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CCD and photon-counting photometric observations of peculiar asteroids

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Abstract. The photometric observational programme of main-belt asteroids undertaken, since 1980, at the Physics and Astronomy Department of Catania University, mainly by using photoelectric acquisition, has been extended to the Near-Earth Objects, because of the importance of their study to improve the knowledge of the mechanics and the physics of the inner Solar System. The wideness of the observational programme was pursued by using an expressly built CCD camera having a Kodak 4200 detector 2048x2048 pixel class 1, front-illuminated chip with 9 μm pixel-size, equipped with BVRI Johnson filters. New observations of 4 *Vesta*, 27 *Euterpe*, 173 *Ino*, 182 *Elsa*, 849 *Ara* (carried out at M.G. Fracastoro Station of Catania Astrophysical Observatory), 984 *Gretia*, 3199 *Nefertiti* and *2004 UE* (carried out at Asiago Station of Padova Astronomical Observatory) are presented. The improvement of the rotational period value (for 182 *Elsa* and *2004 UE* it is the first determination), of the lightcurve amplitude and of the B-V colour index was obtained. For 4 *Vesta* indications on surface mineralogic morphology are deduced from the UBV photometric behaviour while for 182 *Elsa*, the H-G magnitude relation was carried out.

Key words. Asteroids: photometric observations – lightcurve – synodic rotational period – color index – *H*-*G* relation

1. Introduction

At the Physics and Astronomy Department of Catania University a long and intense series of photometric observational campaigns was devoted to collect lightcurves that allow us the determination of asteroidal rotational parameters and properties. In particular objects with few known lightcurves were selected to obtain their minimum number needed to apply pole coordinates and shape computational methods (Blanco & Riccioli 1998). Now the efforts are directed towards fainter or peculiar asteroids like those with observational constrains or those that do not show classical lightcurves. Since the Near-Earth Objects (NEOs) revealed the importance of their study to improve the knowledge of the inner Solar System mechanics and physics (like the resonance mechanisms, the smaller bodies dynamics and the connection with meteorites), relevant attention was given to them by making astrometric and photometric observations and also the follow-up of the new detected ones.

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To allow their observation, to the photon counting photoelectric photometer attached to the 91-cm cassegrain telescope of M.G. Fracastoro Station of Catania Astrophysical Observatory, by means of which all previous observational campaigns were made, it was recently added an expressly built CCD camera (*ITANET* camera) having a Kodak KAF 4200 detector, 2048x2048 pixel class 1, front-illuminated chip (with 9 μm pixel-size), manufactured in Multi Pinned Phase (MPP) techonology (Blanco et al. 2004). The camera, normally placed at the primary focus of Schmidt telescopes, is equipped with BVRI Johnson filters. At the 41/61-cm Schmidt primary focus of M.G. Fracastoro Station of Catania Astrophysical Observatory its sensitive area is able to cover a field of view of 1 square degree (Bonanno et al. 1999).

At 91-cm telescope of Fracastoro Station, the next use of a CCD Kodak MPP camera, 1024x1024 pixel front-illuminated B chip, field of view 13'x13' with 0.77"/pixel and a cooling system that allow exposition until 20 min, we hope will allow us the observation of fainter NEOs and of a large number of Trans Neptunian Objects (TNOs) to build their lightcurves and to improve the knowledge of the outer Solar System too.

Meanwhile, to utilize both CCD cameras at Fracastoro Station telescopes, new photometric observations were carried out at the 67/92 Schmidt of Asiago Station of Padova Astronomical Observatory, by using two CCD cameras, and at the 91-cm telescope of Fracastoro Station, by using the cooled photon-counting photoelectric photometer.

The analysis and the study of observational data of 4 *Vesta*, 27 *Euterpe*, 173 *Ino*, 182 *Elsa*, 849 *Ara*, 984 *Gretia*, 3199 *Nefertiti* and *2004 UE* allow us to determine, with some improvements for the almost all observed objects, the value of the synodic rotational period (for 182 *Elsa* and *2004 UE* it is the first determination), the lightcurve amplitude and the B-V color index of photoelectrically observed asteroids. For asteroid 182 *Elsa* also the *H-G* magnitude relation (Bowell et al. 1989) was obtained. The first observed lightcurve of *2004 UE* indicates an elongate shape and a smoothed surface.

2. Observations and data reduction

The photometric observations reported in the paper were carried out at Asiago Station of Padova Astronomical Observatory and at M.G. Fracastoro Station of Catania Astrophysical Observatory.

At Asiago Station, CCD photometric observations were perfomed by using the 67/92-cm Schmidt telescope equipped with the CCD LORAL camera without filters and, for the first time, with the CCD *ITANET* camera (Blanco et al. 2004), with *V* and *R* Johnson filters. Taking into account the telescope plate scale of $95''.9$/mm, as regards the *ITANET* camera, the resulting projected sky area was about $29' \times 29'$ with an angular resolution of $0''.89$/pixel. The exposure times, except for the weaker asteroids or for those with fast motion, normally were 2-3 min. The CCD's images pre-reduction was made with standard *IRAF* routines to remove bias and dark currents from images. Nightly twilight flat-fields were used to correct images for optical vignetting, dust shadow and pixel-to-pixel sensitivity variation. In order to maximize the asteroid S/N ratio (especially in cases of elongated images of fast moving asteroids), elliptical aperture photometry was done by using the software *SExtractor* developed by Bertin & Arnouts (1996). A set of comparison stars having magnitude values similar to the asteroid ones was nightly selected along the asteroid path. From this set of stars, the non-variable star with the smallest error in the flux measurement was chosen as nightly comparison star. The reduction to the Johnson standard system was made by observing groups of standard stars taken from Landolt (1992) and Stetson (2000).

At Fracastoro Station the 91-cm Cassegrain telescope, equipped with a cooled photon-counting single-head photometer and an EMI 9863 QA/35 photomultiplier, was used. The observations were performed with *B* and *V* Johnson filters, using a 1.5-mm diameter diaphragm, limiting the telescope field to about 22 arcsec. Nearby solar spectral type comparison stars were selected along the asteroid path to neglect the effects of extinction chromatic variations compared to asteroids. The observing set-up and the data reduction were the same already adopted during previous observational campaigns (Di Martino et al. 1994). The *B* and *V* extinction coefficients were nightly determined through the comparison stars. As in the CCD photometric observations, the reduction to the Johnson standard system was made by observing groups of standard stars taken from Blanco et al. (1968) and Landolt (1992).

Both for CCD and photoelectric data, the final mean error of the single measurements is ±0.01 mag. The single night lightcurves of each asteroid were corrected for light-travel times and the asteroid *V* magnitudes were reduced to the unit geocentric and heliocentric distances. For each object, the value of the synodic rotational period, the composite lightcurve, the mean reduced magnitude $\bar{V}(1,\alpha)$ and the nightly magnitude shift were obtained by applying the Fourier analysis, as described in Harris et al. (1989).

3. Results

In Figs 1-11 (except Figs. 2 and 7, where are plotted the non linear fit of 4 *Vesta* colour indexes and the $\bar{V}(1,\alpha)$ vs. phase angle of 182 *Elsa*, respectively) the composite lightcurves, obtained after the reduction of the data carried out following our observations, are presented.

In each of them, the different symbols referring to different observing nights and the magnitude shifts, applied by the Fourier analysis method to the single night lightcurve to obtain the composite one (Harris et al. 1989), before and after the date are reported, respectively. The rotational phase was computed according to the period value reported in each Fig. and in Table 1, in which the period reliability code (according Harris & Young 1983), the lightcurve amplitude and the mean *B-V* color index of photoelectrically observed asteroids are also listed.

3.1. 4 Vesta

4 *Vesta*, one of the best known main-belt asteroids, has an orbital plane inclination close to 6° and a triaxial shape, near a 260 Km mean radius spheroid, determined with an error of ±5 Km by Hubble Space Telescope (HST) during two devoted campaigns in 1994 and 1996 (Thomas et al. 1997).

It is a differentiated body with an iron-nickel core, a magnesium-silicate mantle and a basaltic lavas surface, result of an intense volcanic activity, with a structure analogous to our Planet, even if of much lesser dimension. The 0.42 albedo coefficient is higher than the mean one of main-belt asteroids and 4 *Vesta* is the initiator of V taxonomic type asteroids.

Peculiar characteristics of 4 *Vesta* are one maximum and one minimum lightcurve, its behaviour in phase with jumps and falling-in and that of B-V, U-B and U-V colour indexes, probably, all determined by a mineralogic differentiation of the surface, result of a big hemispheric impact craterization and of the following lesser ones. These impacts may also have generated from the mantle and the surface crust, the howardite, eucrite and diogenite (HED) meteorites. In particular, Gaffey's (1997) spectroscopy study indicates that Vesta's primordial surface, which is responsible for the lightcurve minimum and falling-in, seems very similar to howardite and mixtures of eucrite meteorites. Different size regions, mineralogically similar to olivines and diogenite meteorites, are believed to be impact craters showing Vesta's interior and to be responsible for the lightcurve maximum and the jumps.

The presented lightcurve and colour indexes were computed by means of the data collected during three observation nights: 30 December 2005, 3 and 4 January 2006. The best fit was obtained with the rotational period value of $5^h.341 \pm 0^h.002$, in good agreement with many values reported in the literature and in particular with Blanco and Catalano's (1979) value, obtained from observations made at the same telescope with the same equipment. A careful inspection of the lightcurve, reported in Fig. 1 together with B-V, U-B and U-V colour indexes, shows a V amplitude of 0.088±0.002 mag, a falling-in at 0.65 phase and two jumps at 0.05 and 0.20 phase, anomalies visible at the same phases and with the

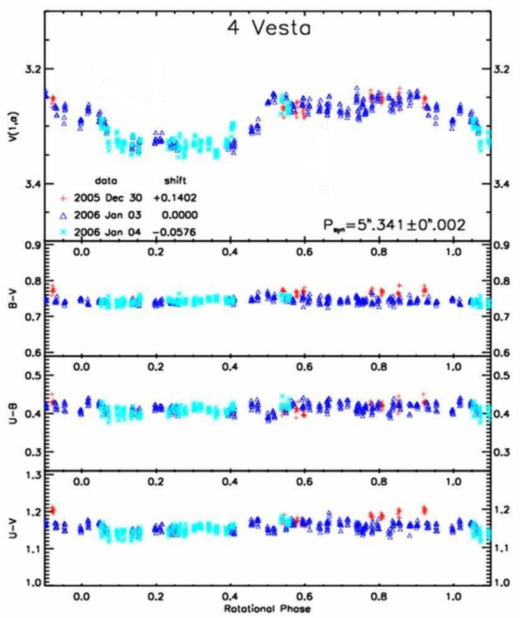

Fig. 1. V lightcurve and B-V, U-B and U-V colour indexes of 4 *Vesta*. The different symbols denote different observing nights. The number near the date of the observing night indicates the shift in magnitude applied by the method to the single night lightcurves in order to obtain the composite curve. The 0 rotational phase corresponds to the 12^h U.T. of the first observing day shown. The phase was computed according to the rotational period value reported in the Figure.

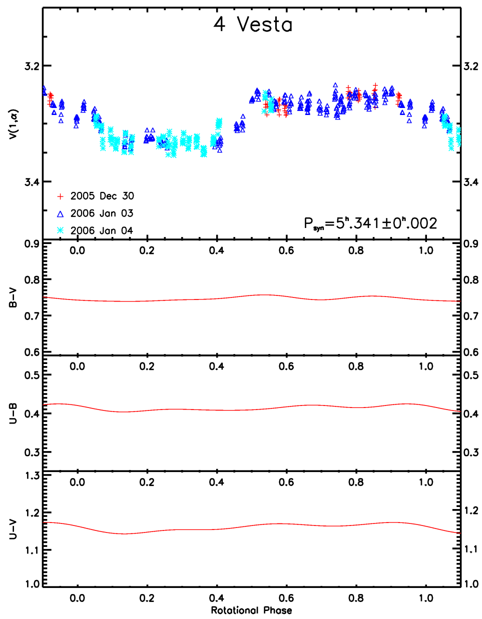

Fig. 2. Non linear fit, made using the Fourier analysis truncated to the 4° order of Vesta's B-V, U-B and U-V colour indexes.

same amplitudes in many lightcurves reported in the literature.

To better estimate these colour indexes amplitudes, a non linear fit was made using the Fourier analysis truncated to the 4° order (Fig. 2). The B-V shows a costant trend, the U-B variations of the order of the errors, while the U-V colour index shows magnitude variations of 0.03 mag, with Vesta's surface "bluer" near 0.10 phase and "redder" at rotational phases 0.55 and 0.90, the last one detectable also from the U-B index colour. These variations happen a few before and a few after light variations, probably due to minor impacts or, more probably, due to the material coming from the sub-crust internal layer and fallen also on the big crater borders.

It is not the appropriate site to discuss Vesta and the related HED meteorites spectroscopic studies (already abundantly treated in the literature) but here we just want to point out that, ion irradiation experiments on HED meteorites to simulate effects of space wheatering, induced on their parent bodies by solar and cosmic ions, are in progress at the Experimental Astrophysics Laboratory of Catania Observatory (Fulvio et al. 2007).

3.2. 27 Euterpe

The first determination of the synodic rotational period value of 27 *Euterpe* was by Chang & Chang (1962), who, by means of three observing nights made at the end of 1961 and January 1^{st}, 1962, found a value

Table 1. Synodic rotational period value, realibilily code, amplitude of V lightcurve and mean B-V color index of observed asteroids

Asteroid	rotational period	reliability code[a]	amplitude (V mag)	B-V (mag)	taxonomic class	diameter (Km)
4 *Vesta*	$5^h.341 \pm 0^h.002$	3	$0^m.088 \pm 0^m.002$	$0^m.74 \pm 0^m.02$	V	520
27 *Euterpe*	$10^h.377 \pm 0^h.008$	2	$0^m.14 \pm 0^m.02$	$0^m.85 \pm 0^m.02$	S	96
173 *Ino*	$6^h.111 \pm 0^h.002$	3	$0^m.14 \pm 0^m.01$	$0^m.71 \pm 0^m.01$	C	154
182 *Elsa*	$80^h.23 \pm 0^h.08$	3	$0^m.69 \pm 0^m.02$	$0^m.86 \pm 0^m.01$	S	44
849 *Ara*	$4^h.117 \pm 0^h.001$	3	$0^m.26 \pm 0^m.01$	$0^m.70 \pm 0^m.01$	M	62
984 *Gretia*	$5^h.780 \pm 0^h.001$	3	$0^m.65 \pm 0^m.02$	—		32
3199 *Nefertiti*	$3^h.021 \pm 0^h.002$	3	$0^m.19 \pm 0^m.01$	—		2
2004 UE	$5^h.6 \pm 0^h.2$	2	$0^m.98 \pm 0^m.02$	—		150 m

[a] Meaning of the reliability code:
2, the result is based on less than full coverage, so that the period may be wrong by 30% or so;
3, a sure result with no ambiguity and full lightcurve coverage;

of $8^h.500$. Their complete lightcurve shows two maxima and two minima not at same height and not symmetrical, with an amplitude A=$0^m.15$. During the 2001 apparition, Stephens et al. (2001) estimated a $10^h.410 \pm 0^h.002$ different period value, obtaining an *interesting lightcurve with a single strong peak confirmed by multiple nights of observation and a very weak secondary peak*.

Our observations, made in November 1993 at M.G. Fracastoro Station, are poor to indicate any period value estimation, while the derived mean B-V value is 0.83±0.02 mag.

We observed again this object at the same Station during three nights in November 2004, obtaining a lightcurve (Fig. 3) covering about 80% of the rotational phase. The derived value of the synodic rotational period is $10^h.377 \pm 0^h.008$, slightly shorter than Stephens et al.'s (2001) one. The amplitude of the V lightcurve is 0.14 ± 0.02 mag and the mean value of the B-V color index is 0.85 ± 0.02. If a maximum should to develop at the 0.2 - 0.4 uncovered phase interval, as it seems to be from the lightcurve behaviour and from Stephens et al.'s (2001) lightcurve, 27 *Euterpe* could have a three maxima and minima lightcurve.

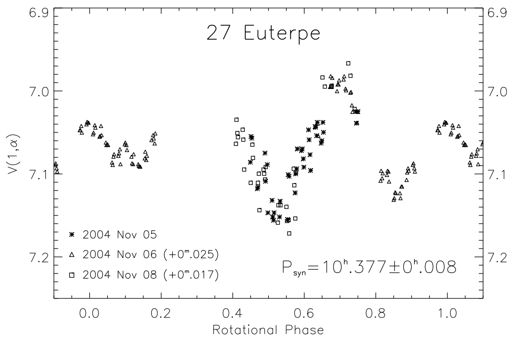

Fig. 3. V lightcurve of 27 *Euterpe* (see Fig. 1).

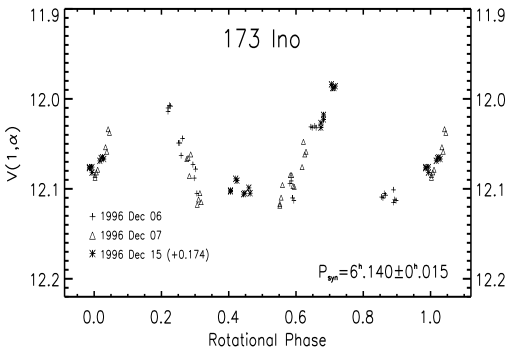

Fig. 4. V lightcurve of 173 *Ino*, obtained in December 1996 (see Fig. 1).

3.3. 173 Ino

Many observations of this C-type asteroid, made since 1978, give different values of the diameter and of the rotational period, included between 142 Km (Zellner & Bowell 1977) and 159 Km (Michalowski 1993) and between $5^h.93 \pm 0^h.01$ (Schober 1978) and $6^h.163 \pm 0^h.005$ (Michalowski et al. 2005), respectively. The uncertainty about the value period determination comes out also from our two campaigns observations, while the B-V colour in-

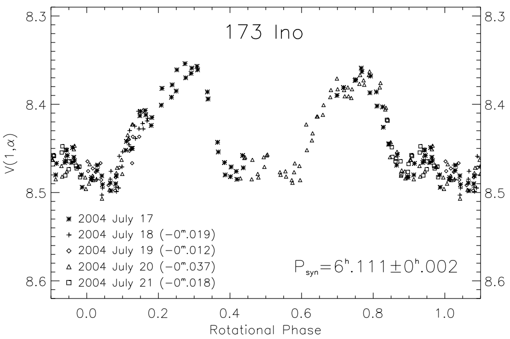

Fig. 5. V lightcurve of 173 *Ino*, obtained in July 2004 (see Fig. 1).

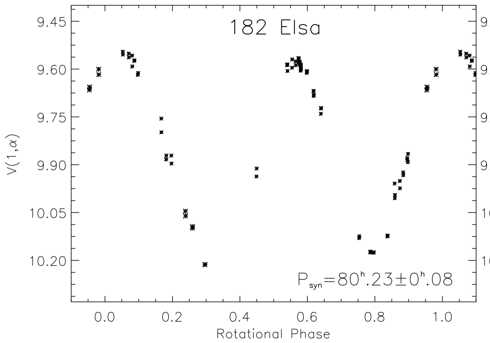

Fig. 6. V lightcurve of 182 *Elsa* (see Fig. 1).

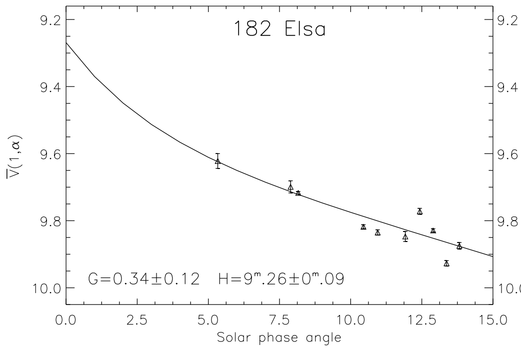

Fig. 7. Mean reduced magnitude $\bar{V}(1, alpha)$, with error bars, and fitted phase curve, both vs. phase angle of 182 *Elsa*.

dex mean value is also in accordance with the one reported by De Angelis (1995).

From three observing nights, made by us in December 1996, using the $6^h.140 \pm 0^h.015$ period, we obtain a two maxima and two minima symmetric lightcurve (Fig. 4). The amplitude is greater than 0.14 mag and the B-V mean colour index is 0.70 ± 0.02 mag. Five other observational nights of 173 *Ino*, carried out at M.G. Fracastoro station in July 2004, allow us to improve the rotational period value. The composite *V* lightcurve (Fig. 5), obtained using a synodic rotational period value of $6^h.111 \pm 0^h.002$ (in good agreement with the Erikson's (1990) one), shows an amplitude of 0.14 ± 0.01 mag and a behaviour in accordance with our 1996 lightcurve. The mean *B-V* colour index is 0.71 ± 0.01 mag.

3.4. 182 Elsa

From the only previous 182 *Elsa*'s photometric observations, carried out by Harris et al. (1980, 1992) during 1978 and 1981 apparitions, an indication of a rotational period value of about 80 hours is given.

Our observations of this S-type asteroid, made at M.G. Fracastoro station, spanned eleven nights, from September 8 to October 17, 2004. The value of the synodic rotational period that we determined is $80^h.23 \pm 0^h.08$. The composite *V* lightcurve shows a nearly symmetrical sinusoidal trend, an amplitude of 0.69 ± 0.02 mag and two maxima at the same height, while the minima seem to be at different levels (Fig. 6). The mean value of the *B-V* maesured colour index is 0.86 ± 0.01 mag. During 182 *Elsa*'s observational run, the solar phase angle varied between 5° and 14°. We used the mean reduced magnitudes $\bar{V}(1, \alpha)$ of each night to obtain a least-squares fit with the *H-G* magnitude relation, as described by Bowell et al. (1989). The mean reduced magnitude $\bar{V}(1, \alpha)$, with the error bars, and the fitted phase curve, both vs. phase angle, are plotted in Fig. 7. The resulting *H* value is 9.26 ± 0.09 mag with a 0.34 ± 0.12 slope parameter *G*.

3.5. 849 Ara

The only published lightcurve of this M-type asteroid was obtained by Harris et al. (1992) by means of the data of six observing nights in May-June 1981. They found a rotational period value of $4^h.11643 \pm 0^h.00005$.

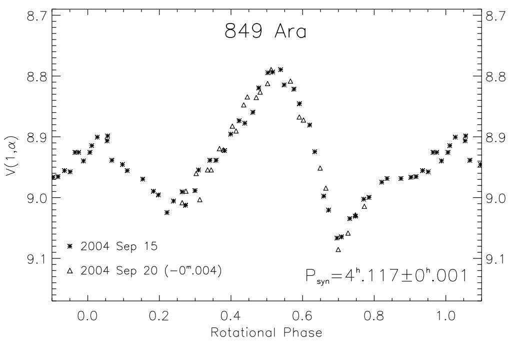

Fig. 8. V lightcurve of 849 *Ara* (see Fig. 1).

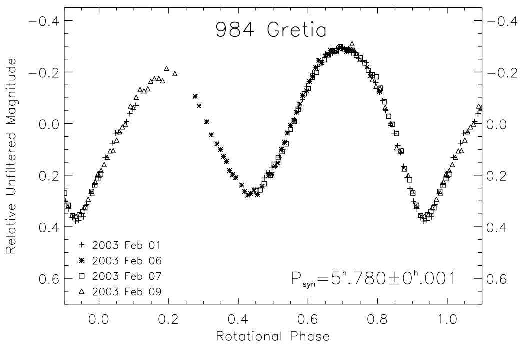

Fig. 9. Lightcurve of 984 *Gretia* without filters (see Fig. 1).

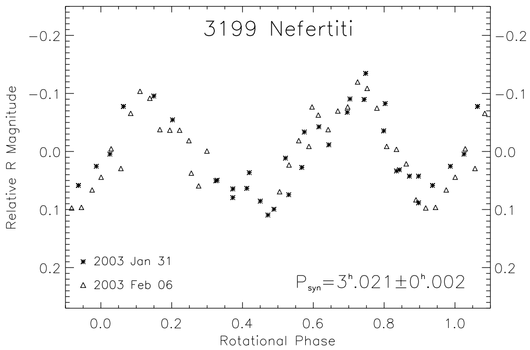

Fig. 10. R lightcurve of 3199 *Nefertiti* (see Fig. 1).

In the framework of our photometric observational program, this asteroid was observed at M.G. Fracastoro station on September 15 and 20, 2004. The found rotational period value of $4^h.117 \pm 0^h.001$ is in very good agreement with the previous published one. The well-covered composite lightcurve (Fig. 8) shows four extrema and an 0.26 ± 0.01 mag amplitude. Their behaviour appears irregular, with a linear trend before and after the highest maximum peak and falling-in and jumps in the remaining lightcurve parts. The mean *B-V* colour index is 0.70 ± 0.01 mag, in good agreement with the one reported by Tedesco (1989).

3.6. 984 Gretia

The need to collect additional lightcurves of this little observed asteroid, to improve the determination of the period value and to be able to apply the pole computational methods, suggests us to include 984 *Gretia* in our observational schedule.

The presented data were obtained in four nights during the first decade of February 2003, at the Schmidt telescope of Asiago Station, using the CCD Loral camera without filters. Fig. 9 reports the related magnitude lightcurve, folded over the $5^h.780 \pm 0^h.001$ rotational period value, in good agreement with Piironen et al.'s (1994). The lightcurve behaviour is regular with four symmetric extrema at different level and an amplitude of 0.65 ± 0.02 mag.

3.7. 3199 Nefertiti

This (1982 RA) S-Amor asteroid was one of the first objects observed with the ITANET CCD camera at the 67/92 Schmidt of Asiago Station. From the previous observations reported in the literature, an uncertain value of the rotational period results.

We observed 3199 *Nefertiti* during two nights in January and February 2003, being able to use only the *R* filter. The composite related *R* lightcurve, plotted in Fig. 10, shows a nearly sinusoidal trend with four well-defined extrema (not at 0.25 phase interval) and an amplitude of 0.19 ± 0.02 mag. The value of the derived synodic rotational period, $3^h.021 \pm 0^h.002$, is in good agreement with Pravec et al.'s (1997).

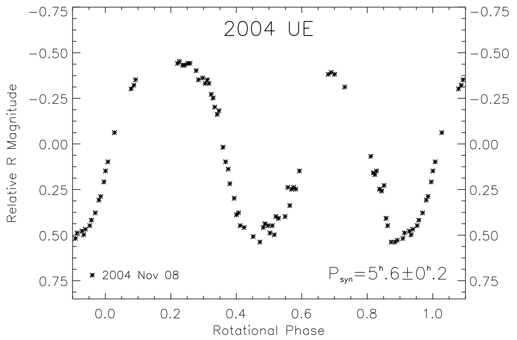

Fig. 11. R lightcurve of 2004*UE* (see Fig. 1).

3.8. 2004 UE

We found any previous lightcurve of this small Apollo-type asteroid (D~150 m), discovered by LINEAR in October 2004, in the literature. Due to bad weather conditions and to $2700''/hr$ asteroid fast proper motion, we were able to observe this NEO only during one night with the ITANET CCD camera. The fast proper motion of *2004 UE* and the crossed crowded stars field did not allow us exposure times of each measurement greater than 30 sec. The related R lightcurve obtained is presented in Fig. 11.

The rotational period value is $5^h.6 \pm 0^h.2$, the light variation amplitude 0.98 ± 0.02 mag. The lightcurve presents a smooth behaviour with the four extrema nearly symmetrical in phase and at the same height. The amplitude value and the rotational characteristics indicate an elongated shape without large surface dishomogeneities.

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