SPECKLE INTERFEROMETRY OBSERVATIONS OF MAIN BELT ASTEROIDS AT TNG

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ABSTRACT

Speckle interferometry observations of eight main belt asteroids (3 Juno, 12 Victoria, 16 Psyche, 30 Urania, 88 Thisbe, 135 Hertha, 230 Athamantis, and 324 Bamberga) were obtained at the Telescopio Nazionale Galileo in La Palma (Canary Islands, Spain). Average sizes and apparent shapes were measured, and were found to fit reasonably the predictions of indirect techniques for size and shape determination (radiometry and photometry). No new binary objects were discovered.

Key words: Asteroids, Speckle Interferometry.

1. SPECKLE INTERFEROMETRY: A BRIEF SUMMARY

It is well known that real telescopes never reach their theoretical diffraction-limited resolution ($1.22\lambda/D$) due to the effect of what is collectively called the "seeing" effect. For a ground-based telescope, the seeing is essentially due to the fact that the refraction index of the air changes over scales smaller than the telescope aperture. As a consequence, random phase delays in the incoming electromagnetic waves are produced, which have the same effect as irregularities in the shape of the primary mirror. In particular, the theoretical diffraction-limited image of a star breaks up into a large number of fainter, distorted images on the focal plane, that are called *speckles*. Moreover, the refraction index varies also over very short timescales, then the speckle pattern on the focal plane changes continuously, and integrations over exposure times longer than 0.1 seconds lead to a single long-exposure image in which all the high-resolution information is averaged away, and essentially lost. This produces a complete blurring of the resulting image, with a huge degradation of the actual resolving power of the telescope, with respect to its theoretical limit. In order to overcome this problem, one of the solutions that have long been proposed [1] is the so-called Speckle Interferometry technique. The general idea is to be able to observe with very short exposure times, in order to "freeze" the effect of the continuously changing atmosphere. The resulting specklegrams, are then analyzed by means of suitable mathematical procedures, in order to reconstruct the undistorted image of the observed celestial object. When one deals with a typical image produced by a telescope, it can be shown that, if the considered field of view (FOV) is sufficiently narrow, the *isoplanatic approximation* holds, and the image produced at any given instant on the detector (CCD or photographic plate) can be expressed in the following simple form:

$$I_{obj}(\mathbf{x}) = O(\mathbf{x}) \bigotimes P(\mathbf{x}) \qquad (1)$$

where the $\bigotimes$ symbol represents the mathematical convolution of two functions, I_{obj} is the intensity measured in the position $\mathbf{x}$ on the detector (we use bold characters to indicate vectors) $O(\mathbf{x})$ is the intensity that would be measured if the image was produced by a perfect mirror of infinite size located outside the atmosphere, and $P(\mathbf{x})$ is the function that describes how the light coming from a point source is distributed on the focal plane (*Point Spread Function*). In the ideal case of a perfect telescope having a circular mirror and located outside the atmosphere, $P(\mathbf{x})$ describes the theoretical Airy figure. We stress that the above relation holds only if the FOV is sufficiently small, otherwise $P(\mathbf{x})$ would not be the same function over the whole domain $\mathbf{x}$. Due to the atmospheric turbulence, which is rapidly changing, $P(\mathbf{x})$ is a function of time. When very short integration times (of the order of 0.01 seconds used in the case of the observations described in this paper) are used, the effects of changing $P(\mathbf{x})$ are "frozen", and one obtains a specklegram, that is a set of speckles containing information on the high-resolution features of the observed object. In order to reconstruct the

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image, a possibility is to make use of some function of the signal recorded in the frames, which retains some information about the shapes of the speckles in spite of their possible overlapping across the field. A classical example of such a function is given by the *autocorrelation* function. It is defined as:

$$\mathcal{I}(\mathbf{x}) = \int I(\mathbf{x}')I(\mathbf{x}+\mathbf{x}')\,d\mathbf{x} \qquad (2)$$

where $\mathcal{I}(\mathbf{x})$ indicates the autocorrelation of the function $I(\mathbf{x})$. When dealing with convolutions of functions (like in the case of Eq. 1), it is generally convenient to work in the Fourier domain. The reason is that the Fourier transform of the convolution of two functions reduces to the simple product of their Fourier transforms in the Fourier domain. Moreover, it is known from the Wiener-Khinchin theorem that the Fourier transform of the autocorrelation function is simply the *power spectrum*, defined as the absolute square of the Fourier transform. In quantitative terms, the following relations hold:

$$FT(O(\mathbf{x}) \bigotimes P(\mathbf{x})) = O(\mathbf{k})P(\mathbf{k}) \qquad (3)$$

$$FT(\mathcal{I}(\mathbf{x})) = I(\mathbf{k})I^*(\mathbf{k}) \qquad (4)$$

where FT means Fourier transform, and * indicates the complex conjugate. As a consequence, when considering the autocorrelation of the signal from an astronomical source (specklegram), the following relation holds:

$$FT(\mathcal{I}_{obj}(\mathbf{x})) = O(\mathbf{k})O^*(\mathbf{k})P(\mathbf{k})P^*(\mathbf{k}) \qquad (5)$$

By considering many different frames (specklegrams), and averaging, one obtains that

$$< I_{obj}(\mathbf{k})I^*_{obj}(\mathbf{k}) >= O(\mathbf{k})O^*(\mathbf{k}) < P(\mathbf{k})P^*(\mathbf{k}) > \qquad (6)$$

under the assumption that the undistorted signal $O(\mathbf{x})$ does not change with time. By considering now an unresolved star, which can be considered as an ideal reference point source, its undistorted image $O(\mathbf{x})$ through a perfect telescope can be represented by a Dirac δ function, whose Fourier transform is a constant. In this case, Eq. (5) can be rewritten, apart from a constant related to the overall brightness of the star, as:

$$< I_{ref}(\mathbf{k})I^*_{ref}(\mathbf{k}) > = < P(\mathbf{k})P^*(\mathbf{k}) > \qquad (7)$$

In other words, observing a reference unresolved star leads to determine the *a priori* unknown Point Spread Function $P(\mathbf{x})$. In papers dealing with Speckle Interferometry, the term $< P(\mathbf{k})P^*(\mathbf{k}) >$ is usually called the *Speckle Transfer Function* (STF). From the knowledge of the STF, it is immediate to derive the undistorted power spectrum of a resolved object:

$$O_{obj}(\mathbf{k})O^*_{obj}(\mathbf{k}) = \frac{< I_{obj}(\mathbf{k})I^*_{obj}(\mathbf{k}) >}{< I_{ref}(\mathbf{k})I^*_{ref}(\mathbf{k}) >} \qquad (8)$$

From this, one can derive the autocorrelation of the undistorted signal, hence it is possible in principle to derive important information on the high-resolution structure of the image (including evidence of binarity, or overall angular size and shape). It is also true that the autocorrelation does not contain the whole information about the true image. In particular, what is really obtained using the technique explained above is the power spectrum $O_{obj}(\mathbf{k})O^*_{obj}(\mathbf{k})$, which is the the absolute square of the Fourier transform of the undistorted signal. In this way, one retains information on the Fourier amplitude of the signal, but any information on the phase of the signal is lost. The Fourier phase is what describes the deviations from the symmetry of reflection through the center of the image. In this way, for instance, one can find evidence of binarity, but it is not possible to say which component is brighter.

Speckle interferometry has been used in the past to measure apparent sizes of some asteroids [2], [3], [4]. The Speckle Camera at the Telescopio Nazionale Galileo (TNG) provides a new opportunity to carry out observations of asteroids, to measure sizes and derive possible evidence of binarity. The major limitation of the instrument is that the individual specklegrams are not stored, and only the power spectra of the specklegrams are saved and can be analyzed to derive estimates of the overall sizes and possible evidence of binarity (fringes).

2. THE OBSERVATIONS

Eight asteroids have been observed during the observing run carried out at the TNG on September 29–30, 2000.

The obtained power spectra were calibrated by dividing them by the STF, and were then approximated by means of elliptic gaussians, characterized by three *a priori* unknown parameters, namely two semi-axes and an orientation angle with respect to a fixed direction. An ellipsoidal fit has been chosen, which appears to be suitable for the purposes of size and shape determination since we deal with relatively big objects, for which we can expect that the sizes are not very irregular, and can be generally approximated by triaxial ellipsoids, the expected equilibrium shapes for objects of this kind [5]. It can be noted that triaxial ellipsoid shapes are also generally assumed by the techniques aimed at obtaining the direction of the spin axes and the overall shapes from available photometric data obtained at different apparitions of each object. The projection of a triaxial ellipsoid on the sky plane, produces then an elliptic shape. Working with the power spectra, the semiaxes of the resulting ellipses in the Fourier domain must be inversely proportional to the semiaxes of the corresponding elliptic undistorted images. The problem reduces then to finding the correct conversion from the Fourier domain to the image space. This was accomplished by means of an extensive set of simulations, in which the light distribution across the image was modeled according to a Minnaert limb-darkening law. Synthetic signals were generated, and

Tab. 1 - Results of the observations

Object		a (arcsec)	b (arcsec)	Φ (°)	a (km)	b (km)	< D > (km)	b/a
3	Juno	0.23±0.04	0.23±0.04	–	287	287	287	1
12	Victoria	0.17±0.03	0.12±0.02	39±1	158	112	133	0.71
16	Psyche	0.21±0.04	0.17±0.03	34±1	315	262	288	0.83
30	Urania	0.13±0.02	0.11±0.02	84±5	111	89	99	0.80
88	Thisbe	0.18±0.03	0.15±0.03	48±5	191	163	176	0.85
135	Hertha	0.11±0.02	0.09±0.01	50±1	93	74	83	0.80
230	Athamantis	0.15±0.02	0.12±0.02	85±1	147	112	128	0.76
324	Bamberga	0.28±0.05	0.28±0.05	–	205	205	205	1

then convolved with the STF, in order to obtain synthetic power spectra, to be fit by an elliptic gaussian. In this way, it is possible to compute the transformation between the parameters describing the resulting gaussians and the *a priori* known sizes of the simulated objects. Different choices of the parameter determining the efficiency of the limb-darkening in the Minnaert law were considered, but the simulations showed that this parameter does not influence significantly the resulting power spectra. The output of this exercise was the final conversion from the Fourier to the image space, obtained by averaging over the results of different simulations. In this way, we obtained the resulting sizes and orientations of the objects in arcsec. The results are shown in Table 1, in which the semiaxes a and b of the elliptic images are given both in arcsec (with their corresponding errors) and in kilometers (nominal solutions). The orientation angles Φ of the ellipses with respect to a fixed direction (along the celestial North), the axial ratios b/a and the average diameters in km (defined as $\sqrt{ab}$) are also listed. The nominal errors listed for the semiaxes in arcsec and the orientation angles correspond to 1-σ uncertainties.

We note that the observations are inherently very short, and thus produce a kind of instantaneous picture of the apparent size and shape of each object, without any blurring due to the effect of spin around the rotation axis. In a couple of cases, the obtained power spectra turned out to be so slightly elongated that a circular solution must be accepted. Of course, in such cases the Φ angle loses any meaning. The speckle results are very interesting because they are *direct* measurements of sizes and shapes. Only a few asteroids so far have been directly measured, due to their small angular sizes requiring very high resolution power. Most of the currently available information on asteroid sizes has been derived by means of indirect techniques, like radiometry and polarimetry. The most extensive data-set is the radiometric catalogue obtained on the basis of the IRAS survey, which was able to detect and measure the thermal flux emitted by about 2,000 asteroids. Thus, it is very important to test the radiometric size estimates by means of direct measurements. The size distribution of the asteroid population is intimately related to the history and collisional evolution of these bodies, then it is of the highest importance to have reliable size estimates. Asteroid shapes are also important, being the products of a complex collisional evolution, and being related to the internal properties of the bodies. So far, asteroid shapes have been mostly derived from photometric lightcurves. The availability of a large number of lightcurves obtained for any given object at different oppositions allows also to derive the likely orientation of the spin axis. So far, this has been possible for a limited number of asteroids, listed in the PDS database available at the web page http://pdssbn.astro.umd.edu/sbnhtml/index.html. Table 2 lists the available IRAS diameters and, when available, the predictions on the orientation angle Φ and apparent axial ratio b/a derived from available photometric data. In particular, photometry leads generally to an inherent ambiguity between two possible pole solutions for each object, and/or between two possible senses of rotation. Each possible pole solution yields a different prediction of the Φ and b/a values at the epochs of our observations, then our speckle data can be used in principle to derive the correct pole solution for the objects.

We note that, in addition to the objects listed in Table 1, we have also observed the binary asteroid 90 Antiope. The obtained power spectrum was very noisy. A single-body solution would lead to an average diameter of 178 km, significantly larger than the IRAS radiometric size of 120 km. The obtained power spectrum might be potentially compatible with a binary solution, but we do not see a really convincing evidence of the presence of fringes, the expected signal from a resolved binary object. On the other hand, we do not know *a priori* whether the binary companion should have been really visible during our observations (carried out around 00:15 TU of September 30, 2000). It might well be possible that the binary system was not detached during our "snapshot", and this might explain qualitatively the peculiar power spectrum, and the discrepancy of a single-object solution with the IRAS listed value of size. Of course, further observations of this object are needed.

3. DISCUSSION

A comparison of the data listed in Tables 1 and 2 indicates that the TNG speckle data are in a good

Tab. 2 - IRAS sizes and photometric predictions for Φ and b/a according to different published poles

	Object	D_{IRAS} (km)	Pole Ecliptic Coordinates B1950 $\lambda(°)$	$\beta(°)$	b/a	Φ (°)
3	Juno	233.9	108	+36	0.80	119
			318	+60	0.78	64
12	Victoria	112.8	9	+55	0.81	37
			189	-55	0.89	0
			176	+40	0.85	129
			356	-40	0.94	179
16	Psyche	253.2	35	-21	0.68	147
			215	-15	0.68	24
30	Urania	100.2	–	–	–	–
88	Thisbe	200.6	40	+70	0.86	71
			200	+70	0.82	63
135	Hertha	79.2	106	+02	0.82	58
			286	-02	0.81	82
			118	+52	0.86	49
			298	-52	0.77	61
			291	+47	0.86	91
			111	-47	0.78	77
230	Athamantis	109.0	–	–	–	–
324	Bamberga	229.4	–	–	–	–

agreement with the IRAS predictions about the sizes of these objects. The discrepancies are on the average less than 10%. The IRAS sizes determinations were generally obtained at different values of aspect angle and rotational phase. In this respect, the agreement with the speckle interferometry measurements appears worth of notice.

Also the overall shapes and ellipse orientations measured by speckle interferometry turn out to fit reasonably the predictions based on available photometric data. In some cases, our observations can be used to definitely confirm one of the two possible pole solutions. The situation is more uncertain in some other cases, but the discrepancies are never dramatic. The axial ratios show in some cases some noticeable discrepancies with the predictions, and this is certainly due to the noise present in the power spectra. However, even taking this into account, we see that the orientation angles are generally within 10 degrees from the expected values, and the average diameters are in agreement with IRAS determinations. This makes us confident that our results are reliable. Moreover, in some cases the two nominal pole solutions produce fairly similar predictions of the axial ratio and/or the orientation angle of the apparent ellipse. In these cases it is certainly hard to discriminate among the two pole solutions. It should always be taken into account, also, that several uncertainties are present in the photometrically-based predictions, since the nominal pole solutions are affected by not negligible uncertainties, and also the computation of the true rotational phase of the objects at the epochs of our observations is subject to errors. On the basis of these considerations, we can conclude that our results are very encouraging, and the TNG speckle camera turns out to be an excellent instrument for obtaining an extensive survey of asteroid sizes and shapes, though forcedly limited to the biggest and brightest objects of the main belt. Of course, there is also the exciting possibility to discover new binary asteroids using this technique. Moreover, obtaining measurements of the same objects at different aspects and rotational phases will lead to noticeable improvements of the determination of the overall triaxial shapes, needed for future determinations of the bulk densities of these bodies.

REFERENCES

1. Labeyrie, A.: 1970, *ASTRON. ASTROPHYS.* 6 85.
2. Drummond, J. D., et al. *ICARUS* **61**, 132–151, 1985.
3. Drummond, J. D., et al. *ICARUS* **61**, 232–240, 1985.
4. Drummond, J. D., and Hege E. K. *ICARUS* **67**, 251–263, 1986.
5. Farinella P., Paolicchi, P., Zappala‘, V.: 1982, *Icarus* 52 409