

# Shape and Spin State of (8567) 1996 HW1 Using Ground-based Photometry

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## **Abstract**

Currently the most bifurcated near-Earth asteroid known, (8567) 1996 HW1 is an Amor-class contact binary with a perihelion distance of roughly 1.13 AU. Relative and absolute photometry was performed at Table Mountain Observatory and elsewhere during two apparitions in 2005 and 2008-2009. Employing the method of Kasaalinen, et al (2001), inversion of light curves subsequently measured a sidereal rotation rate of  $8.76243 \pm 0.00004$  h and pole direction of within  $5^\circ$  of ecliptic longitude and latitude ( $281^\circ$ ,  $-31^\circ$ ). Shape modeling determined 1996 HW1 to be the fourth most elongated radar-observed asteroid with maximum diameters  $3.8 \times 1.6 \times 1.5$  km with its pole roughly bisecting its principal axis. 1996 HW1 is identified as a possible YORP candidate. Using 17 partial nights of photometry performed at Table Mountain Observatory during 2008-2009, Magri, et al (2011) suggests that YORP effects may be measurable in late 2011. During July-August 2011, light curves for 1996 HW1 will be collected at Table Mountain Observatory, and reanalysis of TMO's 2008-2009 data will be performed to include the asteroid's 2011 apparition.

## **Introduction**

In 1596, Johannes Kepler predicted the existence of a missing planet between Mars and Jupiter, and many of history's most brilliant minds from Newton to Kant set about to understand the nature of the gap between the two planets. Johann Elert Bode, director of the Berlin Observatory, wrote in 1772:

*Let the distance from the Sun to Saturn be taken as 100, then Mercury is separated by 4 such parts from the Sun. Venus is  $4 + 3 = 7$ . The Earth  $4 + 6 = 10$ . Mars  $4 + 12 = 16$ . Now comes a gap in this so orderly progression. After Mars there follows a space of  $4 + 24 = 28$  parts, in which no planet has yet been seen. Can one believe that the Founder of the universe had left this space empty? Certainly not. From here we come to the distance of Jupiter by  $4 + 48 = 52$  parts, and finally to that of Saturn by  $4 + 96 = 100$  parts.*

But it was not until mathematician Giuseppe Piazzi discovered Ceres on January 1, 1801 that predictions for the missing planet were confirmed. And it was not long until more bodies were discovered in the region between Mars and Jupiter. In fact, so many have been found that discoveries continue to this day; as of 2000, over 100,000 asteroids had been catalogued in the area now known as the main asteroid belt.

Asteroids are primordial species having existed since clouds of dust and gas began to coalesce in the period following the big bang. First, clumping of materials began to introduce gravitational fields to early planetessimals, which eventually became planetoids and finally planets. But like galactic economics, some planetessimals fared better than others. Those with the strongest gravitational fields pulled in neighboring material until the solar system became effectively empty but with large, dense planets in between. Among the planets, Jupiter grew so large that it appears to have disallowed any cohesion of material anywhere near it. For this reason, the asteroid belt has remained in pieces orbiting in the vast region between Mars and Jupiter (Bottke 2002).

However, not all asteroids remain in equilibrium within the main belt. Gravitational perturbations introduced by Jupiter can slingshot main belt asteroids off of their stable orbits and into the paths of other planets. These asteroids that have gained larger orbital eccentricities are known by the nature of their orbits. Mars crossers, as the name implies, have orbits that intersect with the orbit of Mars. Near-Earth asteroids (NEOs) have even greater eccentricities and approach or cross the orbit of Earth. Craters in Arizona, India, Sweden, Chad, Australia and China present eerie reminders that some of these asteroids will collide with Earth. Indeed, an asteroid impact in Mexico appears to have brought about the extinction of the dinosaurs.

Life on Earth depends on the ability of mankind to anticipate and protect itself from such a major calamitous impact. For this reason, the United States Congress mandated in 1992 that the astronomical community find at least 90% of all near-Earth asteroids greater than 1km in diameter within ten years. The rise of automated sky surveys led to the rapid increase in discoveries during the following decade. Ultimately, the mandate was extended to include asteroids with diameters greater than 300m, a size capable of regional devastation (Bottke 2002).

However, the notion that we might find 90% of near-Earth asteroids implies that the astronomical community knows exactly how many asteroids comprise 100% all of such bodies within the solar system. Further complicating the search is the fact that many NEOs have orbital eccentricities so high that they may remain unknown for decades before they come hurtling toward Earth. Finally, objects behind the Sun from our perspective may prove elusive as well. Hence, the ultimate figure put forth by Congress is an aim rather than a clearly defined goal.

But while the protection of Earth from catastrophic impact may provide an incentive to governments to fund asteroid research, another scientifically important reason exists as well. Indeed, the study of asteroids allows us to answer questions about the origins of the Universe and fundamental concepts of celestial dynamics.

### **Key Concepts**

One such phenomenon has been recently named the Yarkovski—O’Keefe—Radzievskii—Paddack effect, or YORP for short. While asteroid spin is mostly caused by collisions with other asteroids, Pravec, et al refer to noncollisional effects as well (Pravec 2007). As heat is electromagnetic in nature, it can be shown that thermal radiation carries momentum through the following simple derivation using modern physics:

$$E = mc^2 \quad (1)$$

where E is the energy inherent in a photon, m is the mass of a particle, and c is the speed of light.

$$p = mv \quad (2)$$

in which p is the momentum of a particle, m is that particle’s mass, and v is its velocity. Under the particle/wave duality principle, a photon has mass and moves at the speed of light. Therefore;

$$v = c \quad (3)$$

Now, inserting the speed of light for the speed of a particle into equation 2), it can be said that

$$p = mc \quad (4)$$

Finally, using algebra to solve for mc in equation (1), we can arrive at

$$p = E/c \quad (5).$$

Using the Law of Conservation of Momentum, it can be seen that heat radiating unequally from a celestial body will induce acceleration in the direction normal to the dissipation. This phenomenon was noted in the early 20th century by Ivan Osipovich Yarkovsky who noted that small asteroids would undergo minute orbital shifts throughout their seasons when one hemisphere, having been heated by the Sun, would then reradiate that thermal energy back.

A similar and more recent concept, YORP is built on the Yarkovsky effect. Whereas the Yarkovsky effect induces translational shifts of the body as a whole, YORP uses the same idea of thermal radiation inducing forces normal to emission, but with a twist. A perfectly spherical and uniformly characteristic body would radiate thermal energy equally from its heated hemisphere, and therefore all force vectors would pass through the body’s center of mass, causing translation without torque. However, an object with an elongated body and heterogeneous surface will, when radiating thermal energy, have a tendency to experience a torque resulting from a differential in surface area and heat capacity favoring one side over another. Like a propeller, this torque will eventually cause the object to undergo a minute rotational acceleration as it spins in the light of the Sun (Öpik 1951).

Evidence of YORP can be found as small precessions of an asteroid’s pole as well as radial accelerations either up or down. The phenomenon was first observed by Taylor et al in 2007 with 54509 YORP when the asteroid’s period had increased by  $2.0 \pm 0.2 \times 10^{-4}$  deg/d2 between 2001 and 2005 (Bottke, 2002).

Pravec, et al (2007), assert that there exists a correlation between asteroid diameter and period for asteroids with diameters greater than 10km with Maxwellian distributions at ~200km, ~100km, and ~10km; however, below 10km, there exists a non-Maxwellian distribution of periods. But while spin rates vary considerably among smaller asteroids, Pravec et al (2007) have found sharp cutoff spin rates for this group corresponding strongly with the bodies’ bulk densities. Their findings suggest that too fast a period will result in centrifugal forces, which will overcome the tensile strength of the asteroid and break it up. In fact, this notion appears to be at the root of binary systems (Pravec 2007).

(8567) 1996 HW1 was discovered by T. Gehrels under the Spaceguard survey on April 23, 1996 at Steward Observatory. Comparisons of lightcurves obtained in 2005 and 2008-2009 revealed a significant increase in magnitude amplitude from the first to second apparition, suggesting one of the most elongated near-Earth asteroids known. Shape modeling of HW1 from lightcurves obtained in 2008-2009 at Table Mountain Observatory and elsewhere calculated a pole direction of ecliptic ( $281^\circ$ ,  $-31^\circ$ ) with its pole roughly bisecting its principle axis (Pictures 2 and 3). Further, radar imaging of HW1 at the Arecibo Observatory in 2008 showed a markedly bifurcated body. All of these clues pointed strongly toward a YORP target, and Magri et al (2011) suggest the possibility of positively measuring evidence of the effect during HW1's next close approach in the summer of 2011.

### **Game Plan**

We obtained five nights of calibrated R-band photometry of (8567) 1996 HW1 from July 15-29 at the Table Mountain Observatory's 0.6m telescope in Wrightwood, CA with the intention of comparing data obtained during the 2005 and 2008-2009 apparitions in an attempt to confirm or deny evidence of the YORP effect.

One of the key tools employed for the project was the convex inversion method of Kasaalinen et al (2001) which enables pole position and period calculation. The convex inversion algorithm receives a user-generated set of parameters from the standard input and performs a requested number of iterations to arrive at a corresponding best ecliptic pole position, rotation rate, and  $\chi^2$  deviation. Magri et al (2011) specified a pole position of ( $281^\circ$ ,  $-31^\circ$ ) with a possible error of  $5^\circ$  in each direction. A program was written which would output a matrix of 20x20 input parameter files with poles shifted in equal steps to cover the whole range of possible pole solutions within error bars and generate 400 corresponding input parameter files to be fed through convex inversion. The subsequent outputs were sent to files that were then analyzed for average solutions and standard deviations. The results were then plotted for period and pole latitude and longitude (Pictures 1, 2, and 3).

The above method was performed using lightcurves obtained during two apparitions spaced roughly three years apart. The foundation set was obtained at Table Mountain Observatory between July 2008 and January 2009. For this set, nineteen lightcurve blocks have been analyzed. Next, five nights of R-band photometry were performed in July 2011 at Table Mountain Observatory. Six blocks of calibrated and relative lightcurves from June-July 2005 were also downloaded from the Minor Planet

Center's Lightcurve Database, but preliminary inversion calculations have revealed a discrepancy in the 2005 dataset suggestive of perhaps erroneous calibration. Also, while 2005 lightcurves obtained at Hunters Hill Observatory were used in Magri et al (2011), none of the dates employed match the suspect data found on the Minor Planet Center's Lightcurve Database. Trusting only the data obtained by Table Mountain Observatory, we decided to forego the 2005 set. Excluding the 2005 lightcurves, both the 2008-2009 and 2011 sets were normalized and light time corrected and then matched with object-to-Earth and object-to-Sun vectors into a lightcurve file suitable for convex inversion. We set up two combinations of data intervals to analyze: 2008-2009 and 2008-2011. Unfortunately, not enough data has yet been collected during the 2011 apparition to constrain a standalone solution.

Once all datasets were inverted, we generated histograms of period, longitude, latitude, and  $\chi^2$  for each of the respective intervals. Similarly, we plotted the average values found for period, longitude, and latitude during each interval and compared results against the findings of Magri et al (2011) (Pictures 4, 5, and 6).

Also, using the method of Kasaalinen and Torppa (2001), shape models for (8567) 1996 HW1 were generated from convex-inverted solutions at the pole position specified by Magri et al (2011). These models were then rotated 360 degrees in three-space, plotted, and then animated (Picture 7). The purpose of this exercise was to first check the accuracy of data collected in 2011 against the 2008-2009 points. We knew that inversion of the 2008-2009 set produced a convex shape model of the asteroid which displayed proper characteristics, namely that its shape was considerably elongated and that it rotated around its shortest axis. Adding the current points collected during the 2011 apparition to the 2008-2009 dataset produced an almost identical model (Picture 7).

### **Results**

Alone, inversion of the 2008-2009 data using a 20x20 matrix of pole solutions within  $5^\circ$  ecliptic longitude and latitude ( $281^\circ$ ,  $-31^\circ$ ) helped to constrain the pole position during that apparition considerably. Shown in Table 1, we were able to constrain the ecliptic longitude to  $280.484314 \pm 0.285433203$  deg and ecliptic latitude to  $-33.889946 \pm 0.276836842$  deg. The rotation period of HW1 was similarly constrained. Magri et al (2011) suggested a period of  $8.76243 \pm 0.00004$  h whereas our inversion technique resulted in a rotation rate of  $8.76225376 \pm 0.0000271$  h.

While the 2011 data could not yet stand on its own, we leaned it against the 2008-2009 data in an effort to look for differences with the 2008-2009 data alone. Noting the findings of Magri et al (2011) stated above, differences were indeed found in both pole position and period from 2008 to 2011, also shown in Table 1. Pole longitude including the 2011 apparition appears to have shifted to  $279.122253 \pm 0.123066254$  deg while pole latitude appears to have shifted to  $-31.4717464 \pm 0.117989384$  deg. Similarly the period solution including the 2011 data appears to have found a decrease in rotation rate, slowing the asteroid's period to  $8.76241684 \pm 0.00000067$  h.

Picture 1 displays a graph of rotation rate solutions found by Magri et al (2011) alongside the solutions we have calculated for 2008-2009 as well as 2008-2011 so that a clearly suggestive trend may be noted with standard deviation in a side-by-side comparison. Picture 2 uses the same comparisons but displays the longitude solutions calculated in Magri et al (2011) compared with our solutions for 2008-2009 and 2008-2011. Picture 3 compares the pole latitude solutions among Magri et al (2011) and our 2008-2009 and 2008-2011 solutions. Pictures 4, 5, and 6, respectively show histograms of the results for pole latitude and longitude as well as rotation rate we obtained using the Kasaalinen et al (2001) convex inversion technique for both the 2008-2009 apparition as well as the same set including the 2011 points.

### **Discussion**

In all cases, it can be clearly seen that our models are suggestive of both polar shift and period increase from 2008 to 2011; however, a conclusive answer eludes us for now until we have obtained enough lightcurve points from the 2011 apparition to enable standalone calculations of the 2011 dataset. Also, while our analysis is suggestive of YORP effects, all other possibilities must be tested and ruled out before a definitive conclusion may be made on 1996 HW1. Right now, our results are preliminary. We hoped to achieve a more constrained solution by midsummer, but we were unfortunately plagued by poor weather and a catastrophic camera failure in early August which thwarted progress on this front. 1996 HW1 will be observable throughout the remainder of 2011, and many clear summer nights remain during which to obtain many more valuable lightcurves of our target before the apparition reaches completion. Hopefully we will arrive at a conclusion by early 2012.

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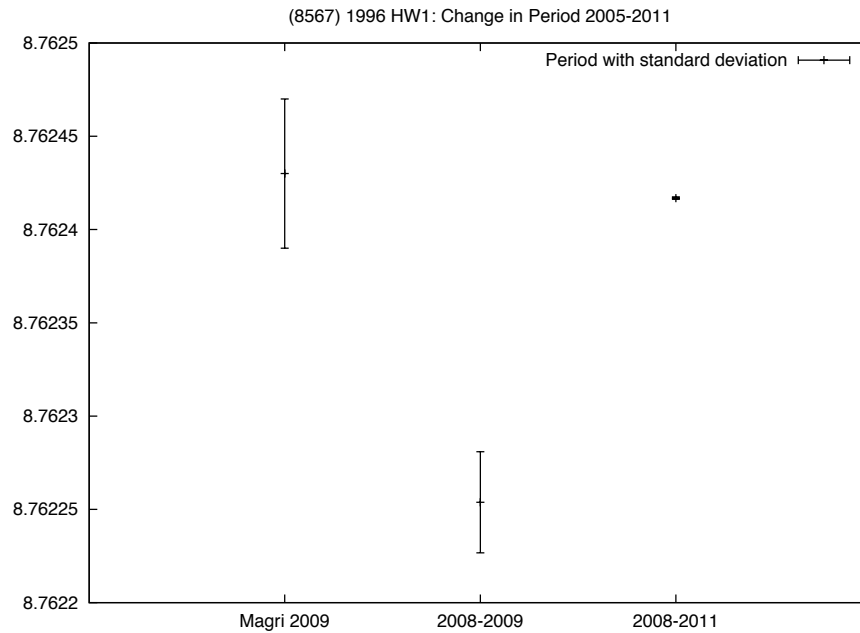
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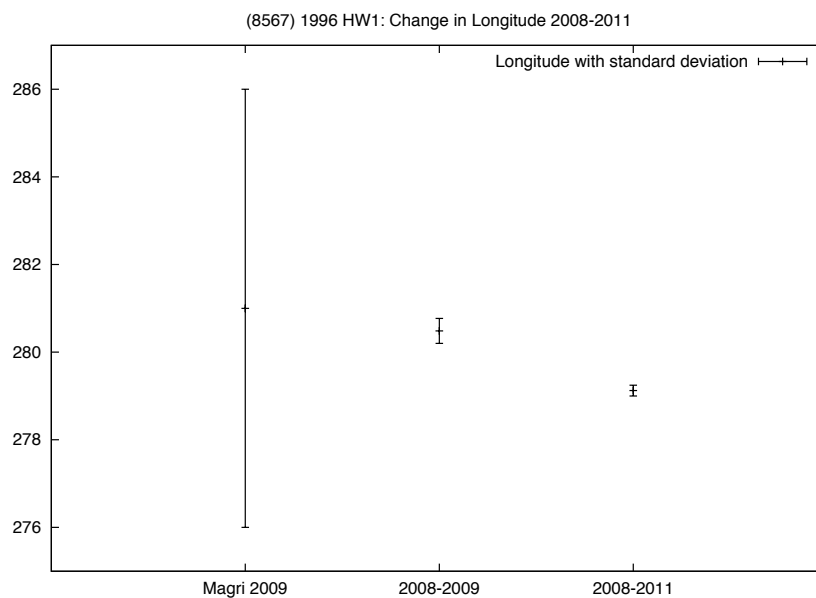
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	$\chi^2$	Period (h)	Longitude (°)	Latitude (°)
<b>2008-2009</b>	$0.452318847 \pm 0.0025082184$	$8.76247215 \pm 3.62807223E-05$	$282.267303 \pm 0.58807838$	$-36.6879311 \pm 0.217349172$
<b>2008-2011</b>	$2.07088995 \pm 0.00795366056$	$8.7624445 \pm 1.26941654E-06$	$289.454376 \pm 0.189865187$	$-23.4908466 \pm 0.192311615$

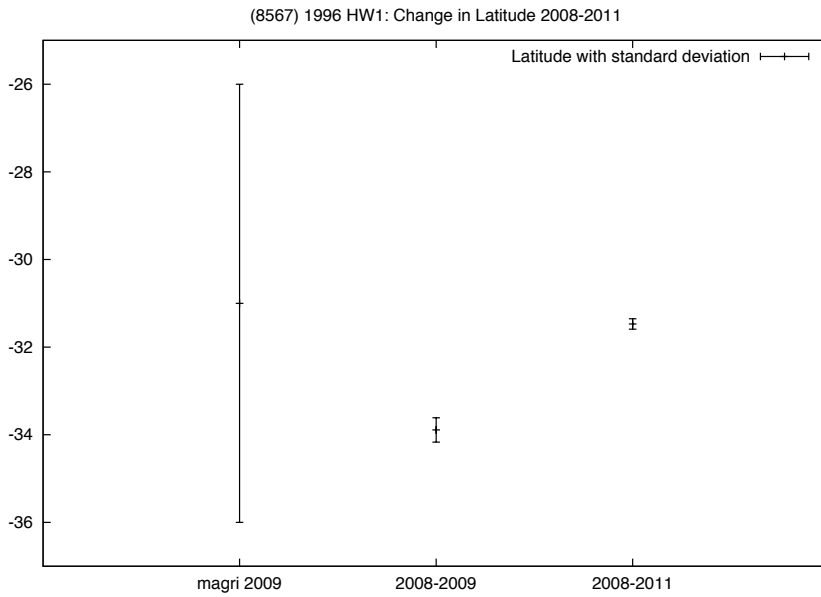
Table 1: Resulting  $\chi^2$ , period, and pole direction for 2008-2009 as well as 2008-2011 for (8567) 1996 HW1.



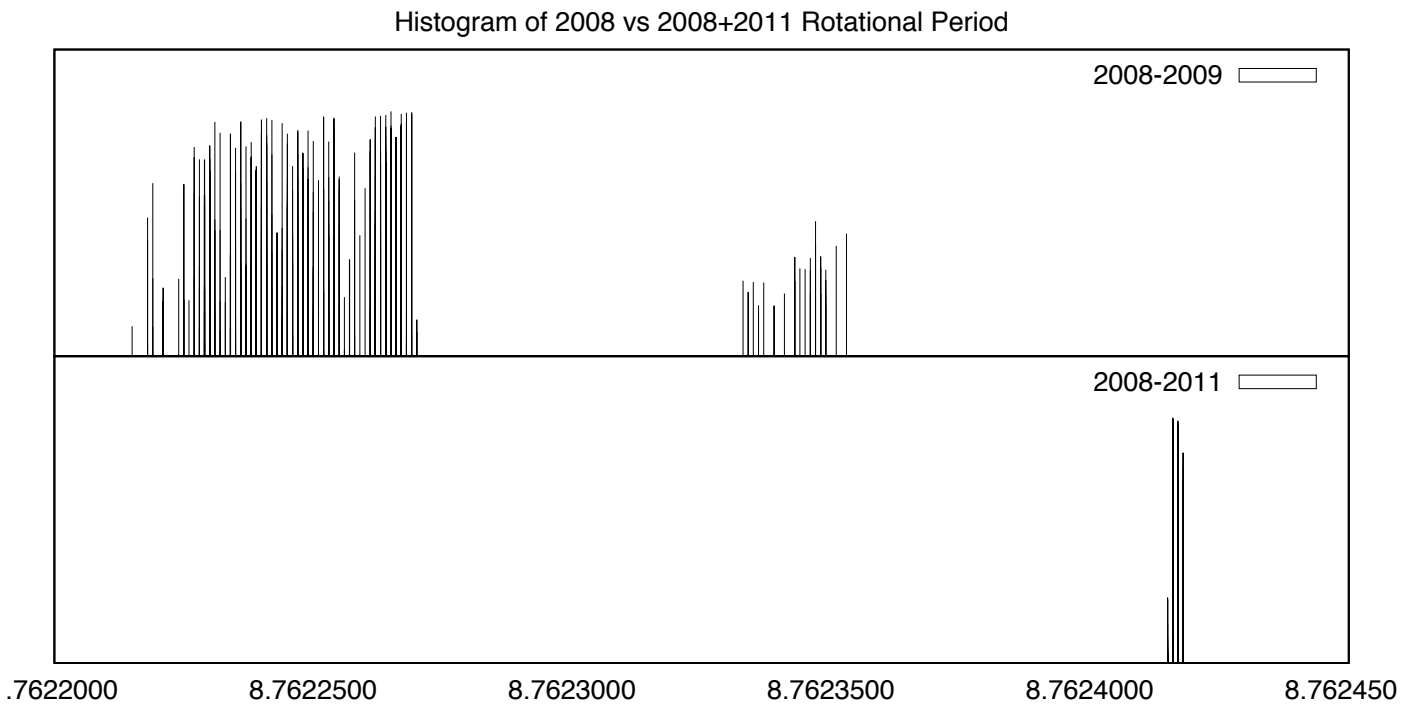
Picture 1: Plot of average period from convex inversion of a 20x20 matrix of possible pole positions including standard deviation error bars.



Picture 2: Plot of average longitude from convex inversion of a 20x20 matrix of possible pole positions including standard deviation error bars.

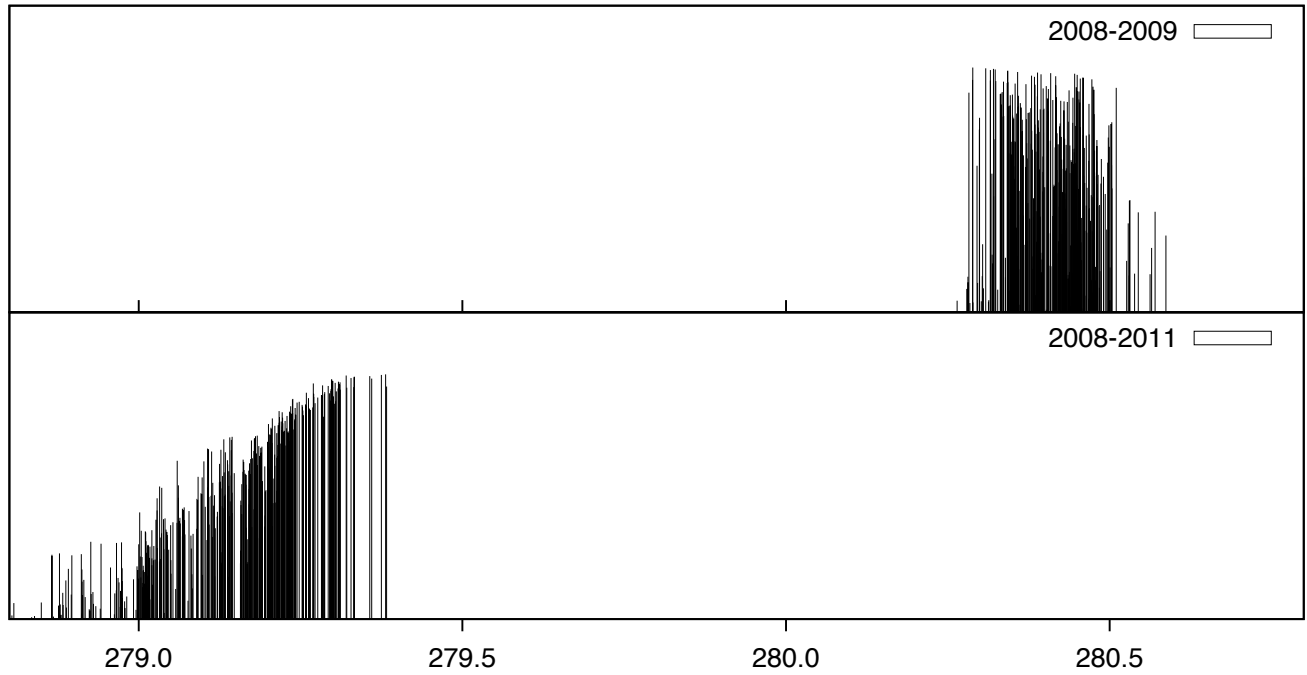


Picture 3: Plot of average latitude from convex inversion of a 20x20 matrix of possible pole positions including standard deviation error bars.



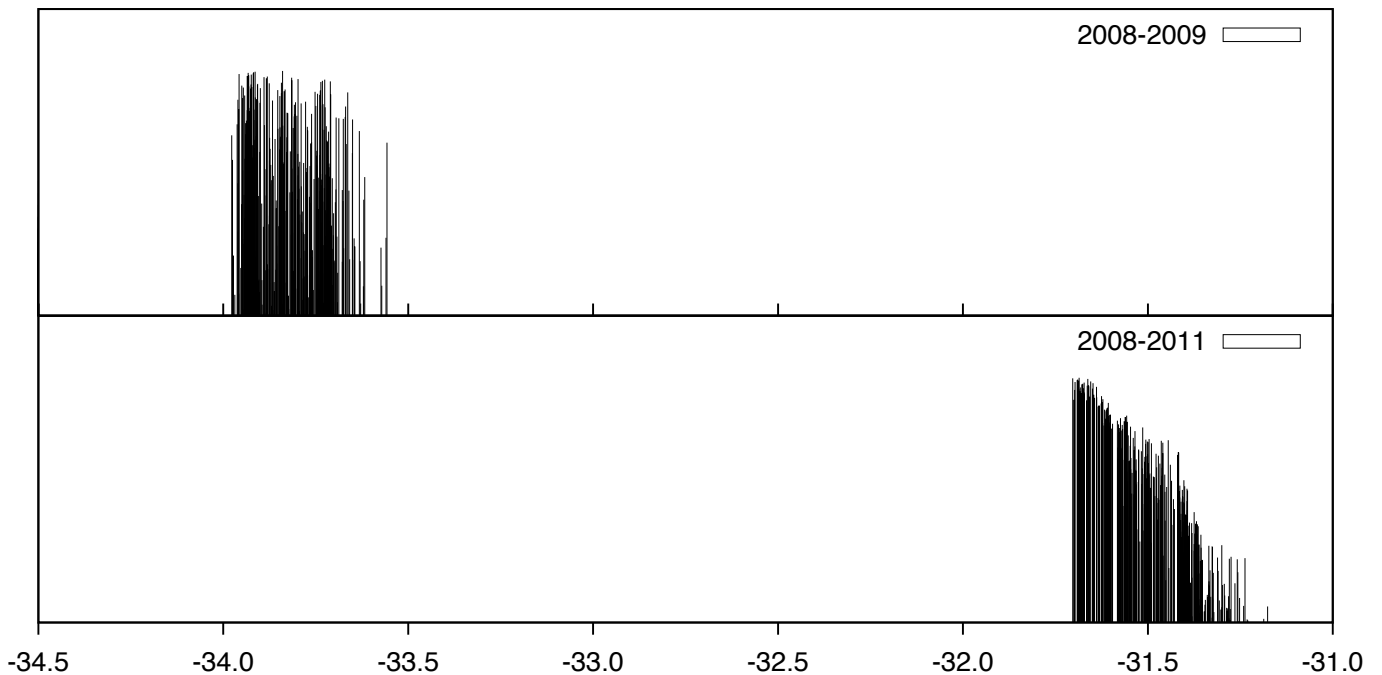
Picture 4: Histogram of rotational periods for (8567) 1996 HW1 calculated from a 20x20 matrix of possible pole solutions within 5° of ecliptic (281°,-31°). Top graph includes only 2008-2009 data while bottom includes lightcurves from 2011.

Histogram of 2008 vs 2008+2011 Ecliptic Longitude

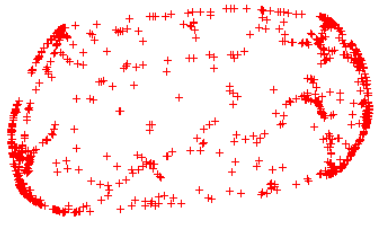


Picture 5: Histogram of pole latitude for (8567) 1996 HW1 calculated from a 20x20 matrix of possible pole solutions within 5° of ecliptic (281°,-31°). Top graph includes only 2008-2009 data while bottom includes lightcurves from 2011.

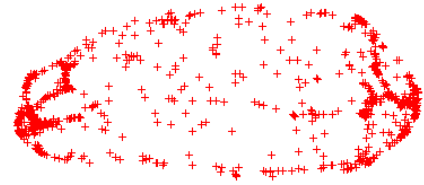
Histogram of 2008 vs 2008+2011 Ecliptic Latitude



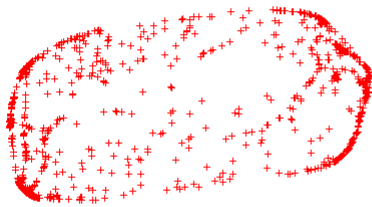
Picture 6: Histogram of pole longitude for (8567) 1996 HW1 calculated from a 20x20 matrix of possible pole solutions within 5° of ecliptic (281°,-31°). Top graph includes only 2008-2009 data while bottom includes lightcurves from 2011.



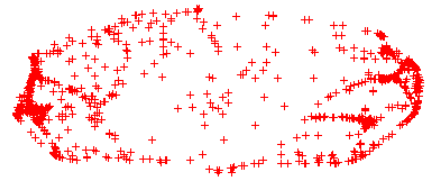
a.



b.



c.



d.

Picture 7: Shape models for (8567) 1996 HW1 produced with convex inversion using a preliminary pole direction of ecliptic ( $281^\circ$ ,  $-31^\circ$ );  
Above: 2008-2009 dataset – top view a., side view b. Bottom: 2008-2011 dataset – top view c., side view d.