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INVERSION METHODS FOR INTERPRETATION OF ASTEROID LIGHTCURVES

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Abstract

We have developed methods of inversion that can be used in the determination of the three-dimensional shape or the albedo distribution of the surface of a body from disk-integrated photometry, assuming the shape to be strictly convex (Kaasalainen et al. 1990a, 1990b, 1991a). In addition to the theory of inversion methods, we have studied the practical aspects of the inversion problem, and applied our methods to lightcurve data of 39 Laetitia and 16 Psyche (Kaasalainen et al. 1991b).

Practical Aspects of Inversion

The result obtained in inversion is a finite spherical harmonics series as a function of the direction of the surface normal. In practice, one must decide in each case whether this result is taken to describe shape rather than albedo features, or if the surface is not convex on a global scale. Fortunately, there are some indicators for this: certain nonzero coefficients in the series indicate albedo variegation, and substantially negative values of the sum of the series imply a nonconvex shape. A solution ascribed to shape is less sensitive to errors in lightcurve data than one ascribed to albedo variegation.

There are many observational factors having an influence on the outcome of inversion. Also, one must make some a priori assumptions that are used in te inversion process. The most important points are:

• The assumed spin vector of the asteroid. The inversion procedures are not too sensitive to the pole position, as long as it is known to an accuracy of about 15°. The sidereal rotation period of the asteroid should be very precisely known if it is to be used in computing the absolute rotational phases, which should be known to the same accuracy as the pole position. Another possibility is to determine the phases using prominent features or other properties of lightcurves. Although this may not always be a properly justified approach, the phases can usually be determined within a reasonable limit of uncertainty. One can also use a series of small deviations from the a priori spin vector and choose the result that gives the best fit in this series.

• The number and the range of the observing geometries. These should, of course, be as large as possible. Especially the aspect angle (the angle between the line of sight and the rotation axis) should extend well outside the equatorial zone; if this is not possible, the solution obtained tends to be numerically not well determined. Nonzero solar phase angles can in principle provide information unobtainable at opposition if the scattering of light is geometric there. In practice, obtaining this information is difficult because of the small phase angles. Accurate observations as far away from opposition as possible are required; also, the light-scattering law should be well known. Aspect angles far from equator, or equatorial aspects when the illumination direction is not near the equatorial plane, are best for this purpose.

• The accuracy of lightcurves. The magnitude of noise in the lightcurve data primarily determines the truncation point of the spherical harmonics series obtained in inversion. This stems from the fact that high-degree components of the shape contribute less to the total

brightness than low-degree ones. A typical truncation point is at degree 4, which is enough to provide a coarse description of the shape.

• The convexity of the surface. If the surface is globally nonconvex, the inversion procedure cannot obtain a description of its shape. However, an indication of nonconvexity can be obtained. Local nonconvex features, such as craters, often make no significant contributions to lightcurves and are thus no real obstacles for inversion under the convexity assumption. For globally nonconvex objects there probably is no analytical or 'numerically algorithmic' inversion scheme.

Applications to Real Lightcurve Data

In testing the inversion methods, we have used synthetic lightcurve data. A strictly convex body without albedo variegation, shown in Figure 1, was used as a test object. A shape solution obtained from 16 lightcurves at well distributed observing geometries is shown in Fig. 2. The lightcurves contained an artificial noise level of about two percent, corresponding to about 0.02 mag.

We have applied the methods to lightcurve data of 39 Laetitia and 16 Psyche (Lumme et al. 1992), which cover observation geometries well. For the former, 16 lightcurves were used (solar phase angle α ranging from 6° to 23°, and aspect θ from 41° to 151°); for the latter, 18 lightcurves (2° $\leq \alpha \leq$ 21° and 17° $\leq \theta \leq$ 150°), ten of which were concentrated within an aspect interval of a few degrees. The pole positions for the asteroids were computed using the spherical harmonics method (Lumme et al. 1990, 1992). Both spherical harmonics series describing the outcomes of inversion were truncated at degree 4. The scattering law used was a combination of the Lommel–Seeliger law and Lambert's law (relative contributions of 1 and 0.3, respectively, provided the best fits) with the Lumme–Bowell phase functions (Lumme et al. 1990).

The result for 39 Laetitia indicated no substantial albedo features. In the case of 16 Psyche, albedo variegations are more probable but still minor compared to the shape effects. The obtained solutions fitted the original data to an average accuracy of about two percent (0.02 mag). The shape results are shown in Figs. 3 and 4. It should be noted that the solutions are the *convex* shapes best reproducing the original data with the assumptions for the scattering law and spin vectors. In both cases nonconvexities are possible, but convex surfaces can probably describe the global shapes adequately.

References

Kaasalainen, M., Lamberg, L., and Lumme, K. (1990a) Photomorphography of atmosphereless bodies: asteroid shapes from lightcurves. In *Asteroids, Comets, Meteors III* (C.- I. Lagerkvist, H. Rickman, B. A. Lindblad, M. Lindgren, eds.), pp. 115–118. University of Uppsala, Uppsala, Sweden.

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Kaasalainen, M., Lamberg, L., and Lumme, K. (1991b) Interpretation of lightcurves of atmosphereless bodies. II. Practical aspects of inversion. Submitted to *Astron. Astrophys.*

Lumme, K., Karttunen, H., and Bowell, E. (1990) A spherical harmonics method for asteroid pole determination. *Astron. Astrophys.*, **229**, 228–239.

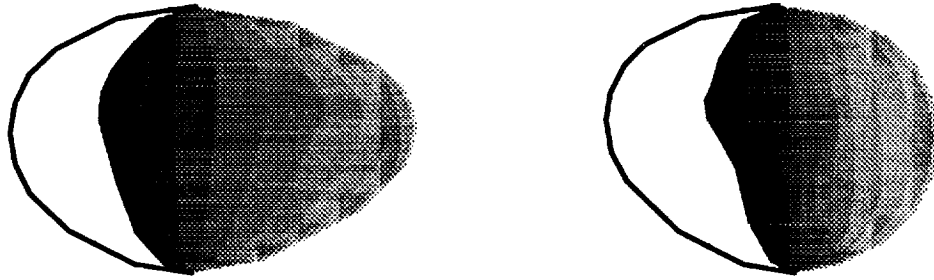Lumme, K., Karttunen, H., and Bowell, E. (1992) In preparation.

Fig. 1. An object used in testing the inversion methods, shown as viewed from two mutually perpendicular directions; the direction of the rotation axis is vertical. Synthetic lightcurves can be produced using this object. In both images the solar phase angle is 60 degrees, the illumination direction being perpendicular to the rotation axis. The shadowed part of the limb is also shown. The 'contours' on the surfaces appear because of the image producing technique. The scattering law used in the images is the Lommel-Seeliger law.
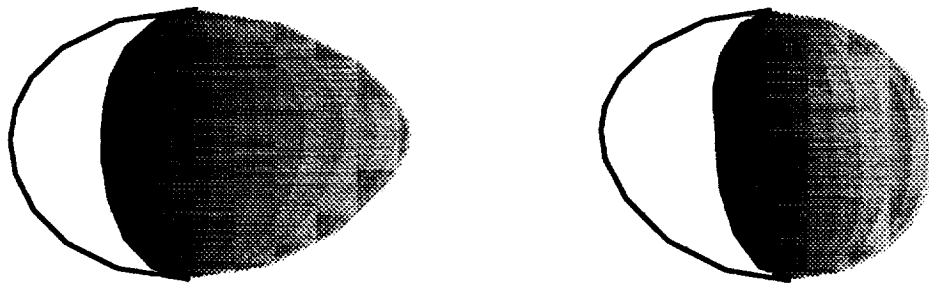

Fig. 2. A solution obtained in inversion from 16 synthetic lightcurves at well distributed observing geometries. An artificial noise level of about two percent was added to the lightcurves. The viewing/illumination directions are the same as in Fig. 1.
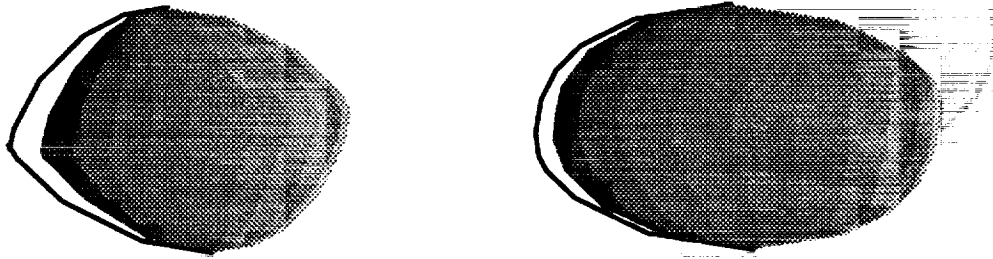
Fig.3. The shape result for 39 Laetitia. The viewing directions are as in
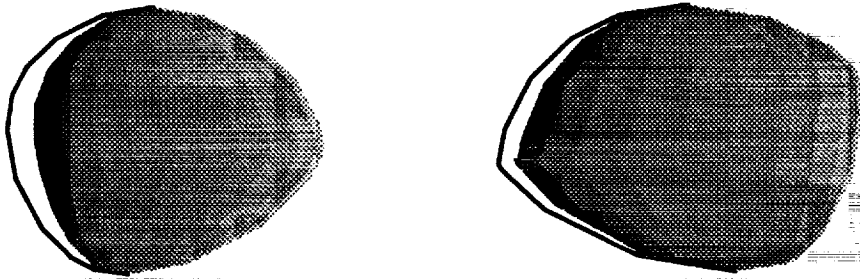Fig. 1; the solar phase angle is 30 degrees.

Fig. 4. The shape result for 16 Psyche, represented in the same manner as
39 Laetitia in Fig. 3.