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Combining Asteroid Lightcurve and Occultation Observations

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For many decades the main purpose of asteroidal occultation observations was to get an estimate of the (mean) size of the sky-plane projected shape of an asteroid (by fitting an ellipse to the measured chords, if enough of them were available). Other applications of asteroidal occultations were very limited in the past, probably because the average number of successful observations in total and per event was low compared to the last 10-15 years, where better predictions, planning and observing tools, (amateur) collaborations etc. increased the amount and quality of data significantly. Although even the possibility of satellites or a binary nature of an asteroid was sometimes suggested on base of occultation reports (unfortunately in most cases single reports), the vast majority of such discoveries were made by other techniques like imaging with adaptive optics, radar and lightcurve observations.

In the past years lightcurve observations were successfully combined with other data like occultation timings. This has added a new, important application to asteroidal occultation work.

Some statistics

Currently we know about 715 000 asteroids (numbered and unnumbered). For less than 1% we have a reliable estimate of the rotation period and just for around 900 asteroids we have a global shape model (from lightcurve inversion mainly). And finally just for some ten asteroids detailed informations coming from HST imaging, adaptive optics, radar, space probes etc. are provided. If we consider further physical parameters like asteroid masses (which would give us, together with sizes and shapes, bulk densities and porosities) we can summarize that we know physical parameters only for a tiny fraction of the whole given population of asteroids. Therefore, it is necessary and important to continue collecting data in all these (among others) fields of asteroid research, i.e. astrometry, photometry and occultations.

Historical outline

About 100 years after the discovery of the first asteroid Ceres in 1801, light variations due to the rotation of the body were detected for the first time on photographic plates (Eros and Iris). In 1906 Russel published a first paper on lightcurve analysis. He attempted to derive the albedo map from the lightcurves observed on the opposition and he found that it was impossible to distinguish between the surface curvature and the spot distribution for a spotted convex surface. This paper contained some important conclusions which were useful for later studies of lightcurves. In 1978 Surdej and Surdej simulated the lightcurves of asteroids assuming tri-axes ellipsoids. And with the definition of a scattering law by Lumme and Bowell in 1981, many analogous methods based on the ellipsoid shape were presented, such as the model introduced by Karttunen (1989) and Karttunen and Bowell (1989). In 1987 Lagerkvist et al. published a first version of the Asteroid Photometric Catalogue, containing more than 2200 lightcurves of 357 asteroids. In 1992 Kaasalainen et al. investigated the lightcurve inversion problem and about 10 years later the group published an optimized and proven inversion algorithm to derive rotation parameters and global (three-dimensional) shape models of asteroids. Based on this, Ďurech et al. (2010) published an online database (DAMIT) which today contains about 1600 shape and rotation models for about 900 asteroids (http://astro.troja.mff.cuni.cz/projects/damit). However, it should be emphasized that several other shape modeling techniques were developed as well (e.g. Bartczak et al., 2013; Lu and Ip, 2015).

While asteroid lightcurve observations were mainly provided by professional astronomers up to the 1980ies, it is meanwhile dominated by amateurs and pro-am collaborations, with the exception of special studies / targets which are outside any amateur instrumentation.

Lightcurves

After removing the distant dependent part of the apparent magnitude of an asteroid (i.e. reducing it to unity distance) the brightness is a function of the shape, the rotation state (spin axis orientation and rotation period) and the surface properties (light scattering behavior, geometric albedo and variations of the latter) of the object. In this consideration we do not take into account any additional variations due to mutual events of binary or multiple asteroid systems. The periodic change of the brightness due to the rotation of the asteroid results into a lightcurve. The rotation period is typically in the order of hours, but values from minutes up to three months are known.

Lightcurve Inversion

In 2001-2002 Kaasalainen et al. provided a robust lightcurve inversion method. From a set of lightcurves, observed over years under different observing aspects we can derive (beside the rotational period and the spin axis orientation) a convex shape model (3D model). Figure 1 shows some examples of shape models compared to images taken by spacecrafts.

Nevertheless the lightcurve inversion scheme has some constraints:

- It is assumed, that the light variation is caused by the shape. The rubble pile model of asteroids implies that in average the surface reflectivity (geometric albedo) is rather homogeneous, therefore it is reasonable to consider most asteroids as uniformly gray (at least in first order). Nevertheless we do know of albedo variations (e.g. the color and albedo heterogeneity of Vesta, but this is a differentiated asteroid).
- The limited observing geometry of an asteroid (orbiting close to the plane of ecliptic), introduces an ambiguity of approximately +/-180°

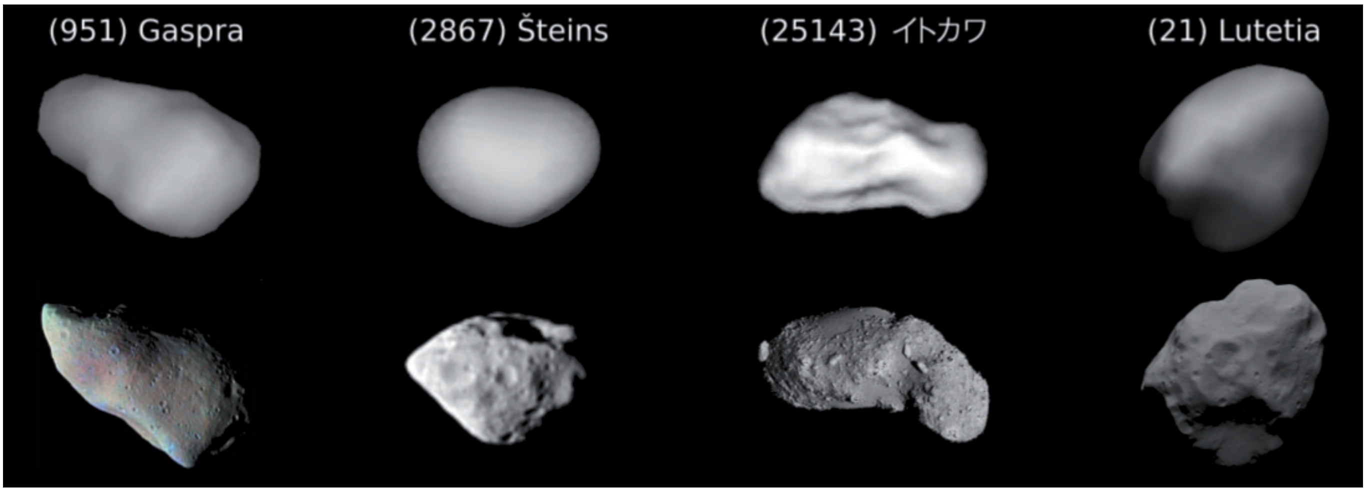

Figure 1: Comparison of four shape models with corresponding spacecraft images. After Carry et al. (2011).

in the ecliptic longitude (λ) of the pole. The corresponding shapes are mirror images of each other. In fact for about 90% of the asteroids with computed shape models / pole parameters we have more than one solution.

- If the real albedo of the asteroid is not known, the resulting shape model is not scaled to a physical size.

The lightcurve inversion allows to derive also non-convex shape models, but most of the shape models in the DAMIT database are convex, because disk-integrated lightcurves contain very little information about shape non-convexities. That means, that non-convex models based on lightcurves only are not stable and the realness of non-convex details can be questionable. By combining lightcurve inversion with other (high-resolution) data like radar, adaptive optics and occultation timings, we can get better and more trustworthy non-convex models. Despite a more realistic "picture" of the asteroid a non-convex model yields to a better volume estimate and thus we get better densities and porosities if the mass of the asteroid is known.

Occultation observations

As pointed out in the introduction, the scientific outcome of asteroidal occultation timings is often limited to fitting an ellipse (if more than one chord is given) to the sky-plane projection of the shape of the asteroid for the time of occultation. But if we use occultation observations as additional information to lightcurve inversions, these occultations can help to overcome some of the constraints mentioned before.

For convex models from lightcurve inversions we can

- scale the model (i.e. physical body size in kilometers) by fitting the chords (Fig. 2),
- solve the pole ambiguity (Fig. 2),
- predict the orientation of the body in space (as shape, pole and period are known) and therefore compute the sky-plane projection for an occultation (in the past or future). This helps to analyze occultation timings and / or to validate the model itself. It also helps to plan occultation observations as we know in advance the projection geometry and shadow shape.

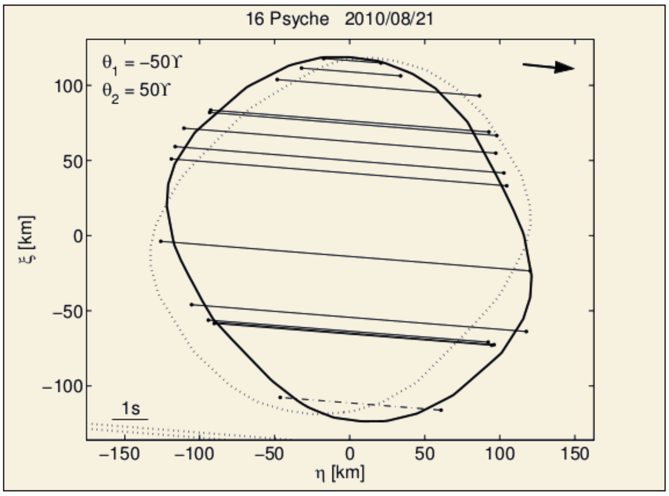

Figure 2: Scaling the model and resolving the pole ambiguity. The solid contour corresponds to the pole (λ,β) = (33°,-7°), the dotted one to (213°,+1°). After Ďurech et al. (2011).

Moreover we can use both occultation and lightcurve data simultaneously to derive a non-convex model (multi-data inversion). Especially non-convex details can be found and verified if enough occultation chords are available, which will in turn improve volume estimations (Figure 3).

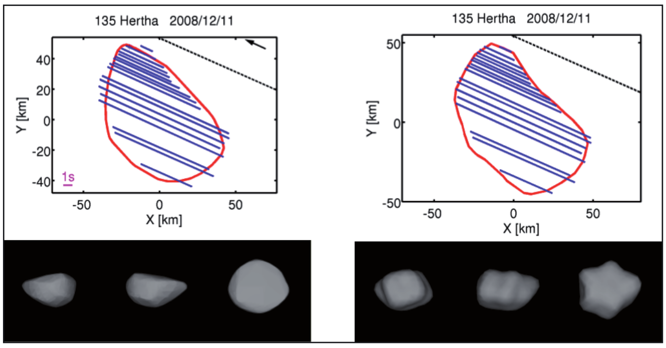

Figure 3: Left: Convex shape model, scaled to fit occultation chords.
Right: Non-convex model derived from simultaneous inversion of lightcurves and occultation timings. After Ďurech (2014).

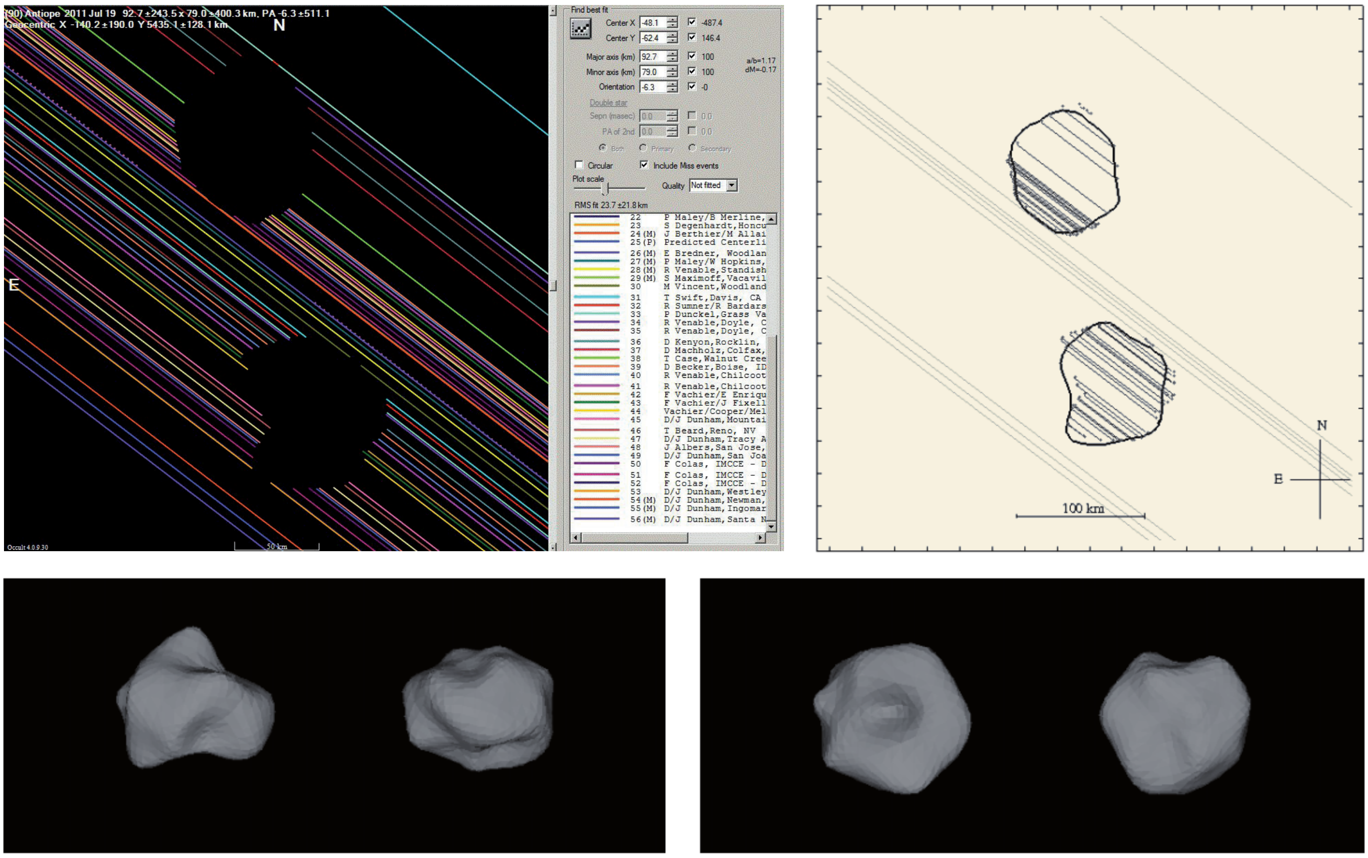

Figure 4: Occultation by 90 Antiope on 2011 July 19. Top left: Occultation chords plotted with Occult. Top right: Best fit of the stellar occultation chords obtained during the 2011 occultation to the solution found for the non-convex shape model of 90 Antiope (Bartczak et al., 2014). Bottom: Two different spatial views of the non-convex model for 90 Antiope shown at equatorial viewing on the left, and the pole-onview on the right.

In Figure 4 the occultation of LQ Aquarii by the double asteroid 90 Antiope in 2011 is shown. Bartczak et al. (2014) derived a non-convex shape model from disk-integrated photometry (using their so-called SAGE technique). The occultation observations were used to scale the shape model and some of the orbital parameters (distance between the two components). Ďurech presented a very similar solution (2014).

Conclusion

The lightcurve inversion method is a powerful tool to derive rotational parameters and global shape models of asteroids. Adding asteroidal occultations measurements helps to overcome some limitations of that method and to gain further scientific informations.

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