBSERVATIONS

Using the Gemini North 8 m Telescope with the Near InfraRed Imager (Hora et al. 1995), we observed the irregular satellites in classical observing mode on 2003 February 17–19. The camera was used in its f/6 direct imaging configuration, giving it a scale of 0'017 pixel\(^{-1}\). All three nights were clear and photometric, with seeing of 0'6–1'3. We used a standard \( \text{JHK} \), filter set, in which \( K_{\alpha} \), (or \( K \) “short”) is a medium-band modified \( K \) filter used to reduce thermal background from the warm telescope and surrounding structures (Persson et al. 1998). The \( K_{\alpha} \) and \( K \) filters have a virtually identical throughput with differences on the ± 0.01 mag level (Persson et al. 1998).

The data reduction was performed in IRAF using the Gemini and DAOPHOT packages. Flat-field and dark exposures were taken at morning and/or evening twilight and were combined to make normalized flat-field images and bad-pixel maps. Sky frames were created from the dithered science images. The science images

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were sky-frame–subtracted and flat-field–divided, resulting in images with less than 2% variation across the field. Some unidentified 60 Hz noise coming from the instrument or telescope was evident in some of the images but was too low to contribute significantly to the estimated errors of the photometry.

Aperture photometry was performed. The signal-to-noise ratio for the observed targets was large enough that aperture-correction photometry was not needed. An aperture of ∼300 (25 pixels) was used along with a sky annulus starting at ∼300 (30 pixels) with a width of ∼2.4 (20 pixels wide).

A number of UKIRT near-infrared standard stars (Hawarden et al. 2001) were taken throughout the night spanning the air mass of our science targets. The standard stars were used to derive zero points, air-mass corrections, and filter-color corrections.

### Table 1: Circumstances and Results of Our Observations

| Object          | Date (UT)      | Air Mass (AU) | ∆ (AU) | α (deg) | K<sub>1</sub> (1 a) | J−H (1 a) | H−K<sub>1</sub> (1 a) | J−K<sub>1</sub> (1 a) |
|-----------------|----------------|--------------|--------|---------|---------------------|-----------|-----------------------|---------------------|
| S IX Phoebe     | 2003 Feb 18 (08:55) | 1.3–1.4     | 9.052  | 8.614   | 5.745               | 14.86 ± 0.01 | 0.22 ± 0.01 | 0.35 ± 0.01 | 0.57 ± 0.01 |
| S XXIX Siarnaq  | 2003 Feb 18 (06:00) | 1.0–1.1     | 8.983  | 8.556   | 5.822               | 18.49 ± 0.01 | 0.35 ± 0.02 | 0.19 ± 0.02 | 0.54 ± 0.02 |
| S XX Paaliaq     | 2003 Feb 20 (06:20) | 1.0–1.1     | 9.114  | 8.721   | 5.827               | 19.43 ± 0.06 | 0.42 ± 0.06 | 0.05 ± 0.08 | 0.47 ± 0.09 |
| S XXV Albiorix   | 2003 Feb 19 (05:15) | 1.0–1.1     | 9.076  | 8.667   | 5.814               | 18.79 ± 0.03 | 0.48 ± 0.06 | 0.33 ± 0.04 | 0.81 ± 0.07 |
| J VI Himalia     | 2003 Feb 20 (09:50) | 1.0–1.1     | 5.254  | 4.315   | 3.727               | 13.35 ± 0.01 | 0.32 ± 0.01 | 0.26 ± 0.01 | 0.58 ± 0.01 |
| J VII Elara      | 2003 Feb 20 (09:25) | 1.0–1.1     | 5.308  | 4.376   | 3.911               | 15.27 ± 0.01 | 0.31 ± 0.01 | 0.37 ± 0.01 | 0.68 ± 0.01 |
| J VIII Pasiphae  | 2003 Feb 19 (08:50) | 1.0–1.1     | 5.203  | 4.269   | 3.932               | 15.10 ± 0.01 | 0.39 ± 0.01 | 0.22 ± 0.01 | 0.61 ± 0.01 |
| J IX Carne       | 2003 Feb 20 (12:00) | 1.3–1.4     | 5.196  | 4.264   | 4.036               | 15.74 ± 0.01 | 0.34 ± 0.01 | 0.21 ± 0.01 | 0.55 ± 0.02 |
| J X Sinope       | 2003 Feb 19 (08:15) | 1.0–1.1     | 5.194  | 4.254   | 3.721               | 16.05 ± 0.01 | 0.38 ± 0.01 | 0.23 ± 0.01 | 0.61 ± 0.01 |
| J XI Lyssithea   | 2003 Feb 20 (08:45) | 1.0–1.1     | 5.366  | 4.425   | 3.538               | 16.30 ± 0.01 | 0.39 ± 0.01 | 0.31 ± 0.01 | 0.70 ± 0.01 |
| J XII Ananke     | 2003 Feb 19 (13:30) | 1.6–2.0     | 5.443  | 4.502   | 3.493               | 17.33 ± 0.01 | 0.24 ± 0.02 | 0.14 ± 0.02 | 0.38 ± 0.02 |
| J XVIII Themisto | 2003 Feb 18 (09:40) | 1.0–1.1     | 5.283  | 4.335   | 2.322               | 18.30 ± 0.02 | 0.33 ± 0.02 | 0.10 ± 0.02 | 0.43 ± 0.02 |
| J XVII Callirhoe | 2003 Feb 19 (11:25) | 1.1–1.5     | 5.231  | 4.277   | 3.861               | 19.17 ± 0.10 | 0.46 ± 0.07 | 0.25 ± 0.12 | 0.71 ± 0.12 |

3. RESULTS

The results of our observations of 10 Jovian and four Saturnian irregular satellites are given in Table 1. Seven of these satellites were previously unobserved in the JHK bandpasses. Our results of the six brightest Jovian irregular satellites are generally consistent with Sykes et al. (2000b), but we have significantly improved on the errors of the photometry (the average of the JHK<sub>1</sub> color errors reported here is ∼0.03). Figure 1 shows the J−H versus H−K colors of the objects observed. In this figure, we have also plotted the areas of JHK<sub>1</sub>, phase space populated by known C-, D-, F-, and P-type asteroids as observed by 2MASS (Sykes et al. 2000a). From Figure 1, we see that most of the satellites are consistent with these outer main belt asteroids. There are, however, three satellites, J VII Elara, J XII Ananke, and S IX Phoebe, that lie outside these areas. It should be noted that the few Centaurs observed in the near-infrared also fall into a similar range of near-infrared colors (Weintraub, Tegler, & Romanishin 1997; Brown 2000).

Figures 2–4 shows the low-resolution spectra of the objects observed. The spectra shown are normalized at the V filter (0.53 μm). The BVRI colors have been taken from Rettig, Walsh, & Consolmagno (2001) and Gray et al. (2003), and solar colors were adopted as B−V = 0.67, V−R = 0.36, V−I = 0.71, V−J = 1.08, V−H = 1.37, and V−K = 1.43 (Jewitt & Luu 1998; Degewij et al. 1980). Note that there are values given for solar H−K and J−K colors by other authors that differ from this (e.g., Johnson et al. 1975).

Only a few V−J colors of irregular satellites are available. Values for J VI Himalia and S IX Phoebe were taken from Cruikshank (1980) and Degewij et al. (1980). To determine values for V−J for the other targets, the V observations from Gray et al. (2003) were corrected for the heliocentric, geocentric, and phase-angle difference between the V and J observations using

\[ H(1, 1, 0) = m - 5 \log \Delta R - \beta \alpha, \]

where \( m \) is the apparent magnitude, \( R \) is the heliocentric distance, \( \Delta \) is the geocentric distance, \( \beta \) is a constant phase coefficient, and \( \alpha \) is the phase angle. However, S IX Phoebe is the only irregular satellite of Jupiter and Saturn for which a phase coefficient has been determined (Kruse, Klavetter, & Dunham 1986). At low phase angles (\( \alpha < 1^\circ \)), Kruse et al. (1986) found \( \beta = 0.18 \pm 0.04 \) mag deg<sup>−1</sup>, but at larger phase angles...
angles ($\alpha > 2^\circ$), they found that the constant phase coefficient falls to $\beta \approx 0.10$ mag deg$^{-1}$. We have adopted the value of $\beta = 0.10$ mag deg$^{-1}$ since all of the observations from Grav et al. (2003) are at higher phase angles than $2^\circ$. Note that no correction due to rotational variations has been applied. To better compare members of the same families, the $V$--$J$ values of the brightest member were used for all the family members. This, of course, makes the spectra seem more similar at first glance than might be justified, but it significantly increases our ability to compare the visual and infrared observations. The errors plotted for the $JHK_s$ colors do not take into account the errors in our derivation of the $V$--$J$ colors since this does not change any of our arguments.

For the Himalia and Gallic (the Saturnian 45$^\circ$ inclination) families, we observed more than one member and thus can test if the homogeneous colors found in Grav et al. (2003) extend into the near-infrared. Figure 3 shows the low-resolution spectra for the four members of the Himalia family (S/2000 J11 has not been observed beyond the discovery apparition and is considered lost). The four spectra are very similar, all consistent with spectra of C-type asteroids. The only noticeable difference lies in the slightly redder color of J XI Lysithea in the visual wavelengths, but these differences are within the 3 $\sigma$ errors. The low-resolution spectra of the two objects observed from the Gallic family, S XX Paaliaq and S XXIX Siarnaq, are plotted in Figure 4. The two spectra are very similar and seem to be consistent with a P-type asteroidal surface. The results from this survey further strengthen the arguments from Grav et al. (2003) for the dynamical families being remainders of larger progenitors captured and subsequently fragmented as a result of collisions.

Using the low-resolution reflectance spectra, we identify J VIII Pasiphae as a C-type asteroid, J XII Ananke and J XVIII Themisto as P-type asteroids, and J IX Carme, J X Sinope, and J XVII Callirrhoe as D-type asteroids. For the Saturnian irregular satellites, S IX Phoebe is identified as having an F-type asteroidal surface, while the surface of S XXVI Albiorix is consistent with that of a P-type asteroid. The low-resolution spectra show the large diversity among the irregular satellites of Jupiter and Saturn, ranging from the slightly blue spectrum of the Himalia family members and S IX Phoebe to the red spectrum of J IX Carme, J X Sinope, and S XXVI Albiorix. Higher resolution spectra are needed, however, to secure these identifications. We looked for correlations between spectral type and orbital parameters, but no apparent patterns were found.
The data seem to indicate that S IX Phoebe and J XII Ananke have some small degree of contamination of water ices. A broad absorption feature centered on ∼2.0 μm as a result of water ices has been detected on S IX Phoebe in spectra by Owen et al. (1999) and Brown (2000). Our observations of S IX Phoebe confirm the colors found by both Cruikshank (1980) and Degewij et al. (1980). Most likely, the two observations by Degewij et al. (1980), which do not agree with our results, are taken at different rotational phases than our observations. S IX Phoebe is known to have a bright spot with a peak albedo of 0.11 that is significantly higher than the 0.07 albedo of the rest of the surface (Simonelli et al. 1999).

4. CONCLUSIONS

We have collected near-infrared colors of 10 Jovian and four Saturnian irregular satellites. The colors are found to be consistent with the C-, F-, D-, and P-type asteroids found in the outer parts of the main asteroid belt. The near-infrared colors show that four members of the Himalia family have homogeneous colors, with weighted mean colors of $J/H = 0.34 \pm 0.02$, $H-K_s = 0.27 \pm 0.02$, and $J-K_s = 0.65 \pm 0.02$. The observed colors, with weighted mean colors of $J/H = 0.37 \pm 0.01$, $H-K_s = 0.16 \pm 0.02$, and $J-K_s = 0.53 \pm 0.01$. The homogeneous colors of these two families further support the hypothesis that these families are the remnants of larger progenitors that were captured and subsequently fragmented (Gladman et al. 2001; Grav et al. 2003).

Adding observations in the visual wavelengths and plotting the results as a reflectance spectra normalized at V show that the irregular satellites of Jupiter and Saturn have surfaces ranging from the neutral members of the Himalia family and S IX Phoebe to the red spectra of J IX Carme, J X Sinope, and S XXVI Albiorix. Furthermore, the low-resolution spectra of J XII Ananke and S IX Phoebe show weak indications of broad absorption features centered on 2.0 μm as a result of water ices. These features have been identified in S IX Phoebe using higher resolution spectra (Owen et al. 1999; Brown 2000).

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