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CERTAINTIES, QUESTION MARKS AND VOIDS IN THE PRESENT-DAY DATA CONCERNING THE ROTATION PERIOD OF ASTEROIDS

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There are more than 700,000 asteroids with well-defined orbits. However, the LCDB data base (version Feb 2017) contains rotation period data for only 17,437 asteroids and yet, more than two thirds of those reported measurements still may be uncertain by 30% (U = 2) and another 10% may be completely wrong (U = 1). It should be possible to know the characteristics of asteroid spins without measuring every last one of them, on condition that our sample (1) is unbiased, and (2) it properly includes odd or outlier objects. In principle, U = 2 data should be good enough for both statistical analysis and for identifying oddballs. Wide-field data now comprise the majority (~63%) of spin rates we have. However, due to the overwhelming volume of W-F data, their corresponding reliability is in practice almost impossible to assess on a case-by-case basis, so that a nominal U = 2 has been basically assigned to them. This poses the question whether including W-F data actually improves or degrades statistical analysis performed using only the smaller but more carefully controlled data from the F-D file. This paper shows that for size ranges where both F-D and W-F data samples contains at least 100 values, the W-F mean significantly differs from the F-D value (with only one exception for the narrow range 1 < D < 0.7 km, where W-F data appears to be as almost unbiased). The spin rate percent difference for asteroids having diameters between 3 to 20 km is consistently uniform, and worsens for larger ones. With respect to studies of extremes of rotation, W-F surveys and less controlled samples can be useful, if the limitations are reasonably characterized.

Studies of asteroid rotation rates and lightcurve properties provide important data for development of theories of asteroid structure and physical processes. The Asteroid Lightcurve Data Base (LCDB; Warner *et al*., 2009) is a set of files that collects and organizes the required information for these studies, obtained from numerous journals and other sources. The LCDB provides a central location for basic information about asteroid rotation rates and related data that can be used in statistical studies involving a few or many parameters.

The LCDB assigns a code – namely the U code – that provides an assessment of the quality of the period solution. A quality code U = 3 means that the corresponding rotation period is basically correct (thus unambiguous and reliable); U = 2 means that the found rotation period is likely correct, although it may be wrong by 30% or it is ambiguous (e.g., the half or double period may be correct); U = 1 means that the established rotation period may be completely wrong; U = 0 means that the period is yet unknown or a reported solution has been determined to be incorrect. The assigned U quality code can also be highlighted with either a plus (+) or a minus (-) sign, meaning that the certainty of the found solution is respectively slightly better or worse than the corresponding grade.

It seems quite reasonable that we can know the characteristics of asteroid spins without requiring the measurement of every last one of them. (From thermodynamics we have learnt that it is possible to characterize the molecules of a gas – that is, the various components by molecular weight and the velocity distribution of the molecules – without measuring every single molecule.) The main problems we have with asteroid spins are: (1) being sure our sample is unbiased, so the spin rate distribution and the separate classes are truly representative of what we intend to be measuring, and (2) seeking and characterizing odd or outlier objects.

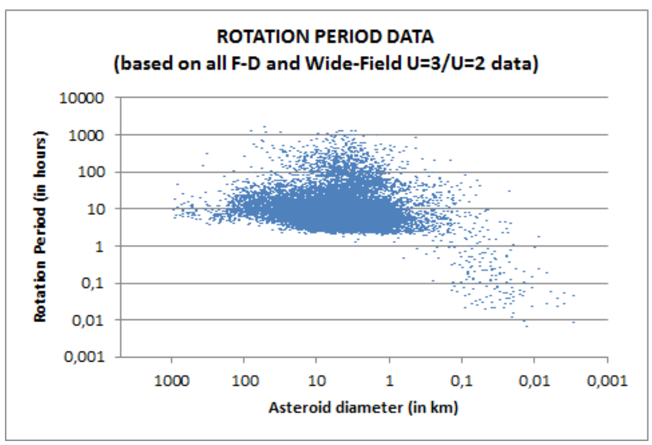

Figure 1. The rotation period data in terms of asteroid diameter. Each dot represents a reported solution been rated either U = 3 or U = 2. Both axes appear in logarithmic scale.

Range of Asteroid Diameter (km)	F-D data			W-F data (only U = 3 and U = 2)			S-D data
	quantity	Mean log	Mlog P (h)	quantity	Mean log	Mlog P (h)	quantity
D > 150	137	0.980	9.55	2			0
150 > D > 100	163	1.137	13.71	0			0
100 > D > 70	242	1.138	13.73	1			0
70 > D > 45	367	1.136	13.67	5			0
45 > D > 30	451	1.092	12.36	27			0
30 > D > 20	495	0.998	9.96	118	1.182	15.21	1
20 > D > 13	476	0.992	9.82	310	1.074	11.86	3
13 > D > 10	381	0.913	8.19	427	0.985	9.67	4
10 > D > 8	354	0.858	7.21	532	0.963	9.18	3
8.0 > D > 6.5	443	0.881	7.60	667	0.943	8.76	3
6.5 > D > 5.2	396	0.893	7.82	804	0.974	9.42	2
5.2 > D > 4.0	434	0.860	7.25	1192	0.927	8.46	4
4.0 > D > 3.0	313	0.885	7.67	1350	0.954	9.00	5
3.0 > D > 2.2	305	1.012	10.29	1398	0.913	8.18	2
2.2 > D > 1.5	187	0.972	9.38	1371	0.918	8.27	1
1.5 > D > 1.0	161	0.836	6.85	1009	0.899	7.92	0
1.0 > D > 0.7	108	0.867	7.37	431	0.858	7.21	0
0.7 > D > 0.5	100	0.936	8.63	111	0.892	7.80	0
0.5 > D > 0.33	111	0.939	8.68	15			0
0.33 > D > 0.2	110	0.923	8.37	5			0
0.2 > D > 0.07	119	0.407	2.55	12			0
D < 0.07	125	-0.601	0.25	0			0
Totals	5978			9787			28

Table I. The overall distribution of present-day rotation period data with quality codes either U = 3 or U = 2, arranged by range of asteroid diameters (rows). In columns, the first arrangement corresponds to data origin: F-D data file, Wide-Field surveys or Sparse-Data objects (e.g. those with fewer than 60 data points from a short span of 2-4 nights). Size ranges go as $D_i > D > aD_i$, where the coefficient a ~ 1.2-1.5. For those asteroid size ranges where there were found at least 100 reliable spin values, the Mean Log column represents the Mean Logarithmic value and the adjacent MPeriod column shows (in hours) the corresponding rotation period for such Mean Logarithmic value.

For this study I utilize the LCDB version released on 2017 February 02, which includes reported rotation rate solutions for 17,437 asteroids. Respective quality codes have been assigned as follows: 4,046 (roughly one fifth) were found to be reliable data and therefore have U = 3; 11,838 (roughly two thirds) were assessed as fairly good quality solutions, so that they have U = 2; and 1,553 (roughly one tenth) were found rather poor quality solutions, achieving U = 1. (In this study I do not take into account the (+) or (-) second order quality assessment, so that all spin data are considered as having U quality codes just equal to 3, 2, 1 or 0.)

According to the U quality code criterion, it seems quite reasonable that data having a quality code of at least U = 2 should be good enough for both statistical spin analysis and for identifying oddballs. Figure 1 shows how present-day rotation period data having either U = 3 or U = 2 is distributed in terms of asteroid sizes. Two features immediately catch the eye: (1) period rate solutions embrace a wide time range (from under a minute to almost 2 months), and (2) period rate solutions are largely concentrated at the lower region of the time range (between 15 h and the so-called spin-barrier at 2.2 h).

Since 2012, wide-field asteroid photometric surveys have been revolutionizing the incoming flow of new data to the LCDB, now comprising the majority of data we have. Unlike “conventional” observing campaigns targeting just one single object’s lightcurve, wide-field photometric surveys are capable of measuring hundreds of asteroid lightcurves simultaneously.

However, period rotation data from wide-field photometric surveys were typically derived from undersampled lightcurves, thus making them often ambiguous (Harris *et al.*, 2012). Moreover, due to the overwhelming volume of these data, their corresponding reliability is in practice almost impossible to assess on a case-by-case basis. (As a matter of fact, with regard to a large majority of wide-field survey results, it has been adopted the policy of automatically assigned them a nominal U = 2 without much scrutiny.) Consequently, the LCDB authors emphasize that data from wide-field surveys may be contributing biased statistics in Frequency versus Diameter (F-D) analyses. Thus the LCDB maintains a selective file for such studies, the so-called F-D data file, which does not include data rated lower than U = 2, wide-field or sparse-data objects (i.e., all data considered less than fully-reliable for rotation or other studies have been especially precluded).

The LCDB version I analyze contains 11,033 spin rates obtained from wide-field surveys, thus representing almost two thirds (63%) of the grand-total of published rotation period data. With regard to quality codes, those 11,033 solutions are divided as follows: only 235 (2%) correspond to U = 3 data; the large majority 9,552 (87%) have U = 2, while the remaining 1,246 (11%) have U = 1. On the other hand, the F-D data file only contains 5,978 spin rates, but all of them are at least of fairly good quality – almost two thirds (3,811 entries) were assessed U = 3, while the remaining (2,167 entries) were assessed U = 2. Figure 2 shows how reliable U = 3 and fairly good U = 2 present-day data are distributed according to their wide-field or “conventional” (non-wide-field) origin.

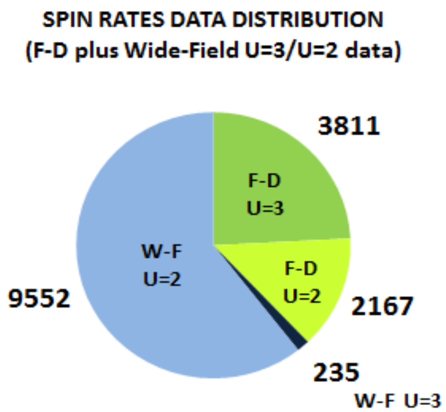

Figure 2. The 15,765 rotation period data that have been assigned either U = 3 or U = 2, divided with regard to their wide-field or non-wide-field origin. The reliable U = 3 spin rates represent about 25% of the overall "correct" and "likely correct" data.

Table I presents how the present-day U = 3 and U = 2 rotation rate solutions are distributed among different ranges of asteroid size. For each range, data have been separated according to their wide-field or non-wide-field origin. (Each size range embraces asteroid diameters from 1 D to ~1.5 D; I choose those size ranges in order to work with a meaningful range quantity (~20), but on condition each one having at least 100 reliable spin data from the same origin.) For those asteroid size ranges fulfilling such requirement, in adjacent columns appear the Mean Logarithmic value for that sample, and its corresponding rotation period (in hours). Figures 3 and 4 show the histogram distribution for F-D and W-D U = 3 and U = 2 data according to the chosen asteroid ranges.

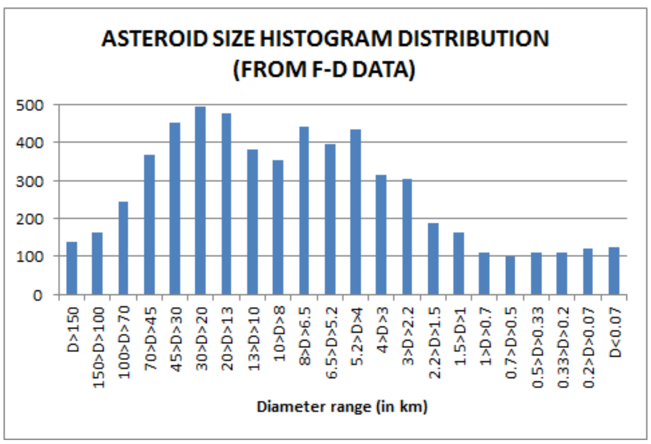

Figure 3. The histogram distribution according to the asteroid diameter ranges of Table I. As shown, ranges have been selected so that each one currently has at least 100 reliable spin data.

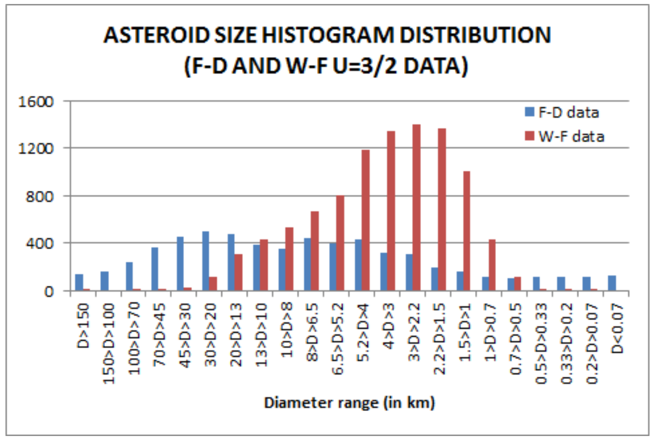

Figure 4. A comparison of the histogram distribution for F-D data (in blue) and W-F data (in red) from Table I. For those asteroids in the size range 0.7 < D < 10 km, data from W-F largely exceed corresponding F-D data.

Clearly, present-day W-F data is heavily concentrated in a much narrower size range than F-D data, showing a Maxwellian-like distribution peaking at D ~3 km.

Except for just an insignificant number of radar and direct flyby observations, all of our asteroid spin rate data have been derived from photometric measurements. Given the observational nature of such technique, it seems quite logical that all our data have been biased against faint, low-amplitude, or slowly rotating asteroids.

In spite of such "intrinsic" observational biases, present-day W-F data are inevitably *additionally* biased given the low success rate such surveys still yield. In effect, spin rate data from wide-field surveys were found for only about 20% of all observed objects, *"meaning that only the 'easier' results were found"* (Warner *et al.*, 2015).

How biased is our wide-field data?

The logarithmic mean spin rate for the controlled, reliable F-D data corresponding to each one of the diameter ranges (as defined in Table I) is shown in Figure 5. In order to find out the degree of bias in the W-F data, in Figure 6 I compare the log mean period between wide-field surveys versus the F-D data in each size range having at least 100 U = 3 or U = 2 values.

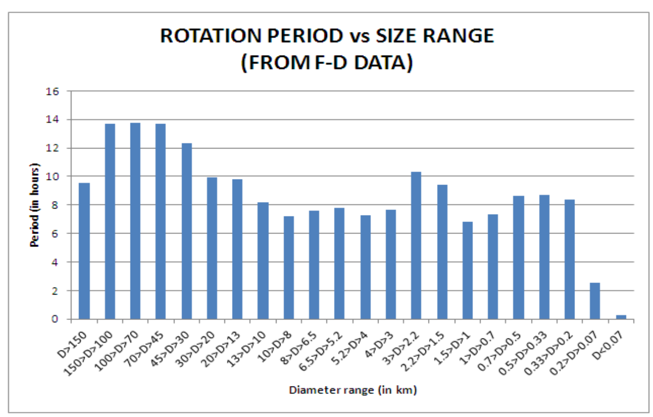

Figure 5. The log mean rotation rate distribution (plotted in terms of corresponding hours) for each one of the diameter ranges defined in Table I, according to our reliable F-D data.

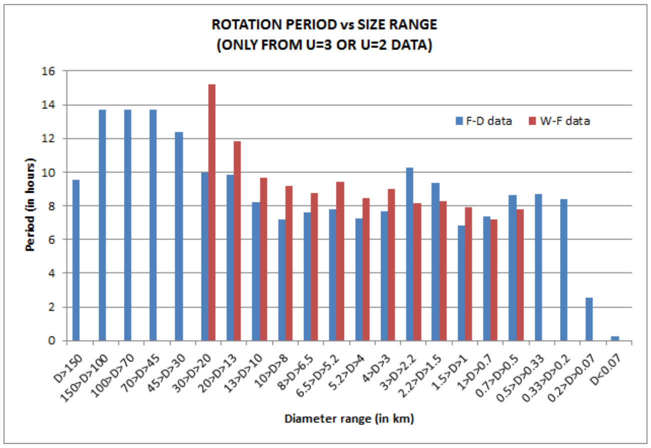

Figure 6. The comparison of the log mean period (in hours) between W-F data versus F-D data in each size range having at least 100 reliable values.

Figure 7 enlarges the results of such comparison. Of the thirteen size ranges considered, the W-F log mean spin rate significantly differs (by more than 15%) from the F-D value for ten of them, and for another two the difference still is important (~10%). Only for one particular diameter range (0.7 < D < 1 km) there seems to be no 'extra' bias in W-F spin rate data, while quite the opposite occurs for the largest size compared (D > 20 km) for which the discrepancy in the log mean spin rate is statistically remarkable (53%). The observed bias in the W-F data consistently enlarges the measured periods for asteroids having D > 3 km. Interestingly, this trend seems to abruptly end and even reverse for the size range between 1.5 to 3 km.

The obvious conclusion is that the so-far available wide-field data are essentially and notoriously biased, most likely against faint, low amplitude and very short or long period asteroids, as already been warned by Warner and Harris (2011) and Harris *et al*. (2012).

Therefore, with regard to asteroid rotation statistics, the inclusion of the vast new sample from wide-field surveys to the smaller but more carefully controlled F-D data clearly degrades the results.

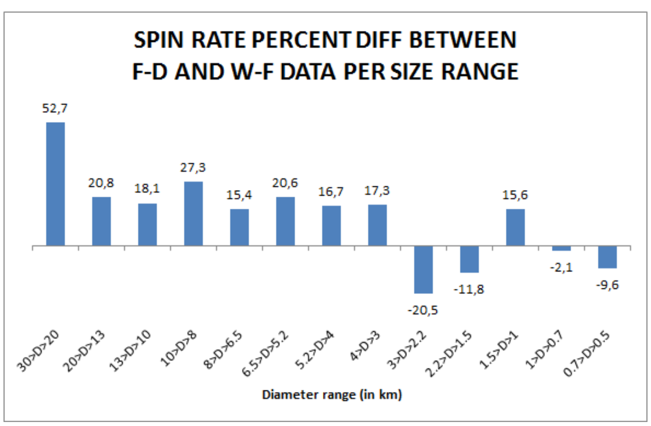

Figure 7. The percent difference in the log mean periods between F-D and W-F U=3/2 for each one of the considered size ranges.

The search for oddballs

Especially interesting and fruitful for development of theories of asteroid structure and physical processes are studies of extremes of rotation, both fast and slow rotators (Pravec and Harris, 2000).

Figure 8 shows the histogram of number vs rotation period (logarithmic binning) distribution for large asteroids (D > 30 km) from F-D data (since so far there is almost no W-F data for those large asteroids). A Maxwellian-like distribution appears, peaking at P ~9 hours.

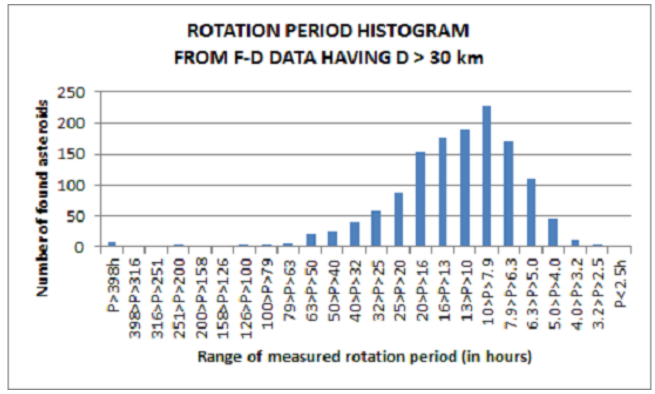

Figure 8. The histogram distribution corresponding to those currently known 1360 asteroids having a diameter larger than 30 km whose spin rate data have been rated either U = 3 or U = 2.

Figure 9 shows the histogram of number vs rotation period (logarithmic binning) distribution for smaller asteroids (D < 500 m) from F-D data (since, once again, so far there is almost no W-F data for those smaller asteroids). Two subsets are shown: <150 meters and those in the range 150-500 meters. For those slower rotators greater than 2.5 hours the distribution resembles the left-side of a typical "bell-curve" shape; these are primarily the larger members of this subgroup. However, for the < 150 m subgroup, they appear to show a relatively flat distribution down that extends to extremely short periods to ~0.025 hours. These fast rotators are the "monoliths" having enough strength to spin faster than the "spin barrier" described by Harris and Pravec (2000).

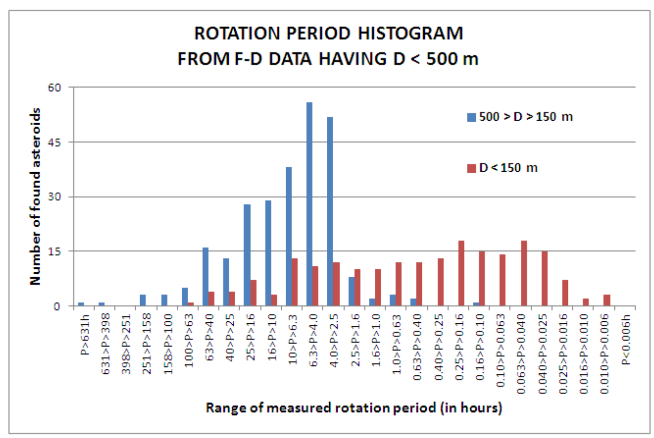

Figure 9. The histogram distribution corresponding to those currently known 465 asteroids having a diameter smaller than 500 m whose spin rate data have been rated either U = 3 or U = 2. The overall distribution is shown separated into two subsets: those 261 asteroids having 500 > D > 150 m for which the 2.5 "spin barrier" becomes evident, and those 204 asteroids having D < 150 m for which no "spin barrier" prevents them from achieving faster spin rates (likely due to being coherent bodies)

Seeking and characterizing odd or outlier objects does involve "fishing" a larger sample and paying less attention to biases of the sample. Observing single asteroids one at a time for that goal clearly represents an inefficient endeavor. Therefore, wide-field surveys and less controlled samples can be very useful particularly for identifying oddballs, on condition the limitations are reasonably characterized.

As a matter of fact, of the currently known 10 slowest rotating asteroids with quality code either U = 3 or U = 2 (Figure 10), four of them (those 5-digit numbered) were found from wide-field surveys. The present-day record holder is 846 Lipperta, having a rated U = 2 rotation period of 1641 h. On the other hand, as expected, the currently known 10 fastest rotator asteroids are all from the F-D data set.

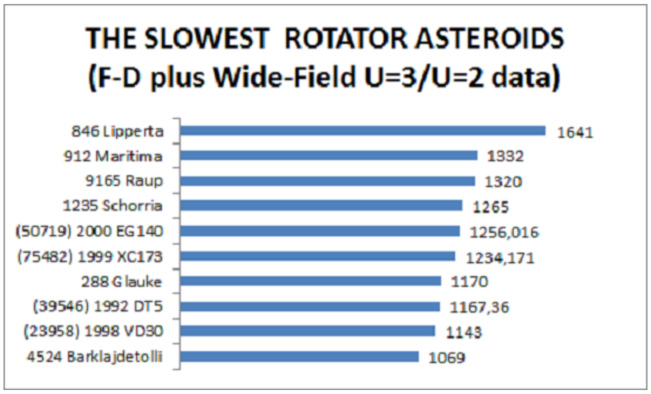

Figure 10. The 10 slowest rotator asteroids with reliable data (rated either U = 3 or U = 2) known at the beginning of 2017. The correspondent periods are expressed in hours.

At the beginning of the century, Pravec *et al*. (2002) had anticipated that in the following 10 years we would have had a much more detailed and complex picture of the asteroid rotational properties over wide range of sizes and orbits. We are seeing some fulfillment of this prediction, but much remains to be done. Wide-field asteroid photometric surveys certainly hold promise as important contributors, particularly if they can be conducted in ways that mitigate against the inherent biases identified.

Acknowledgements

Thanks to Alan W. Harris for several pertinent and fruitful suggestions that certainly corrected and improved this study.

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ROTATION PERIOD OF ASTEROID 3494 PURPLE MOUNTAIN

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Data for asteroid 3494 Purple Mountain were collected from 2015 June 25 to 2015 August 17. The rotation period was determined to be 2.928 ± 0.0012 h.

Asteroid 3494 Purple Mountain is located in the main belt. It has a semi-major axis of 2.349 AU, orbital period of 3.60 years, and eccentricity of 0.131 (JPL 2016). It was discovered by Purple Mountain Observatory at Nanking, China in 1980 (Zhang et al. 1983). Near-infrared reflectance spectra showed that Purple Mountain is a daughter of 4 Vesta (Kelley et al. 2003).

Data Collection and Analysis

Thirteen nights of data were collected at the MIT George R. Wallace Jr. Observatory from 2015 June 25 to 2015 August 17. Data were collected using two 14-inch Celestron Schmidt-Cassegrain telescopes equipped with SBIG STL-1001E cameras. Table I describes the location of Purple Mountain and number of images taken on each night.

In order to produce astronomical lightcurves, the data were first reduced using flats, darks, and biases in AstroImageJ (Collins & Kielkoph, 2013). Then, aperture photometry was performed on the reduced data to find the relative magnitude of Purple Mountain. We obtained apparent magnitudes by comparing Purple Mountain to field stars listed in the USNO-A2.0 Catalogue (Monet et al.,1998). Afterwards, the asteroid motion was corrected to determine the absolute brightness using the Earth-asteroid and Sun-asteroid distance. Then a linear fit to the data was used to account for the phase angle change and to further correct for the motion.

After performing motion corrections, the data were binned by five and a lomb scargle periodogram was used to find the period of Purple Mountain (Vanderplas et al., 2012). The highest peak corresponded to 2.928 ± 0.0012 h, with lesser significant peaks at 2.609, 3.339, 3.879, 4.627, 5.731 h. Next, the binned data were phase folded over each of the significant peaks. The best visual fold matched the period of 2.928 ± 0.0012 h (Fig. 1), which agrees with Cantu et al. (2016).