

**THE 2004 OPPOSITION OF CERES OBSERVED WITH ADAPTIVE OPTICS ON THE VLT** S. Erard<sup>1</sup>, O. Forni<sup>1</sup>, M. Ollivier<sup>1</sup>, E. Dotto<sup>3</sup>, T. Roush<sup>2</sup>, F. Poulet<sup>1</sup>, and T. Müller<sup>4</sup>, <sup>1</sup>IAS/CNRS, bât. 121 Université Paris-Sud, 91405 Orsay, France <sup>2</sup>NASA Ames Research Center MS 245-3 Moffett Field, CA 94035-1000, <sup>3</sup>INAF-OAR Via Frascati 33 I-00040 Monteporzio Catone, Italy <sup>4</sup>MPE, Giessenbachstrasse, 85748 Garching, Germany

**Introduction:** The close opposition of Ceres in January 2004 has been observed with the NACO adaptive optics system on the VLT. Both imaging and spectroscopy were performed in the 1.1-4.1  $\mu\text{m}$  range. Extensive longitudinal coverage was acquired during a three days run, with spatial resolution up to 50 km in imaging mode. The scientific objectives are 1) to provide the first IR map of Ceres; 2) to map possible compositional variations at the surface. Only imaging results are presented here.

**Observations** were performed on January 12th to 14th, 2004 (three days after opposition) at phase angles of 3.5-4°. Ceres diameter was  $\sim 0.8''$  and visible magnitude was 6.8. Ceres was visible from Paranal only 4 h / night with airmass less than 2 at this time. Accounting for the 9h rotation period, 3 half nights were required to span the whole longitude range. Imaging and spectroscopy data were acquired in J (1.1-1.4  $\mu\text{m}$ ), short K (1.95-2.3  $\mu\text{m}$ ) and L' (3.35-4.1  $\mu\text{m}$ ) bands during clear or photometric nights. The adaptive optics system provided a resolution of  $\sim 50$  km at Ceres, that can be improved up to 16 km if the PSF can be deconvolved (60 pixels on the disk).

**Image reduction** is first performed according to NACO recipes. L' images are subtracted from one another in order to correct from sky thermal emission. Dark frames are subtracted from images in J and Ks filters. Averages of 5 consecutive images provide a signal to noise ratio  $\sim 400$ . At this step however, a high frequency instrumental pattern remains in the J and Ks images, apparently due to small non-linearity effects between odd and even lines/columns. The magnitude of this pattern is  $\sim 4\%$ , comparable to Ceres surface contrast. The pattern is simulated and divided with a coefficient fit for each individual image. Whenever it is still visible after this division, the image is filtered in Fourier space with a very sharp Butterworth filter, basically removing the highest frequency only. Finally, images are coregistered and the average of the normalized images is computed (this provides better looking results than a median). At this stage, images are not calibrated in flux, and no attempt has been made to deconvolve the PSF.

**Pole and dimensions:** Averaged images have been fit with elliptic shapes, providing radii and tilt estimates. According to rotational ephemerid from [1] the polar axis is nearly perpendicular to the ecliptic and tilted by 5.8° from the North. Apparent

diameters are therefore close to the actual diameters. Before deconvolution, our best fit is an oblate ellipsoid with  $a = 948.5$  km,  $b = 878.1$  km with an absolute accuracy on the order of 30 km, and much better relative accuracy ( $\sim 3$  km). The ratio of polar to equatorial radii is  $1.080 \pm 0.005$ , consistent with independent estimates from [2], [3] and [1]. Such a polar flattening has been considered inconsistent with a pure rocky composition, and interpreted as a possible signature of ice [2] or liquid water [4] in the bulk of the planet in its early history. Relative to the expected North pole direction provided by [1] from 1993 data, our estimated axis is tilted by  $1.3 \pm 0.2^\circ$ . Observation of surface markings confirms the prograde rotation previously mentioned by [3].



Fig.1: L' filter image of January 14th centered at 2.9°N-69.5°E. The dark region is located where the Piazzzi feature is expected (N on top, contrast enhanced with exponential scale).

**Surface markings** are distinctly observed in the equatorial regions in Ks and L' filters, although the contrast is only  $\sim 4\%$  at the 50 km scale. The contrast is similar in J filter, but surface markings are more difficult to observe owing to the large limb darkening effects.

One main focus of the imaging effort was to independently confirm the presence of Piazzzi, a dark feature previously reported by [5] from HST UV measurements. On the 1995 HST images, Piazzzi appears as a 250 km-diameter feature centered approximately 30°N-75°E (using North pole determination from [1]), with 20% contrast. We do

observe a large surface marking at the expected location, although with smaller dimensions (~150 km), and reduced contrast (~4% in Ks and L' filters). This spot is surrounded by a large, intermediate albedo region extending 400 km southward (Fig. 1 and 2). The uncertainty in the pole direction used makes the identification with the HST dark region only tentative however, since the data sets were acquired more than 8 years apart.

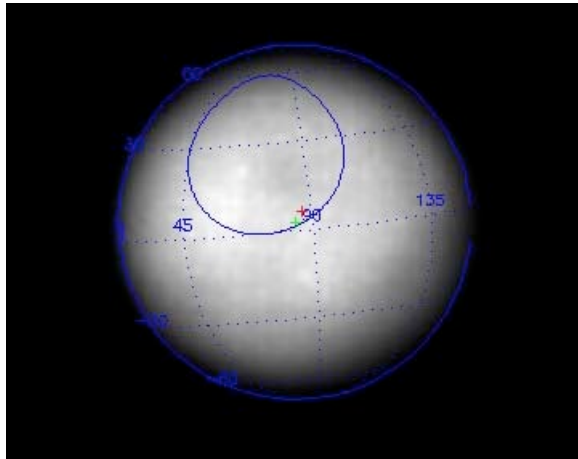


Fig.2: short K filter image centered at 2.9°N-81.3°E. The dark region in Fig.1 is compared to the approximate outline of Piazzzi from [5]. The green cross is the disk center, the red one is the sub-solar point.

Another large dark region is observed opposite Piazzzi at 30°N-210°E, which is slightly larger and more regular (180 km diameter). Several dark features ~100 km in size are also observed at the mid-southern latitudes from 120 to 320°E at least (Fig. 3).

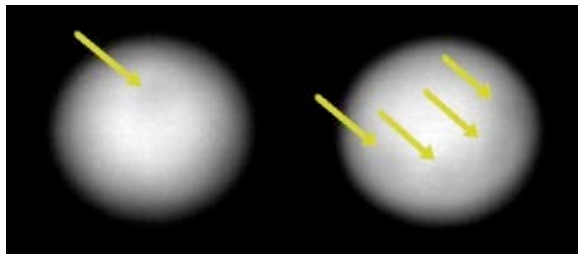


Fig.3: Other dark markings observed on short K images centered at 210°E (left) and 130°E (right).

**Limb darkening** has been fit with Minnaert functions. The Minnaert exponent usually ranges from 0.6 to 0.8 in short K and L filters. An apparently more Lambertian darkening rate in J light may be related to blurring by a wider PSF. Large departures from this behavior exist however (Fig. 4 and 5). Although surface features contrast is limited to 4-5%,

limb darkening may be strongly asymmetric, particularly in the L' filter (3.35-4.1  $\mu\text{m}$ ). This suggests variations in surface properties, perhaps of compositional variability. The asymmetry in L' filter may in particular be related to variations of hydration signatures across the disk. The NIR spectra acquired during this run are currently under study to address this issue.

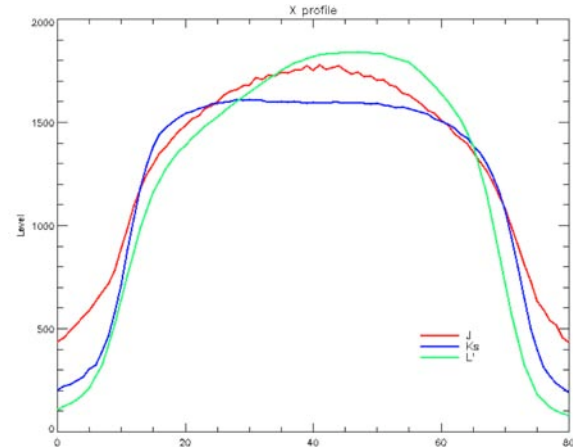


Fig.4: Photometric profiles in 3 filters. J and short K images are centered near 75°E (Piazzzi), the L' image is centered at 320°E. The J profile appears more Lambertian, although these may be due to a wider PSF. The L' image is strongly asymmetrical.



Fig.5: L' image centered at 320°E, showing large brightness asymmetry.

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#### References:

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