Acknowledgments

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A NINE MONTH PHOTOMETRIC STUDY OF THE VERY SLOWLY ROTATING ASTEROID 288 GLAUKE

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Fifteen images of the extremely slowly rotating 288 Glauke were obtained every clear night except when the target was very close to the Moon in the interval 2013 Nov. 5 - 2014 July 27 during which the object was more than 60 degrees from the Sun, a total of 187 nights. Tumbling behavior was found, with possible periods near 1170 hours and 740 hours, respectively, and uncertainties probably no larger than 2%. The reliability of tumbling behavior was assessed as PAR=-2. The color index was also determined as V-R=0.48. Magnitude parameters in the V photometric system H=9.99 ± 0.04 and G=0.24 ± 0.02 were found

Minor Planet 288 Glauke was the first minor planet ever to be found to have an extremely long rotation period. Harris et al. (1999) found on the basis of observations in 1982 a period between 1110 and 1210 hours with a value dependent upon an assumed value of G between 0.12 and 0.34. Binzel (1987) obtained a period near 1150 hours that Harris et al. (1999) reanalyzed to 1296 hours. Kryszczynska et al. (2003) found an irregular lightcurve which they suggested as indicative of NPA rotation (tumbling). A stated equivalent single period of 77 days cannot be considered reliable. Ostro et al. (2001) made radar observations of the bandwidth of the echo. Due to uncertainties in the effective diameter of the asteroid, the orientation of its rotation axis relative to the line of sight, and noisy data, the rotation period could only be established as less than 2100 hours.

An ephemeris of 288 Glauke between 2013 November and 2014 August shows that it was consistently farther than 60 degrees from the Sun and brighter than magnitude 15 during this interval, approximately five rotational cycles. The goal of the new observations was to obtain a reliable and fairly accurate rotation period and look for possible tumbling behavior. The observational strategy was to obtain fifteen 60 second exposures every clear night except when the Moon was close during this time frame and establish the R magnitude within a few x 0.01 on each night. A mean magnitude for each night would constitute an effective single data point. On some nights one or more of these fifteen exposures was defective and could not be reliably measured, and on a few nights unusual circumstances recommended obtaining more than fifteen exposures. This observational procedure was made on a total of 187 nights from 2013 Nov. 5 through 2014 July 27, an interval of nearly 9 months.

Author FP made all the observations at the Organ Mesa Observatory with a 0.35-meter Meade LX200 GPS Schmidt-Cassegrain (SCT) and SBIG STL-1001E CCD. All exposures were 60 seconds, unguided, with a clear filter. Photometric measurement calibrated in the Cousins R magnitude system by stars with near solar colors was with *MPO Canopus* software. The Comparison Star Selector in this software identifies stars with near solar colors in the range B-V = 0.54 to 0.9 and V-R = 0.31 to 0.57 computed from the 2MASS catalog by formulas developed by Warner (2007). A further improvement in the R magnitudes of these stars is achieved by the method of Dymock and Miles (2009) and CMC14 (Carlsbad Meridian Circle) catalog as presented by the VizieR Service (2014). The magnitudes of stars in the CMC14 catalog, and in the CMC15 catalog which became available on line 2014 March from VizieR (2014), have a much better internal consistency than those in the MPOSC3 catalog. The Sloan r' magnitudes of the calibration stars in these catalogs are converted to the R magnitude system by R = r' - 0.22, and then substituted for their MPOSC3 values. The *MPO Canopus* software constructs the lightcurve by further adjusting these calibrated R magnitudes to changes in the heliocentric and geocentric distances and an assumed G = 0.15. A raw lightcurve based on these values with no adjustments of instrumental magnitudes has a night to night behavior smooth within a few x 0.01 magnitudes which we interpret as the internal consistency of the calibration star R magnitudes for all of the 187 sessions. The raw lightcurve is however quite irregular on a time scale of 10 to 20 days, which suggests large amplitude tumbling.

Color indices were found on two nights, 2013 Dec. 18 at phase angle 25 degrees, and 2014 April 8 at phase angle 3.6 degrees. Fifteen 60 second exposure images were made in with the R filter and converted from CMC14 r' magnitudes to Cousins R magnitudes by R = r' - 0.22. An additional fifteen 60 second exposure images were made with the V filter and converted from CMC15 r', J, and K magnitudes to Johnson V magnitudes by V = 0.9947*r' + 0.6278*(J-K). Both magnitude conversion procedures are from Dymock and Miles (2009). At 25 degrees phase angle R=13.97, V=14.47, V-R=0.50. At 3.6 degrees phase angle R=11.68, V=12.14, V-R=0.46. I consider the difference between these values of V-R to be within reasonable observational error and not definitive of a change of color index with phase angle. Hence I adopt the mean V-R = 0.48.

We present the raw lightcurve of all data points as prepared with *MPO Canopus* software, in which the calibrated magnitudes are adjusted to changing heliocentric and distances and assumed G = 0.240 (Figure 1). The lightcurve of each rotational cycle is presented separately in Figures 2-7.

With strong evidence of tumbling indicated in the raw lightcurves, we first used the dual period procedure in *MPO Canopus* software (Warner, 2012). The dual period procedure removes the Fourier average of the lightcurve for each period from the combined lightcurve to produce that part of the variation due to each period separately. A primary period 1169 ± 1.5 hours, amplitude 0.38 magnitudes, and secondary period 737 ± 0.5 hours, amplitude 0.22 magnitudes, are clearly shown in Figures 8 and 9, respectively. The scatter is, however, greater than can reasonably be explained by errors of a few x 0.01 magnitude in the CMC14 and CMC15 catalogs and changes in aspect and solar phase angle through the nine-month interval of observation. The largest source of error arises from the dual period procedure of *MPO Canopus*, which does not model a tumbler's lightcurve fully. There are missing terms with linear combinations of the two tumbling frequencies. See Pravec et al. (2005) for details. The commonly-used technique of adjusting instrumental magnitudes of different sessions for best fit cannot be applied to this data set. In Figure 10 we separately plot the curves of Fourier components of primary and secondary periods, their sum, and include a single data point for each night so that a direct comparison with the data can be made.

If P1 and P2 are, respectively, the primary and secondary periods as found by the dual period procedure above, let the corresponding rotational frequencies be f_1=1/P1 and f_2=1/P2. A 3rd order 2-period Fourier procedure, containing all terms with frequencies (i*f_1+j*f_2) where i, j are integers between -3 and 3, and described by Pravec et al. (2005), was applied to all the data ignoring, however, effects of changing aspect and solar phase. The largest amplitudes are for f_1, 2*f_1, 2*f_2, and 2*f_2-2*f_1. A primary period 1174 hours and secondary period 747 hours are suggested. Unfortunately the data are not quite sufficient to determine a secure second period by this method. The two evaluations of the primary period agree within 0.5%, and those of the secondary period within 2%. Tumbling behavior is clearly shown, with reliability assessed at PAR=-2. Pravec et al. (2005) define the reliability PAR=-2 as "Non principal axis rotation detected based on deviations from the single periodicity but the second period is not resolved." Figure 11 illustrates the sum of the Fourier components of all of the periodic terms listed above and compares with the data.

The dual period complicated the analysis of the absolute magnitude H and slope parameter G with the H-G calculator tool of *MPO Canopus* version 10. The calculations were performed in the Cousins R magnitude system of the calibrated data. Values of H = 9.51 ± 0.03 (R magnitude) and G = 0.24 ± 0.02 have been obtained. Given the directly observed V-R = 0.48, the value of H as conventionally defined in the V magnitude system is 9.99 ± 0.03. This agrees closely with the value of 10.00 quoted in Harris et al. (1999). The H-G plot, in the V magnitude system, is presented in Figure 12.

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First author FP wishes to thank Alan W. Harris for endorsing this project.

EDITOR'S NOTE: The enormity of the effort required to fully reveal Glauke's long period lightcurve cannot be understated. To commemorate this accomplishment, two invited commentaries follow. The first is by long-time *MPB* advisor Dr. Alan W. Harris who gives a perspective on the history of asteroid lightcurve work as recorded on the pages of the *MPB*. The second is a more personal tribute to Dr. Frederick Pilcher by long-time ALPO Minor Planet Section member Frank J. Melillo, who gives a thirty year perspective on Professor Pilcher's broad role in encouraging and promoting amateur astronomers toward minor planet research.

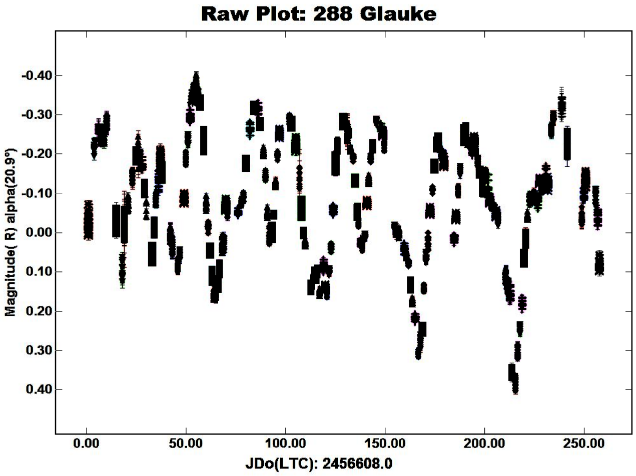

Figure 1. Raw lightcurve of 288 Glauke 2013 Nov. 12 - 2014 July 27.

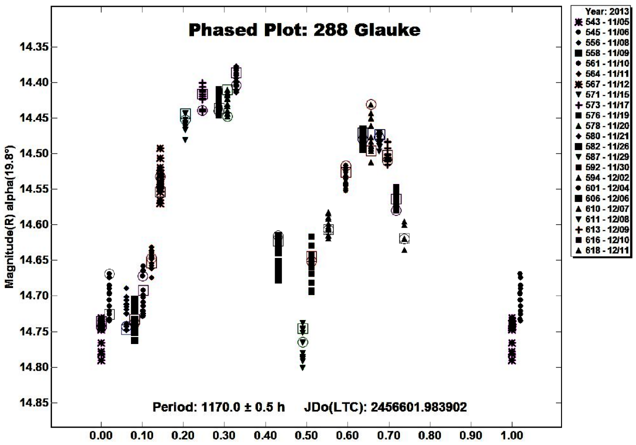

Figure 2. One cycle lightcurve of 288 Glauke 2013 Nov. 5 - Dec. 11.

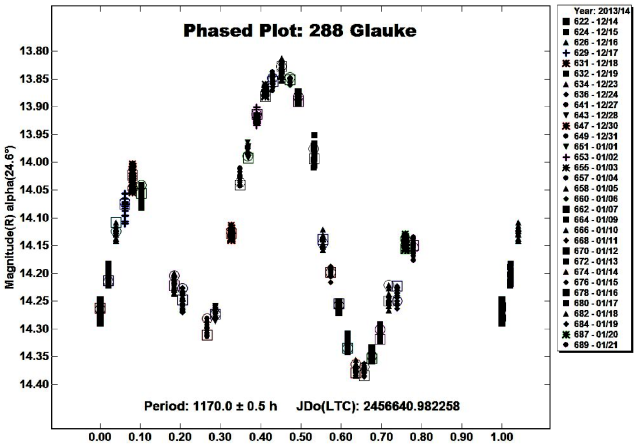

Figure 3. One cycle lightcurve of 288 Glauke 2013 Dec. 14 - 2014 Jan. 21.

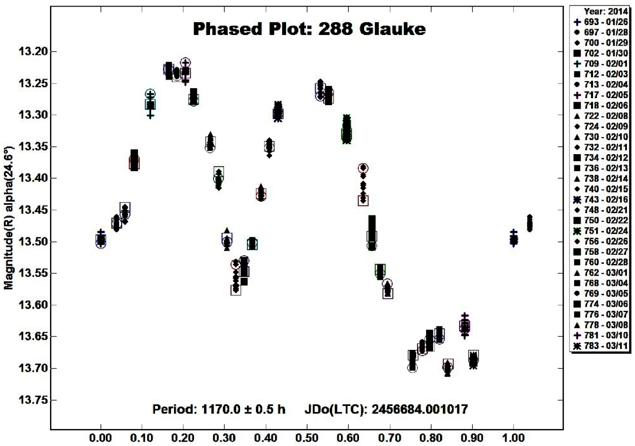

Figure 4. One cycle lightcurve of 288 Glauke 2014 Jan. 26 - Mar. 11.

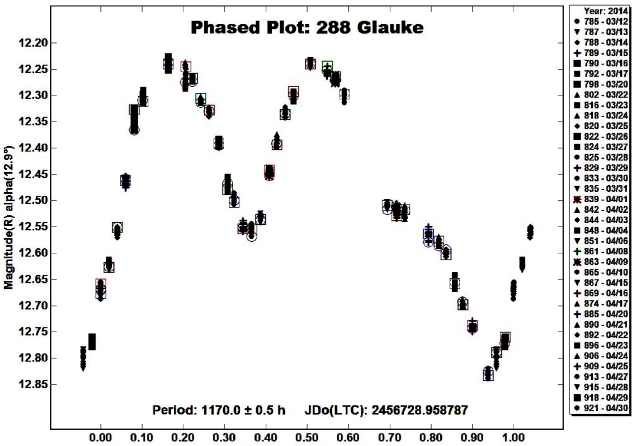

Figure 5. One cycle lightcurve of 288 Glauke 2014 Mar. 12 - Apr. 30.

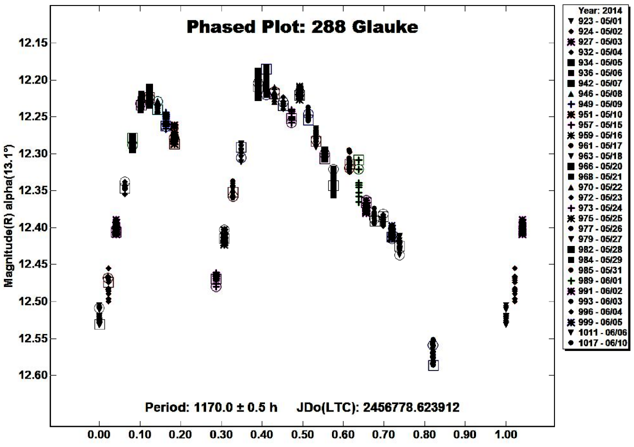

Figure 6. One cycle lightcurve of 288 Glauke 2014 May 1 - June 10.

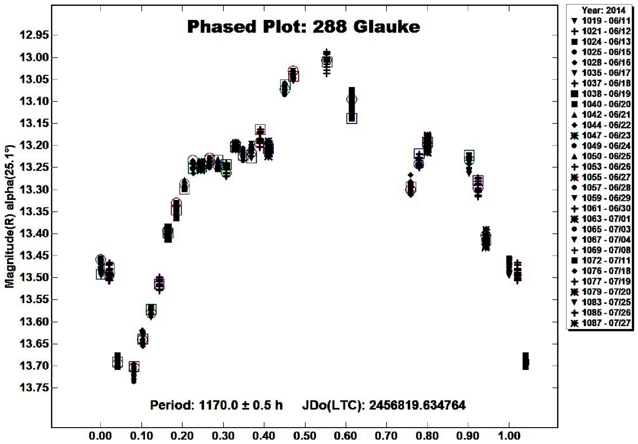

Figure 7. One cycle lightcurve of 288 Glauke 2014 June 11 - July 27.

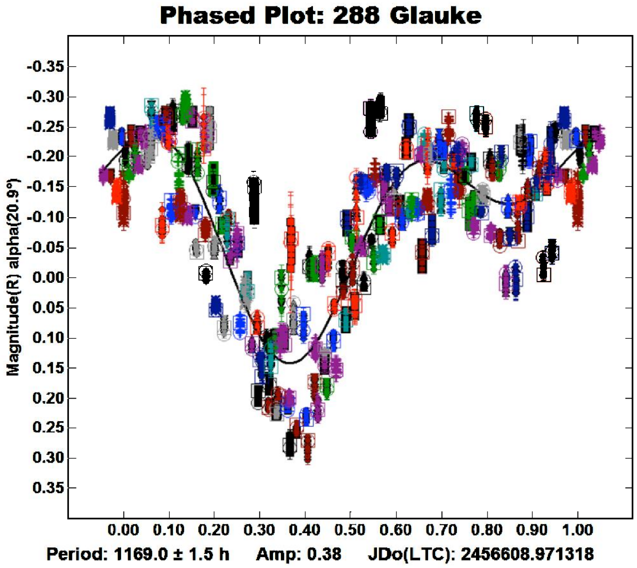

Figure 8. Lightcurve of 288 Glauke phased to the primary period 1169.0 hours with the contribution of the secondary period subtracted out.

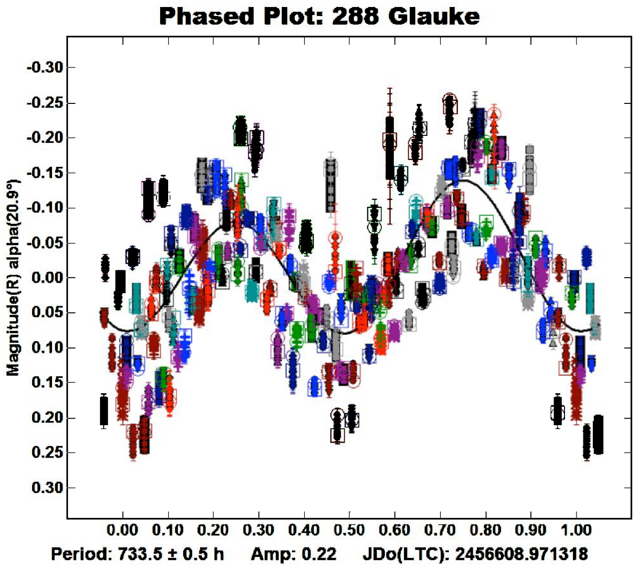

Figure 9. Lightcurve of 288 Glauke phased to the secondary period 733.5 hours with the contribution of the primary period subtracted out.

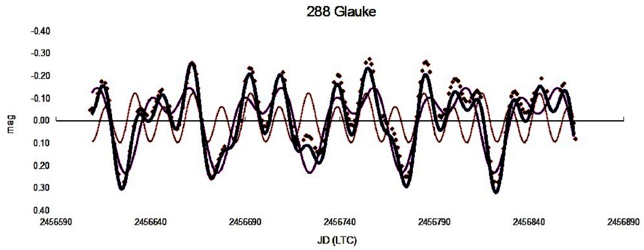

Figure 10. Graphs of second order Fourier coefficients of the primary 1169 hour period (pink), the secondary 733.5 hour period (orange), and their sum (blue). A single data point representing the mean for each night is shown in red for comparison.

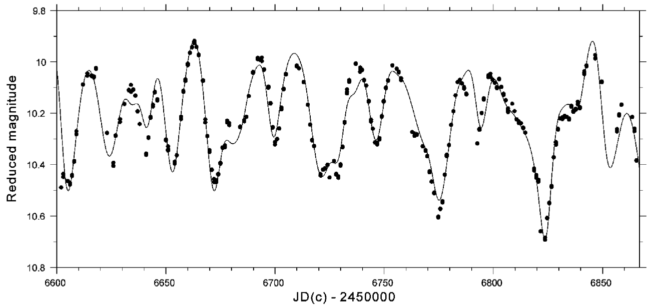

Figure 11. Graph of the third order Fourier components of primary 1174 hour period, secondary 747 hour period, and all other terms as explained in the text, with data points superimposed, all converted to R(1, 15 deg) using G=0.24.

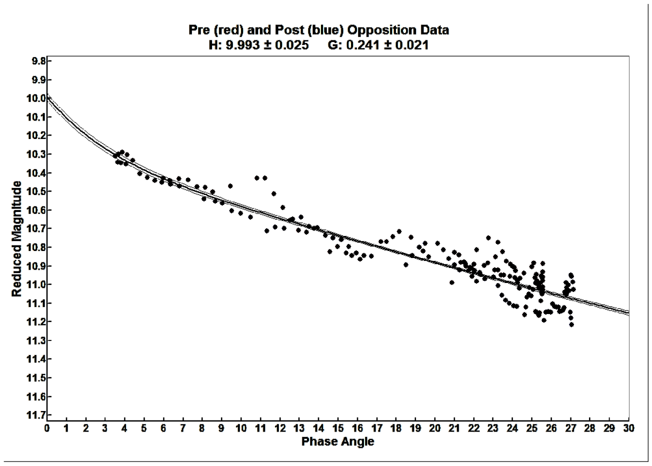

Figure 12. H-G plot for 288 Glauke, with pre-opposition data in red and post-opposition data in blue.

A PERSPECTIVE ON HOW FAR ASTEROID PHOTOMETRY HAS COME IN THE PAST FORTY YEARS

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One of the first papers in the *Minor Planet Bulletin* reporting photometric lightcurve observations appeared forty years ago – and the contrast of what can be achieved by modern amateur astronomers is beautifully put into perspective by the gargantuan accomplishment on asteroid 288 Glauke published by Pilcher *et al.* (this issue, page 6). The contrast is with those first *MPB* asteroid lightcurve observations published by Welch, Binzel and Patterson (*MPB* **2**, 20-21, 1974), reporting photoelectric observations of 18 Melpomene, correcting a previously reported period by professional astronomers. A note following the article from Joseph Patterson, Director of Camp Uraniborg (and recently honored by naming asteroid 8794 Joepatterson), pointed out that the two observers, Douglas Welch and Richard Binzel, were 15 year old high school students when they made the observations. In addition to these familiar names, it can be noted that another, Frederick Pilcher, was a Corresponding Editor of *MPB* at that time. Now, 40 years later, much has changed, yet much remains the same. All the individuals named are still active and accomplished astronomers, Welch, Binzel and Patterson are full professors of astronomy in their respective universities, and Pilcher is a retired professor who is now a very active amateur observer, as demonstrated by the current paper. Binzel, of course, is the current Editor of *MPB*, so roles are a bit reversed 40 years on, but the enthusiasm for research and learning is undiminished.

But much has changed, most dramatically the volume of asteroid lightcurve data nowadays, the methods of observation, and the highly computerized methods of analysis. Figure 1 well illustrates this dramatic growth and reveals the key role played by Brian D. Warner in opening a new gateway to the field. Prior to 1974, there were "known" rotation periods for 64 asteroids, and some of those initially published (18 Melpomene, for example) were wrong; today we have fairly reliable periods for more than 5000 asteroids. In the 1974 paper, Welch *et al.* described taking data by reading the needle position (in the dark) on a microammeter coming from the output of a 1000 volt 1P21 photomultiplier tube. And that was high-tech; Frederick Pilcher at that time was actively doing asteroid photometry – visually! Today, observations are often taken with robotically, sometimes remotely, controlled telescopes, with highly sensitive CCD cameras that allow a "backyard" telescope of modest aperture (0.3-0.4 m) to work targets as faint as could be reached only with major observatory telescopes (~2 m aperture) using a photoelectric photometer. In 1974, data analysis was done by plotting the few preciously derived data points from each night on graph paper and overlaying them on a light table to estimate the cycle period. Welch *et al.* describe a crude estimation of the pole orientation of Melpomene based on the differences in amplitude of variation at two different longitude aspects in the sky. They were roughly right, not bad for just two observing aspects. The computational power that is now brought to bear on lightcurve analysis, both hardware and software, is truly remarkable and advanced. It is now possible to do "lightcurve inversion" to obtain detailed shape models of asteroids from their lightcurves. The amount of computation to run such solutions boggles the mind and would be impossible with the computing power available even a couple decades ago, now it can be done on a home computer or even a laptop. The *Minor Planet Bulletin* itself has experienced a similar explosion of volume. In 1974, *MPB* Volume 2 consisted of 46 pages, for all four issues. The most recent *MPB* ran 106 pages, the most recent volume (41) concluded with 308 pages. With smaller type and more efficient page layout, the published volume is at least ten times greater. Along with its growth in volume, the *MPB* has become *the* journal for publication of asteroid lightcurve results, by both amateurs and professionals and combinations of both, as in the present publication. With its editorial review practices well established, the *MPB* is recognized as a professional level refereed journal, with articles indexed in the SAO/NASA Astrophysics Data System.

Lastly, it can be noted that with the vast improvement in technology has come greater challenges in observation. We have now discovered asteroids with rotation periods from under a

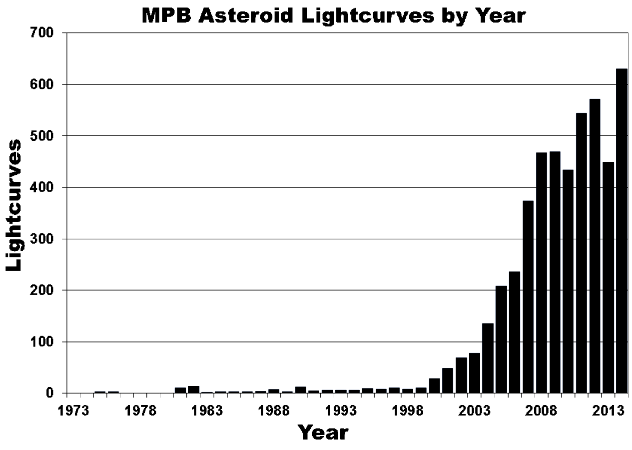

Figure 1. The growth in the number of lightcurves published in *The Minor Planet Bulletin* over the past 40 years. Notable growth spurts commencing in 1999 and 2003, respectively, coincide with the release of the popular *Canopus* software by Brian D. Warner and the subsequent publication of Warner's first edition *A Practical Guide to Lightcurve Photometry*. An even more popular second edition of Warner's book published in 2006 has certainly helped fuel the ongoing growth and what appear to be sustaining numbers of lightcurve measurements.