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Absolute magnitude and slope parameter *G* calibration of asteroid 25143 Itokawa

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Abstract–We present results from an observing campaign of 25143 Itokawa performed with the 2.2 m telescope of the University of Hawai‘i between November 2000 and September 2001. The main goal of this paper is to determine the absolute magnitude *H* and the slope parameter *G* of the phase function with high accuracy for use in determining the geometric albedo of Itokawa. We found a value of *H* = 19.40 and a value of *G* = 0.21.

INTRODUCTION

The present work was performed as part of our collaboration with NASA to support the space mission Hayabusa (MUSES-C), which in September 2005 had a rendezvous with the near-Earth asteroid 25143 Itokawa. We used the 2.2 m telescope of the University of Hawai‘i at Mauna Kea. The main goal of this work was to determine the absolute magnitude *H* and the slope parameter *G* of the phase function of Itokawa, which were impractical to obtain by the spacecraft because of the limited geometry of the encounter. Another important goal of these observations was to collect more data for a possible future detection of the YORP effect acting on this asteroid.

During the years before the in-situ observations of Itokawa various determinations of *H* and *G* have been published (Abe et al. 2002; Dermawan et al. 2002; Nishihara et al. 2005), often in mutual disagreement. A more recent and accurate determination of these parameters has been published in Thomas-Osip et al. (2008). However, we will keep our work totally independent from their study to be able to use it as a comparison for our results. The major advantage of our work is the use of a synthetic light curve extracted from the accurate three-dimensional model produced by the Hayabusa mission.

Some other works mentioned provided also an estimate of the geometric albedo p_V computed from their optical observations and from an assumed diameter, often taken from the radar observations (Lowry et al. 2005). Others (Sekiguchi et al. 2003; Ishiguro et al. 2003; Müller et al. 2005) provided albedo values from mid-IR thermal observations, with assumptions about asteroidal thermal models. Another independent determination for the albedo was obtained by Cellino et al. (2005) via a polarimetric method, assuming an empirical relation between a polarization curve and the albedo. Our work will take advantage by the post-encounter size determination obtained by Hayabusa, allowing a more direct conversion of the ground-based photometric information into a physically meaningful value for the albedo.

Another important goal of these observations was to collect more data for a possible future detection of the Yarkovsky-O’Keefe-Radzievskii-Paddac (YORP) effect acting on this asteroid.

DATA SET

We performed 7 observing runs for a total of 12 nights between November 2000 and September 2001, 11 of which were photometric, using the R Cousins filter or the v ECAS filter (Tedesco et al. 1982) and a 2k × 2k Tektronix CCD camera. We covered phase angles between 12.5° and 115.2°, with *V* magnitudes ranging between 14 and 21 and a typical photometric error less than 0.05 magnitude. We converted all the magnitudes (*R* or *v*) to the *V* magnitude. We are aware that there is a phase angle reddening effect that can influence the estimate of the *G* parameter (in the *H*-*G* formalism), but this effect is small in the *V* and *R* range and it is probably within our error estimates.

Calibration

During each night, we obtained many exposures of photometric standard stars (from the list published in Landolt) at various air masses. The flux and its error from each of them (within an aperture with radius ~1.3 × θ_{FWHM} have been computed and then used to determine the R band found to be consistent during the various runs, and

Table 1. Date, phase angle and $V(1,1,\alpha)$ for each night.

Date	α (°)	$V(1,1,\alpha)$	Filter
2000-11-30	39.90	20.885 ± 0.041	R
2000-12-01	39.88	20.878 ± 0.059	R
2001-01-23	31.44	20.629 ± 0.033	R
2001-01-24	31.13	20.654 ± 0.037	R
2001-02-27	20.71	20.378 ± 0.032	R
2001-02-28	20.69	20.332 ± 0.040	v
2001-03-23	47.50	21.001 ± 0.038	v
2001-03-24	51.13	21.126 ± 0.036	v
2001-04-19	15.16	24.260 ± 0.053	R
2001-07-17	56.96	21.569 ± 0.116	R
2001-09-19	11.76	20.038 ± 0.033	R
2001-09-20	12.56	20.005 ± 0.106	R

The quantity $V(1,1,\alpha)$ is the measured V magnitude of the object, normalized to one astronomical unit (AU) from the Earth and the Sun, and observed at a phase angle α.

compatible with zero −0.007 ± 0.008). We also assumed an atmospheric extinction of 0.08 ± 0.01, the central value, and the uncertainty being typical of the conditions on Mauna Kea in R band.

Using these parameters, we determined a specific photometric zero point (and its error) for each night using a weighted average procedure. These values are found to be mutually consistent in most of the runs, confirming the good photometric quality of the sky. Only one of the nights (2001 July 17) has a zero point significantly noisier than the others, probably due to some high level clouds. This problem is clearly marked by the biggest of the error bars shown in Fig. 2.

Photometry

A similar procedure is then used to determine the flux from the asteroid in all the available frames. These values are then converted in calibrated apparent R magnitudes using the specific zero points, extinction, and color term obtained above. The absolute magnitude is then obtained using the heliocentric and geocentric distances, and the V magnitude is derived from an assumed color V-R = 0.482 ± 0.006 (the weighted average of various values found in Abe et al. [2002], Nishihara et al. [2005], Lowry et al. [2005], and Lederer et al. [2005], avoiding the value from Thomas-Osip et al. [2008], consistent with this average, to keep our results totally independent from them). Each observation time is then corrected to include the light travel time. In each step, the photometric error (both from the photometry itself and for the various parameters) is accurately computed and saved for subsequent use.

ANALYSIS

The most important aspect of our analysis is the use of a synthetic light curve for the fitting procedure, provided by Hirata (personal communication) from the shape model of Itokawa from Hayabusa (Gaskell et al. 2008). The use of this detailed model is particularly important at high phase angles, where the light-curve coverage on a given night is less complete because of the long rotation period (~12 hours) and the short observation window, and only the synthetic light curve allowed us to determine the mean light curve value used in the photometric model discussed below.

Lightcurve Fit

The synthetic lightcurve is used as a fitting function on the photometric data obtained above. Only a vertical offset is allowed, because the synthetic lightcurve was generated using arbitrary units.

The best estimate V_{min} is assumed to be coincident with the minimum of the associated χ^2 surface. Its error is determined with a two-step procedure: first, we compute the reduced χ^2 (with $N_I - 1$ degrees of freedom, where N_I is the number of photometric data) at this minimum, then we use its square root as a correction factor (usually close to one) to multiply all the photometric errors of our data. With these updated errors we compute a new $\tilde{\chi}^2$ function, whose minimum is now imposed to $\tilde{\chi}^2_{min} = N_I - 1$ band it is still in V_{min}. The uncertainty interval for V_{min} is now determined as the region in which this rescaled chi-square function is below a certain level $\chi^2_{min} + \Delta\chi^2 = (N_I - 1 + \Delta\chi^2)$, where $\Delta\chi^2 = 1$ is the appropriate value for our case, that is a fit with only one parameter and a 68.3% uncertainty region. Each absolute magnitude and error obtained in this way is then saved, together with the phase angle of the asteroid at the observation date.

Phase Function Fit

The absolute magnitudes obtained in the previous steps are now fitted with a standard H–G phase function, to determine the best values for H and G, and their errors. The fitting procedure is again a χ^2 minimization, but this time in a two-dimensional space. During the fitting procedure we found that the high–phase point at $\alpha = 115.2°$ cannot be fitted in an acceptable way within our assumed H–G formalism. The same problem can be seen in the data from Thomas-Osip et al. (2008) (see discussion below). Therefore, we excluded this point from the fitting.

For the remaining data, the associated χ^2 surface has a minimum in H = 19.40, G = 0.217, with $\chi^2_{min} = 11.8$. Having 9 degrees of freedom (11 used observations minus 2 fitted parameters), the error normalization used for the lightcurve fit is unnecessary in this case. The contour plot presented in Fig. 1 shows the confidence levels of 68.3%, 95% and 99.73%, computed again from the three $\Delta\chi^2$ values appropriate for them and for the 2 degrees of freedom of our fit. The resulting phase function is shown in Fig.2.

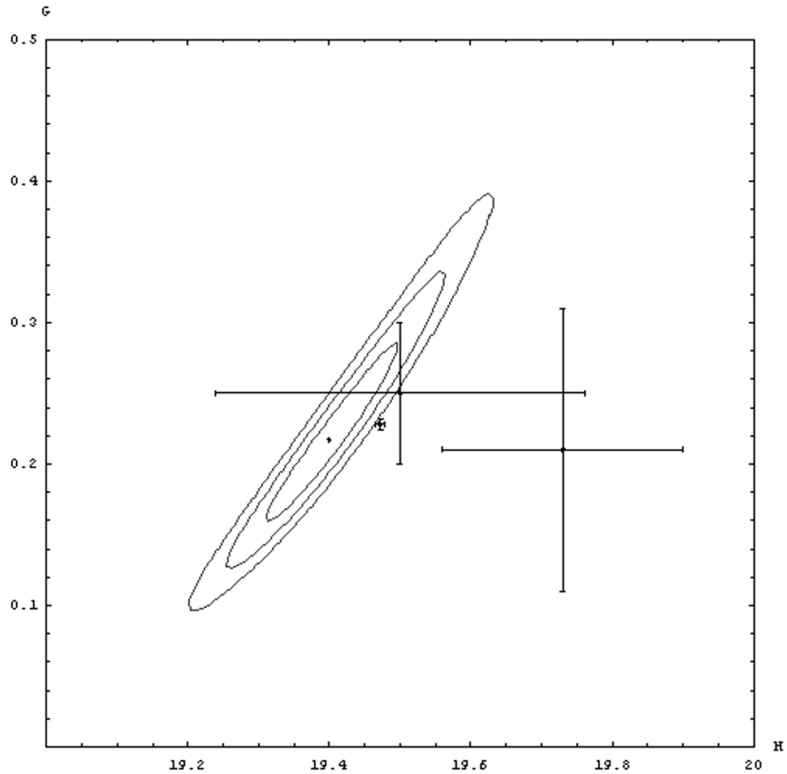

Fig. 1. Region in the *H*-*G* space allowed by our data (the three contours represent 68.3%, 95%, and 99.73% confidence levels). The black points are values found in the literature (from left to right in Thomas-Osip et al. [2008], Nishihara et al. [2005], and Abe et al. [2002]).

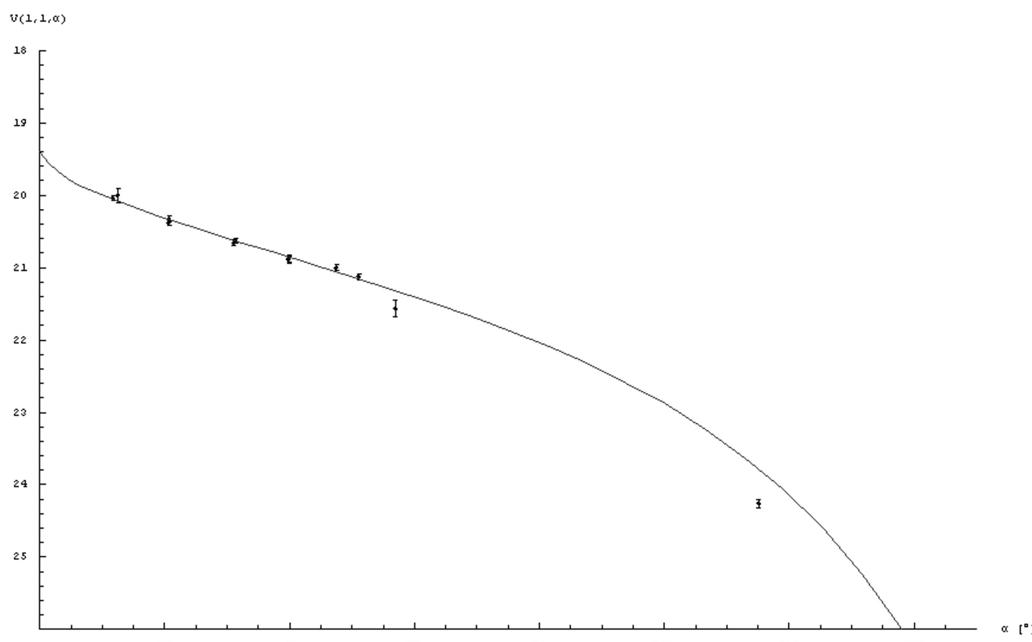

Fig. 2. Our photometric data and the fitted phase function. The point at $\alpha = 115.2°$ is shown but it is not used in the fitting.

RESULTS

The results shown graphically in Fig. 1 can be roughly converted in a numerical estimate for *H* and *G*, resulting in $H = 19.40^{0+10}_{-0.09}$ and $G - 0.21^{+0.07}_{-0.06}$ (1σ error bars). With these values we can compute some other physical quantities, but we can also compare our results with other values published in the literature.

Physical Quantities

Assuming an average diameter of 0.332 km (from Demura et al. 2006), we can use the relations in Bowell et al. (1989) to convert H and G to more physical quantities. We therefore obtain a geometric albedo $p = 0.29 \pm 0.02$, a phase integral $q = 0.44^{+0.05}_{-0.04}$, and a Bond albedo $A = 0.125^{+0.017}_{-0.016}$. These are all reasonable values for an S-type asteroid.

Comparison with Existing Literature

The comparison of our data with other similar studies found in the literature is summarized in Fig. 1. Our values are compatible with the ones proposed in Nishihara et al. (2005), but not with those published in Abe et al. (2002).

A new and very detailed analysis of Itokawa has recently been published in the already cited Thomas-Osip et al. (2008). The work presents values for H and G and with extremely small error bars (shown in Fig. 1); they are compatible only at the 3σ level with our values. However, our values for q and A agree with theirs within 1σ, while p agrees around the 1.5σ level. The same work (Thomas-Osip et al. 2008) also uses a photometric point obtained at $\alpha \sim 129°$, in various photometric bands. For all of them, the *H-G* fit misses the point by about half magnitude, confirming the result we discussed above. The reasons for this anomaly at high phase angles can be found by the fact that the *H-G* formalism was calibrated at moderately low phase angles for asteroids, while only the Moon and Mercury were used at high phase angle. Because the surface properties, like the roughness, can be quite different between big objects and small asteroids, we are not surprised that the shadowing from small scale structures can affect the *H-G* fitting, resulting in a fainter magnitude at higher phase angles.

CONCLUSIONS

The results of our work are generally in agreement with other data in the literature, and we suppose that the marginal disagreement with some values is due to the analytical phase function which does not describe accurately the behavior of the magnitude dependence to the phase angles at high phase angles.

The most important contribution from our work is the fact that our data were calibrated by a synthetic curve obtained by in situ observations. This means that, even if the error bars are comparable to other previous works, the values (H and G) were better determined. Moreover, we took into considerations also the correlations between H and G that all the previous works did not do.

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