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Do we observe light curves of binary asteroids?

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Summary. Among the asteroids of intermediate size, whose shape is probably controlled by self-gravitation, we have selected a sample of 10 objects for which some "anomalous" light curve features (strong dependence of the amplitude on the phase angle; flat minima and changes of slope suggestive of eclipses and mutual shadowing) indicate a possible binary nature. Applying the procedure described by Leone et al. (1984), we have derived from the rotational properties of these hypothetical binary systems (whose components are assumed to roughly fit the gravitational equilibrium figures), the values of the geometrical and physical parameters yielding a satisfactory agreement between the light curves computed from the models and the observed ones. In particular we have obtained shapes, densities and mass ratios of the suspected binary asteroids; only the latter parameter is found to be remarkably sensitive to a possible contribution of surface scattering effects to the light curve amplitude.

Key words: asteroids – asteroid light curves – binary asteroids – eclipsing binaries

1. Introduction

The first clues on the possible existence of binary or multiple systems among asteroids came from the observation of a stellar occultation by the asteroid 532 Herculina (Bowell et al., 1978), even if a binary model had been already proposed by Cook (1971) for the Trojan object 624 Hektor, whose unusual shape had been revealed by light curve data. Subsequently, the issue has been discussed by several papers both analyzing additional data and presenting new theoretical arguments (Van Flandern et al., 1979; Tedesco, 1979; Zappalà et al., 1980; and others). In particular, the most promising research programs have appeared to be, on the one hand, the analysis of light curve morphology in cases displaying some analogy with eclipsing stars; on the other hand, the study of the possibility of forming binary objects as the outcomes of catastrophic collisional events (Weidenschilling, 1980, 1981; Farinella et al., 1981a, 1982). More recently Leone et al. (1984) have computed the equilibrium shapes for binaries having a wide range of mass ratios, pointing out that the geometrical parameters relevant for deriving the light curve morphology can be readily determined once the physical properties of a system are known.

The purpose of the present paper is first to select a sample of asteroids for which some "anomalous" light curve features can be interpreted as clues of a binary nature; then, to derive for these objects (assuming that their shapes approximately fit the equilibrium figures) physical parameters like mass ratio and density which yield "simulated" light curves in good agreement with the observed ones.

As stressed by Leone et al. (1984), the basic observational parameters from which one can compute binary models consistent with gravitational equilibrium are the so-called rotational properties, i.e. the spin period and the maximum light curve amplitude (here "maximum" refers to the light curve observed when the polar axis is perpendicular to the line of sight). The amplitude is clearly dependent mainly on the relative size and shape of the two ellipsoidal components, the shape being specified by the axial ratios b/a, c/a ($a \geqq b \geqq c$ are the semiaxes of an ellipsoidal object). However, while the period is in general determined unequivocally from the observations, the maximum amplitude is affected by a number of phenomena of both physical and geometrical character which cannot always be separated and/or quantified in a reliable way. For instance, there is an obvious dependence on the aspect angle (i.e. the orientation of the polar axis as seen by the observer) and only a series of observations carried out at different oppositions can allow to extrapolate reliably to the amplitude value corresponding to an "equatorial" view [determining at the same time the direction of the polar axis; see Zappalà and Kneževič (1984)]. Another source of uncertainty which cannot be easily modelled comes from the scattering effect experienced by the sunlight diffused by the asteroid surface; as a result of this effect, the brightness is not a linear function of the object's cross-section and amplitude is not simply related to the asteroid's shape. Moreover, when the observations are performed at non-zero phase angles, a variable fraction of the rough asteroid surface is in shadow; if the object is double, the two components can produce also mutual shadowing effects influencing significantly the shape of the light curve (see Zappalà et al., 1980).

As a consequence of scattering and shadowing phenomena, the observed amplitude is normally increased above the value which would derive from the purely geometrical factors. The problem of shadowing is not very important provided observations at small phase angles are available for the analysis; but it is always difficult to assess the contribution of the scattering effect. While in statistical studies (e.g., Catullo et al., 1984) a reasonable procedure is the systematic reduction of the observed amplitudes by a fraction fixed once for all, it would be quite arbitrary to apply the same method to correct the amplitudes in single cases; as a matter of fact, the scattering properties of a rocky surface are related to such variables as composition, texture, topography, about which our knowledge is poor. Therefore, we believe that the adoption of

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an unique method to correct all the amplitudes on account of the scattering effect could introduce errors not lower than neglecting at all the need for a correction.

On the other hand, the purpose of the present paper is mainly to check whether for several asteroids the equilibrium binary models are plausible, rather than to determine very accurately the physical and geometrical parameters in the individual cases. Thus, we have decided to employ for our analysis in a first stage the maximum amplitudes with no corrections; then, in few cases of particular interest, we have tried to verify how much a change in the amplitude could affect a correct determination of the interesting parameters (see Sect. 4). The results of these tests show that while the resulting mass ratio of the system may be seriously affected, the fractional errors of the density and of the linear dimensions of the components are less significant, because the light curve shape is more sensitive than its amplitude to variations of these parameters.

2. Selection of the suspected binary asteroids

Two mechanisms have been proposed so far for the formation of binary objects as a consequence of collisional events involving asteroids:

(a) the post-breakup expulsion of fragments with very low relative velocities, such that the mutual gravitational attraction prevents the ultimate separation of some objects and gives rise to gravitationally bound systems (Hartmann, 1979; Van Flandern et al., 1979);

(b) the collisional formation of "piles of rubble" (i.e., loosely consolidated aggregates of fragmented material), receiving from the impacting body an angular momentum of rotation exceeding the threshold for binary fission (Weidenschilling, 1981; Farinella et al., 1982).

In the former case the resulting binary components should have small or intermediate sizes, because they should be fragments escaped after the disruption of target asteroids for which self-gravitational forces did not play a decisive role. These objects are presumably dominated by solid-state forces, thus presenting irregular shapes. Even neglecting the scarce probability of observing eclipses in this type of binary systems, it seems likely that in the light curves the effects of irregular shapes would mask any evidence of eclipse events. Therefore light curve data do not appear to have the potential of leading to the identification of these binaries, and even less to the determination of their physical properties.

In case (b) the components should be moulded mainly by gravitational forces, and provided that tidal effects have synchronized the rotational and orbital periods, the shapes should relax to figures of gravitational equilibrium (Leone et al., 1984). These figures are close to spheres provided the orbital distance between the two asteroids is large enough with respect to their size; when this is the case, although the probability of observing mutual eclipses is again low, the "equatorial" light curves should appear remarkably similar to those of detached binary stars (with wide and flat maxima), and therefore easy to recognize. Following this argument, a few light curves of this type were selected and studied by Van Flandern et al. (1979), and a detailed plausibility test was applied by Wijesinghe and Tedesco (1979) to a binary model of 171 Ophelia, assumed to be formed by a couple of spherical objects. In the course of the present work, starting from the results by Leone et al. (1984) we have reconsidered the plausibility and self-consistency of this kind of models for the four asteroids 46, 49, 111, and 171: from the constraints imposed by the data on the orbit of the binaries (taking into account possible effects due to phase angle, eccentricity and inclination), two general conclusions can be inferred: first, the densities are always low, of the order of 1–1.5 $\mathrm{g\,cm^{-3}}$, and this could be reasonable for reaccumulated "piles of rubble"; second, the orbital separations are not high enough to imply equilibrium shapes really close to the spherical ones, and this appears as a major failure of the basic assumptions of the models. For instance, in the case of 171 Ophelia, one derives a mass ratio of 0.04 and a separation of 9 times the mean radius of the secondary component; but in such a system, the equilibrium shape of the secondary would by quite elongated, so as to produce even out of the eclipses a light variation of about 0.1 mag, that is of the same order of the total observed amplitude (in fact a "hump" of 0.05 mag is present during the maximum, but its shape is clearly inconsistent with the expected light change due to a rotating ellipsoidal object). Thus the assumed spherical components would not be in equilibrium, and we may wonder whether they could instead be strength-dominated. The answer is very probably negative, because for solid fragments (made presumably of compact rocky material) the inferred densities seem really too low; on the other hand, the assumption of sphericity would be again unrealistic, as this shape is very unlikely for an "irregular" fragment (Capaccioni et al., 1984). These arguments show that the models based on the analogy with eclipsing binary stars, with nearly-spherical components, are not consistent from a physical point of view, and we are led to believe that alternative models, based on single objects having peculiar shapes, are much more plausible in these cases. We recall that for instance a truncated sphere could give raise to a light curve of the type described above (Zappalà, 1980).

On the other hand, a much more promising class of light curves in our opinion are those of sizeable objects showing large amplitudes and fairly short periods. As discussed by Leone et al., these light curves are consistent with nearly-contact binary models with components close to equilibrium (i.e., with a "rubble-pile" structure). Even if it is often difficult to discriminate between binary and single, highly elongated shapes, we can list some criteria based on features which should be typical for light curves of binary asteroids: (i) existence of flat minima, occurring presumably as a consequence of total eclipses; (ii) strong amplitude-phase dependence, due to mutual shadowing effects being more and more important for increasing phases; (iii) significant changes of slope in the descending and ascending parts of the light curve, related to beginning or/end of eclipses (these features have been discussed in more detail by Zappalà et al., 1980).

Beside these positive criteria, we have used also negative ones to select our sample of suspected binaries: we have excluded asteroids smaller than 50 km, because they are probably irregular fragments for which self-gravitation is unimportant (Farinella et al., 1982; Catullo et al., 1984); asteroids having amplitudes less than 0.2 mag, for which light variations might not be due only or mainly to shape (Lupishko et al., 1983); asteroids with very short rotational periods, which have been shown by Leone et al. (1984) to be inconsistent with binary models having reasonable densities.

According to these criteria, we have selected for a more detailed analysis a sample of ten objects: 15 Eunomia, 39 Laetitia, 43 Ariadne, 44 Nysa, 61 Danae, 63 Ausonia, 82 Alkmene, 192 Nausikaa, 216 Kleopatra, 624 Hektor. Then, we have followed the procedure outlined by Leone et al.: plotting each object in the $A-\omega$ plane (A is the maximum amplitude defined in Sect. 1, ω the rotational frequency in cycles per day), we derive a range of "allowed" values for q, the mass-ratio between the components, and ϱ, the density (assumed to be the same for both objects). Every choice of these parameters yields unequivocally the light curve morphology, in terms of quantities like A_{WE} (amplitude without eclipses), A_P (amplitude of the primary were it single), φ_1 and φ_2 (half-durations of eclipse and of totality); for more details, see Leone et al., Sect. 5 and Figs. 5–7. We have then used the observed light curves of the selected asteroids to get the best-fit values of q and ϱ, i.e., we have selected, in the range of "allowed" values of these parameters, those giving a "theoretical" light curve as similar as possible to the observed one.

We have generally used observed light curves obtained at phase angles not larger than few degrees and at nearly-equatorial views, in order to prevent the uncertainties in A discussed earlier. The latter condition has not been fulfilled for three objects (61, 82, 192), since the available observations were not sufficient to permit a reliable determination of the maximum amplitude. In the following section, we give a more detailed description of the data we have employed, of the procedure and of the results for the individual asteroids of our sample.

3. Analysis of individual cases

15 Eunomia

For this sizeable *S*-type object (diameter $D=216$ km, according to Bowell et al., 1979), we have used a light curve obtained in 1952 (Groeneveld and Kuiper, 1954) at a phase angle of about 13 degrees. Its amplitude – 0.47 mag – possibly underestimates slightly the maximum amplitude (0.50 mag according to Piironen et al., 1984); however the light curve, shown in Fig. 1, displays maxima of different height, possibly as a result of albedo changes or spots (Lupishko et al., 1983), and the lower maximum would lead to an amplitude of only 0.40 mag. Because of this uncertainty, we have decided to treat separately the two cases with $A=0.47$ mag and $A=0.40$ mag. The best-fitting simulated light curves (Fig. 1, solid lines) corresponding in the former case to choosing $q=0.21$, $\varrho=3.7\,\mathrm{g\,cm^{-3}}$ (the "allowed" ranges are 0.21 to 0.28 for q and 3.7 to $5\,\mathrm{g\,cm^{-3}}$ for ϱ); for the smaller amplitude, the best fit is obtained for $q=0.16$, $\varrho=3.9\,\mathrm{g\,cm^{-3}}$. In Table 1 we have listed for the two cases of Eunomia (as well as for the other objects of our sample) the geometrical parameters of the binary models, i.e., the semiaxes of the ellipsoidal components and the orbital separation. These quantities are given both using as unit of measure "a", the longest semiaxis of the primary component, and directly in km. These latter values were computed from the absolute magnitude of the asteroids at maximum brightness, by applying the standard relationship which connects this quantity to the albedo and to the "mean" diameter D of the object (see Zellner, 1979). Data on albedos were derived from Morrison and Zellner (1979), while for magnitudes, when the extrapolation to the equatorial view was possible, we have used the results by Zappalà and Kneževič (1984) together with some unpublished observations performed at the Turin Observatory; for objects 61, 82, and 192, on the other hand, we have used values from Bowell et al. (1979). Obviously the relationship between the mean diameter and the semiaxes of the components is:

$$\pi d^2/4=\pi ac+\pi a'c'\,.$$

39 Laetitia

This asteroid is classified as *S*-type, with a mean diameter of 158 km. We have used in the analysis the light curve obtained in the 1972 opposition (Sather, 1976), with a phase angle of about 8 degrees and an amplitude of 0.50 mag. The best-fitting simulated light curve is shown in Fig. 2, and corresponds to $q=0.25$ and $\varrho=5\,\mathrm{g\,cm^{-3}}$ (other parameters of this model are given again in Table 1). The high value of the density of the binary model suggests, in our opinion, that a single triaxial model is more plausible; an equilibrium triaxial shape (Jacobi ellipsoid) fitting Laetitia would imply a density of only $1.6\,\mathrm{g\,cm^{-3}}$ [see Farinella et al. (1981); the small discrepancy in the density value is due to different assumptions on the maximum amplitude].

43 Ariadne

Even if its size is not very large ($D=78$ km), this object has been included in our sample because its maximum amplitude (0.63 mag) is quite uncommon among main-belt asteroids; moreover, the light curve amplitude has proven to be rather strongly dependent on phase. The light curve employed for our test has been obtained in the 1972 opposition (Lustig and Dvorak, 1975), with a phase angle less than 10 degrees. The best-fit parameters (see Fig. 3) have resulted to be $q=0.36$ and $\varrho=3.9\,\mathrm{g\,cm^{-3}}$.

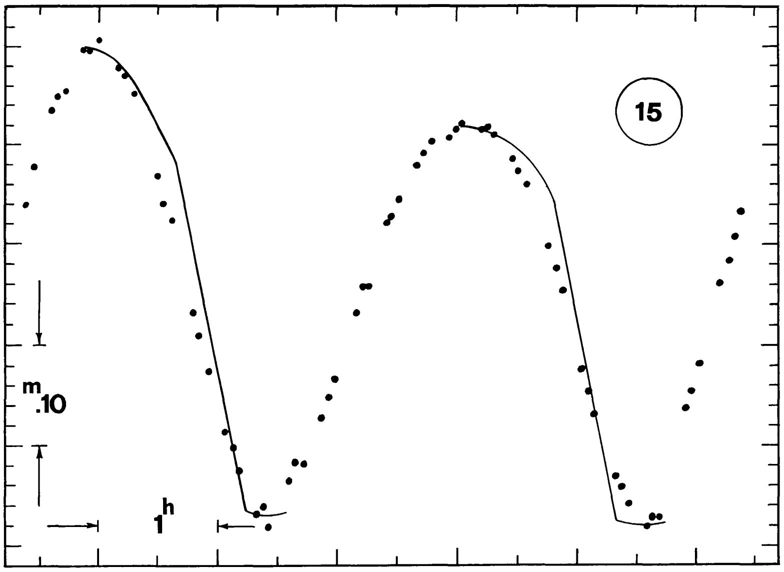

Fig. 1. 15 Eunomia; dots: observed light curve; solid lines: computed light curves for cases I and II (see text)

Table 1

Asteroid no.	Ampl. (mag)	Rotation period (h)	Density (g/cm^3)	Mass ratio	Distance $a=1$	Distance (km)	Primary body a $a=1$	(km)	b $a=1$	(km)	c $a=1$	(km)	Secondary body a' $a=1$	(km)	b' $a=1$	(km)	c' $a=1$	(km)
15 (I)	0.47	6.08	3.7	0.21	2.28	290	1.00	127	0.94	119	0.85	108	0.87	111	0.46	59	0.43	54
15 (II)	0.40	6.08	3.9	0.16	2.56	333	1.00	130	0.95	124	0.86	112	0.82	106	0.43	55	0.39	51
39	0.50	5.14	5.0	0.25	2.34	168	1.00	72	0.92	66	0.84	60	0.82	59	0.50	36	0.47	34
43	0.63	5.75	3.9	0.36	2.29	85	1.00	37	0.89	33	0.80	30	0.93	34	0.56	21	0.51	19
44	0.30	6.44	3.6	0.10	2.37	83	1.00	35	0.97	34	0.88	31	0.73	26	0.35	12	0.34	12
61	0.28	11.45	1.1	0.09	2.41	101	1.00	42	0.97	41	0.89	37	0.64	27	0.38	16	0.36	15
63	0.90	9.30	1.4	0.65	2.22	100	1.00	45	0.80	36	0.72	33	1.02	46	0.65	29	0.59	27
82	0.40	13.00	1.0	0.18	2.43	66	1.00	27	0.95	26	0.88	24	0.70	19	0.47	13	0.47	13
192 (I)	0.19	13.62	1.5	0.06	2.65	132	1.00	50	0.99	50	0.91	46	0.51	26	0.33	16	0.32	16
192 (II)	0.29	13.62	2.0	0.14	3.63	171	1.00	47	0.98	46	0.95	45	0.56	26	0.48	23	0.45	21
216	0.90	5.40	3.9	0.60	2.15	221	1.00	103	0.80	82	0.72	74	1.11	114	0.59	60	0.54	56
624	1.06	6.92	2.5	0.90	2.19	241	1.00	110	0.74	81	0.67	74	1.01	111	0.71	78	0.64	70

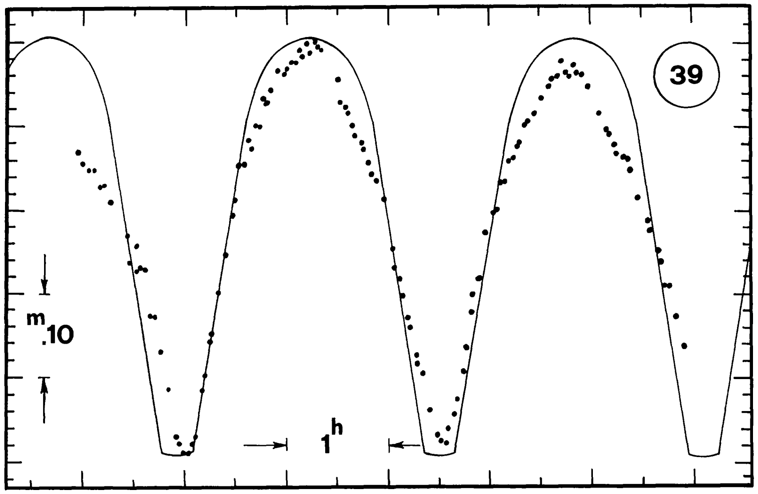

Fig. 2. As Fig. 1 but for 39 Laetitia

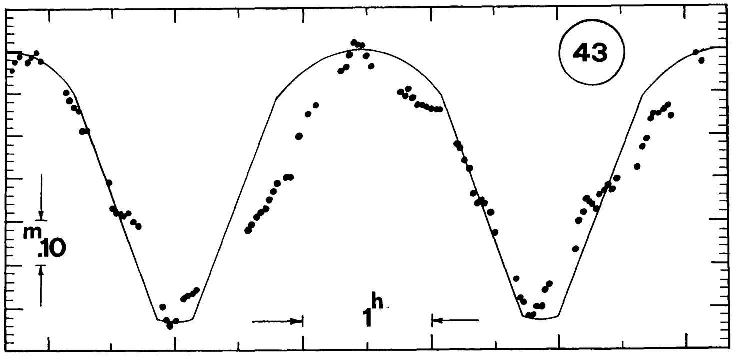

Fig. 3. As Fig. 1 but for 43 Ariadne

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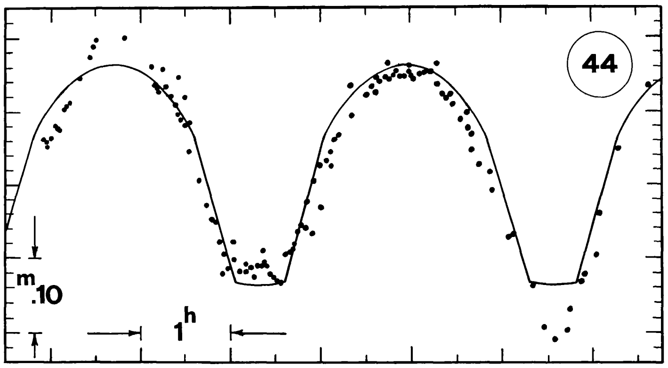

Fig. 4. As Fig. 1 but for 44 Nysa

44 Nysa

This comparatively small asteroid ($D=68$ km), classified in a quite rare taxonomic type (E), has been for a long time an intriguing object, owing to two peculiar features of its light curve: a strong dependence of amplitude on phase (about 0.1 mag per 10 degrees increase of the phase) and the existence of a flat secondary minimum. Both these features support a binary interpretation for the light curve of Nysa, which is in fact one of the best candidates for binarity in our sample. We recall that in 1979 a wide international campaign for photometric observations of Nysa has been carried out (Birch et al., 1983), providing light curves obtained at a number of different phases. For our analysis we have used the light curve observed on September 25, 1979, corresponding to a phase of approximately 2 degrees. The value of A refers to the secondary minimum (displaying a flat bottom), while we have neglected the deeper (and sharper) primary minimum, whose shape is considerably phase-dependent and is probably determined mainly by shadowing effects. The best-fitting simulated light curve shown in Fig. 4 corresponds to $q=0.10$ and $\varrho=3.6\,\mathrm{g\,cm^{-3}}$.

61 Danae

Unfortunately this object (of type S, $D=88$ km) has been observed during one opposition only (Wood and Kuiper, 1963), so that for lack of better assumptions we have quite arbitrarily identified the observed amplitude with the maximum amplitude A. During the observation, the phase angle was 7 degrees. The choice of this asteroid was justified by existence of flat minima coupled with a significant change of slope in the ascending and descending portions of the light curve. The simulated curve of Fig. 5 has been generated choosing $q=0.09$ and $\varrho=1.1\,\mathrm{g\,cm^{-3}}$.

63 Ausonia

The unusual amplitude (0.90 mag) and the intermediate period (9.3 h) of this main-belt asteroid ($D=94$ km, S type) are clearly suggestive of a binary nature. Moreover observations carried out during the 1976 opposition (Scaltriti and Zappalà, 1977) evidence a remarkable change of the amplitude with the phase angle. Figure 6 has been obtained by superimposing on a light curve observed in the 1980 opposition (Lagerkvist, 1981) a simulated curve corresponding to $q=0.65$ and $\varrho=1.4\,\mathrm{g\,cm^{-3}}$.

82 Alkmene

This asteroid, though having a diameter less than 100 km ($D=66$ km, S type) displays a light curve with several features diagnostic of a binary nature: at least one minimum with a flat bottom, very wide maxima and manifest changes of slope. Moreover the sharper primary minimum appears to have a variable shape related with the phase angle, and at small phases it becomes significantly flatter. The light curve observed in the 1979 opposition (Harris et al., 1984), which is shown in Fig. 7, has been obtained by superimposing a number of data obtained at different phases. Although we have to notice that the maximum amplitude may be higher than shown in the figure, because the asteroid has

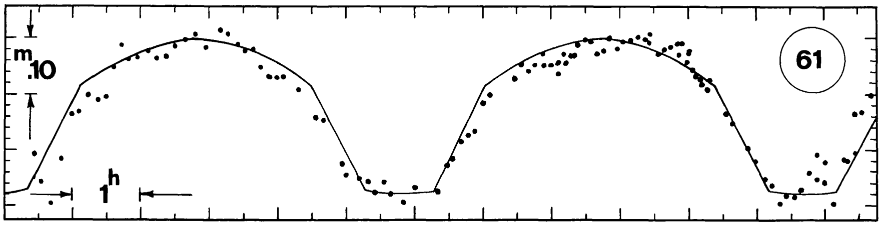

Fig. 5. As Fig. 1 but for 61 Danae

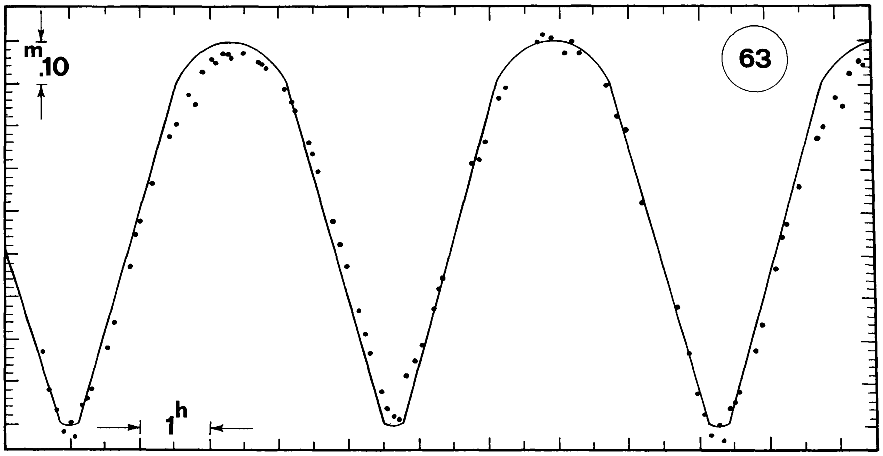

Fig. 6. As Fig. 1 but for 63 Ausonia

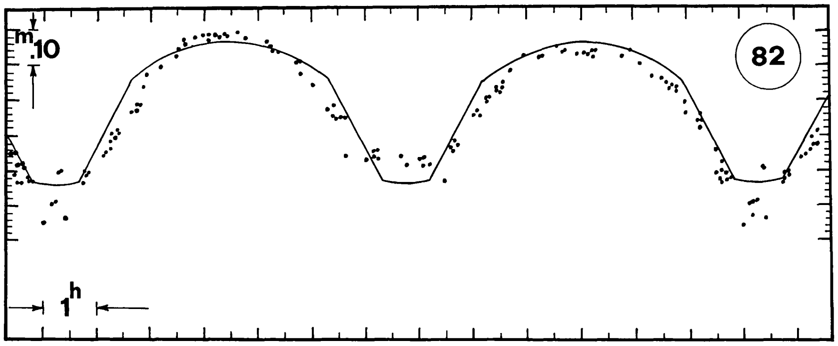

Fig. 7. As Fig. 1 but for 82 Alkmene

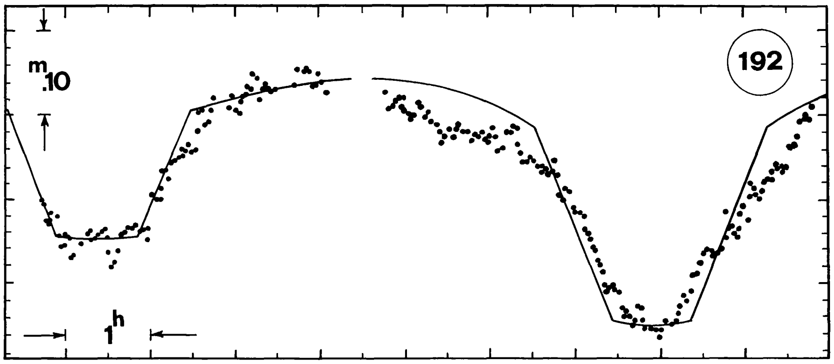

Fig. 8. As Fig. 1 but for 192 Nausikaa

been observed only in one opposition, it has been easy to find an equilibrium binary model yielding a satisfactory fit with the data. The corresponding physical parameters have been found to be $q=0.18$ and $\varrho=1.0\,\mathrm{g\,cm^{-3}}$.

192 Nausikaa

This S-type object, having a diameter of 99 km, has been considered in past as a possible binary system owing to a very remarkable dependence of amplitude on phase and to the peculiar behaviour of the primary minimum, which at large phases displays features similar to those that are expected to arise as a consequence of eclipses (Zappalà et al., 1980). The significant difference in the depth of the minima has forced us to consider two possible models, based on different values of the amplitude. The light curve plotted in Fig. 8, obtained at a phase of 12° (Scaltriti and Zappalà, 1976) has been fitted either by a model with $q=0.14$ and $\varrho=2.0\,\mathrm{g\,cm^{-3}}$ (using the primary minimum) or by a model with $q=0.06$ and $\varrho=1.5\,\mathrm{g\,cm^{-3}}$ (using the secondary minimum).

216 Kleopatra

Kleopatra, a CMEU object with a diameter of 236 km, shows the largest light curve amplitude presently known in the main asteroid belt. Equilibrium models of this object, both binary and single, have been proposed in past by Weidenschilling (1980) and by Zappalà et al. (1983) respectively. In the latter paper it was found that a single Kleopatra, with a maximum amplitude at 0° of phase of about 0.90 mag, would have just the most elongated shape that is theoretically possible for a stable triaxial Jacobi ellipsoid. We have to notice, however, that $A=0.90$ mag is not an observational result, but only a plausible estimate proposed by Zappalà et al. (1983); in fact this asteroid has presented amplitudes very strongly dependent on the phase (up to 1.3–1.4 mag at 25° of phase reported by Tholen, 1980). In Fig. 9 we have plotted a composite light curve obtained from observations carried out in 1982 at a phase of about 6° (solid line); the light curve has been scaled to a 0° of phase (and $A=0.90$ mag; dashed line) and then fitted by a binary model (dotted line). The corresponding physical parameters are $q=0.60$ and $\varrho=3.9\,\mathrm{g\,cm^{-3}}$ (see Leone et al., 1984, for further details on the models of Kleopatra).

624 Hektor

A well-known puzzling case, interpreted in terms of a nearly-contact binary system already in 1971 by Cook, is that of the largest Trojan asteroid, 624 Hektor ($D=234$ km). Starting from the unusual light curve amplitude, a little larger than 1 mag, a variety of models (both single and double) have been proposed by several authors (Hartmann and Cruikshank, 1978; Weidenschilling, 1980; Poutanen et al., 1981; Farinella et al., 1982). In the latter paper it was shown that a nearly-catastrophic collision is a

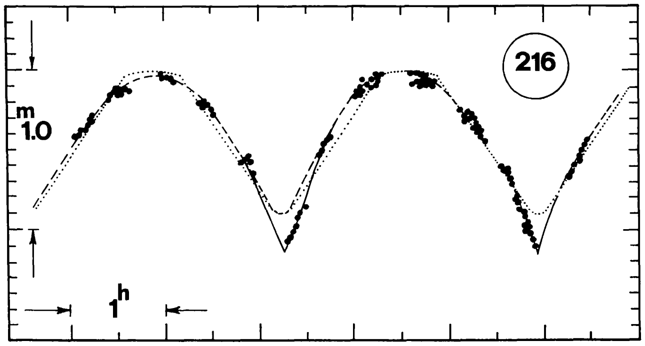

Fig. 9. 216 Kleopatra; solid line: observed light curve; dashed line: "scaled" light curve at phase angle 0°; dotted line: computed light curve

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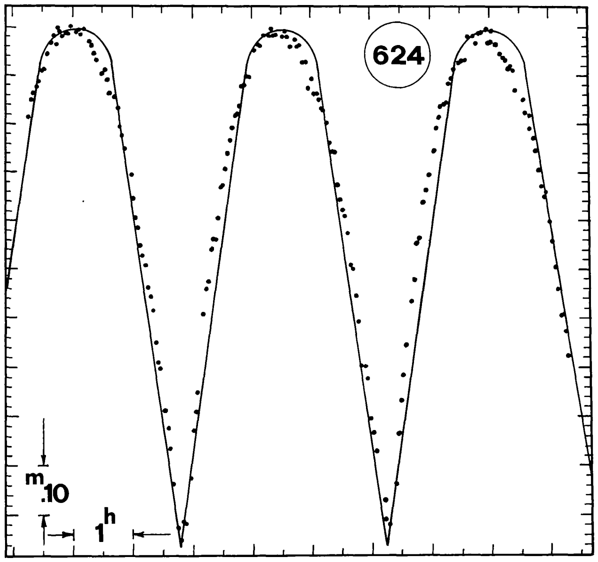

Fig. 10. As Fig. 1 but for 624 Hektor

plausible mechanism to give rise to a Hektor-like binary system in the Trojan clouds. A preliminary discussion of the equilibrium binary models of Hektor is given by Leone et al. (1984); here we present the fit of a 1968 light curve (Dunlap and Gehrels, 1969) by a model with $q=0.90$ and $\varrho=2.5\,\mathrm{g\,cm^{-3}}$ (Fig. 10).

4. Sensitivity to scattering effects

As we have briefly discussed in Sect. 1, light scattering effects can increase the light curve amplitude with respect to the value related only to a changing cross-section. Therefore, the use of the maximum amplitude to constrain the geometrical properties of the models, neglecting altogether the contribution of scattering, can lead to some error in the derived physical parameters. In order to assess the sensitivity of the models to some uncertainty in A (or, better, in the value of A which would be caused by purely geometrical factors), we have tried a simple test: choosing two large-amplitude asteroids like 624 Hektor and 63 Ausonia, for which the scattering effect should be more relevant than in other cases, we have decreased by 25% the observed maximum amplitude, and then this "reduced" amplitude has been used as starting value for obtaining the models. Although the 25% reduction, in absence of reliable theoretical or experimental assessments, is somewhat arbitrary, it appears reasonable in view of the few results recently obtained on this problem (Poutanen et al., 1981; Barucci and Fulchignoni, 1983). For Hektor the "reduced" amplitude is 0.8 mag, which would lead to a best-fitting value of q of about 0.5, remarkably less than in the "nominal" case. On the other hand, the density is again of $2.5\,\mathrm{g\,cm^{-3}}$; the new values of the semiaxes and orbital separation, to be compared with the ones of Table 1, are listed in Table 2. No striking variation in the shape of the components is caused by the "reduced" amplitude.

Similar results are obtained for Ausonia: with the "reduced" amplitude of 0.68 mag, the best fit comes from the choices $q=0.40$ and $\varrho=1.5\,\mathrm{g\,cm^{-3}}$, while the axial ratios (listed in Table 2) do not change by more than 15%. These results show clearly that, even if the scattering effect introduces some quantitative uncertainty in the properties of our models, it cannot cause significant qualitative changes. In particular it appears remarkable that the density values are almost coincident, what can be explained in the following way: while q must be adjusted to account for the "reduced" amplitude, a change of the density would affect mainly the morphology of the light curve (for instance very high densities, keeping constant the orbital period, would lead to very detached systems with short eclipse events). But while scattering effects could change the maximum amplitude, it seems unlikely that they cause significant variations of the general shape of the light curve.

Table 2

	624 Hektor	63 Ausonia
Reduced amplitude (mag)	0.80	0.68
Density (g/cm^3)	2.5	1.5
Mass ratio	0.50	0.38
Distance ($a=1$)	2.26	2.28
b/a	0.83	0.87
c/a	0.75	0.79
a'/a	1.06	0.96
b'/a	0.56	0.56
c'/a	0.52	0.52

5. Discussion

In the present paper we have analysed the plausibility of binary models for asteroids whose light curves, for different reasons, appeared suggestive of a binary nature. The first interesting conclusion was that objects considered in past as likely binary candidates, owing to their light curve morphology similar to that of detached eclipsing binary stars, can no more be viewed as such. The reason is that equilibrium shapes, at least for the secondary components, do always present a significant elongation, and this would rule out the flat shape of the light curve maxima which on the other hand was the determining factor for choosing these objects. This argument is based on the properties of the equilibrium figures and is not valid for rigid, irregular asteroids: but in this case the assumption of spherical shapes is clearly inconsistent, and the low densities implied by the models ($\sim 1\,\mathrm{g\,cm^{-3}}$) appear unrealistic.

More promising results come from the analysis of light curves having other peculiar features, even if less striking than in the previous case: unusual amplitudes, strong amplitude-phase dependence, etc. In these cases the equilibrium models lead to simulated light curves compatible with the available data, and indeed Figs. 1–10 show in general a satisfactory agreement with observed light curves. The crucial parameter for the plausibility of these models is the density, which for the objects of our sample is not outside the range of physically reasonable values. Looking at Table 1, we can notice that, with the exception of Hektor, the derived densities tend to group into two distinct ranges: higher than $3.5\,\mathrm{g\,cm^{-3}}$ and lower than $2.0\,\mathrm{g\,cm^{-3}}$. Interestingly enough, only to Hektor has been assigned an intermediate density, close to the values commonly assumed to be representative for the whole asteroid population (even if the experimental bases for such an estimate are not really sound). If these asteroids have "rubble-pile" structures, the higher densities seem less plausible than the lower ones; in the former case, we have to consider as a viable alternative the triaxial single models, for which the equilibrium theory yields density values ranging from 1 to $2\,\mathrm{g\,cm^{-3}}$ (see Leone et al., 1984,

Table 3

Asteroid	Angular separation	Difference of magnitudes
15 Eunomia (I)	$0.''24$	$0.^{m}9$
15 Eunomia (II)	$0.''28$	$1.^{m}1$
39 Laetitia	$0.''13$	$0.^{m}8$
43 Ariadne	$0.''10$	$0.^{m}6$
44 Nysa	$0.''08$	$1.^{m}4$
61 Danae	$0.''07$	$1.^{m}5$
63 Ausonia	$0.''10$	$0.^{m}2$
82 Alkmene	$0.''05$	$1.^{m}1$
192 Nausikaa (I)	$0.''13$	$1.^{m}9$
192 Naukisaa (II)	$0.''17$	$1.^{m}5$
216 Kleopatra	$0.''17$	$0.^{m}2$
624 Hektor	$0.''08$	$0.^{m}1$

Fig. 4). On the contrary the binary models with lower densities appear to be quite plausible, in particular if we take into account the fact that their size is just in the range for which the largest collisional events are expected to transfer huge amounts of angular momentum (Farinella et al., 1982). Anyway, the best candidate is certainly 624 Hektor, for which we believe that the binary model is supported by several lines of evidence and has no serious objection to face.

In any case, we stress that our results cannot be considered proofs that the considered asteroids are really binary. Such a conclusion cannot be reached by analysing light curves only, which cannot give a unique solution for the shapes of the objects. On the other hand, it is quite possible that a number of existing binary asteroids cannot be identified by light curve analysis because their physical and geometrical properties do not cause peculiar light curve features. Definitive conclusions on the existence and frequency of binary asteroids will probably come from other techniques, like high-resolution observations from space-based instruments (Hipparcos, Space Telescope, etc.) or direct exploration by probes. In Table 3 we have listed for the models of our sample the angular separations between the components (as seen from the Earth) and their magnitude difference: these numbers confirm that while for direct Earth-bound observations there is little hope to resolve these hypothetical systems, in the next decade space observations could shed some light on the real nature of these asteroids.

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