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Research Note

Adaptive optics observations of asteroid (216) Kleopatra⋆

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Abstract. The large main-belt asteroid (216) Kleopatra has been for long suspected to be a binary object, mainly due to its large lightcurve amplitude. However, recent observations suggest that it is a single "bone-shaped" or bi-lobated body (Ostro et al. 2000; Tanga et al. 2001). We present results obtained from ground-based adaptive optics observations, and in agreement with the radar raw-observations, the images show two prominent lobes. Making use of the MISTRAL deconvolution technique, the restored images yield a well-separated binary object. Nevertheless, the spatial resolution of the 3.6 m ESO telescope is limited and a dumbbell-shaped body could yield similar features. Further simulations show that adaptive optics observations with an 8-meter class telescope analyzed with the powerful MISTRAL deconvolution technique could overcome this limitation.

Key words. instrumentation: adaptive optics – minor planets, asteroids

1. Introduction

At the beginning of last century, by analyzing the asteroid (433) Eros, André made the hypothesis that asteroids could have satellites (André 1901). Since then, however, we know that Eros is actually an elongated single-body. But, since the discovery of Dactyl, the moon of Ida, by the Galileo space probe, it has been established that some asteroids do have satellites. Merline et al. (1999) reported the first ground-based detection of an asteroid satellite using adaptive optics (AO). These fundamental findings have motivated a systematic search for possible satellites of main-belt asteroids using AO imaging-systems and discoveries are now accumulating (Merline et al. 1999, 2000; Brown et al. 2001; Merline et al. 2001). However, one should distinguish among different types of asteroid binaries: whether the system is composed of similarly-sized bodies such as (90) Antiope or whether a small moon is orbiting around a larger attracting asteroid such as (22) Kalliope. The events or physics underlying the formation of such systems are surely different, and they may also be different for Earth-crossing asteroids which can be affected by larger tidal evolution. An accurate orbit analysis is of great importance for studies of the internal structure, formation and evolution of such systems (Marchis et al. submitted). In this respect the asteroid (216) Kleopatra is of particular interest: should its binary nature or dumbbell-shaped nature be confirmed, it would provide additional constraints on collisional-evolution and binary-formation models.

Direct or indirect imaging of Kleopatra in the past showed it to be a very elongated body but was not able to conclusively prove or disprove its binary nature (Dunham 1992; Mitchell et al. 1995; Storrs et al. 1999). For instance, the direct imaging data from the HST/WFPC1 of Storrs et al. (1999) had limited resolution, and artifacts, due to the restoration technique used, arose in the image reconstruction (Storrs et al. 2000). Analysis of recent observations with the HST Fine Guidance Sensor interferometer provide a bi-lobated shape-model (Tanga et al. 2001), consistent with the images obtained from the Keck telescope (Hammergren et al. 2000). At present, the best resolution model obtained for Kleopatra is given by radar observations (Ostro et al. 2000). However the radar data do not rule out the presence of an empty gap between the two lobes and could be consistent with a binary model.

We present results from observations using the ADaptive Optics Near Infrared System (ADONIS, Marchis et al. 1999; Roddier 1999) installed on the 3.6 m ESO telescope at La Silla (Chile), on October 25, and December 3, 1999. The observations and restored images using the MISTRAL technique are presented in Sect. 2. Simulations of observations with higher resolution, e.g. with the VLT/NAOS instrument are presented in Sect. 3.

2. Observations

Kleopatra was observed by one of us (F.M.) using the ADONIS system on October 25, 1999 from 6.7 to 7.4 h UTC

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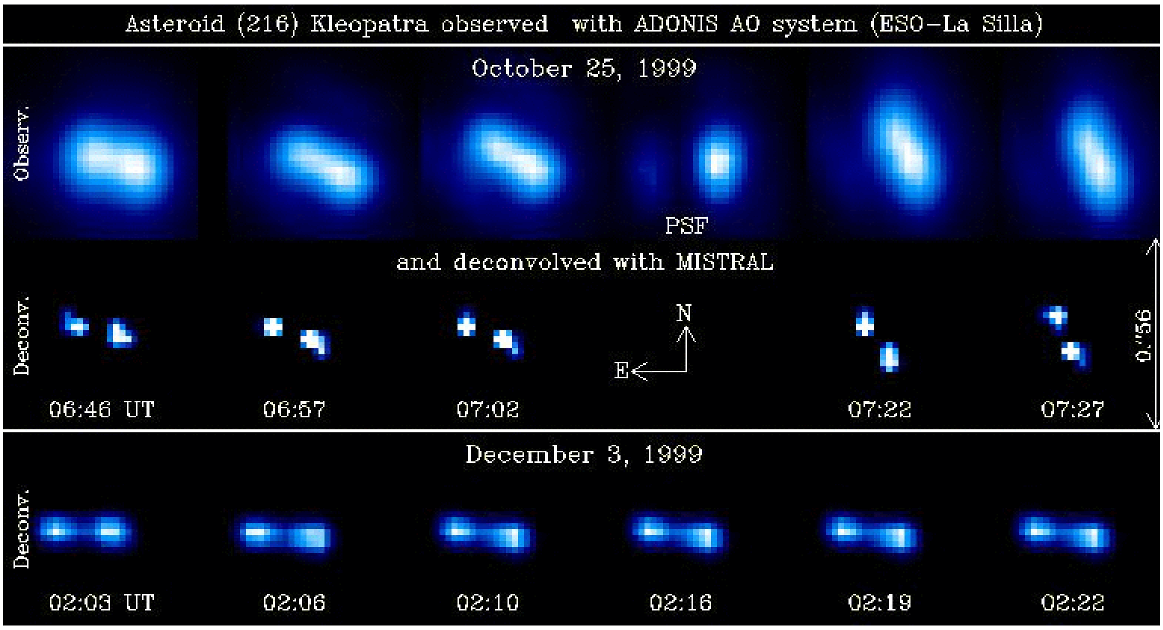

Fig. 1. Observed and restored images obtained at the ESO-La Silla 3.6 m telescope. Upper panel: October 15, 1999 run; lower panel: December 3, 1999 run. The restored images are shown on a linear scale.

(i.e. over approximately one eighth of its 5.385 hr rotational period). Observations were performed in the near infrared using the SHARPII+ camera in the *K*s band ($\lambda = 2.154\,\mu$m, $\Delta\lambda = 0.323\,\mu$m) and with a 35 mas/pixel scale (corresponding to 30.5 km/pixel at 1.2 AU). Wavefront sensing was performed at optical wavelengths using Kleopatra itself as the reference. The object brightness ($m_V \sim 9.7$) and predicted angular diameter (less than 0.2 arcsec) made it an excellent target for adaptive optics observations during a night characterized by good and stable seeing conditions (~0.6 arcsec). In order to enhance the signal-to-noise ratio, each image used for the analysis is the result of adding 32 single exposures, corresponding to a total integration time of approximately 2.7 min. During the night, an image of a single star was also taken in order to obtain a point-spread function (PSF), required to estimate the observation quality and to apply further deconvolution procedures. The Full Width at Half Maximum (*FWHM*) of the PSF (0.14 arcsec) and the relatively good Strehl ratio ($SR = 22\%$) indicate that, although the AO correction is not perfect, the signal-to-noise ratio is high enough to ensure that the deconvolution is reliable. Subsequent observations were obtained in the same band and following the same procedure on December 3, 1999 from 2.1 to 2.4 UTC with lower quality and degraded resolution.

In addition to the usual MLR technique, the MISTRAL (Myopic Iterative STep-preserving Restoration ALgorithm) deconvolution technique (Conan et al. 1998, 1999), specially adapted to planetary objects, was applied. The main difference between this technique and other more "classical" methods is the avoidance of both noise amplification and creation of sharp-edges artifacts or "ringing effects", and better restoration of the initial photometry. However, since the actual PSF is unknown, two basic parameters representing the image noise and the object sharpness need to be optimized. The restored images however are not highly sensitive to these two parameters. On the other hand, simulations show that different shape models would produce similar restored images with two separated spots. Figure 1 displays the basic and restored images of the October run. The restored images display a well separated binary system. The two components have similar sizes and magnitudes with a measured flux ratio $F = 0.81 \pm 0.03$. These confirm the bimodality of the spectral signature from radar observations (Mitchell et al. 1995; Ostro et al. 2000) and the characteristic interferogram shape of the HST/FGS observations (Tanga et al. 2001). Nevertheless the resolution limit together with the pixel scale, and to a lesser extent the PSF variability, limit the accuracy of the deconvolved-image model. Simulations of our present observations show that we cannot preclude a dumbbell-shaped model.

Our estimated pole direction[1] of $\lambda = 72°$ and $\beta = 23°$ for the ecliptic B1950 coordinates matches within ±5° the observed orientation of the majority of the observations found in the literature. In the case where the two apparent lobes are well separated with a center-to-center separation of 129 km and an orbital period equal to the known rotation period, the binary system would have a total mass of 3.4×10^{18} kg. The component separation being close to the Roche limit, mutual tidal distortions are expected to occur. Under the assumptions of two Roche ellipsoids of *fluid* in hydrostatic equilibrium and in synchronous orbit (Leone et al. 1984), the measured flux ration F, together with an assumed maximum amplitude $A = 0.9 \pm 0.25$ (Zappalà et al. 1983), yields a density in the range of 4–5 g/cm^3 (assumed to be the same for each body). Such a relatively large value for the bulk density suggests that the M-type asteroid Kleopatra contains a significant fraction of metals. This seems realistic for a rubble-pile body (i.e. of non negligible porosity) composed of differentiated material, but it does not

[1] Note that with such observations, the pole ambiguity that usually arises from the analysis of light-curves disappears.

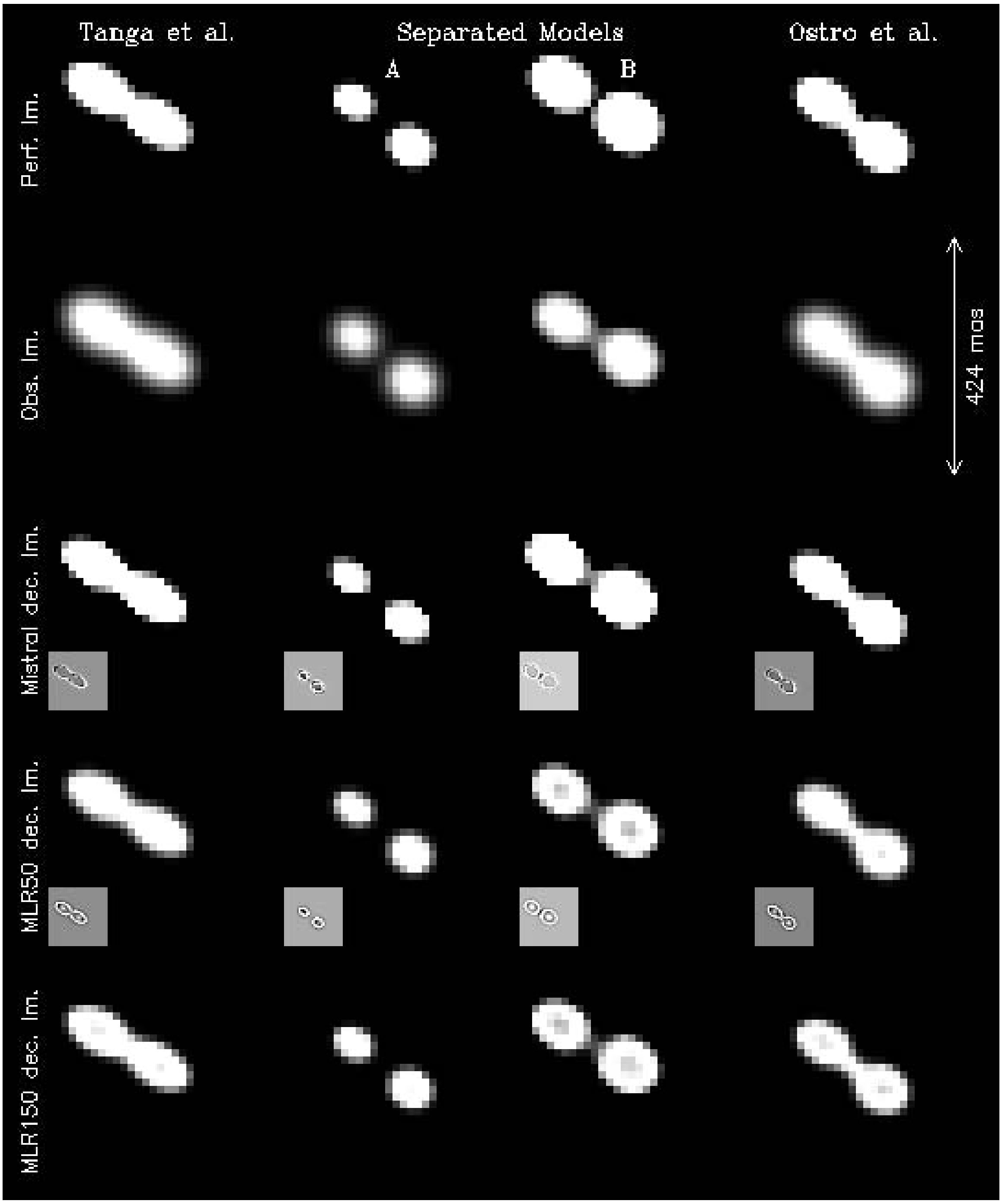

Fig. 2. Simulated and restored images for three shape models (see text) from the VLT/NAOS adaptive optics system. The first row shows the simulated pixel-sampled shape. The observed image is the result of the convolution with the instrument PSF. The last three rows give the restored image when applying the MISTRAL and MLR techniques. The restored images are presented on a linear scale. The small insets provide the residuals: deconvolved minus perfect images.

preclude a monolithic-like body. It is moreover consistent with the asteroid surface bulk density (>3.5 g/cm^3) determined by Ostro et al. (2000) and marginally consistent with the value of (3.9 g/cm^3) predicted by Cellino et al. (1985). Depending on its actual nature, the non family-member asteroid Kleopatra could be the result of a catastrophic collision inducing binary fission (Hartmann 1979; Farinella et al. 1982) or the result of a more subtle collision (Leinhardt et al. 2000).

3. VLT/NAOS simulations

The relatively large pixel size together with the modest spatial resolution of the ESO 3.6 m telescope strongly limits the deconvolution process. The marginal high-resolution that can be achieved with the present data preferably yields a binary system, but conversely we know that such a result can also be obtained if the object is dumbbell shaped. Larger telescopes with a 15–25 mas/pix scale could overcome this limitation.

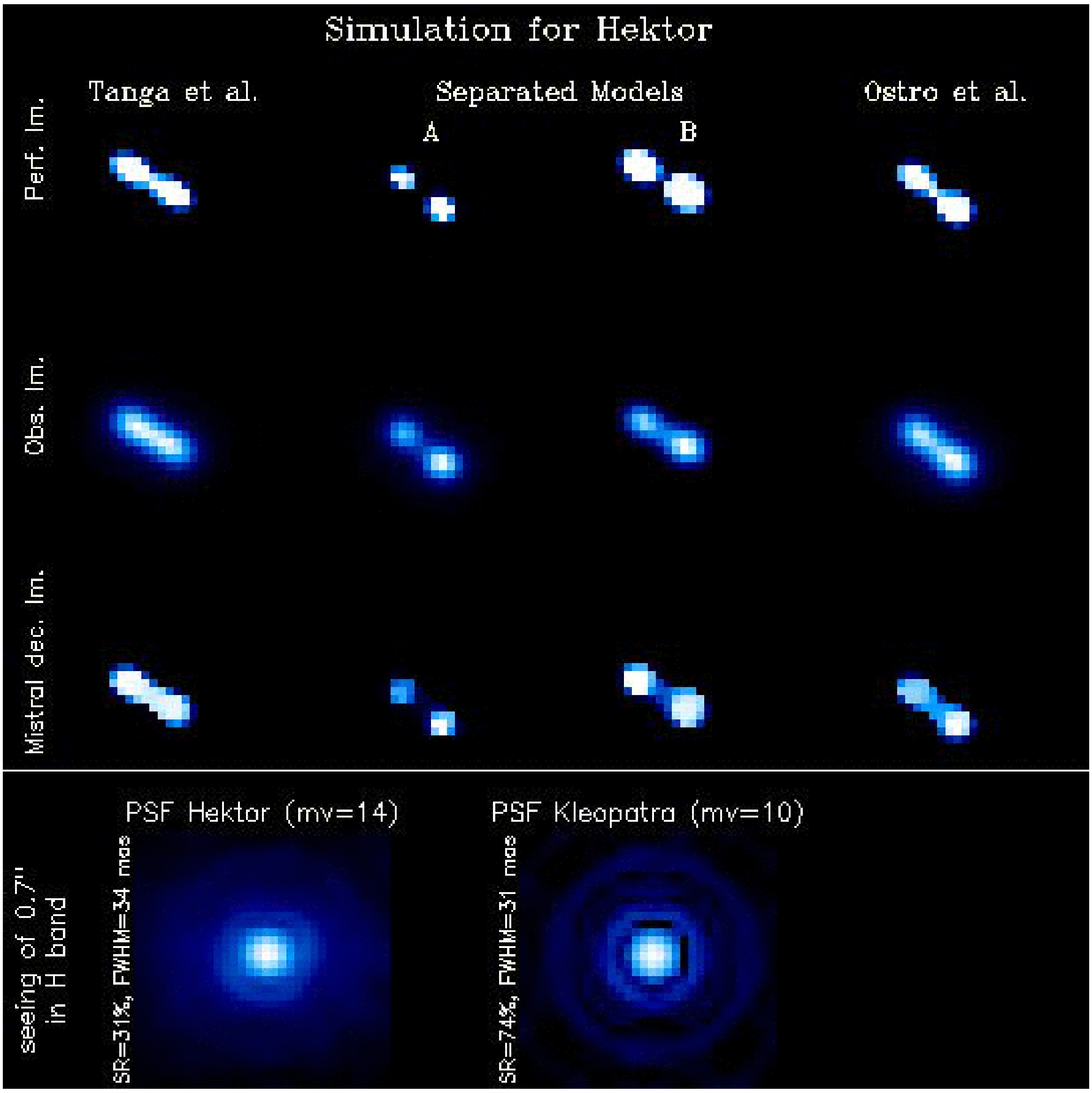

Fig. 3. Same as Fig. 2 for an Hektor-type asteroid in the *H* band. Only the restored images using the MISTRAL procedure are shown. The last row is a display of two PSFs used for the simulation of the observations of Hektor and Kleopatra. Note the presence of several Airy rings for the brightest star.

To illustrate this claim, we have constructed simulated images from the NAOS/CONICA camera (with a 13.25 mas/pixel scale) installed on the ESO VLT/UT telescope at Paranal (Chile). Four cases are analyzed corresponding to the dumbbell shape of Tanga et al. (2001), the two binary models obtained (A) from the restored images and (B) from the Roche ellipsoids model described in Sect. 2, and the "bone-shape" model of Ostro et al. (2000). The images are obtained by convolution of these shape models with a simulated H-band (1.64 μm) NAOS/CONICA PSF profile under an atmospheric seeing which varied between approximately 0.6 and 1.0 arcsec (Rousset et al. 1998). The set of PSF indicates a highly stable correction of the AO system with a Strehl ratio between 56 and 80% and a *FWHM* of ~31.5 mas. Additional noise corresponding to photon noise and the readout noise of the detector (with $\sigma = 120$ e-) have been included in these convolved images. Results from the restoration process with the MLR and MISTRAL techniques are shown in Fig. 2. We stress that the PSF applied for the construction of the simulated image (second row of the figure) is not used during the myopic deconvolution. Instead, we used a mean PSF estimated from several PSFs taken at different seeing conditions for which we can also estimate the variability per element of frequency in Fourier space (the Density Spectral Point or DSP). Comparison of the original model (first row of the figure) with the restored object (last three rows of the figure) shows the advantage of the MISTRAL over the classical MLR method. Moreover, it appears that VLT/NAOS/CONICA observations of (216) Kleopatra would be of great value since they could conclusively reject an incorrect shape-model. The same procedure was applied with appropriate scaling for the apparent size and signal-to-noise ratio to an asteroid similar to (624) Hektor (V = 14 and about half the apparent size of Kleopatra, see Fig. 3). Here the

H-band PSF is simulated for a fainter object, and the correction is not as good as for Kleopatra. For instance, under a seeing of 0.7 arcsec the PSF nominal Strehl ratio is 31% and its *FWHM* is 34 mas, but the variation with the seeing quality is much larger (we have $SR = 14\%$ and $FWHM = 50$ mas under a seeing of 0.9 arcsec). Even though the restitution is degraded in this case, the MISTRAL deconvolution method linked with the intrinsic resolution of the 8 m size telescope still enables us to reveal the binary nature of close pairs among the Trojans.

4. Conclusion

The ADONIS AO system installed on the 3.6 m ESO telescope at La Silla (Chile) was used for direct imaging of the main-belt asteroid (216) Kleopatra in near infrared wavelengths. Since the achieved resolution is limited, the observations are consistent with the shape model of Ostro et al. (2000) obtained from radar observations but do not rule out a separated-binary model.

The MISTRAL deconvolution technique shows promise for resolving suspected binary asteroids with adaptive optics systems implemented on larger 8–10 m class telescopes (e.g. VLT, Subaru, Keck, or Gemini). The simulations performed in this work show that this technique would provide accurate restored images of suspected binaries or uncommonly shaped bodies and hence would provide strong evidence regarding their actual nature and valuable data to better understand their origin.

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