Identifying Short-Term Variations in Hyperion's Light Curve

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The chaotic rotation of Hyperion has been studied in the past for a series of days. This project incorporates short continuous exposures over the course of a night for three nights in June 2011. The small steps produced detailed light curves of Hyperion's movement. Using Astro-ImageJ and Matlab, the images were processed and Fourier transforms were taken of sections of data. The fits of two runs were calculated and compared. Causes for the waves in the short-term measurements were discussed.

INTRODUCTION

Hyperion is a large, irregularly shaped icy body in the Saturnian system. It orbits Saturn every 21.28 days and has a 4:3 resonance with Titan [1]. Its high eccentricity of 0.1 and irregular shape contribute to its chaotic rotation [1]. Currently, Hyperion is not in a periodic rotational state [2]. As Hyperion tidally evolves, it falls into a large chaotic zone. All irregularly shaped objects must spend time in this chaotic zone before latching into a synchronous rotation [3]. The despinning of Hyperion and eventual capture into a stable state is on the order of one billion years [4].

Hyperion was discovered in 1848 by G. Bond and W. Lassell [1]. It was suggested by Peale in 1977 that Hyperion would not be tidally locked with Saturn [5]. Since then, there have been many studies of Hyperion's rotation, shape and composition. In particular, Klavetter observed Hyperion for 38 nights and took an average of nine independent observations each night [2]. Other studies include Goguen *et al.* (1983), Wisdom *et al.* (1984), Thomas and Veverka (1985), Binzel *et al.* (1986), Wisdom (1987), Black *et al.* (1995), and Harbison *et al.* (2011) [2] [3] [4] [6] [7]. Klavetter reported that Hyperion's brightness was constant to the 0.01 magnitude level for a time period of 6 hours. He found no nightly variations [2]. Using a high speed time-series CCD photometer, measurements can be made every second for around four hours a night.

During the summer of 2011, the star Spica lies very close to Saturn on the celestial sphere. Spica is used as a guiding and recalibrating star. For all the measurements Hyperion is divided by another object to produce relative brightness. The absolute magnitude of the object would be inaccurate due to seeing conditions. Because Titan's light curve is constant and well known, it was used as a comparator [2]. In this way, short-term rotation or wobble can be observed.

Theory

To find any periodic motion within the measurements discrete Fourier transforms will be used. Matlab's `fft` function starts with Equation 1. The Fourier transform $X(f)$ can be separated into real (R) and imaginary (I) parts, producing Equation 2.

$$X(f) = \sum x(t)e^{\frac{-2\pi i}{N}(t-1)(f-1)} \tag{1}$$

$$X(f) = R(f) + iI(f) \tag{2}$$

Using the relations $e^{i\theta} = cos\theta + isin\theta$ and $sin(-\theta) = -sin(\theta)$, Equation 3 becomes Equation 4. To fit the measurements, the sum of Equation 4 for each frequency is plotted with time.

$$x(t) = \frac{1}{N}\sum (R(f) + iI(f))(cos(\theta) + isin(\theta)) \tag{3}$$

$$x(t) = \frac{1}{N}\sum R(f)cos(\phi) + I(f)sin(\phi) \tag{4}$$

Here, f stands for frequency, t stands for time, and $\phi = \frac{2\pi}{N}(t-1)(f-1)$. The result is $x(t)$, the fit of the measurements.

OBSERVATIONS

Observations at Paul and Jane Meyer Observatory started June 7 and June 9, 2011. These "testing" days

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Runs of Each Night		
Day	Run #	Run
June 24, 2011	1	hyp110628
-	2	hyp110624b2
-	3	hyp110624c
June 25, 2011	4	hyp110632
-	5	hyp110625
-	6	hyp110625b
-	7	hyp110625b4
-	8	hyp110625b5
-	9	hyp110625b7
-	10	hyp110625b12
-	11	hyp110625b13
June 26, 2011	12	hyp110626a2
-	13	hyp110626a3
-	14	hyp110626a4
-	15	hyp110626a5
-	16	hyp110626a9

TABLE I.

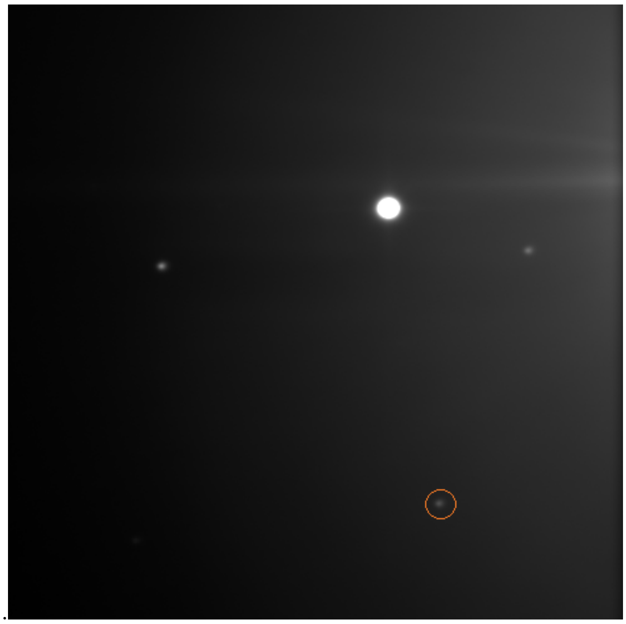

FIG. 1. This image is a z-projection of one-thousand, continuous 1 second exposures from Run 3 on June 24. The largest object is Titan; Hyperion sits down and to the right of Titan. The circled object is the comparator star. All other objects are background stars. The horizontal artifact is from Saturn, which sits to the right of the image's boundaries.

produced light curves, but no darks or flats were taken for later calibration. The main purpose was to become familiar with the equipment and procedure.

A special camera developed by Princeton Instruments, the Raptor Camera, is attached to the 24 inch Ritchy-Chretien telescope. This camera does not have a shutter. Downstairs in the control room are the ACE and Dawkins systems. The ACE Control System controls all movement of the telescope, changes filters, moves covers on and off the mirror, and positions the dome. This system also allows tracking of objects as they move across the sky. This tracking can be altered (sped up or slowed down) if desired. Usually the Dawkins system is used in conjunction with the Raptor camera to produce light curves of white dwarf stars. Dawkins uses software called Quilt 12.05 to automatically take exposures based on the user's initial conditions. To distinguish Hyperion and Titan from background stars, a field image from STScI Digitized Sky Survey was viewed using the coordinates of Hyperion from the JPL's HORIZONS Ephemeris System. A field image was generated for all observing days. A catalog of Hyperion's position for each observing day was used within the ACE system for easy and fast positioning.

The main imagining days were June 24, June 25, and June 26, 2011. For each day, a general procedure was followed. First, the Raptor camera is turned on. The team logs into ACE and Dawkins. Fans, nitrogen, and dome lights are turned on. The filter is set to "clear." The dome shutters are opened, and the dome is set to track. Before any images are taken, the mirror covers are removed. The telescope is initially pointed toward Spica and centered. All coordinates in ACE are re-calibrated using this centering. Because Dawkins is taking 1 to 2 second exposures, the positioning is nearly in real time. For Quilt to measure and save the brightness of Hyperion and Titan, the team "marks" the desired objects, in this case: Hyperion, Titan, and background stars. The exposure time is also chosen; for most runs, this was 2 seconds. The team then monitors the position and tracking speeds to keep the objects within the limits of the image.

Unfortunately, Quilt often would "lose" an object and give that object a brightness value of 1. To fix this, the exposure was decreased until the object could be marked again and accurate values could be recorded. So, for each night a set of runs were recorded. The runs included the fits images and the Quilt data file. Table I lists the runs of each night and the exposure times of the images.

As Saturn approached the horizon, the objects became dimmer and eventually the telescope's altitude was too low for it to continue tracking. On average the team stopped imaging around 6:00 UTC all three nights. Because there is thermal and electronic noise in the CCD chip, a series of thirty dark images are taken.

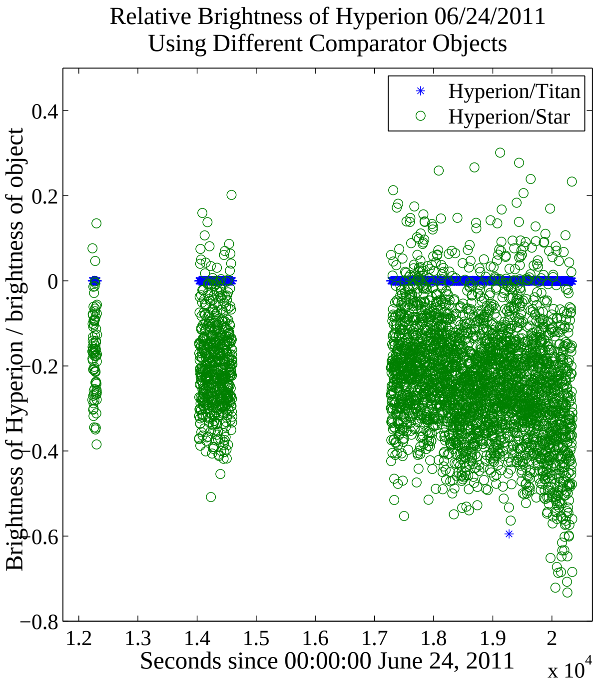

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FIG. 2. This plot was produced to compare the comparator objects. Hyperion divided by Titan is the blue level line. Hyperion divided by the star is the spread out green measurements. Because Titan's average value is much greater than the star's, the ratio has less noise and is on a much smaller scale then the star's ratio. Thus, Titan is used as a comparator. To check the consistency across the images, the star is divided by Titan. The result had a mean of 0.0026 and a standard deviation of 0.0369.

This is done by using a blocking filter. Thirty flat field images are taken with a dome flat. This is a silver plane that is evenly lit with full spectrum light. The flats are necessary to account for uneven sensitivity in the CCD chip, dust, and vignetting in the optics.

IMAGE PROCESSING

Initially, Matlab was used to process the images. Quilt's measurements included the frame, Hyperion's brightness, Titan's brightness, other objects, and the sky brightness. Hyperion was divided by Titan to remove variation between images. A code was made to take the Fourier transform of the division. While measurements were found for three to four hours a night, many runs were littered with 1 values. A linear fit was chosen to remove many of the 1 values, but some runs were almost entirely corrupt.

For more accurate the measurements, Astro-ImageJ from the department of Astronomy at the University of Louisville is used to remove noise, level sensitivity, and re-measure object brightness. First, the thirty dark images are converted to 32-bit. A plug-in, `create master dark`, combines the dark images for the user. The master dark image for each night is saved. If 1 second and 2 second exposures are used that night, then two sets of darks must be processed. The thirty flat images are opened and the plug-in, `create master flat`, subtracts the master dark image and normalizes the stack. The product is a master flat that is also saved for each night. The plug-in, `process images`, removes the darks and flats from the images. Next, each run is aligned and saved in its new processed, aligned state. The `multi-aperture` plug-in runs through the images focusing on the same objects. It measures the total brightness minus the surrounding sky.

To obtain the relative brightness of Hyperion, it is divided by another object. Two objects were compared: Titan and a background star that was visible throughout the three days. Because the average value of Titan is on the order of 7×10^5 counts and the star's average value is on the order of 2×10^3, Hyperion divided by Titan is a more accurate method. As seen in Figure 2 the scale of the star's ratio is much larger than Titan's ratio. A rescaled image of Titan is seen in Figure 3. The overall shape of the ratio is the same as the star's ratio; however, the star's ratio has more uncertainty. For the Fourier transform, only Titan will be used as a comparator.

A Matlab function called `fft` does a discrete Fourier transform of the brightness measurements. Initially, the mean of all measurements was removed from all the measurements so that a frequency does not appear at 0 Hertz. This is done only for the initial results that encompassed the three day span. The `fft` function used did not account for nearly twenty hour gaps in the measurements. This Fourier transform measurement was thrown out. To account for the gaps while still finding frequencies, certain runs and days are selected for separate Fourier transforms. The mean from that run or day is removed from itself. Then, the `fft` is used.

Using the Fourier transform and the frequencies, a fit was easily calculated. Equation 4 is used to find a fit involving all the frequencies found in the Fourier transform. Another fit is performed that consists of the two frequencies with the highest amplitude in a Fourier transform.

RESULTS

Figure 3 contains Hyperion's light curves for the 24th, 25th, and 26th of June, as well as the Fourier transforms of the 25th, 26th, Run 3, and Run 11. Top-left in Figure

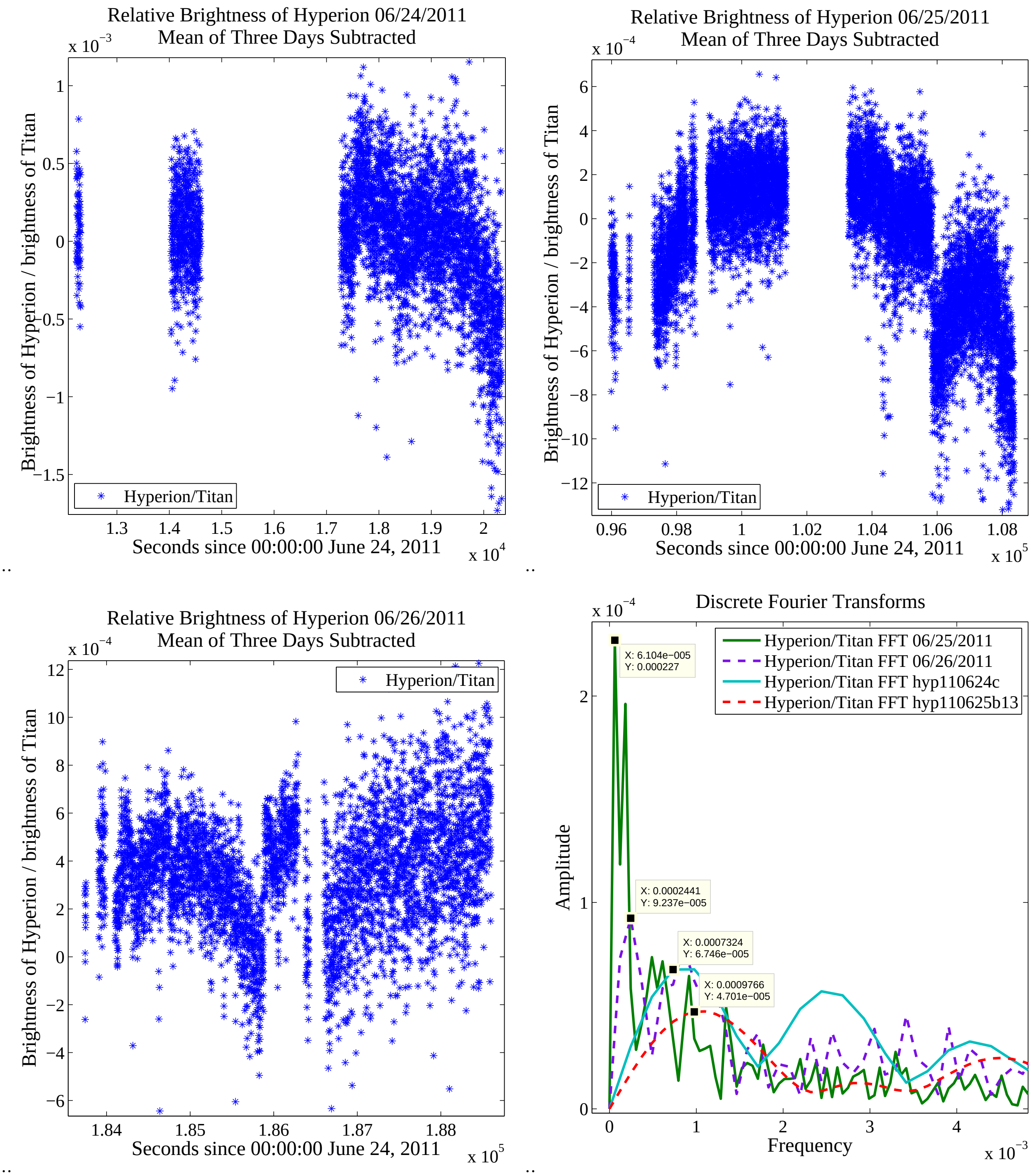

FIG. 3. Top-left: June 24 light curve. Top-right: June 25 light curve. Bottom-left: June 26 light curve. Bottom-right: Fourier transforms of June 25, June 26, Run 3, and Run 11.

3 contains the largest measurement gaps. To avoid taking the Discrete Fourier transform with the gaps, the longest run from that day, Run 3 is chosen. The same problem is present in June 25th. The Fourier transform is taken of Run 11. A Fourier transform of all of June 26th is taken. The Fourier transforms of these three measurement sets are seen bottom-right in Figure 3. The period of the 26th is 1.14 hours, of the 25th is 4.55 hours, of Run 3 is .38 hours, and of Run 11 is 0.25 hours.

The fits involving all the frequencies are seen top-left and top-right in Figure 4. The fits involving only the two frequencies with the highest amplitude are seen bottom-left and bottom-right. As examples of this

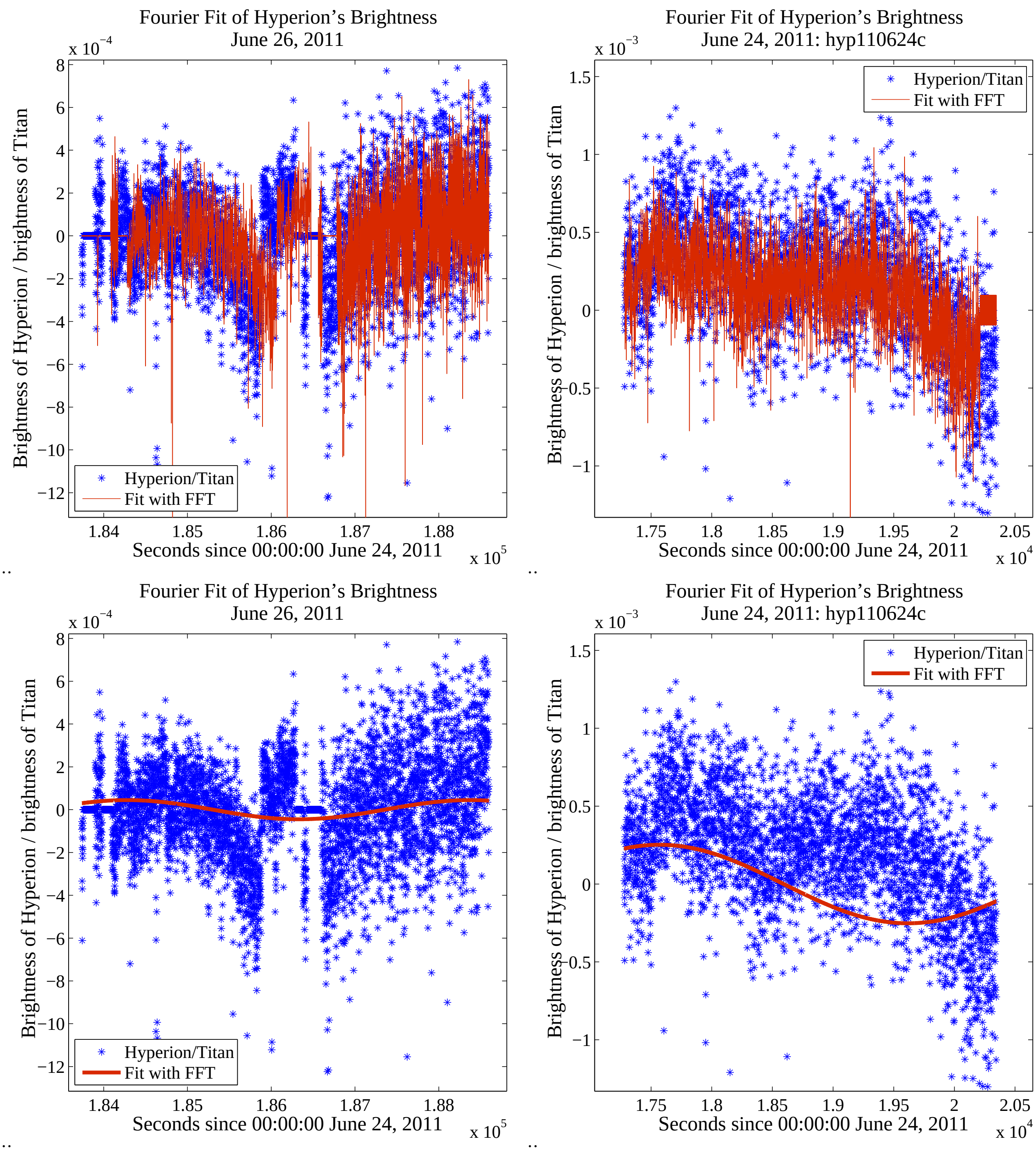

FIG. 4. Top-left: June 26 light curve with overlaid fit. All the frequencies in the Fourier transform (seen bottom-right in Figure 3) are used in Equation 4 and summed. Top-right: Run 3 light curve with overlaid fit of all the frequencies in the Fourier transform. Bottom-left: June 26 light curve with overlaid fit of the two highest-amplitude frequencies. Bottom-right: Run 3 light curve with overlaid fit of the two highest-amplitude frequencies.

method, only two sets of measurements are shown in this paper: June 26 and Run 3. The fit of June 26 stays within the limit of the wave; the fit of Run 3 is slightly off course.

DISCUSSION

Previous work found no variation over the course of a night; however, it was safe to assume that short, nearly continuous measurements would produce a gradual change in the relative brightness of Hyperion

[2]. Upon plotting the light curves, waves appeared in measurements that lasted a short amount of time (minutes). Longer wavelengths that span more time than the measurements are unlikely to be seen. Thomas experienced a similar situation when analyzing Voyager 2 images [1]. The periods of these waves seem to be unrelated; chaotic. While Klavetter took several observations a night over the course of 64 days, this work involved thousands of observations a night over the course of three days [2]. It seems that either method produces insufficient data to determine a rotational period or a lack of a defined one. There are a few ideas on the cause for such variations that range from inside less than an hour to four hours.

It is possible that the wobble and rotation of Hyperion are causing the variations. This is in conjunction with Hyperion's irregular shape, surface composition, and its surface features. As different areas of Hyperion face Earth, surface area, craters, dents, and scars appear. This changes its albedo. Water ice is present on Hyperion's surface, as well as hydrocarbons [1]. The differing reflectance of these substances may affect the brightness. Another possibility is that the sky background in the images is uneven, resulting in a light curve of the sky rather than Hyperion. However, "shifts" such as the one seen top-right in Figure 3, are not present in Titan's light curve or the star's light curve. The shifts are unique to Hyperion. If sky background has affected the measurements, it would be near the end of each observation day when the atmosphere thickens.

CONCLUSIONS

Over a period of three nights, thousands of 1 and 2 second exposures were imaged and fit. It is likely that relative magnitude of Hyperion changed due to wobble or rotation. It is also likely that the changes were chaotic, for the frequencies seen in bottom-right of Figure 3 are not similar. Future work with these measurements would include the Thomas *et al.* solution of a rotation rate of $72 \pm 1°/day$ and Hyperion's pole orientation [1].

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