Investigations into u'-band Photometry of the Haumea System

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INVESTIGATIONS INTO U’-BAND PHOTOMETRY OF THE HAUMEA SYSTEM

by

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Submitted to Brigham Young University in partial fulfillment of graduation requirements for University Honors

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Brigham Young University
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INVESTIGATIONS INTO U'-BAND PHOTOMETRY OF THE HAUMEA SYSTEM

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The dwarf planet Haumea orbits near the edge of the Solar System in the Kuiper Belt. As it rotates, different parts of the object can be seen from Earth, so observing Haumea as it rotates allows us to see whether the surface is uniform or varied. Previous work has shown that one part of Haumea has a reddish dark spot, as opposed to the bright gray surface, and that Haumea has two nearby moons, the larger of which is called Hi’iaka. To better understand Haumea’s surface and Hi’iaka, we gathered new observations using BYU time at the Astronomical Research Consortium 3.5-m telescope at Apache Point Observatory. These data include ultraviolet measurements of the Haumea system in order to determine relative colors for Haumea (including its dark red spot) and its largest moon Hi’iaka. We fit sinusoidal models to this Haumea system data, including the unresolved contribution of Hi’iaka, using Bayesian parameter inference powered by Markov Chain Monte Carlo methods. We here present our model fits for the rotational light variation of Haumea and Hi’iaka, with implications for Haumea’s surface and formation. We also discuss the results of the model fits in terms of the relative colors of Haumea and Hi’iaka. This new information may lead to a better understanding of the origins and interactions of Haumea and Hi’iaka.
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INVESTIGATIONS INTO U’-BAND PHOTOMETRY OF THE HAUMEA SYSTEM

INTRODUCTION: THE HAUMEA SYSTEM

Haumea is a dwarf planet located in the Kuiper Belt, discovered in 2004 [1]. As a dwarf planet, Haumea is relatively small and has not cleared its orbit. According to the JPL Horizons ephemeris, it has a semimajor axis of 42.9 AU, an inclination of 28.2 degrees, and an eccentricity of 0.2. The Haumea system is comprised of Haumea itself, two moons (Hi'iaka and Namaka) [2], a thin ring [3], and a family of associated Trans-Neptunian Objects (TNOs). Haumea is the largest member and likely source of this collisional family. Although such collisional families are common in the asteroid belt, the Haumea family is unique among TNOs [4].

In addition to this complex system, Haumea is interesting for its rapid rotational period of 3.9 hours, and its resulting unique triaxial Jacobi ellipsoid shape. Essentially, Haumea can be modeled as an ellipsoid with each axis having a different length. The shape is often compared to an egg or a rugby ball. Haumea's egg-like shape results in a variable lightcurve with a shape best described as a double-peaked sinusoid [5]. Additionally, Haumea is known to have significant color-rotational variability, suggesting the presence of a Dark Red Spot on its surface [6] (see Figure 1). These unique aspects of Haumea and its family make it an interesting subject of study in its own right, but Haumea could also teach us about the history of other parts of the Solar System.

Characterizing the surface of Haumea and its moons will lead to a more complete understanding of the Haumea family and how it formed [7]. Currently there are several
theories for the family's formation, including a grazing collision and a binary merger. More clearly characterizing Haumea and its moons, and comparing their characteristics with those of other objects in the Haumea family in turn, will provide clues about which Haumea family formation theories are most accurate, as well as inform us about the formation of the solar system as a whole, including how, when, and where the planets formed.

PHOTOMETRY AND ASTRONOMICAL COLOR

In order to move towards a more complete understanding of the Haumea family and its history, we conducted u'-band photometry of Haumea. Photometry is a method where the observer uses a telescope to measure the amount of light emitted (or in the case
of TNOs, reflected) by an astronomical object. This flux is measured in "counts" by a CCD detector chip attached to the telescope. By gathering data through a variety of wavelength bandpass filters, the astronomer records how much light is reflected by an astronomical object within those different wavelength bands (see Figure 2).

![Filter Transmission SDSS ARCTIC](image)

**FIGURE 2.** Wavelength bands for filters used in this project (u', g', r'). Source: Apache Point Observatory Filter Database.

In the past, TNO photometry has been primarily conducted in the visible and near-infrared range. Initial work with u'-band (near-ultraviolet and a very small amount of visible blue) photometry has shown that it can reveal surface information not found in other visible wavelength bands, including potentially confirming Haumea family members. In addition, the Legacy Survey of Space and Time (LSST), conducted at the Vera Rubin Observatory, will soon revolutionize u'-band photometry for small bodies by significantly increasing the amount of u'-band data available for these objects. Looking
forward to this promised future bounty of data increases the importance of obtaining good u'-band photometry now.

Time-resolved photometry allows us to create and compare Haumea's lightcurves in different filters. Comparing lightcurves can give us an idea of relative surface variability in different wavelength bands (see [6]). These relative surface variations can be described quantitatively by comparing the amount of light passed through different filters to obtain the object's color. Because different materials reflect different wavelengths of light in different amounts, measuring color leads to clues about surface characteristics. We analyzed time-resolved u'-band photometry of the Haumea system in order to determine the relative u’-g’ colors for Haumea, including its Dark Red Spot.

METHODS

We began by applying standard corrections to the photometric images and then obtaining effective point-spread functions (ePSFs) and lightcurves from the time-resolved photometry. We then fit models to these lightcurves and compared the models in order to obtain relative colors. Separate scripts were used for data reduction and model fitting, all of which were developed uniquely for this project. The data reduction script took as an input the raw images, and output the cleaned images after applying bias, dark, and flat correction frames and making other corrections, which will be described below. A new, customized data reduction script was created specifically for this project, leading to a higher quality of data reduction than could be obtained with a more generic process. The model fitting code utilized Emcee, a Markov Chain Monte Carlo sampler, to fit a double-
sinusoid model to the data through Bayesian parameter inference [8]. In addition to finding the best fit, we also compared a number of satisfactory-but-not-best fits to determine a reasonable estimate for the model error. We then used the best-fit models and errors to find relative color measurements for each night of data.

OBSERVATIONS

Observations were performed remotely using the Astrophysical Research Consortium Telescope Imaging Camera (ARCTIC) instrument on the Astrophysical Research Consortium 3.5-meter telescope at Apache Point Observatory, New Mexico. We used a STA4150LN BI 4096 × 4096 pixel charge-coupled device (CCD) detector with 15-micron pixels, which yielded a plate scale of 0.114 arc seconds per pixel and a 7.85 square arc minute field of view. A complete description of the instrument can be found on the Apache Point Observatory website. ARCTIC employs the Sloan Digital Sky Survey filters. Photometric data was obtained using the SDSS u', g', and r' filters [9].

Imaging was conducted over four nights: March 7, 23, and 27, 2021, and April 8, 2022. However, after evaluating the resulting data the decision was made not to use data obtained the night of March 27, 2021 in the modeling, because poor observing conditions stopped us from observing in all but the r' filter. Therefore, our results are based on the data from the other three nights. We also note that on the night of March 7, images were also taken in the SDSS near-infrared i' and z' filters. However, due to the low number of usable images in the near-infrared data, along with the widespread availability of near-IR data on Haumea, the decision was made to prioritize the visible spectrum for future
observations. Table 1 lists specific information about the images taken in each observing run, including number of images, total observing time in hours from first to last science image, exposure times for each filter in seconds, and filter sequence. Work on this thesis began in summer 2021, and the decision to focus on u’-band photometry was made then, based on preliminary results from the 2021 data. For this reason, the data obtained in 2022 includes more and higher quality u’ exposures than the other datasets.

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Number of Images</th>
<th>Total observing time</th>
<th>Exposure time (u’)</th>
<th>Exposure time (g’)</th>
<th>Exposure time (r’)</th>
<th>Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>210307</td>
<td>107</td>
<td>4.984584</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>g’g’g’r’r’u’z’i’</td>
</tr>
<tr>
<td>210323</td>
<td>123</td>
<td>3.616536</td>
<td>120</td>
<td>90</td>
<td>90</td>
<td>r’r’r’u’r’r’r’g’</td>
</tr>
<tr>
<td>220408</td>
<td>70</td>
<td>3.674496</td>
<td>180</td>
<td>120</td>
<td>120</td>
<td>u’g’u’r’</td>
</tr>
</tbody>
</table>

**Table 1.** Observation details: UT date, number of images, total observing time in hours from first to last science image, exposure time for each filter in seconds, and filter sequence.

We noted a relatively high separation for Haumea and Hi’iaka on the nights of March 7 and 23 (approximately 0.78" and 1.3" respectively). Although the two bodies were not distinguishable in the photometry by eye, the point spread function of Haumea did appear elongated in some images (see Figure 3). This high separation allowed us to investigate the signal of Hi’iaka in more detail than we otherwise could have done.

In addition to ARC observations, we also reanalyzed data published in [6] and [10]. This was done for two purposes. First, to make sure our methods produced good quality results, we compared the results of our analysis to those obtained by [6]. Second, because we assessed a slightly different wavelength range using different modeling methods, we assessed whether our analysis would lead to any additional insights, especially when decades-old and recent data were compared.
DATA REDUCTION

We developed a new data reduction script using Python, which is customized to accommodate unique features of the ARCTIC instrument. The reduction code makes standard bias, dark, and flat corrections, removes overscan areas, and cleans cosmic rays. The overscan area is an electronic artifact where rows or columns of empty pixels appear on the image and does not represent useful information. Unlike most astronomical images, ARCTIC images obtained using the instrument’s quad readout mode are composed of four quadrants stitched together, so that the overscan areas form a cross in the middle of the image. Our data reduction code removes this unique overscan area and

FIGURE 3. Portion of an image obtained on March 23, 2021, where the asymmetry in the point spread function (PSF) due to Hi'iaka is especially evident. Compare the PSF of the Haumea system (top left) to the PSF of a star (lower right).
then stitches the resulting four images back together in order to create a usable image (see Figure 4).

![Figure 4](image)

*FIGURE 4. Comparison of unprocessed (left) and processed (right) images.*

Of the three sets of data used, standard star exposures were only taken on one night. As a result, we choose to use relative, flux-based photometry rather than absolute, magnitude-based photometry in analyzing the data. This approach, while less general, increases the amount of information available for analysis as well as the time span from which data can be drawn.

After correcting the images and obtaining relative fluxes using aperture photometry via AstroImageJ, we also normalized the data by dividing each measured flux by the arithmetic mean of all measured fluxes. This normalization was applied separately for each night and each filter. Due to differing photometric conditions on each night, the actual measured flux baselines varied between each night and filter. Normalizing the relative flux allowed comparison between multiple nights of data taken under different conditions. Because each of our observing periods ended at dawn, the normalization was
applied before conducting analyses on the data in order to minimize the impact of increasing sky brightness near the end of the observation period.

Effective point spread functions (ePSFs) were obtained for each image using the EPSFBuilder class in Photutils, which follows the methodology of [11] to empirically model the spread of point sources in the detector. An example of an ePSF for this data is shown in Figure 5, which illustrates the general shape of the point-spread function for a representative image. As previously discussed, for the high-separation images, Haumea's PSF differed significantly from the ePSF for each image (see Figure 3).

FIGURE 5. ePSF for a u' image from April 8, 2022. The horizontal and vertical axes represent pixel positions.
MODEL FITTING

We used Bayesian parameter inference powered by Markov Chain Monte Carlo methods to fit models to the Haumea system photometry. We included the unresolved influence of Hi’iaka’s lightcurve in the combined photometry, which has not been done before. Hi’iaka is about 10% as bright as Haumea and has approximately a 10% variation in its lightcurve, which can lead to small systematic effects in the Haumea data ([12]; Fernandez-Valenzuela et al., in preparation). In lieu of a specific physical model, we used a Fourier model for both Haumea and Hi’iaka. We used a double-sinusoid model based on the models used by [13] to parameterize our photometry of Haumea and Hi’iaka according to Equations 1 and 2. Note that the double-sinusoid term has a higher amplitude than the normal sinusoid, because we expect to see a double-peaked lightcurve for Haumea due to its unique shape. We chose to characterize Hi’iaka the same way (with the double-peaked sinusoid stronger than the single-peaked). This was based on the work of [12], who favored a double-peaked model for the lightcurve of Hi’iaka due to the likely nonspherical shape of the body.

EQUATION 1.

\[ F(t) = A_0 \sin(2\pi(\phi_0 + 2(t - t_0)/P)) + A_1 \sin(2\pi(\phi_1 + (t - t_0)/P)) \]

EQUATION 2.

\[ F_{total}(t) = F_{Haumea}(t) + F_{Hi'iaka}(t) + C \]

In Equations 1 and 2, \( A \) represents the amplitude of the curve, \( \phi \) represents the phase, \( t \) is the observation time, \( t_0 \) is a reference time (in our case, the date of the first observation), \( p_0 \) is the rotation period of the body, and \( C \) is an arbitrary offset. In order to
decrease the number of parameters and increase the accuracy of the model, we set fixed values of $P=3.915341$ hours for Haumea [14] and $P=9.79736$ hours for Hi'iaka [12].

We tested both two and three-term sinusoidal fits for both bodies and found that the addition of a third term improved the likelihood by less than 1, which was not enough to justify the additional parameters required. Therefore, we chose a double-sinusoid model to represent both Haumea and Hi'iaka individually. The lightcurve of Hi'iaka is thought by some to be more sawtooth-shaped than sinusoidal [12]. However, because Hi'iaka was unresolved in our observations, and because we never observed a full, unbroken period for Hi'iaka, uncertainties were high enough to make a double-sinusoid model sufficient.

Parameter fitting used Bayesian parameter inference powered by Markov Chain Monte Carlo using the Emcee package [8]. Holding the known spin periods fixed, each night and filter of data was analyzed separately to determine the amplitude and phase of each of the two components of Haumea and Hi'iaka and an overall offset. The parameter fitting MCMC script we used was called LCfit. LCfit takes as input the relative fluxes and relative flux errors of the reduced data files, and outputs a model fitted to those data points with their errors. Emcee also creates a posterior distribution, a collection of the final parameter sets obtained by every walker. This posterior distribution was accessed to ascertain as a visual means of ascertaining the fit quality: we represented the uncertainties by 500 random draws from the emcee posterior distribution, which provide the parameter sets of 500 good-but-not-best fits to the data. We created two separate scripts to analyze the whole system, first treating the combined sources as one body, then treating Haumea and Hi'iaka separately. The contributions of Namaka were too small to effectively
separate from the rest of the system. With this model, we can estimate the relative brightness of each component individually in each color at any time.

We note that light-time corrections were not included in the final analysis because they presented difficulties in phasing the data for analysis. This introduced only a small error because fits were done for each night individually, so the light-time variation between the included observations was small. However, there is a nonzero effect. Additionally, we chose not to include corrections for Haumea's phase angle due to the small duration of our observations compared to the 284-year orbital period of Haumea. Because we considered each observing period separately in our analyses, phase-angle corrections would have been minimal at most. Corner and likelihood plots were created to assess the quality of each fit (e.g. Figure 6). Corner plots utilized the Corner Python module created by [15].

This fitting process was also applied to the data published by [6] and visually compared to their best fits in order to validate our modeling methods (see Figure 8). Although we used a different modeling method from that used by these authors, the best fit found by our methods closely matched all of their models.

nPSF

In addition to analyzing these model fits and plots, we used the new code nPSF to investigate the point-spread function of the Haumea system in the observational data. As previously noted, the visual separation of Haumea and Hi'iaka was high on two of the nights of observing. We hoped that by comparing the image point spread function to that
of Haumea, we might see whether the model analyses were accurate in their predictions of Hi'iaka's colors. Point-spread functions were analyzed one image at a time, so that each corresponded to a different filter and night.

We compared the light variation between the lightcurve peaks of Haumea and Hi'iaka in the nPSF results with the values predicted by our model. For each filter, we found the measured difference in magnitude between the peaks of the lightcurve. We used a simple flux-magnitude conversion, without a baseline or standard stars, to obtain
this value. We then compared these measured values with the values expected from the best fit models. In general, we found that the lightcurve models predicted a smaller difference in magnitude between peaks than was calculated by nPSF.

RESULTS

Through lightcurve fitting, we obtained flux-based rotational u’-g’ and g’-r’ color variability models for the combined system. We here present our lightcurve fits for both Haumea and Hi‘iaka. The flux variation findings from the lightcurve fits were double checked against results obtained from PSF fitting. The colors were obtained by subtracting the best fit flux models for each filter and night of data, including uncertainties. These models show significant variations in u’-g’ color, as well as the expected variations in g’-r’ color, as a function of rotation. Although relative, our u’-g’ and g’-r’ colors still provide important insight into the characteristics of Haumea and its moon. We confirm the Dark Red Spot observed by [6] and others, validating our methods. We also observe regions bright in the u’-band, especially on Haumea.

We used the model plots more extensively than the data points to interpret our results. Bayesian modeling methods allow confidence in the predictive ability of the model to represent the behavior of the light curve between observed data points. Due to the constantly changing nature of Haumea's lightcurve, combined with the inability to obtain simultaneous observational data points for each filter, this is the best way to obtain colors at specific points in Haumea's phase. The final fit values can be found in the appendix.
In the following sections, we will give an overview of the fitted u', g', and r'-band lightcurves of Haumea and Hi'iaka, as well as the u'-g' and g'-r' colors of each body obtained from these lightcurve models. We describe qualitatively the results obtained, the assumptions and reasoning behind them, and the role these results may take in developing our understanding of the Haumea system.

LIGHTCURVE FITS FOR HAUMEA

The double-peaked sinusoidal model lightcurve fits for Haumea produced results with the expected peak height ratios. Because the data was normalized prior to the creation of the models, each curve integrates to zero. The error bars produced by the initial data reduction were smaller than expected, so we added the original errors in quadrature to a higher error value (0.005) to account for possible underestimates of error by AstroImageJ. This seemingly arbitrary higher error value was inspired by [6], as it was the roughly average value of the error in their data. Because we compared our results with this paper, we found it appropriate to include comparable errors in our analysis. Figure 7 shows an example of one of our lightcurve fits juxtaposed with the data.

Comparing our lightcurve fit results with those of [6] yields some insights, especially when we consider the subtle differences between methodologies (see Figure 8). For instance, [6] conducted observations in B and R wavelength bands approximating the coverage of the Johnson-Kron-Cousins system, which partially overlaps with the SDSS u', g', and r' filters. In particular, B covers g' and a small part of u', and R covers r'
and some higher wavelengths (including SDSS i’ and part of z’). Thus, shifting the "window" of observable wavelengths from visible-near infrared to visible-near ultraviolet
allows us to compare the ends of the spectrum. R and r' were seen to be similar, showing that the near-infrared brightness of Haumea has only a small effect. This was expected due to the primarily water ice composition of Haumea, but it also confirmed the ability of our models to accurately reproduce Haumea's lightcurve. Comparing u' and B showed some parts of Haumea's surface may be bluer, or more reflective in the near-ultraviolet, than others, which was not seen before due to the wavelength cutoff of the B filter. Overall, the relative flux fits produced similar lightcurves to those found using magnitudes by [6].

**RELATIVE COLORS OF HAUMEA**

The relative flux model fit results lead us to the rotational variability of Haumea in each color. By isolating the sinusoidal model for the contribution of Haumea ($F_{\text{Haumea}}$ from Equation 2), we obtained the rotational color variability of Haumea alone. Comparing these plots to the combined color plots suggests that Haumea is responsible for most of the total system color variability (as expected); however, Hi’iaka does have a small effect. Figures 9 and 10 show how the modeled color of the combined system lines up with the observed and modeled lightcurves. Note that the x-axis (time) is the same for the two plots.

In contrast, Figures 11 and 12 show the Haumea-only modeled colors as a function of time for the same two observational periods. We note the consistent amplitude of Haumea's u’-g’ variability within each night, as opposed to the less consistent amplitude of the g’-r’ variability. The generally flat g’-r’ rotational model, with
the exception of one region where r’ is notably stronger, confirms the existence of the Dark Red Spot. The phase position of the Dark Red Spot in the lightcurve of Haumea is also consistent with the results of [6].
We particularly note the comparative value of $u' - g'$ to that of $g' - r'$ at the Dark Red Spot. In Figures 9 and 11, $u' - g'$ is slightly higher than $g' - r'$ (with some overlap). Meanwhile, in Figures 10 and 12, $u' - g'$ is lower than $g' - r'$. We also note the two regions bright in $u' - g'$ on either side of the spot, for both nights. Although the colors plotted are relative, and therefore amplitudes are only somewhat meaningful, the consistent nature of the $u' - g'$ color variations is notable. These $u' - g'$ relative color variations could be comparable to the scale of the variations caused by the Dark Red Spot, which suggests we may also be seeing a blue spot on the surface, or that the Dark Red Spot may be surrounded by a bluer region. Again, however, we acknowledge that the relative nature of the results, along with the normalized sinusoidal nature of the model (which requires that all fits integrate to zero over one rotational period) may unduly influence these results.

**FIGURE 11.** Relative colors for Haumea alone for data obtained on April 8, 2022. This plot is similar to the bottom panel of Fig. 9, with the effect of Hi'iaka removed and the posterior draws removed for clarity.
One additional complication to any model of Haumea is a possible degeneracy between the influences of both the Dark Red Spot and Haumea's nonspherical shape on Haumea's lightcurve. This spot-shape degeneracy is exacerbated by the fact that there are still many unknowns about both Haumea's shape and spot. Although Haumea is well modeled as a triaxial Jacobi ellipsoid, it is unknown exactly how accurate such a model is. Additionally, the observed darker, redder portion of the lightcurve could be caused by a variety of different surface color configurations, as explored in [6]. Devising a way to estimate, or ideally remove, this spot-shape degeneracy would make Haumea lightcurve models more informative.
LIGHTCURVE FITS FOR HI’IAKA

On the nights of March 7 and 23, 2021, Hi’iaka had an angular separation from Haumea of approximately 0.77 and 1.3 arcseconds respectively, according to the JPL Horizons ephemerides. This was far enough from Haumea that the point-spread function appeared asymmetrical in the photometry. We obtained effective point spread functions for these images and used the nPSF code to justify or confirm our color results.

We note that our model, while detailed, is not complete. The model does not account for the possible sawtooth shape of Hi’iaka’s lightcurve as found by [12], but rather approximates it using a double-sinusoid model, the same as the one used for Haumea. Without the advantage of observing Hi’iaka as the only object in the aperture, the uncertainties in the magnitude and shape of lightcurve variations cannot be discounted. This is why we chose to take two approaches (photometry and PSF fitting) to addressing Hi’iaka.

RELATIVE COLORS OF HI’IAKA

Preliminary results suggest Hi'iaka has a small (~1%) rotational surface color variation in g'-r', and possibly a larger (up to 2%) rotational surface color variation in u'-g'. See Figures 13 and 14 for modeled colors of Hi'iaka for two individual nights. As noted before, the small size of Hi'iaka, combined with the closeness of its orbit compared to the distance from Earth, created additional difficulties in separating its lightcurve from that of Haumea. This resulted in large errors compared to possible relative color variations. More detailed observations of Hi'iaka are necessary to confirm these results.
FIGURE 13. Relative colors for Hi'iaka alone for data obtained on April 8, 2022.

CONCLUSIONS: SUMMARY AND DISCUSSION

The unique dwarf planet Haumea, as well as its associated system, is unique among TNOs [4]. Learning more about the characteristics of Haumea and associated objects, such as its moons, could lead to a better understanding of not only the history of the Haumea family, but also the history of the Solar System [7]. One of the simplest ways to characterize the surfaces of these bodies is by relative color analysis through photometry and lightcurve modeling, especially for wavelength bands that have not been investigated before. We observed Haumea and its moons in near-ultraviolet and visible wavelengths and obtained relative u’-g’ and g’-r’ colors in order to expand the current description of Haumea’s rotational color variability, as well as of Hi’iaka’s colors.

Our preliminary analyses show that we can recover the Dark Red Spot, that Haumea has u’-g’ rotational color variability, and that the regions surrounding “Red Spot” may be relatively blue in u’-g’, suggesting an interesting insight into Haumea’s surface. Because we previously could describe the surface colors only in terms of visible and infrared wavelengths, this u’-band photometry provides new insights that expand our understanding of Haumea’s surface. Because most TNOs are typically redder than Haumea, the question of potential causes of u’-band variability for TNOs has not been addressed by many groups, although [16] did recently publish a paper describing ultraviolet spectroscopy of asteroids.

As discussed above, TNO photometry has been and currently is primarily conducted in the visible and near-infrared range. Our initial work with u’-band (visible blue and near-ultraviolet) photometry has shown that it can reveal surface information not found in other visible wavelength bands, including potentially confirming Haumea family
members. This insight is especially significant looking forward to the observations of the Large Synoptic Survey Telescope (LSST), which will soon provide high-quality new u’-band photometry for many small bodies. As our ability to observe these small bodies in the u’-band grows, the importance of older observations for comparison, as well as observation of long-term patterns will increase.

FUTURE WORK

Although we obtained initial results for the rotational color variability of Hi‘iaka, the high measurement errors for its unresolved contribution to the lightcurve made it impossible to confirm the accuracy of the results, even when combined with PSF analysis. Further photometric investigation of Hi‘iaka as an individual body is the best way to overcome these issues.

In the future, we will also investigate the u’-g’ and g’-r’ colors of Haumea family members using archival data. Comparing the visible colors of Haumea family members to those of Haumea and its moons will allow us to compare the compositions of these objects in the future, especially as more visible-spectrum data of TNOs becomes available through LSST and the larger-scale Hubble Space Telescope general infrared-visible color project being conducted by this and other research groups.
BIBLIOGRAPHY


APPENDIX 1: FIT RESULTS

TABLE A-1. Two-body fit parameters for each filter and night, presented as median fit values with 84\textsuperscript{th} and 16\textsuperscript{th} percentile values.

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<td>LT 1</td>
<td>0.364 ± 0.005</td>
<td>0.285 ± 0.005</td>
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TABLE A-2. Best two-body fit parameters for each filter and night.