Physical characterization of 2002 VE68, a quasi-moon of Venus

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Introduction

The Near-Earth Object (NEO) 2002 VE68 was first discovered by the LONEOS Survey on November 11, 2002 (MPEC 2002-V52). It has a semi-major axis of 0.723 AU, and is in 1:1 mean motional resonance with Venus. It can therefore be considered a quasi-satellite of the planet, the first known object of this dynamical class. Orbital integrations by Mikkola et al. (2004) suggest that 2002 VE68 was most likely a NEO injected into its current orbital state by a close Earth encounter approximately 7000 years ago, and will remain a Venusian quasi-satellite for another 500 years, when a subsequent encounter will push it back out. It has a highly eccentric orbit ($e \approx 0.4$) that brings it close not only to Earth, but to Venus and Mercury as well. Due to its proximity to us, 2002 VE68 has been designated a Potentially Hazardous Asteroid by the Minor Planet Center.

Although 2002 VE68's orbit, and the evolution of its orbital state, has been well studied, no published literature exists on the object's size, shape, or rotational period. This project's goal, then, is to characterize these physical properties through rotationally resolved photometry in the optical wavelengths.

Methods

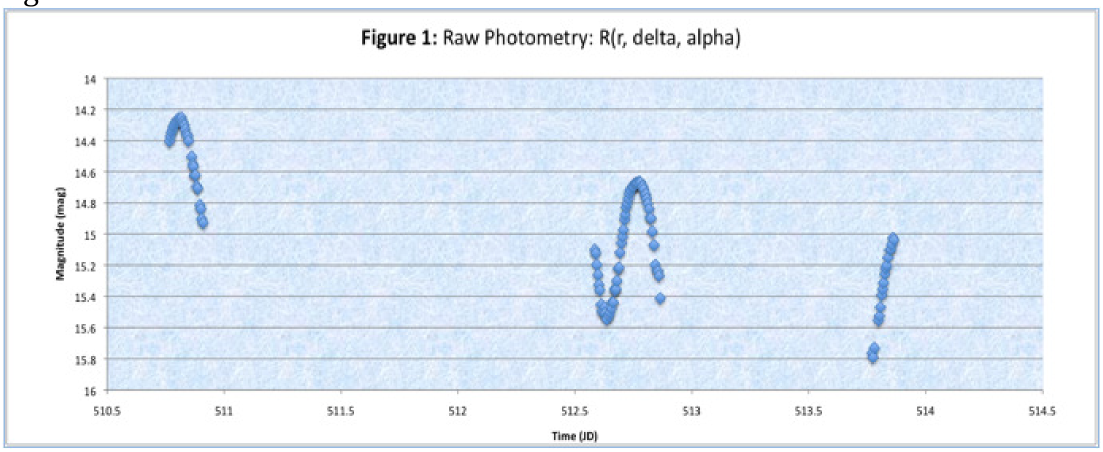
We took advantage of the object's 2010 apparition to collect rotationally resolved Bessel BVRI photometry over the course of three nights (Nov 10/12/13) using Table Mountain Observatory's 0.6-m telescope. Table 1 lists the observational circumstances, with heliocentric and geocentric distances, solar phase angle, and expected magnitude as computed by the JPL HORIZONS ephemeris service.

Table 1: Observational Circumstances

UT Date	r (AU)	delta (AU)	Solar Phase α (deg)	V (mag)	Exposures	Observer
2010 11 10	1.021	0.039	38.1	14.9	63	Mayes
2010 11 12	1.021	0.043	44.3	15.3	121	Mayes
2010 11 13	1.020	0.047	48.1	15.6	35	Barajas

We used IRAF to process the images and extract the raw observed magnitude of the object for each image. When we plotted this magnitude as a function of time in Figure 1, we see that we have a periodic function that seems to decrease steadily over time. This is because our raw magnitude is a function of not only rotational phase, but of the object's distance to the sun (heliocentric distance, r), its distance to Earth (geocentric distance, *delta*), and its solar phase angle (α).

Figure 1:



From Table 1, we can see that although r and *delta* do not vary significantly over our period of observation, the solar phase angle does vary substantially. As this solar phase angle becomes larger, less light is reflected our way, and this is what accounts for the drop in magnitude we see in the preceding graph.

It is our goal to reduce the data in such a way that the variation in magnitude of the object is due to rotation only. To do so, we used the H, G magnitude system that was adopted by the IAU Commission 20 in 1985. Bowell, et al. (1989).

First, heliocentric, geocentric, and phase angles at the time of observation were extracted from the JPL HORIZONS database. Using a C-program we wrote, we were able to match the closest timestamps of the ephemeris data to the timestamp of each individual image.

The raw magnitudes are a function of heliocentric distance, geocentric distance, and solar phase angle. To normalize our lightcurve, we want to reduce this magnitude to what is called the object's absolute magnitude, what the object's brightness would be if it was exactly 1 AU from the Sun, 1 AU from the Earth, and at a solar phase angle of 0 deg. We account for the heliocentric and geocentric distances first, using the following equation:

$$H(1,1,\alpha) = H(r,delta,\alpha) - 5\log(r \times delta)$$

Then, using the H, G Magnitude system, we convert from $H(\alpha)$ to H, the absolute magnitude. To do so, the function of α, Φ, is calculated from the solar phase values as shown below. The two constants A and B were determined through fits with empirical data of asteroids by Bowell et al. (1989). Therefore, Bowell explained, the calculations for the mean V-band magnitude of an asteroid (without rotational or aspect variations) could be calculated by the formula:

$$H(\alpha) = H - 2.5\log[(1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)]$$

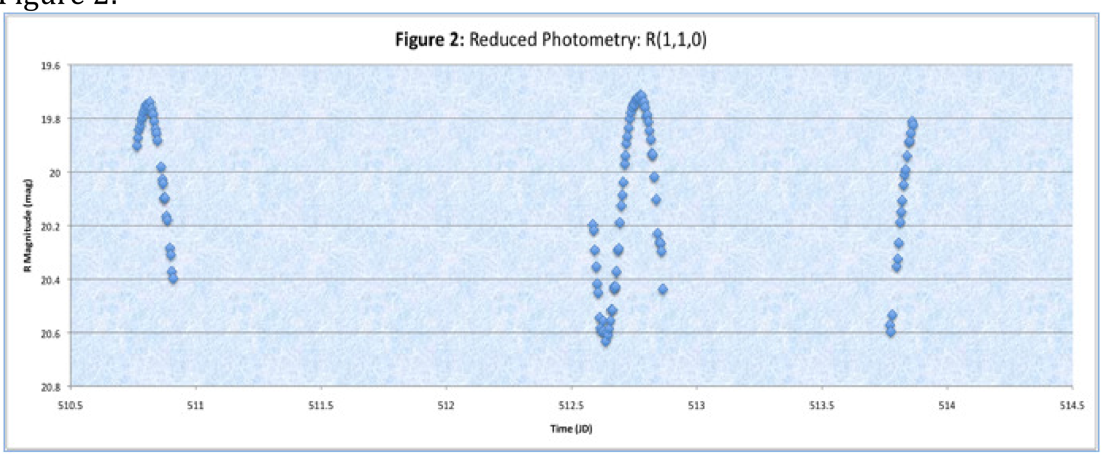
$$\Phi_i = \exp[-A_i(\tan 0.5\alpha)^{B_i}]; \qquad i = 1,2$$

$$A_1 = 3.33 \qquad B_1 = 0.63$$
$$A_2 = 1.87 \qquad B_2 = 1.22$$

Where $H(\alpha)$ is the V-band magnitude, at solar phase angle α, reduced to unit heliocentric and geocentric distances, and H is the absolute magnitude. The slope parameter G is indicative of the gradient of the solar phase (α) curve, and has been scaled in such a way that $G \approx 0$ for steep phase curves and $G \approx 1$ for shallow phase curves (Bowell et al. 1989).

When we plot this absolute magnitude, H, as a function of time, as shown in Figure 2, we see that we now have what looks like a periodic function that varies about a horizontal line. Our next task is to phase this data in order to find 2002 VE68's rotational period.

Figure 2:



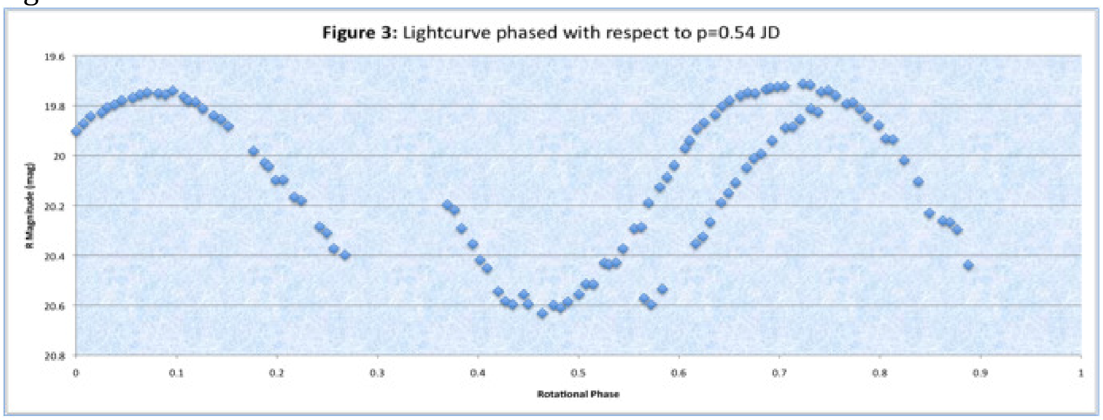
In order to find the best period for the object, we wrote a C-program that, for each arbitrary period, p_i, it converted the timestamps of the lightcurve from JD to rotational phase (φ), such that φ is always between 0 and 1, in the following way:

$$\varphi = (t_j - np_i - t_0)/p_i$$

where t_j is the timestamp of the image, n is the number of periods p that have elapsed since time t_0, and t_0 is the timestamp of the first exposure.

Since these periods are arbitrary, the lightcurves of the three separate nights, seen clearly in Figure 1 and 2, are not necessarily going to overlap nicely with each other. When it is offset in this way, we can see that there is substantial error between the data points. This is illustrated in Figure 3.

Figure 3:



We can use this error to find the best fit for our period, since the sum of all errors associated with the correct period will be much smaller than the total error associated with incorrect periods.

Our observations, and subsequently this data reduction, were done across all four Bessel BVRI filters. Since the magnitudes of the object are not equal across all filters, the BVI data points are plotted after offsetting relative to R by the nightly colors listed in Table 2. We found that the photometric behavior of 2002 VE68 was the same across all four filters.

Table 2:

UT Date	B-R (mag)	V-R (mag)	R-I (mag)
2010 11 10	1.112+/-0.014	0.432+/-0.022	0.338+/-0.013
2010 11 12	1.094+/-0.018	0.404+/-0.028	0.347+/-0.013
2010 11 13	1.107+/-0.020	0.422+/-0.012	0.367+/-0.013
mean	1.106+/-0.019	0.419+/-0.021	0.348+/-0.014

An additional advantage of observing across the four filters is that we can use object's relative colors to learn something more about the object's spectral class. Asteroids are grouped into spectral classes based on their spectral behavior.

Spectral classification is useful because objects that fall in the spectral class, i.e. that exhibit similar spectral behavior, also share many physical characteristics, such as chemical make-up, place of origin within the asteroid belt, and albedo.

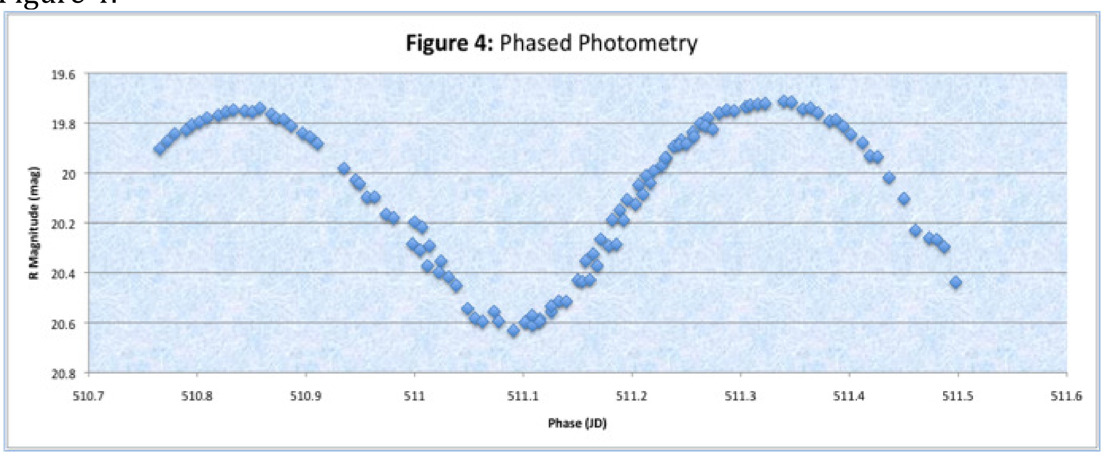
In order to find 2002 VE68's spectral type, we compared the object's colors to the over 1300 asteroids in the SMASS II database, in order to find the asteroids whose spectral behavior most closely matched that of our object.

Results

When we ran our data through our rotational period search program, we found that the best fit for our period was 0.5625 days, or, 13.50 hours, making 2002 VE68 a relatively slow rotator.

We can see in Figure 4 that 2002 VE68's lightcurve shows an amplitude of about 0.9 mag. Since brightness is a function of the surface area of the asteroid that faces us at any time, and that surface area changes as the asteroid rotates, this amplitude in brightness can be used to find the relative shape of the asteroid.

Figure 4:

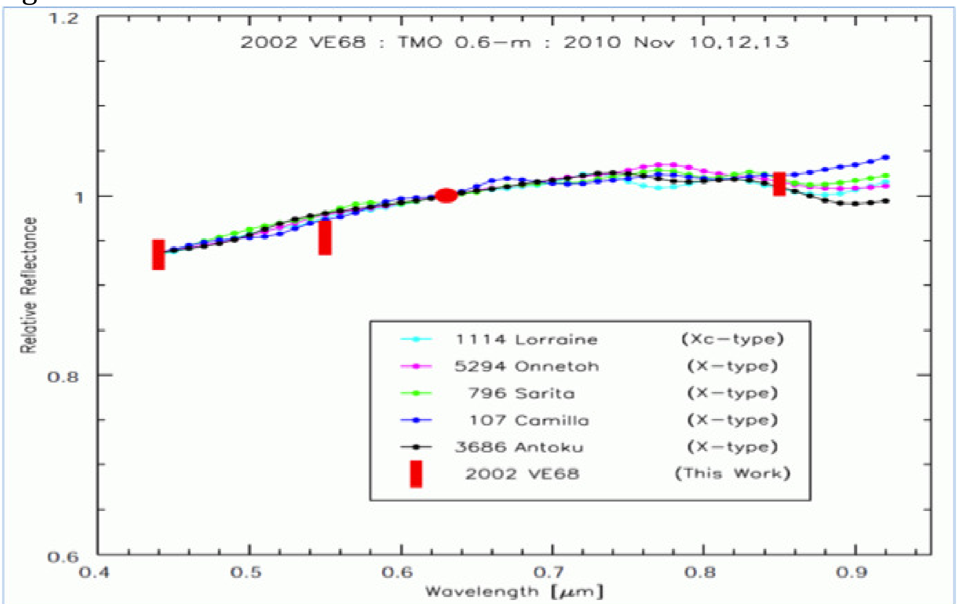


Magnitude is calculated on a logarithmic scale, so that an amplitude of 0.9 mag means that 2002 VE68 is approximately two and a half times brighter at the peaks of its lightcurve than at the troughs. Brightness is related to surface area by:

$$D = (1329 \times 10^{-0.2H})/\sqrt{\rho}$$

where D is surface area, and H is absolute magnitude, and ρ is albedo. This same relation can be used to find the size of the asteroid. 2002 VE68 was found to have an effective diameter of about 200m.

Figure 5:



Comparison of 2002 VE68's mean colors, listed in Table 2, to the spectra of asteroids in the SMASS II database showed that it is most likely an X-spectral type asteroid (Bus Taxonomy), as shown in Figure 5. The slight reflectance dip at 0.55 micron is consistent with the deep 0.50 micron feature observed in the spectrum of the E-type asteroid 2867 Steins (Weissman et al. 2008). The spectral resolution that our BVRI photometry affords is often insufficient to resolve the E-M-P sub-classes within the X-spectral complex (Tholen Taxonomy).

In general, X-type asteroids have relatively flat to slightly red spectra, implying they tend to be Iron poor. Since sampling across our four filters does not give a high enough resolution to verify the slight reflectance dip at 0.55 micron, we differentiate between the three subclasses, E, M, and P, by looking at the asteroid's solar phase curve. 2002 VE68 is most likely an E-type asteroid. These typically have moderate albedos of around 0.25.

Conclusion

2002 VE68's mean colors are most compatible with an X-type spectral classification, implying an albedo of about 0.25. After converting photometry from magnitude to flux units, we found a best-fit synodic period of 13.50+/-0.01 hr, as shown in Figure 4. This is in agreement with the value reported by Petr Pravec and colleagues (private communication). Our photometry yields an absolute magnitude of 20.59+/-0.02 mag, implying a effective diameter 200m. The lightcurve amplitude of 2002

VE68, at 0.9 mag, suggests that it is elongated in shape, with a surface ratio of roughly 2:1, and that it may be a contact binary.

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Acknowledgements

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