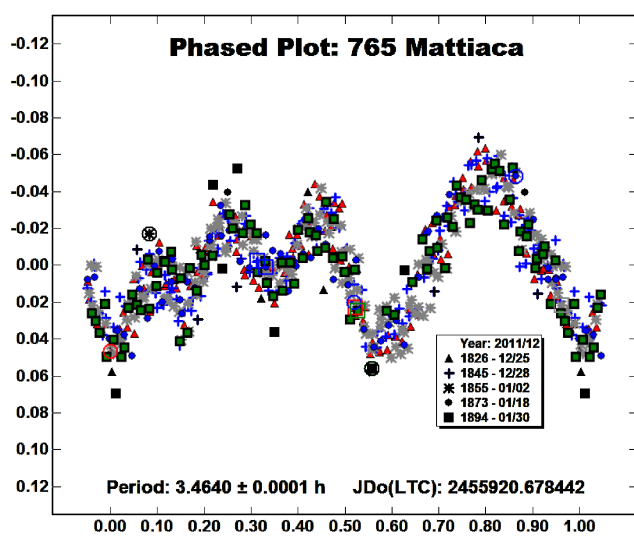




A SHAPE MODEL OF THE TAXONOMIC A-CLASS ASTEROID 446 AETERNITAS

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We acquired dense rotational lightcurves for the taxonomic A-class asteroid 446 Aeternitas during three apparitions in 2006, 2007–2008, and 2009. Our results show that 446 Aeternitas is a prograde rotator, has a distinct angular shape, and is moderately elongated. Several planar areas in the convex shape model suggest concavities, possibly large craters or saddles. These features suggest that 446 Aeternitas is likely to be a collisional fragment. We found a pole solution of $\beta = +52^\circ$, $\lambda = 356^\circ$ with no mirror solution apparent. However, low chi-square pole solutions centered on ecliptic longitude $\lambda = 210^\circ$ cannot be ruled out, leaving the ecliptic longitude of 446 Aeternitas unconstrained. Lightcurves measured over three asteroid apparitions were used during the inversion process to determine a refined rotational period of 15.73743 ± 0.00005 h. Typical errors for ecliptic latitude and longitude values are ± 10 degrees.

The taxonomic A-class asteroids are thought to represent olivine-rich mantle remnants (Reddy et al., 2005), or possibly core-mantle boundary fragments of shattered protoplanetary bodies from the

early solar system (Cruikshank and Hartmann, 1984; Gaffey et al., 2002). If so, it is reasonable to expect they should be relatively abundant among the asteroid population. However, A-class objects are extremely rare. Overall, the A-class asteroids represent $<1\%$ of the total number of individual spectrally surveyed asteroids (17 out of ~ 2150) from the four major asteroid taxonomic surveys conducted during the last three decades. The apparent scarcity of these objects poses a significant paradox for our understanding of asteroid evolution (Xu et al., 1995) and for studies of the dynamical evolution of the early solar system (Bottke et al., 2006).

The main-belt asteroid 446 Aeternitas was discovered on 1899 October 27 by M.F. Wolf and A. Schwassmann at Heidelberg. Cruikshank and Hartmann (1984) were the first to suggest a meteorite/parent-body connection for the A-class asteroids, linking near-infrared (NIR) spectra of two A-type objects with the pure olivine assemblage of the brachinite meteorites or the olivine/iron-alloy pallasite meteorite group. Lucey and Keil (1998) compared NIR spectra of 446 Aeternitas and three other A-types to olivine samples from the U.S. Geological Survey spectral library, and concluded that the olivine silicate assemblage for A-class objects is solely represented in the meteorite collections by pallasite meteorites. Sunshine et al. (2007) analyzed nine olivine-rich asteroid NIR spectra (including Aeternitas) and concluded that the majority (7 out of 9) are forsteritic olivine and therefore sample differentiated mantle sources from melted ordinary chondritic material (e.g. pallasites).

In order for mantle material to be exposed, the parent body must be fragmented or its deep interior exposed by large impacts (Reddy et al., 2005). Therefore, we are interested in resolving the shapes of the known A-class asteroids in order to determine if their morphology is consistent with collisionally-derived fragments.

The Lightcurves: 446 Aeternitas has previously reported rotational periods of 15.85 ± 0.01 h (Florczak et al., 1997), 15.736 ± 0.001 h (Fauerbach et al., 2008 – Figure 1), 15.740 ± 0.003 h (Lucas et al., 2011 – Figure 2), and 15.7413 ± 0.0004 h (Behrend, 2011). The three most recently derived periods are in excellent agreement and compare well with our previously unpublished lightcurve of 446 Aeternitas from the 2007–2008 apparition (Figure 3), which yielded a period of 15.7405 ± 0.0005 h.

The Model: Dense photometric observations of 446 Aeternitas were acquired over three apparitions in 2006, 2007–2008, and 2009 (Table I) at the Evelyn L. Egan Observatory (MPC code H72) on the campus of Florida Gulf Coast University, Fort Myers, Florida. Lightcurve analyses were performed using MPO Canopus v.10.3 to produce 28 individual lightcurve data sets, these data were then inverted using the Kaasalainen code (Kaasalainen et al., 2001a; 2001b) in the LCInvert v.2.3 processing software. A period search function was performed in LCInvert, starting with the synodic periods derived from the 2006–2009 lightcurves, to yield a sidereal rotational period for the asteroid. This period was input as a “free” parameter in the “Medium” (50 iterations each of 264 test orientations in 15° increments of β and λ) pole-search function using discrete, fixed longitude-latitude pairs, which generated an initial ecliptic latitude β and longitude λ best-fit pole solution (Figure 4).

The results of this initial pole search are shown in Figure 4. Dark blue indicates the lowest values of $\log(\text{chi-square})$ in the range of possible pole solutions. Colors progress toward bright red with increasing $\log(\text{chi-square})$ with the highest value indicated by maroon (dark red). An initial pole solution centered near ecliptic latitude $\beta = +45^\circ$ and longitude $\lambda = 0^\circ$ is apparent, however low

log(chi-square) values centered near $\beta = +60^\circ$ and $\lambda = 210^\circ$ cannot be ruled out as a possible pole solution (Figure 4).

The most probable solution centered near $\beta = +45^\circ$ and $\lambda = 0^\circ$ was then refined by running the pole search function again, allowing the preliminary pole solution as well as the sidereal rotational period to be free parameters in 50 more iterations. The iteration that produces the lowest relative standard deviation and chi-square value is the most probable solution of the pole orientation and convex hull shape model of the asteroid. Figure 5 shows the phase angle bisector (PAB) longitude plot for the dense lightcurve data used in the modeling. The PAB longitude coverage could be improved with more data, as such we inverted two separate shape models that included a sparse set of USNO Flagstaff data (173 photometric data points). These iterations greatly improved the PAB longitude coverage, however, the chi-square values (~ 4.2) for both models yielded unacceptable results, and therefore only the dense lightcurve data was used in the final model.

Our results show that the A-class asteroid 446 Aeternitas is a prograde rotator, has a distinct angular shape, and is moderately elongated (Figures 6 and 7). Several planar areas in the convex shape model suggest concavities, possibly large craters or saddles. These features suggest that 446 Aeternitas is more likely to be a collisional fragment than an intact object. The solution for the pole orientation of $\beta = +52^\circ$, $\lambda = 356^\circ$ (Figure 7 and Table II) stood out from 264 trial solutions with no mirror pole solution apparent. However, low chi-square pole solutions centered on ecliptic longitude $\lambda = 210^\circ$ cannot be ruled out, leaving the ecliptic longitude of 446 Aeternitas unconstrained (Figure 4). Twenty-eight input lightcurves measured over three asteroid apparitions were used during the inversion process to determine a refined rotational period of 15.73743 ± 0.00005 h (Table II).

As a test of the robustness of the convex shape obtained for the asteroid, actual lightcurve sets were compared to the synthetic model lightcurve (based on a reference time and geometry). The lightcurve fits obtained matched the synthetic lightcurves very closely (Figure 8). Typical errors for ecliptic latitude and

longitude values using robust photometric data are $\pm 10^\circ$ for this method; this error estimate is based on comparisons with in situ spacecraft exploration of asteroids and from laboratory experimental data (Kaasalainen et al., 2005).

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References

- Behrend, R. (2011). Observatoire de Genève website, http://obswww.unige.ch/~behrend/page_cou.html
- Bottke, W.F., Nesvorný, D., Grimm, R.E., Morbidelli, A., and O'Brien, D.P. (2006). "Iron meteorites as remnants of planetesimals formed in the terrestrial planet region." *Nature* v. 439, pp. 821-824
- Cruikshank, D.P., and Hartmann, W.K. (1984). "The Meteorite-Asteroid Connection: Two Olivine-Rich Asteroids." *Science* v. 233, No. 4633, pp. 281-283
- Fauerbach, M., Marks, S.A., and Lucas, M.P. (2008). "Lightcurve Analysis of Ten Main Belt Asteroids." *The Minor Planet Bulletin* v. 35, no. 2, pp. 44-46
- Florczak, M., Dotto, E., Barucci, M.A., Birlan, M., Erikson, A., Fulchignoni, M., Nathues, A., Perret, L., and Thebault, P. (1997). "Rotational Properties of main belt asteroids: photoelectric and CCD observations of 15 objects." *Planet. Space Sci.* v. 45, no. 11, pp. 1423-1435
- Gaffey, M.J., Cloutis, E.A., Kelley, M.S., and Reed, K.L. (2002). "Mineralogy of Asteroids" in Bottke, Jr., W.F. et al. ed. *Asteroids*

Table I. Observational circumstances for 446 Aeternitas over three apparitions, a total of 1787 data points were used in the lightcurve inversion technique to produce the shape model of the asteroid; λ_{pab} = ecliptic longitude phase angle bisector, β_{pab} = ecliptic latitude phase angle bisector.

Asteroid	Date Range	Data Points	Phase	λ_{pab}	β_{pab}	V (mag)
446 Aeternitas	2009 04 23 to 2009 04 29	397	10.3 to 12.1	186.4 to 186.5	6.6 to 6.3	13.5 to 13.7
446 Aeternitas	2007 12 13 to 2008 05 03	988	11.6 to 17.6	111.5 to 121.5	11.4 to 10.4	13.8 to 14.9
446 Aeternitas	2006 10 26 to 2006 11 19	402	6.8 to 15.3	18.6 to 19.9	-4.8 to -3.3	12.5 to 13.1

Table II. Parameters for the derived shape model of 446 Aeternitas.

Asteroid	β	λ	Per. (h)	Obs. Years	Phase Range	N_{lc}	χ^2	rms Δ (mag)
446 Aeternitas	+52°	356°	15.73743	2006-09	6.8°-17.6°	28	0.3126	0.0134

β and λ are the ecliptic latitude and longitude of the pole

Obs. Years - the length of time the observations span

N_{lc} denotes the number of lightcurves used

χ^2 denotes the chi-square value of the model fit

rms Δ - the rms deviation of the model fit

III University of Arizona Press, pp. 183-204

Kaasalainen, S., Kaasalainen, M., and Piironen, J. (2005). "Ground reference for space remote sensing: Laboratory photometry of an asteroid model" *Astronomy & Astrophysics* v. 440 pp. 1177-1182

Kaasalainen, M., and Torppa, J. (2001a). "Optimization Methods for Asteroid Lightcurve Inversion I. Shape Determination" *Icarus*, v. 153 pp. 24-36

Kaasalainen, M., Torppa, J., and Muinonen, K. (2001b). "Optimization Methods for Asteroid Lightcurve Inversion II. The Complete Inversion Problem" *Icarus*, v. 153 pp. 37-51

Lucas, M.P., Ryan, J., Fauerbach, M., and Grasso, S. (2011). "Lightcurve Analysis of Five Taxonomic A-class Asteroids." *The Minor Planet Bulletin* v. 38, no. 4, pp. 218-220

Lucey, P.G., and Keil, K. (1998). "The influence of temperature on the spectra of the A-asteroids and implications for their silicate chemistry." *Journal of Geophysical Research* v. 103 pp.5865-5871

Reddy, V., Hardersen, P.S., Gaffey, M.J., and Abell, P.A. (2005). "Mineralogic and Temperature-Induced Spectral Investigations of A-type Asteroids 246 Asporina and 446 Aeternitas." *Lunar and Planetary Science XXXVI*, Abstract no. 1375

Sunshine, J.M., Bus, S.J., Corrigan, C.M., McCoy, T.J., and Burbine, T.H. (2007). "Olivine-dominated asteroids and meteorites: Distinguishing nebular and igneous histories." *Meteoritics & Planetary Science* v. 42 No. 2, pp. 155-170

Warner, B.D., Harris, A.W., and Pravec, P. (2011). Asteroid Lightcurve Database, 2011 March
<http://www.minorplanet.info/lightcurvedatabase.html>

Xu, S., Binzel, R.P., Burbine, T.H., and Bus, S.J. (1995). "Small Main-Belt Asteroid Spectroscopic Survey: Initial Results." *Icarus* v. 115 pp. 1-35

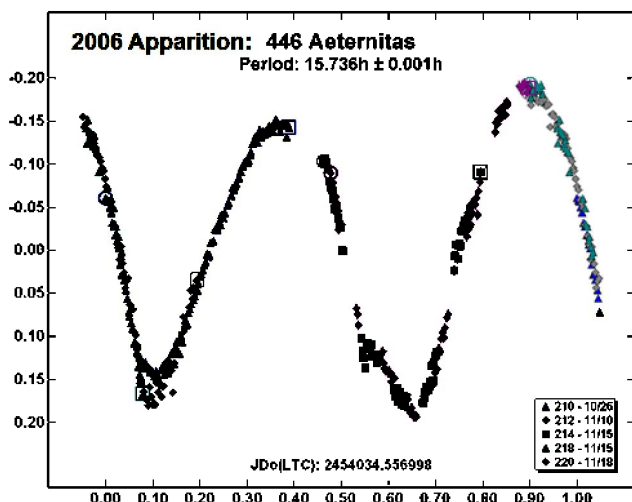


Figure 1. Lightcurve of 446 Aeternitas from the 2006 apparition (Fauerbach et al., 2008).

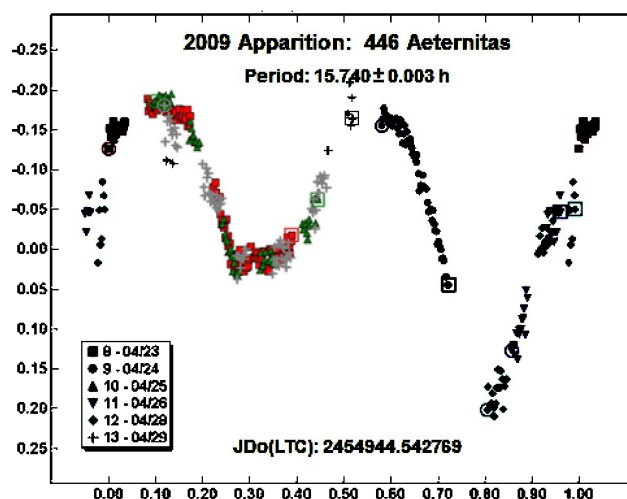


Figure 2. Lightcurve of 446 Aeternitas from the 2009 apparition (Lucas et al., 2011).

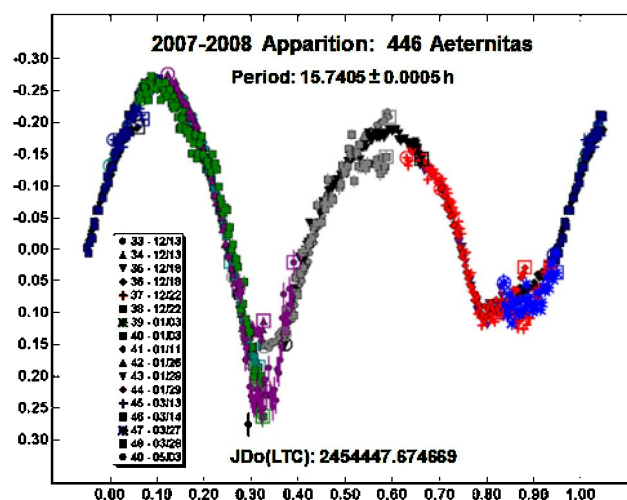


Figure 3. Previously unpublished lightcurve of 446 Aeternitas from the 2007-2008 apparition.

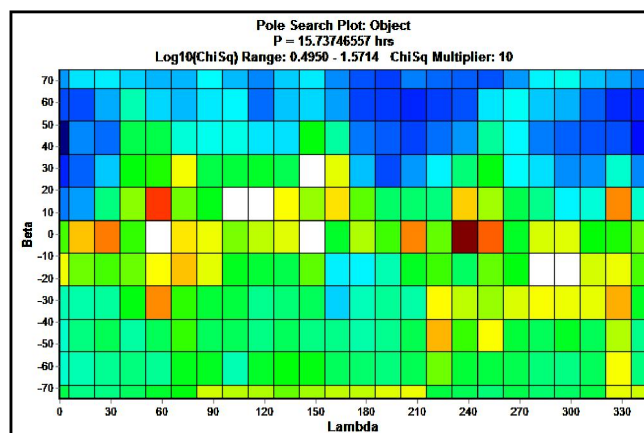


Figure 4. Plot of the log chi-square values obtained from the initial pole-search function. Dark blue represents the lowest chi-square value.

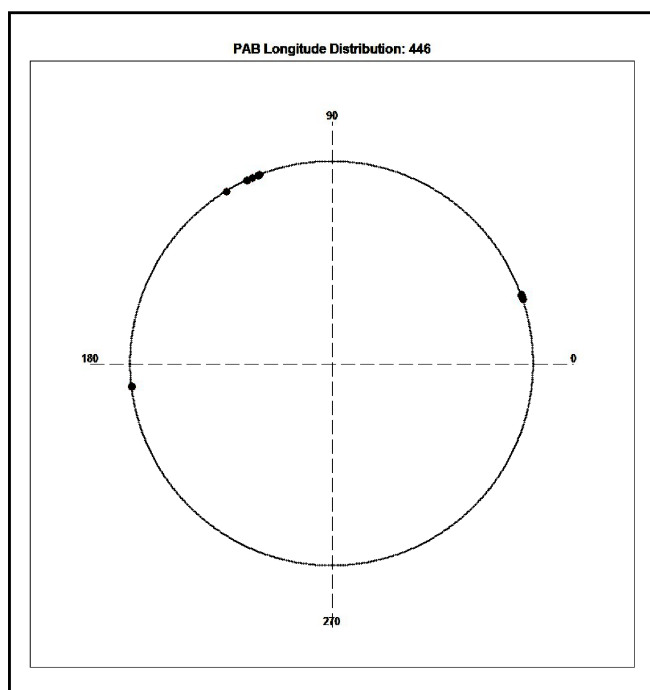


Figure 5. PAB longitude distribution of the dense lightcurve data (red circles) used in the model.

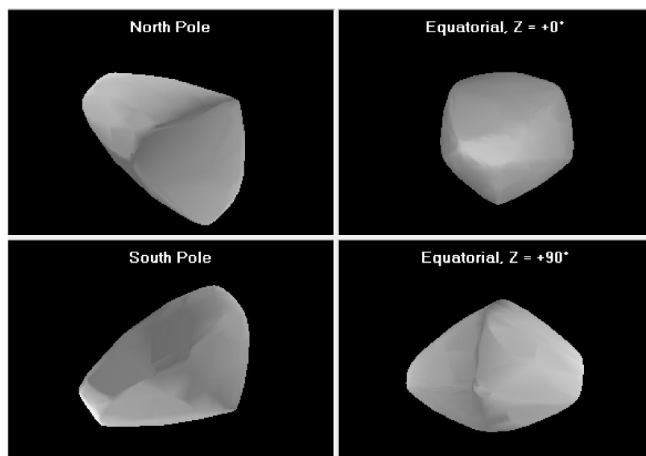


Figure 6. The shape model of 446 Aeternitas with the lowest chi-square value, the IRAS determined diameter of Aeternitas is 45.4 km for scale.

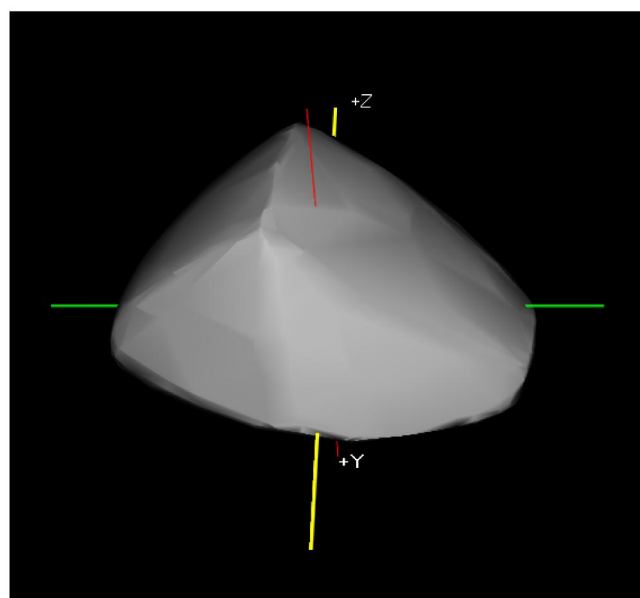


Figure 7. Shape model of 446 Aeternitas shown in ecliptic view with pole solution (z-axis) of $\beta = +52^\circ$, $\lambda = 356^\circ$ indicated. In this view the observer and asteroid are on the ecliptic plane (asteroid on ascending or descending node of orbit) with phase angle of 0° . The IRAS determined diameter of Aeternitas is 45.4 km for scale.

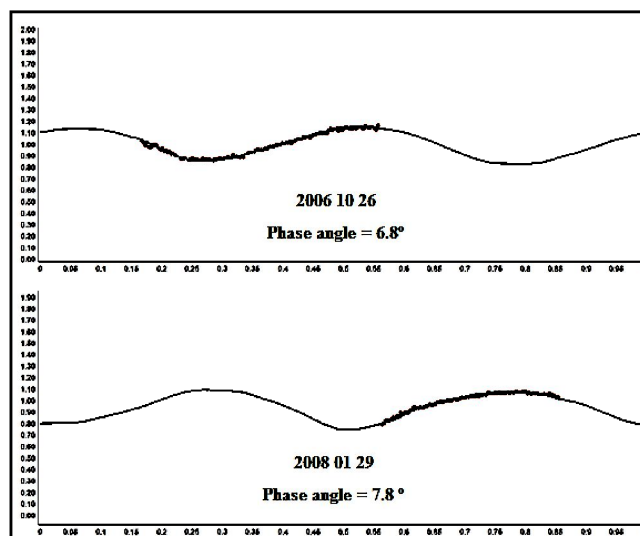


Figure 8. Lightcurve fits for measured photometric lightcurves (red dots) compared to the synthetic model lightcurve (black curves) for two observation dates, 2006 10 26 and 2008 01 29.