Astrometric Relative Photometry Experiment for Dwarf Planet Haumea (Postprint)

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Abstract

Two rounds of observations of the dwarf planet Haumea were conducted using the 80 cm telescope at the Yaoan Station of Purple Mountain Observatory from February to April 2022. Interference fringe removal techniques were applied to all observational images, and relative photometry was utilized to derive the instrumental magnitudes of Haumea. Finally, the photometric results from the two rounds were normalized to enable combined analysis. The rotation period of Haumea was determined separately using the Phase Dispersion Minimization (PDM) method and the Lomb-Scargle periodogram method. The rotation periods obtained by the two methods differ by only 0.072 s, indicating good consistency. The photometric measurements of Haumea reveal a clearly double-peaked rotational light curve, with a rotation period of 3.9154 ± 0.0002 h and a peak-to-peak amplitude of 0.26 ± 0.01 mag. Based on the derived rotational light curve, the maximum influence of Haumea's brightness variation due to rotation on astrometric position measurements was estimated to be -9 to 9 mas. These photometric observations are of fundamental significance for subsequent high-precision astrometric measurements.

Full Text

Astrometry-Oriented Relative Photometry Test of Dwarf Planet Haumea

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Abstract

The 80 cm telescope at Yaoan Station of Purple Mountain Observatory was used to conduct two runs of observations of the dwarf planet Haumea from February to April 2022. Interference fringes were removed from all frames using fringe removal techniques, and instrument magnitudes were derived through relative photometry. The photometric results from the two runs were then normalized for combined analysis. The rotation period of Haumea was determined using both Phase Dispersion Minimization (PDM) and Lomb-Scargle periodogram methods. The two methods yielded rotation periods differing by only 0.072 s, demonstrating excellent consistency. Our photometric measurements reveal a distinct double-peaked rotational light curve with a period of 3.9154 ± 0.0002 h and a peak-to-peak amplitude of 0.26 ± 0.01 mag. Based on the derived rotational light curve, we estimate that the maximum influence of Haumea's photometric variation due to rotation on astrometric position measurement is -9 to 9 mas. This photometric test is fundamentally significant for subsequent high-precision astrometry of Haumea.

Keywords: relative photometry; Kuiper belt; period determination; CCD image processing

1. Introduction

Kuiper Belt Objects (KBOs) typically orbit beyond Neptune's orbit and represent primordial remnants of the planetary accretion disk. As such, they carry valuable information about the physical and chemical processes of planet formation. Currently, over 2000 KBOs are known (https://www.minorplanetcenter.net). During 2004-2005, Ortiz et al. claimed the discovery of a dwarf planet (https://archive.org/details/howikille), which was provisionally designated 2003 EL61 and officially recognized as 136108 Haumea on September 17, 2008. Haumea is one of the largest KBOs and, after Pluto and Makemake (136472), the brightest trans-Neptunian object. Its orbit ranges from 35 AU to 51 AU with a period of 283 years, an eccentricity of 0.19, and an inclination of 28°.

Light curves serve as a primary source for obtaining physical properties of celestial bodies and provide crucial clues for studying the origin and evolution of minor planets and planetary systems. Previous photometric observations using the University of Hawaii's 2.2 m telescope in B, V, and R filters revealed a double-peaked rotational light curve for Haumea with a period of 3.9154 ± 0.0002 h and a peak-to-peak amplitude of 0.28 ± 0.02 mag. The B-V color index was measured as 0.97 ± 0.03 mag. Due to its short rotation period, Haumea is believed to be a rapidly rotating Jacobi ellipsoid that has reached hydrostatic equilibrium. Combining these characteristics, its density was estimated as =

2,500 $\mathrm{kg \cdot m^{-3}}$. Haumea has two satellites, Hi'iaka and Namaka, with magnitudes 2.98 ± 0.03 mag and 4.6 mag fainter than Haumea, respectively. While ground-based telescopes cannot resolve these satellites during observations, astrometric measurements can determine the photocenter orbit, which represents the relative orbit of the binary system. The photocenter orbit is a scaled version of the relative orbit of the binary system, and by combining it with radial velocity measurements and other available astrometric data, orbital and mass solutions can be derived for the binary system. However, mass measurements remain primarily limited by relative position measurement precision.

For objects with large photometric variations like Haumea, position measurements are affected by brightness changes. When measuring the photocenter orbit of Haumea and its satellites, this effect must be accounted for. Therefore, we must first determine Haumea's rotational light curve characteristics to correct its position measurements. This study presents relative photometry of Haumea based on observations from the 80 cm telescope at Yaoan Station of Purple Mountain Observatory, laying the foundation for improving relative position measurements.

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2. Observations and Data Processing

2.1 Observations We conducted two runs of observations of Haumea using the 80 cm telescope at Yaoan Station of Purple Mountain Observatory. The telescope and CCD specifications are detailed in Table 1 . The observation summary is presented in Table 2 . Johnson-Cousins I filter was used for all observations. The raw images were preprocessed using MaxIm DL software (https://diffractionlimited.com/maxim-dl/), including bias, dark, and flat-field corrections [6].

2.2 Interference Fringe Removal Due to the CCD's silicon layer structure, low-energy photons undergo multiple reflections within the thin silicon layer before being fully absorbed, creating interference fringes and non-uniform background that compromise precise photometry. We developed a "3-2" technique to remove these fringes:

1. From each night's observations, we selected images for sky background estimation
2. After subtracting the background estimate from each selected image, we performed median combination of the corresponding pixel values across all images
3. The median result served as the interference fringe template
4. The template was multiplied by a scaling factor (the ratio of the exposure time of the image to be corrected to 360 s) for normalization
5. The normalized fringe template was subtracted from the original image

Typical results of this processing are shown in Figure 1 [Figure 360: see original paper]. Example field-of-view images from both runs, after fringe removal, are displayed in Figure 2 [Figure 12: see original paper].

3. Photometric Measurements and Analysis

3.1 Photometric Data We employed relative photometry to obtain the relative instrument magnitudes of Haumea. During each observation run, the target moved only a short distance, ensuring stable photometry. Since the fields contained few stars, we could use the same reference stars for both runs [7]. All reference stars were confirmed to be non-variable. Figure 2 shows typical images of the target and reference stars, with Haumea marked by green circles and reference stars by red circles.

We used a two-dimensional Gaussian centering algorithm to determine pixel coordinates of the target and reference stars. The "3-2" formula estimated sky background in annular regions around each star. Aperture photometry was performed using the photutils library (https://pypi.org/project/photutils/), which allowed testing various aperture radii. The aperture yielding the highest photometric precision was selected as optimal. This produced relative instrument magnitudes for each night, with errors based on the target's signal-to-noise ratio within the aperture. Color differences between target and reference stars were also considered.

Without standard photometry, we normalized the two runs by fitting constant offsets between them. Each fit used data from multiple nights within a run rather than individual nights. The primary error sources were photon noise and flat-fielding residuals [8]. The final normalized relative instrument magnitudes were used for period analysis.

3.2 Period Determination Methods We applied two independent methods to determine Haumea's rotation period: Phase Dispersion Minimization (PDM) and Lomb-Scargle periodogram.

Phase Dispersion Minimization: This method identifies the period by minimizing the statistical quantity . For N discrete data points with variance σ^2, where x represents the magnitude observed at time t and x̄ is the mean of N data points, we define:

$$\sigma^2 = \sum (x_i - \bar{x})^2$$

For M bins with n points sharing the same phase Φ , where s^2 is the variance of the j-th bin, is defined as:

$$s^2 = \sum \frac{(n_j - 1)s_j^2}{\sum(n_j - 1)}$$

When the correct period is found,   reaches a local minimum. The PDM method calculates   as a function of frequency, showing a clear local minimum at 12.25939 cycles/day (Figure 3 [Figure 12: see original paper]). Using the relationship between rotation frequency Ω and period P (Ω = 1/P), we derived P = 1.95768 h.

Lomb-Scargle Periodogram: This Fourier-based method is suitable for unevenly sampled data. For N data points h observed at times t , the normalized periodogram is:

$$P_N(\omega) = \frac{1}{2\sigma^2}\left[\frac{\left[\sum_j (h_j - \bar{h})\cos\omega(t_j - \tau)\right]^2}{\sum_j \cos^2\omega(t_j - \tau)} + \frac{\left[\sum_j (h_j - \bar{h})\sin\omega(t_j - \tau)\right]^2}{\sum_j \sin^2\omega(t_j - \tau)}\right]$$

where τ is defined by:

$$\tan(2\omega\tau) = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}$$

The maximum of the normalized power spectrum corresponds to the best-fit period. Our Lomb-Scargle analysis shows a prominent peak at 12.25940 ± 0.00004 cycles/day (Figure 4 [Figure 4: see original paper]), yielding P = 1.9577 ± 0.0001 h. This differs from the PDM result by only 0.072 s, demonstrating excellent consistency.

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4. Rotational Light Curve Analysis

Haumea is a rapidly rotating Trans-Neptunian Object (TNO) that has been deformed into an ellipsoid. Its complete light curve should contain two maxima (representing side views) and two minima (representing end views). The true rotation period is therefore twice the derived period: P = 3.9154 ± 0.0002 h, with a peak-to-peak amplitude of 0.26 ± 0.01 mag, consistent with previous results [2-3].

We fitted the photometric data using linear least squares with the model:

$$m_i = c + \sum_j [a_j \sin(j\omega t_i) + b_j \cos(j\omega t_i)]$$

where t represents the observation time corrected for light-travel time. The fitted coefficients and their errors are listed in Table 3 . The observational data and fitted light curve are shown in Figure 5 [Figure 5: see original paper], displaying two maxima at 0.14 mag and 0.12 mag, and two minima at 0.09 mag and 0.10 mag. The ^{2} value of 252 with appropriate degrees of freedom indicates a good fit, though some data points show larger residuals due to sparse sampling or larger inherent errors, possibly influenced by Haumea's two satellites.

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5. Impact of Photometric Variation on Astrometry

For binary systems like Haumea with its satellites, the photocenter position is affected by brightness variations. Let d be the angular separation between primary and satellite, Δ be the angular distance between the system's barycenter and photocenter, and P and S represent the primary and satellite respectively. According to the lever principle:

$$\Delta = k \cdot d$$

where k depends on the brightness ratio between components. The variation in Δ due to photometric changes is:

$$\delta\Delta = \frac{\delta k}{k + \delta k} \cdot d$$

The brightness variation δk depends only on brightness changes of the primary and satellite. Using magnitude conversions and data from the IMCCE ephemeris service (https://www.imcce.fr/), we obtained the satellite separation d 1.446 . With Haumea's brightness variation δL/L = 5.9% and the brightness ratio Σ = 1/17.9 [4], we calculated the maximum influence of Haumea's photometric variation on position measurement as -9 to 9 mas (Figure 7 [Figure 7: see original paper]). This demonstrates the necessity of applying light-curve corrections to Haumea's astrometric measurements.

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6. Summary and Outlook

We observed the dwarf planet Haumea using the 80 cm telescope at Yaoan Station of Purple Mountain Observatory, successfully removing interference fringes from CCD images and obtaining relative instrument magnitudes through relative photometry. By combining data from two runs, we investigated Haumea's photometric variability using both PDM and Lomb-Scargle methods, yielding a consistent rotation period of 3.9154 ± 0.0002 h with a double-peaked light curve of amplitude 0.26 ± 0.01 mag. We estimated that rotational photometric variation affects Haumea's position measurement by up to -9 to 9 mas. In future work, we will integrate photometric and astrometric measurements to improve position measurement precision using Haumea's light-curve characteristics.

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References

[1] ORTIZ J L, SANTOS-SANZ P, SICARDY B, et al. The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation. *Nature*, 2017, 550: 219-223.

[2] RABINOWITZ D L, BARKUME K, BROWN M E, et al. Photometric observations constraining the size, shape, and albedo of 2003 EL61, a rapidly rotating, Pluto-sized object in the Kuiper belt. *The Astrophysical Journal*, 2006, 639: 1238-1251.

[3] LACERDA P, JEWITT D C, PEIXINHO N. High-precision photometry of extreme KBO 2003 EL61. *The Astronomical Journal*, 2008, 135: 1749-1756.

[4] BROWN M E, VAN DAM M A, BOUCHEZ A H, et al. Satellites of the largest Kuiper belt objects. *The Astrophysical Journal*, 2006, 639: L43-L46.

[5] TORRES G. Orbital solution and dynamical masses for the nearby binary system GJ67AB. *The Astronomical Journal*, 2007, 134: 1916-1926.

[6] SHEPARD M K. *Introduction to Planetary Photometry.* Cambridge: Cambridge University Press, 2017: 175-176.

[7] STELLINGWERF R F. Period determination using phase dispersion minimization. *Astrophysical Journal*, 1978, 224: 953-960.

[8] LOMB N R. Least-squares frequency analysis of unequally spaced data. *Astrophysics and Space Science*, 1976, 39: 447-462.

[9] SCARGLE J D. Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data. *The Astrophysical Journal*, 1982, 263: 835-853.

[10] THIROUIN A. Study of trans-neptunian objects using photometric techniques and numerical simulations. *Astronomical Research & Technology*, 2023, 20: 234-241.

[11] GUO B F, PENG Q Y, LIN F R. Applications and technology research for astrometrica. *Astronomical Research & Technology*, 2023, 20: 195-202.

[12] GUO B F, PENG Q Y, SHANG Y J, et al. Technology research and precision premium in relative photometry based on CCD images. *Astronomical Research & Technology*, 2023, 20: 111-117.

[13] PENG Q Y, GUO B F, VIENNE A, et al. CCD astrometric measurements for the dwarf planet Haumea by ground-based telescopes. *Astronomy & Astrophysics*, 2023, 1-7. https://www.aanda.org/articles/aa/pdf/forth/aa44816-22.pdf. DOI: 10.1051/0004-6361/202244816.

[14] RAGOZZINE D, BROWN M E. Orbits and masses of the satellites of the dwarf planet Haumea (2003 EL61). *The Astronomical Journal*, 2009, 137: 4766-4776.

Note: Figure translations are in progress. See original paper for figures.