Asteroidal Occultations

High precision astronomy for all

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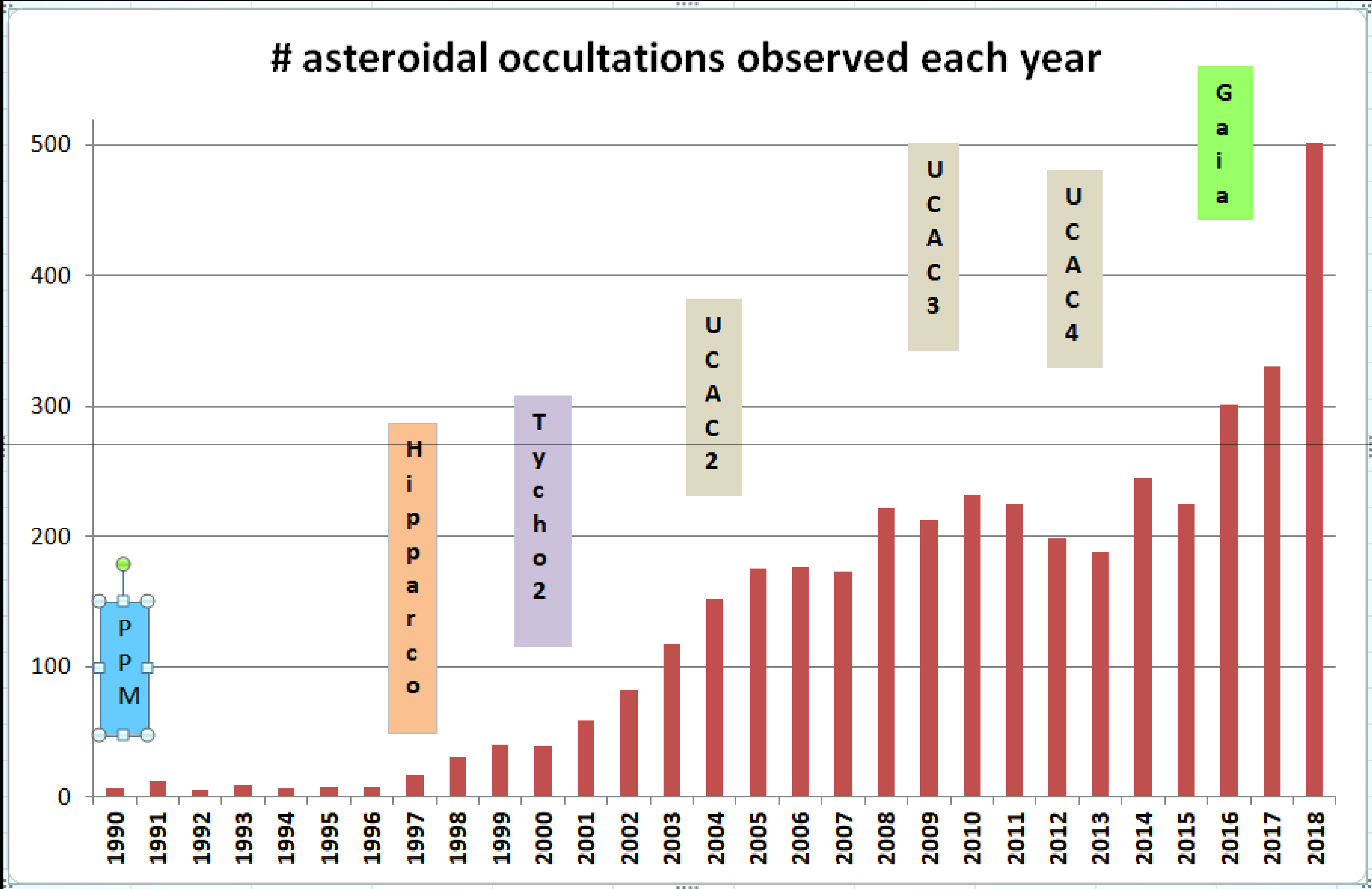
A little history

- Efforts to observed started in the 1980's
- Predictions initially very poor
- Improvements as a result of:
  - Hipparcos
  - UCAC2, then UCAC4
  - Gaia, then Gaia DR2

=> Steady increase in successfully observed occultations, from 39 in 2000 to 502 in 2018



asteroidal occultations observed each year
500
400
300
200
100
0
PPM
Hipparco
Tycho2
UCAC2
UCAC3
UCAC4
Gaia
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

The objective

- To accurately measure the size and shape of asteroids
- Potentially discover satellites or rings around asteroids

The problem

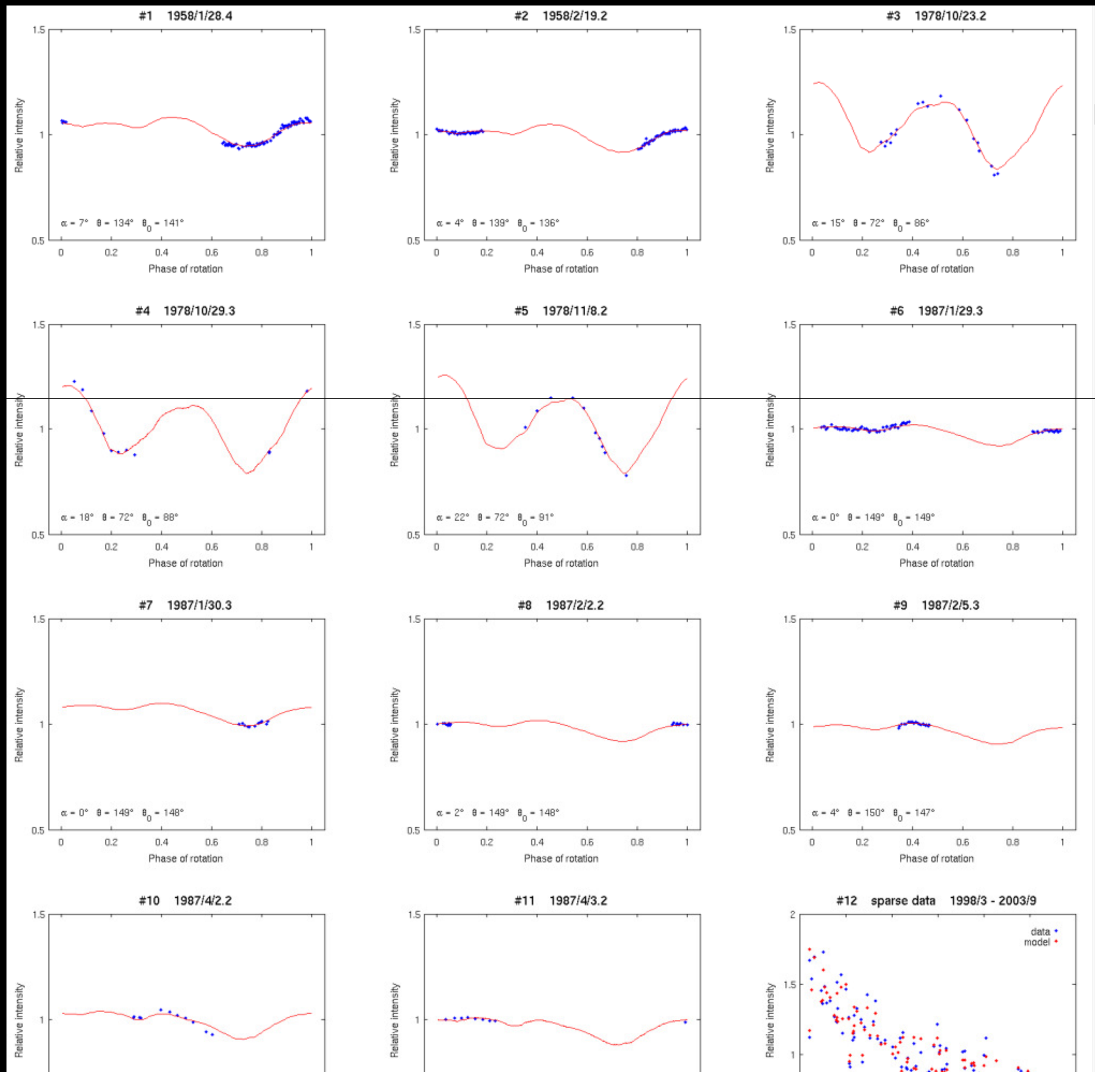
- An occultation gives an accurate profile of an asteroid for its orientation at the time of an event
- Asteroids are irregular to greater or lesser extents

=> an accurate asteroid diameter can't be determined from one or two occultations – only an approximate diameter

Asteroid Shape Models

- A group of astronomers (largely ‘unpaid’ astronomers) measure the light curves of asteroids in different parts of their orbit
- These light curves can be ‘inverted’ to derive the shape of the asteroid

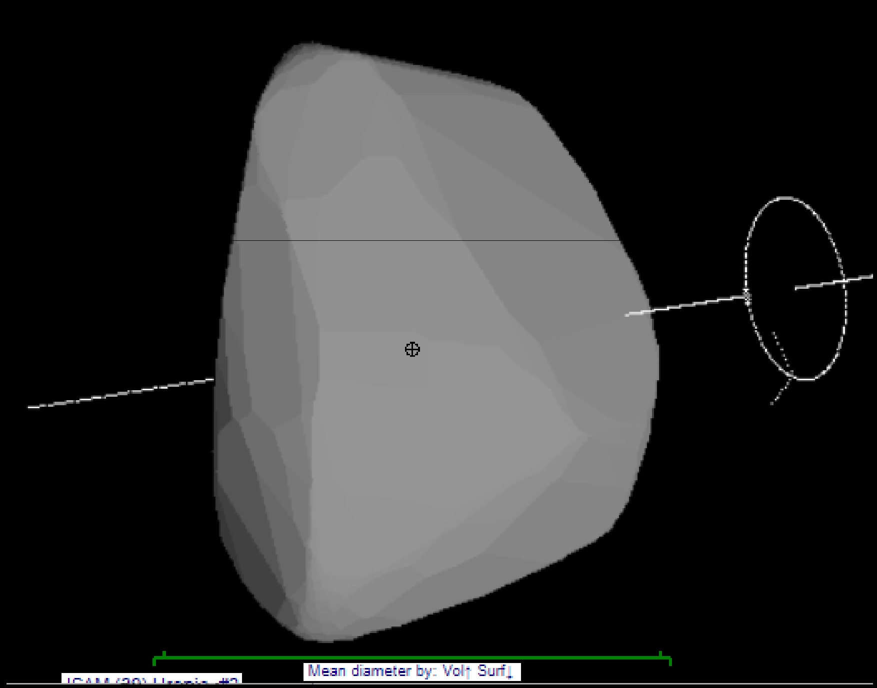
(30) Urania Light curve measurements (Blue dots) and light curve from a model (Red line)

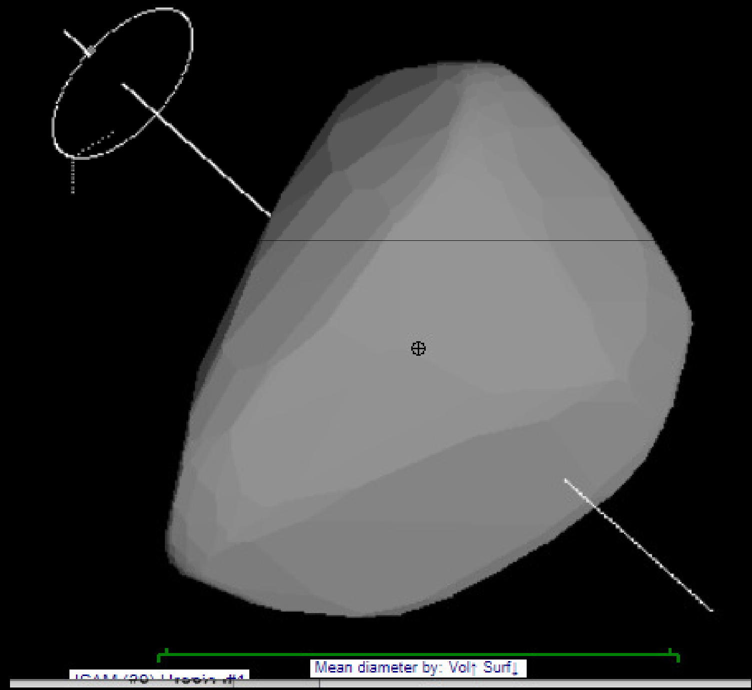


Shape model 'issues'

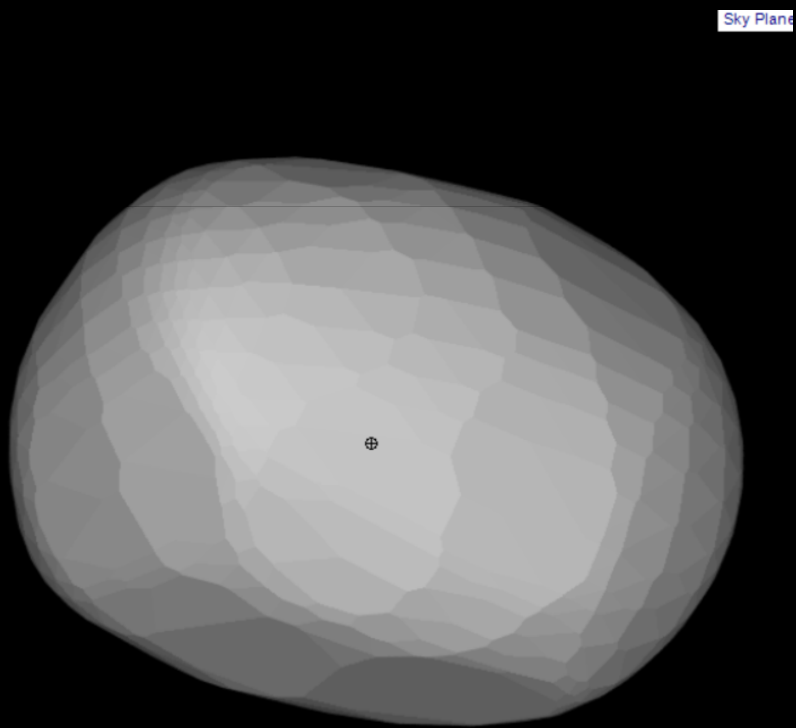
- A shape model has no size – just shape
- The inversion process usually results in two different orientations of the axis of rotation – with differing shapes. Inversion process cannot determine which one is correct
- The inversion process is complex. Early models were limited to convex surfaces. Over the last few years models with concave surfaces have been developed
- Inversion assumes uniform surface reflectivity

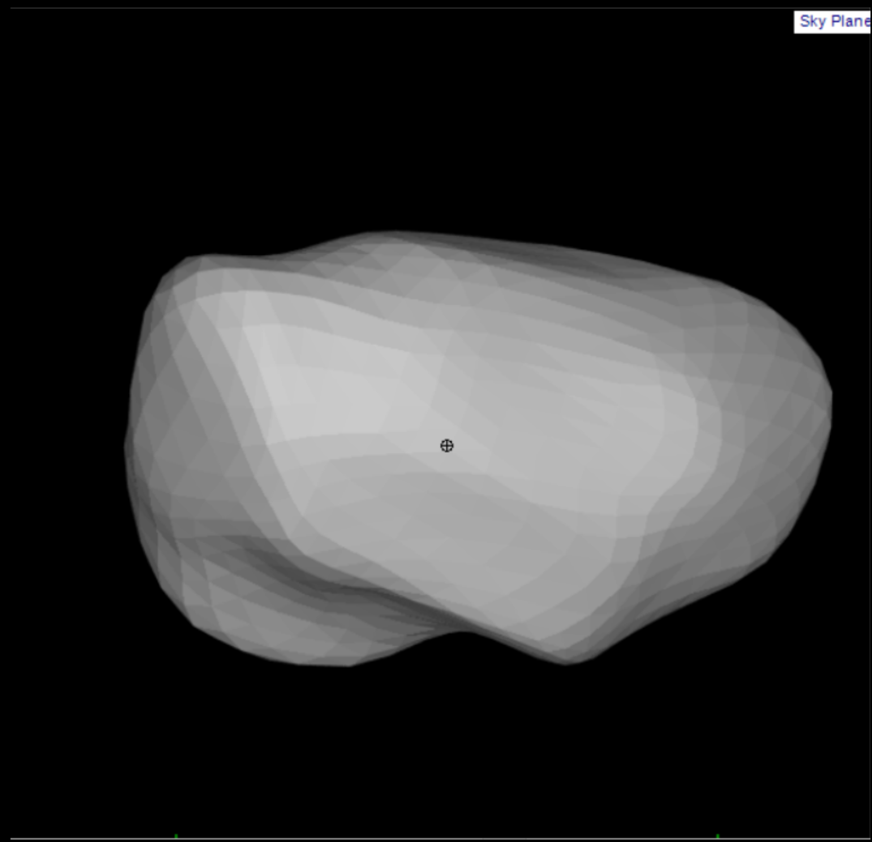
The two shape models for (30) Urania, with different rotational axes





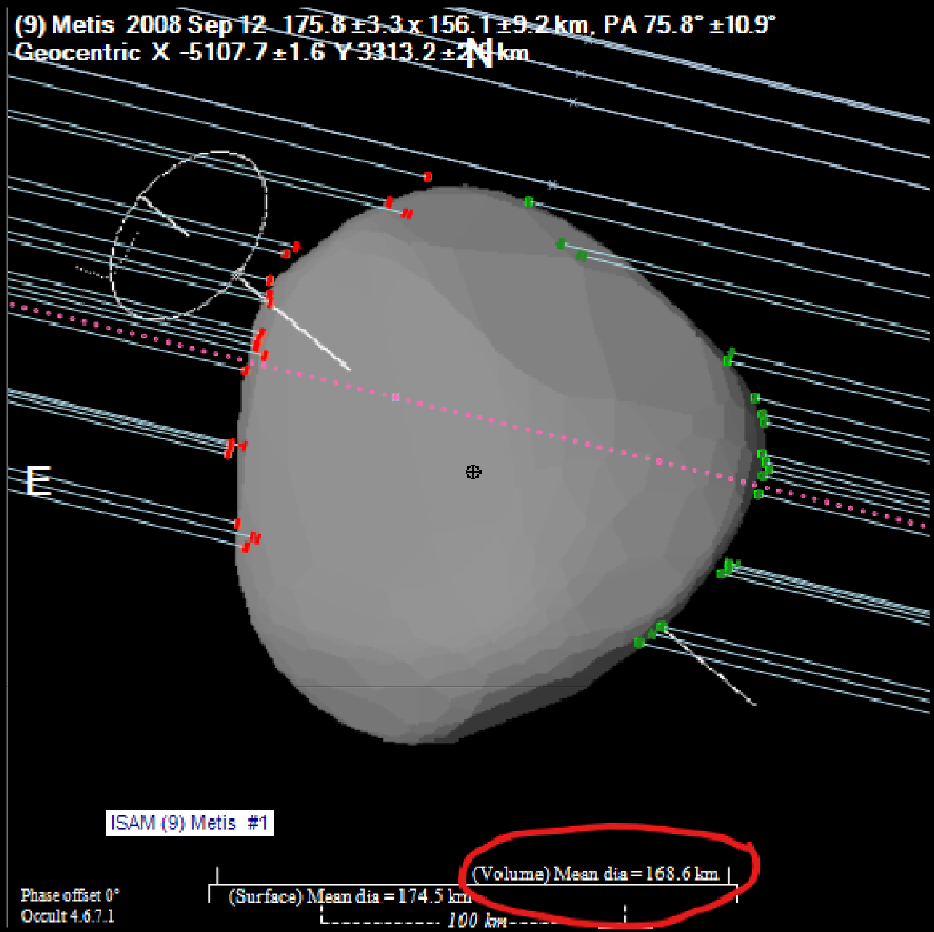
Two shape models for (130) Electra one convex, and one concave, model



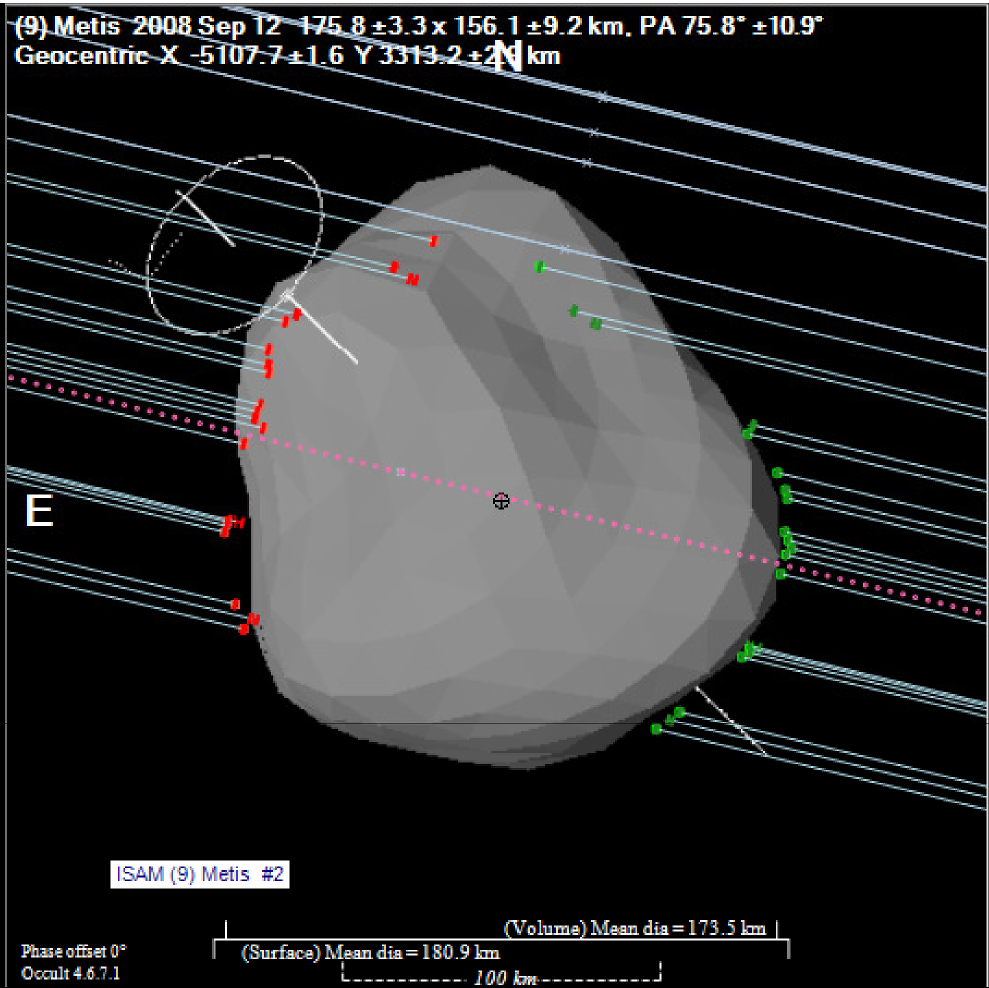


Fitting occultations to shape models

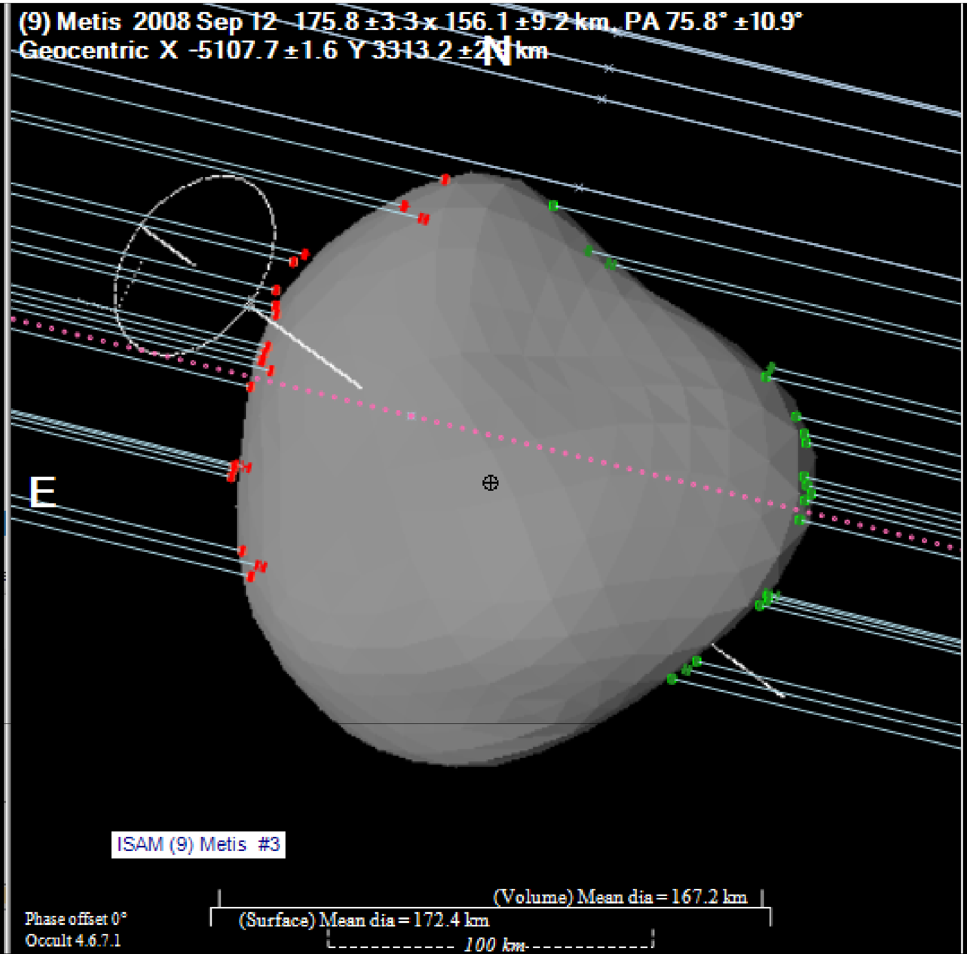
- The next three slides show fits of the occultation of (90) Metis on 2008 Sept 12 to three shape models available for Metis, and the conclusions to be drawn.
- The derived diameter is a ‘volume-equivalent’ diameter – that is, the diameter of a sphere having the same volume. This is relevant for determining density.
- A ‘surface-equivalent’ diameter can also be derived.



- A fairly good fit to convex shape model derived in 2011
- Measured 'volume-equivalent' diameter 169km

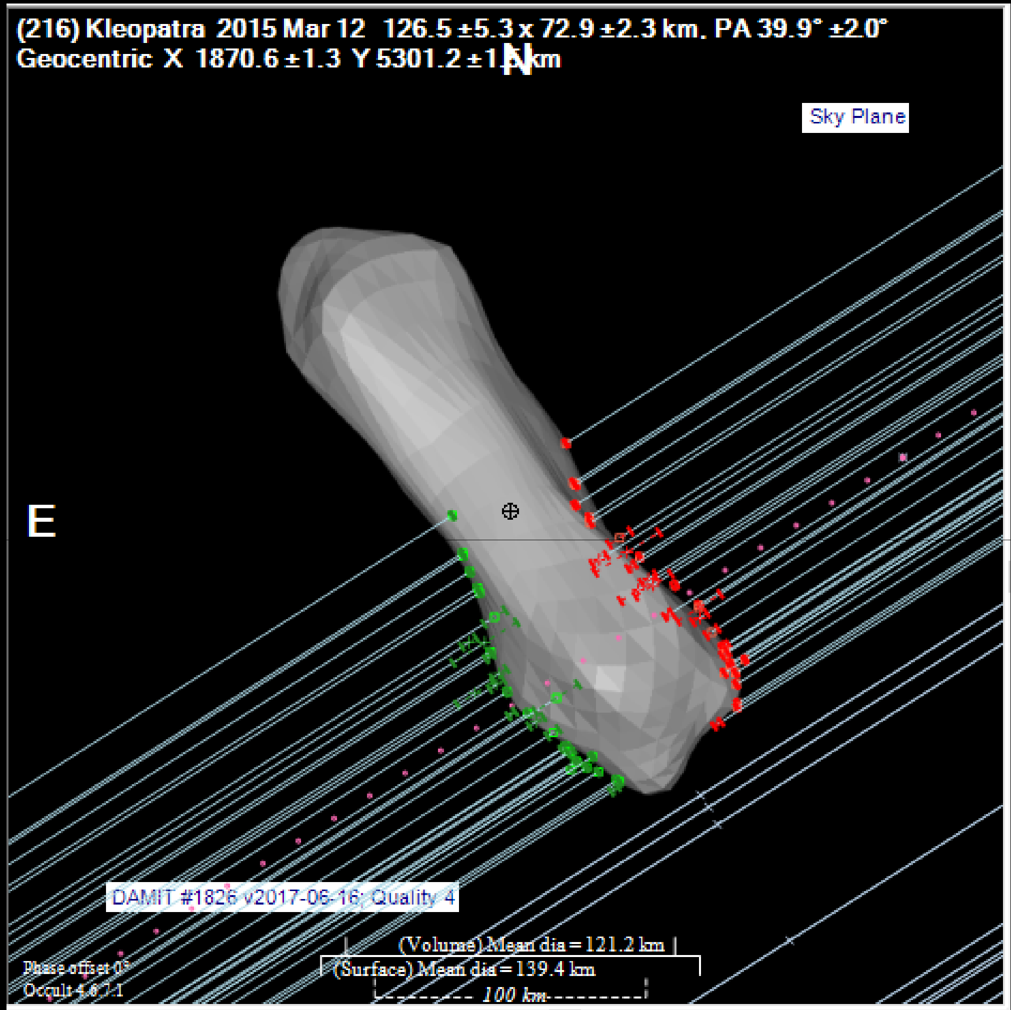


- A fit to a concave shape model derived in 2013
- The fit is clearly poor. Even so, the diameter can be assessed as being about 170km



- Fit to a 2017 convex shape model
- (note the smoother surface cf. 2013)
- Derived diameter 167 km

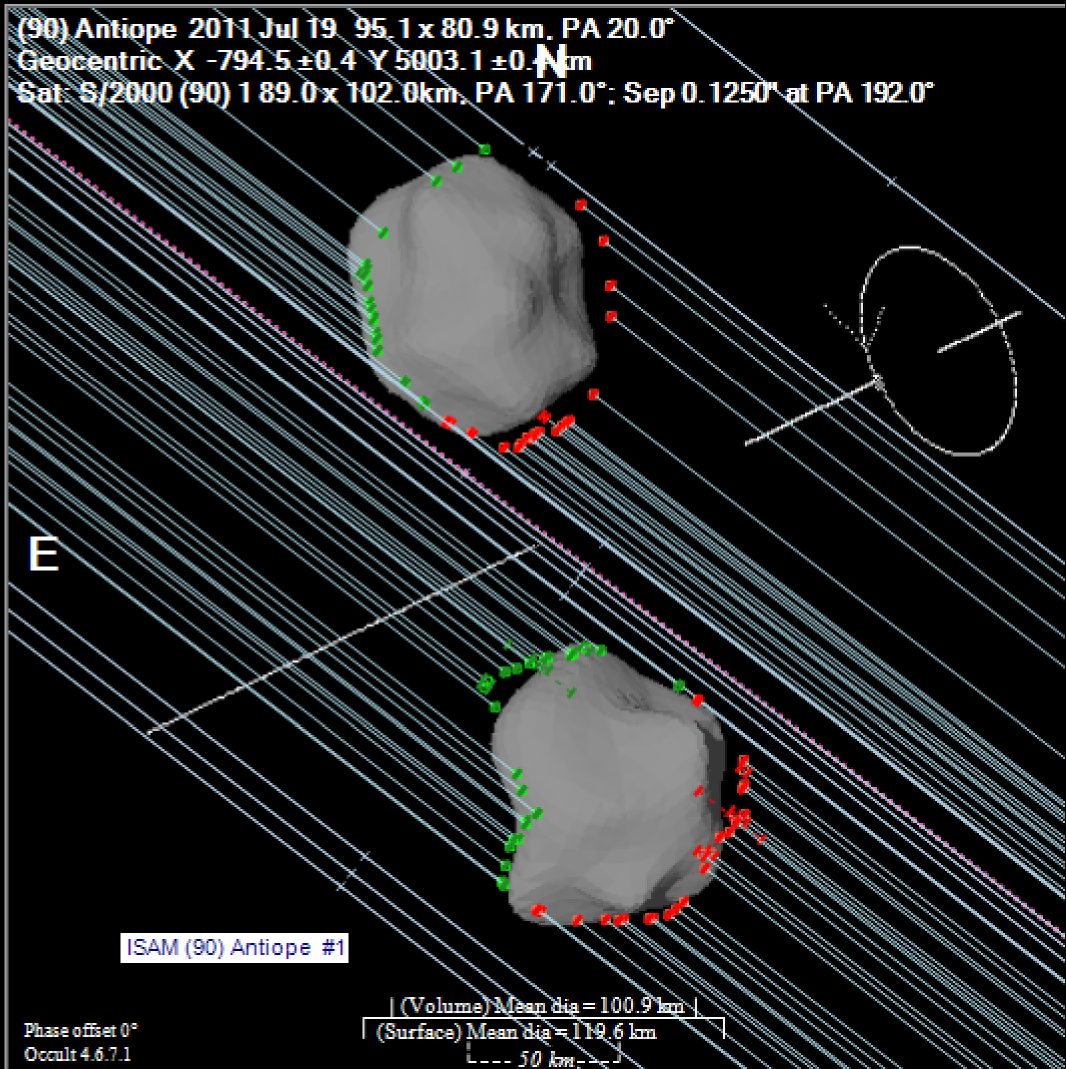
(216) Kleopatra

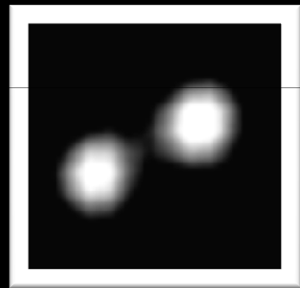


Occultation against the radar-based shape model for this extremely elongated asteroid

Resolve (90) Antiope

at <u>much</u> greater resolution than a 10-meter telescope!





Adaptive optics image from the 10-m Keck telescope

High precision astrometry

- Occultation astrometry is reported as an offset from the occulted star.
- 99.7% of occulted stars have Gaia DR2 positions
- For a well-observed occultation, the astrometric uncertainty can be as low as 0.0001” – that is, 100 µ-arcsec [typical CCD astrometry using modest ‘scopes has an uncertainty of around 200 mas.]

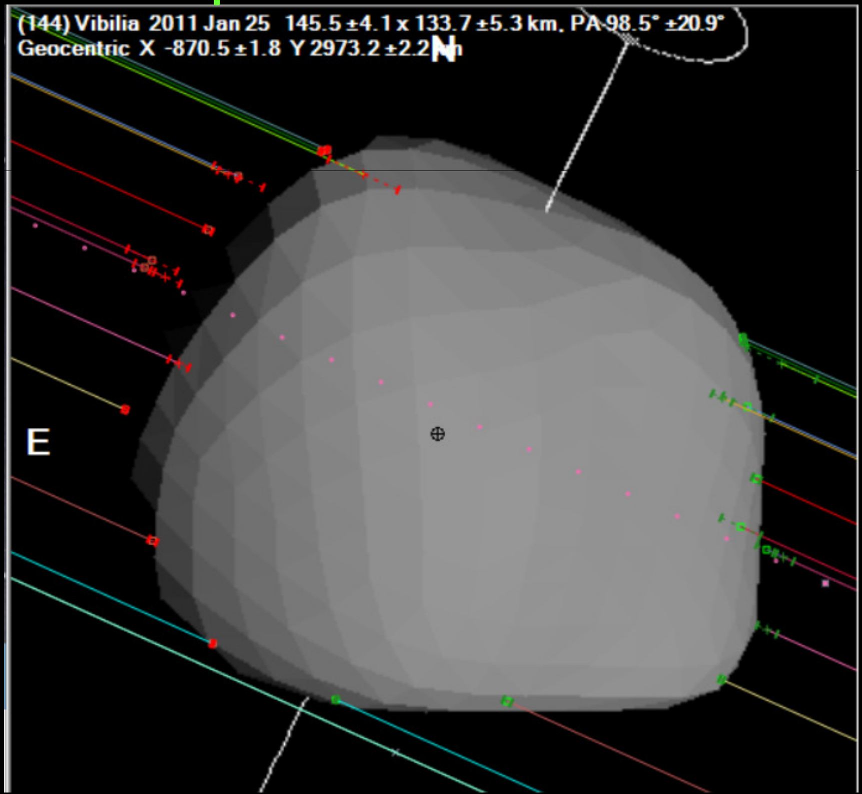
Limitations on CCD Astrometry

- Traditional CCD astrometry measures the centre of light of an asteroid
- Orbital motion is dictated by the location of the centre of mass, *not* the centre of light.
- The center of light will differ from the center of mass because of:
  - Solar illumination phase
  - Differences between the location of centre of mass and the centre of figure

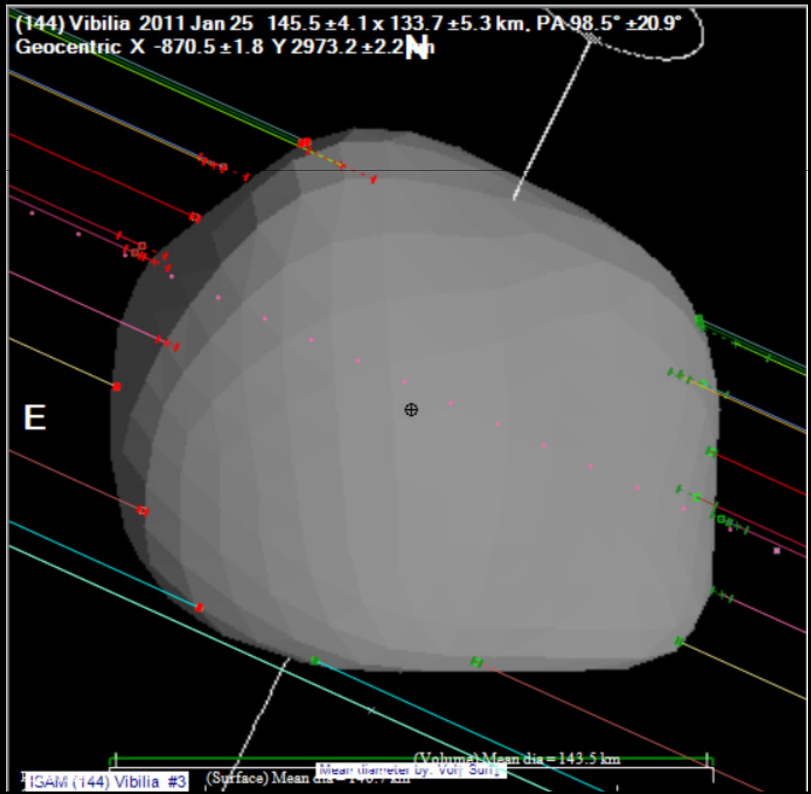
Effects of Phase

- Occultations locate the centre of mass.

Solar illuminated, phase affected

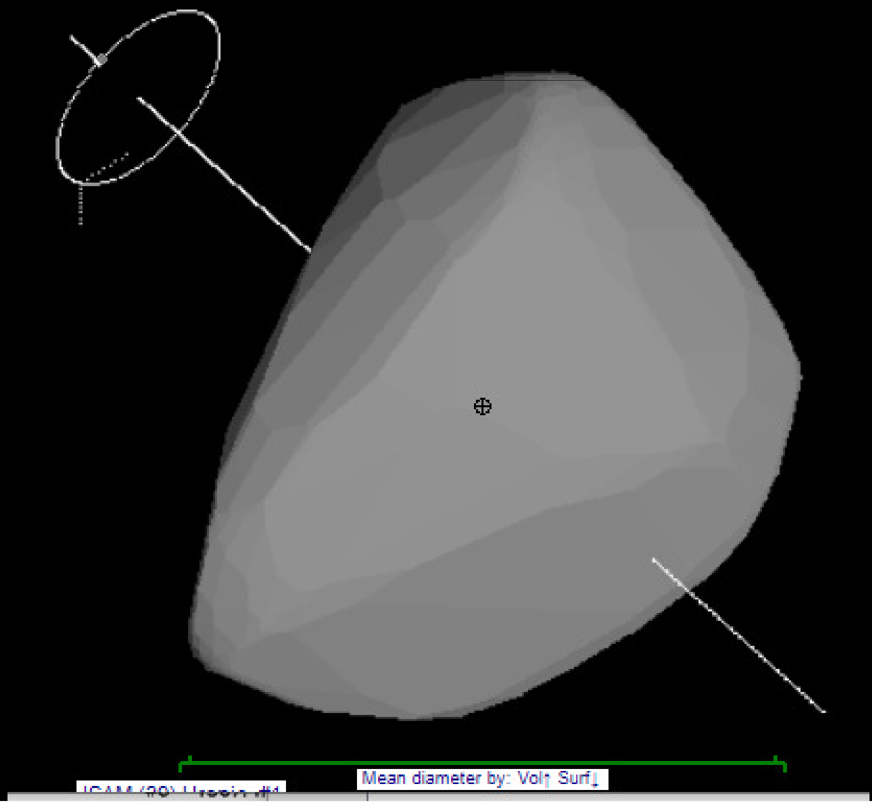


True profile



Centre of Mass/Figure

- When a shape model is available, differences between the centre of figure and centre of mass are relevant



Black marker is centre of mass (assuming uniform density). The centre of figure is clearly located to the right of the marker.

Asteroid density

- Combine the volume-equivalent diameter of an asteroid with its mass as estimated from orbital perturbation effects => density
- Astronomy & Astrophysics 601, A114 – gives densities derived in this manner for 40 asteroids
- Following slide lists some of the values. Note in particular the range of densities.

Examples of derived densities

Asteroid	Diameter (km)	Mass (10^{18}kg)	Density
2 Pallas	523 ± 10	204.0 ± 4.0	2.72 ± 0.17
5 Astraea	114 ± 4	2.6 ± 0.4	3.4 ± 0.7
8 Flora	140 ± 4	6.3 ± 0.7	4.4 ± 0.6
9 Metis	168 ± 3	8.4 ± 1.7	3.4 ± 0.7
10 Hygiea	412 ± 20	86.3 ± 5.2	2.3 ± 0.4
11 Parthenope	153 ± 5	5.9 ± 0.5	3.2 ± 0.4
13 Egeria	209 ± 8	9.4 ± 2.4	2.0 ± 0.6
94 Aurora	202 ± 4	6.2 ± 3.6	1.4 ± 0.9
165 Loreley	173 ± 5	19.1 ± 1.9	7.1 ± 0.9

Acknowledgments

- The database of occultation observations with at least one observed occultation has
  - 4160 events, involving
  - over 3000 individual observers, who have made
  - over 15,000 individual observations

Without the involvement of these (mainly unpaid) astronomers from around the world, the exciting results we are now seeing would not be happening.

Questions?