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Eclipsing events in the binary system of the asteroid 90 Antiope

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Abstract. CCD observations of the binary asteroid 90 Antiope were carried out at four observatories (Borowiec, Pic du Midi, Kharkiv, and Chateau Renard) on 26 nights from October 2001 through February 2002. The results show a two–component lightcurve with each showing the same period of 16.505 ± 0.002 hours. The first component (with the amplitude of 0.10 mag) is associated with the rotation of two non–spherical bodies of the system; the second one, showing two sharp minima (with the amplitude in the range 0.05–0.12 mag, depending linearly on the phase angle) is due to eclipses in the binary system. The lightcurve suggests a synchronous rotation. The orientation of the system's orbit has been determined from the analysis of both the amplitudes and the duration of the eclipses. Some predictions of the possibility of observations of the eclipsing events during future oppositions have also been made.

Key words. techniques: photometric – minor planets, asteroids

1. Introduction

The first satellite of an asteroid was discovered on 17 February 1994 during the playback of approach images from the Galileo spacecraft's encounter with the asteroid 243 Ida (Belton et al. 1996). Forty seven images of the pair Ida and its small moon Dactyl were found. The following years have revealed discoveries of some binary objects among the near-Earth asteroid population (Pravec & Hahn 1997; Pravec et al. 1998, 2000, 2001, 2002; Motolla & Lahulla 2000). The binarity of these asteroids was deduced from their complex lightcurves. They can be described as a sum of two independent components, one with a short synodic period of several hours, and another with a longer period. In some cases it was possible to notice that the rotation of the secondary component was tidally coupled to the orbital motion and the longer period was also the system's orbital period. The secondary-to-primary-diameter ratios were usually about 0.2–0.3. These binary objects among near-Earth asteroids are so similar in their characteristics that most of them are expected to be formed by the same mechanism, such as the tidal disruption during close encounters with Earth, as proposed by Bottke & Melosh (1996).

Mutual eclipse/occultation events were observed for three known binary near-Earth asteroids: 1994 AW_1 (Pravec & Hahn 1997), 1991 VH (Pravec et al. 1998), and 1996 FG_3 (Pravec et al. 2000; Motolla & Lahulla 2000).

The case of 1996 FG_3 seems to be very interesting; Motolla & Lahulla (2000) observed it during two apparitions: in April 1996 and December 1998. They developed a numerical model of two co-orbiting ellipsoids and applied it to the asteroid. A fit of this model to the observations produced synthetic lightcurves that reproduced the amplitudes, the timing, and other features of the eclipse events. They obtained the circular orbit of the system and normalized semiaxes of the ellipsoids that described the shapes of two bodies. Moreover, they obtained two possible orientations of the orbital plane, one for retrograde and one for prograde orbital motion of the components.

Recently the population of the known binary near-Earth asteroid was enlarged by radar observations (Benner et al. 2001a, 2001b; Margot et al. 2002; Nolan et al. 2002). Results of both radar and photometry show that the population of the binary systems among NEAs seems to be significant. Recent studies suggest that about 20% of these asteroids are binary (Merline 2002).

At present, in addition to 243 Ida, we know other main–belt asteroids to be binary. For these discoveries, the largest telescopes plus adaptive optics systems or HST have been used, giving direct images of the objects. The following asteroids were reported to have moons: 45 Eugenia (Merline et al. 1999), 760 Pulcova and 90 Antiope (Merline et al. 2000), 107 Camilla (Storrs et al. 2001), 87 Sylvia (Brown et al. 2001), 22 Kalliope (Merline et al. 2001a), and 3749 Balam (Merline et al. 2002). With exception of 90 Antiope, the moons are only a few kilometers in diameter, which makes them much smaller than the primary bodies of the systems.

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Table 1. Aspect data, times of observed minima and *eclipsing* amplitudes of 90 Antiope.

Date (UT)	r (AU)	Δ (AU)	Phase angle (°)	λ (J2000) (°)	β (J2000) (°)	Obs.	$m1$ Julian Days +2 452 000	$m2$ Julian Days +2 452 000	Ampl. (mag)
2001 Oct. 20.1	3.365	2.763	15.0	87.4	0.1	Bor		202.4508	0.12
2001 Oct. 22.1	3.368	2.740	14.6	87.3	0.1	Pic		204.5150	0.12
2001 Oct. 25.0	3.372	2.708	14.1	87.3	0.1	Bor	207.6036		
2001 Oct. 27.0	3.374	2.687	13.7	87.2	0.1	Bor	209.6673		
2001 Nov. 11.0	3.393	2.551	10.2	85.9	0.3	Bor		224.4597	0.10
2001 Nov. 14.1	3.396	2.530	9.3	85.5	0.3	Bor	227.5455		
2001 Nov. 15.0	3.398	2.523	9.1	85.4	0.3	Bor			
2001 Nov. 17.0	3.400	2.510	8.5	85.1	0.3	Bor	230.2988	230.6482	0.09
2001 Nov. 19.9	3.404	2.494	7.6	84.7	0.3	Bor		233.3982	0.09
2001 Dec. 13.9	3.432	2.448	0.6	80.1	0.5	Bor		257.4633	0.05
2001 Dec. 18.1	3.437	2.458	2.0	79.3	0.6	Pic		261.5896	0.05
2001 Dec. 20.1	3.439	2.464	2.7	78.9	0.6	Pic	263.3044	263.6525	0.06
2001 Dec. 21.0	3.440	2.468	3.0	78.7	0.6	Bor, Pic			
2002 Jan. 01.8	3.453	2.535	6.8	76.6	0.7	Kha			
2002 Jan. 03.9	3.455	2.551	7.4	76.2	0.7	Bor			
2002 Jan. 04.9	3.456	2.559	7.7	76.1	0.7	Bor			
2002 Jan. 06.0	3.458	2.568	8.1	75.9	0.7	Bor, ChR	280.4977		
2002 Jan. 08.8	3.461	2.593	8.9	75.6	0.7	Kha	283.2475		
2002 Jan. 09.9	3.462	2.604	9.2	75.4	0.7	ChR		284.2863	0.09
2002 Jan. 16.8	3.469	2.674	10.9	74.6	0.7	Bor			
2002 Jan. 28.9	3.482	2.821	13.4	73.9	0.8	Pic		303.5429	0.12
2002 Jan. 29.9	3.483	2.834	13.5	73.9	0.8	Pic			
2002 Jan. 30.9	3.484	2.847	13.7	73.9	0.8	Pic	305.2592		
2002 Jan. 31.9	3.485	2.862	13.9	73.8	0.8	Pic		306.2940	0.12
2002 Feb. 01.9	3.486	2.875	14.0	73.8	0.8	Pic	307.3239		
2002 Feb. 07.9	3.492	2.960	14.8	73.9	0.8	Pic			

Observatory Code: Bor – Borowiec; Pic – Pic du Midi; Kha – Kharkiv; ChR – Chateau Renard.

According to Prokof'eva et al. (1995) it was also possible to discover the binarity of asteroids by the frequency analysis of photometric data. Using this method they found that the asteroids 87 Sylvia and 423 Diotima were binary systems. It was confirmed later for Sylvia as mentioned above.

The largest telescopes with adaptive optics systems and HST made it possible to discover binary systems among more distant asteroids. Merline et al. (2001b) found that the Trojan asteroid 617 Patroclus was also a double object. In the past two years, the discoveries of a few binary systems among Transneptunian Objects (TNO) were reported (Veillet 2001; Kavelaars et al. 2001; Trujillo & Brown 2002; Brown & Trujillo 2002; Noll et al. 2002a, 2002b).

Observations and modelling of rotational characteristics of binary systems are very important for our understanding of asteroid composition and collisional evolution. They allow determination of the bulk density of these bodies – a parameter that is otherwise very difficult to obtain. Such determinations were done for most of the objects mentioned above.

2. Asteroid 90 Antiope – previous work

Photometric observations of 90 Antiope, a member of Themis family, were performed by Hansen et al. (1997) on four nights in December 1996. This asteroid displayed light variation similar to a typical lightcurve of an eclipsing binary star. The period of rotation was determined as 16.509 hours and the amplitude was about 0.70 mag.

In August 2000 the binarity of this asteroid was confirmed by Merline et al. (2000) with the Keck Adaptive Optics system. They found that 90 Antiope was a double asteroid with similar–sized components, separated by 170 km. The orbital period was found to be 16.5 hours, consistent with the period derived from the 1996 photometric observations.

Assuming that Antiope is a binary system of two sherical objects and its *IRAS* diameter of 120 km (`http://pdssbn.astro.umd.edu/`), we have found the diameter of each component to be 85 km. The distance between the two components and the rotational period implies the mass of 4.12×10^{20} g of each of them. Thus the density is 1.3 g cm^{-3}.

Weidenschilling et al. (2001) expected that the binarity of Antiope cannot be primordial, but was formed during or after breakup of the parent body forming the Themis family. However, they concluded that the formation of such a large binary system was an improbable event, even for the relatively favorable velocity environment within an asteroidal family. By this reasoning, Antiope should be unique. The discovery of another large binary system with equal components could help us understand the collisional history of the asteroids.

Michałowski et al. (2001a) obtained lightcurves of the asteroid 90 Antiope on 14 nights in September through November 2000. A synodical period of 16.496 hours and the observed amplitude of brightness variation of 0.08 mag were found. This small amplitude was due to the noncircular shapes of the components of the binary system rather than to mutual occultations. The lightcurve was asymmetrical as the interval between two maxima (and minima, respectively) was larger than a half of the rotational cycle. The available data allowed some predictions of the possibility of observations of the eclipsing events during future oppositions. Eclipses were predicted during the 2003, 2005, and 2008 apparitions, and not in 2004 and 2006. The prediction for the opposition in December 2001 was not certain. In some optimistic circumstances the observed amplitude associated with the eclipse could reach a value of 0.05 mag.

3. CCD photometry in the 2001/02 apparition

We started our observations of Antiope in October 2001 (Michałowski et al. 2001b) and performed them on 26 nights until the beginning of February 2002. Most of these data were obtained with 0.40 m (at Borowiec near Poznań, Poland) and 1.05 m (Pic du Midi, France) telescopes. Some additional measurements were made at the Chateau Renard Observatory (in the French Alps) and Kharkiv (Ukraine) with 0.62 m and 0.70 m telescopes, respectively. All four telescopes were equipped with *CCD* cameras. Other details concerning the instruments and the reduction procedure can be found in Michałowski et al. (2000) and Shevchenko et al. (2002).

The aspect data of the asteroid are listed in part of Table 1. The columns give the date of the observation referring to the mid–time of the observed lightcurve, asteroid–Sun (r) and asteroid–Earth (Δ) distances (in AU), solar phase angle, ecliptic longitude (λ) and latitude (β) for the J2000 epoch, and the name of the observatory.

The observations are presented as composite lightcurves in Figs. 1–4. The vertical shift of each lightcurve was obtained by minimizing the dispersion of data points relative to their neighbours. The abscissa is the rotational phase with zero point corrected for light–time. The observed minima ($m1$, $m2$) are indicated in the graphs.

The asteroid 90 Antiope displayed a two–component lightcurve with each showing the same period of 16.505 ± 0.002 hours as indicated in all four graphs. The first component is associated with the rotation of two non–spherical bodies (*rotational* lightcurve); the second one, showing two sharp minima, is due to mutual occultation/eclipse events in the binary system (*eclipsing* lightcurve). One minimum of the *eclipsing* lightcurve (indicated as $m2$ in the figures) occurred in the same phase as the shallow *rotational* minimum. The *eclipsing* minima were always a half period apart, so $m1$ did not appear exactly at the phase of the deeper *rotational* minimum. The total lightcurve of Antiope is a sum of the symmetrical *eclipsing* lightcurve and the asymmetrical *rotational* one. The times (corrected for light–time) of the observed *eclipsing* minima ($m1$, $m2$) are displayed in Table 1.

The *rotational* amplitude of 0.10 mag was almost constant during the whole observational interval. However, the *eclipsing* amplitude revealed a different property. Its values for symmetrical minimum $m2$ are given it the last column of Table 1. Figure 5 shows the relation between this amplitude and the phase angle. The slope of the linear relationship is found to be 0.005 mag/deg. Zappala et al. (1990) showed that the slopes of analogous dependencies for normal lightcurves (i.e. *rotational*) might be different for different oppositions. We will be able to check whether the *eclipsing* amplitude has the same properties if we perfom the observations during the next apparition of this asteroid (December 2002–April 2003).

A very interesting feature can be seen for the 0.5–0.6 phase of rotation (see Figs. 1–4). The results of the October–November observations over a few nights are puzzling, see Fig. 1. Some measurements for this interval showed a small maximum while the others indicated a minimum. This specific behaviour did not appear for the other intervals as for them we only had data from one night. We believe that it was not due to errors in our observations as the 1996 observations (Hansen et al. 1997) showed a similar feature. Some possible explanation will be presented below.

4. Orbit of the binary system

A half period distance between the minima in the *eclipsing* lightcurve suggests circular orbits of both components in the binary system of Antiope. Both amplitudes have similar depths in relation to the *rotational* lightcurve, which means that the two components have the same diameters assuming the same albedo for each of them. The amplitude of *rotational* brightness variation implies that the bodies (at least one of them) are not spherical. The fact that the *eclipsing* minima are in the same phase in respect to the *rotational* lightcurve indicates that the rotational periods of both bodies are equal to the orbital period, which is characteristic for synchronous rotation. Moreover, the longest axes of both bodies are always oriented along the same line.

Some small modification to this model can explain the lightcurve feature at the 0.5–0.6 phase of rotation. We can assume that only one of components is nonspherical and its shape is responsible for the *rotational* lightcurve. Its rotational period $P_{\rm rot}$ is equal to the orbital one $P_{\rm orb}$. The other body is nearly spherical and its shape does not affect the *rotational* brightness variation. If we put a dark spot on the right place on the surface of this body and assume that its rotational period is equal to $2P_{\rm orb}$ we can obtain an occurrence of the above mentioned small maximum or minimum every second orbital cycle, respectively, which is in agreement with the observations. We think future observations can help us verify the above presented modification.

4.1. Timing method

In a binary system of two equal components the decrease in brightness, during the total eclipse, is 0.75 mag at each minimum. In December 1996 the observed amplitude of the lightcurve of Antiope was 0.70 mag (Hansen et al. 1997),

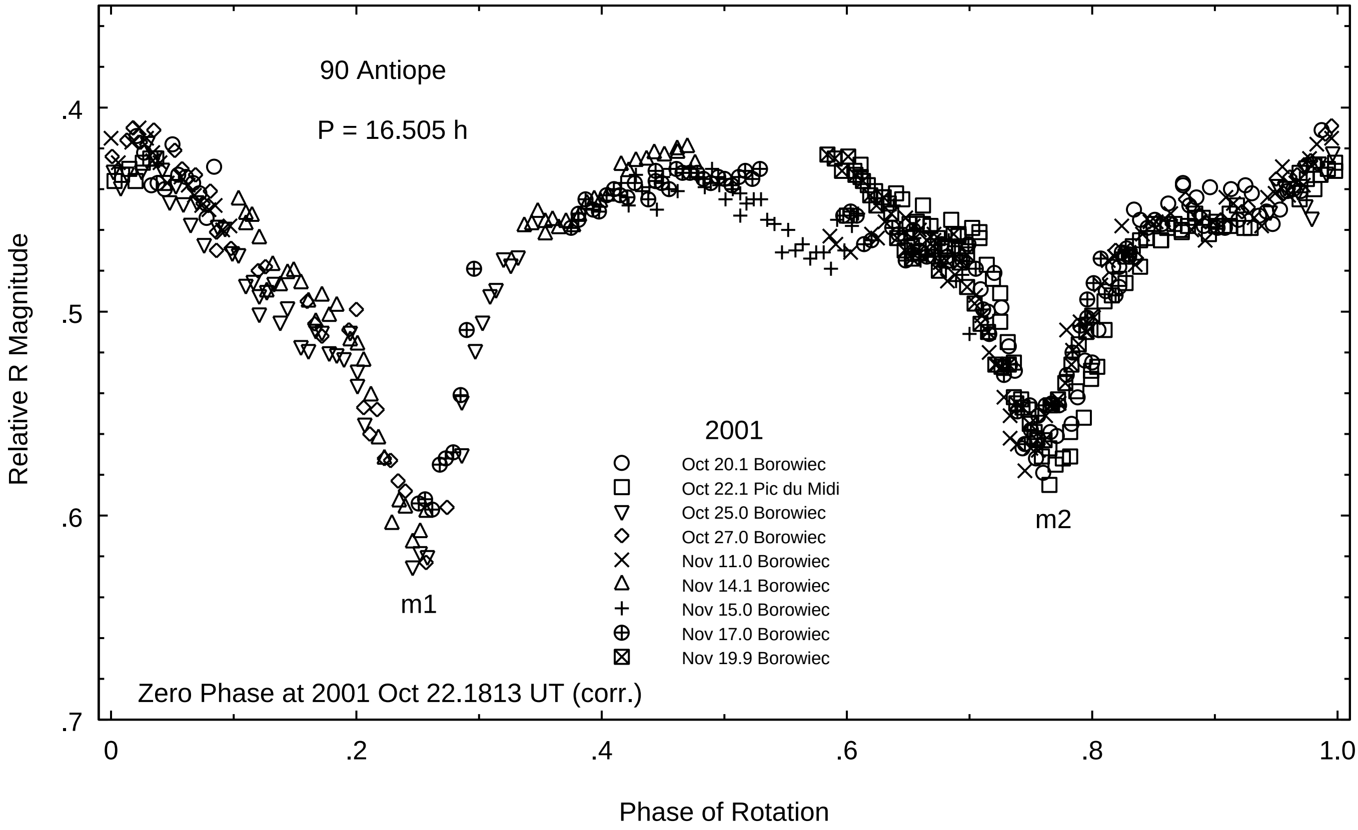

Fig. 1. Composite lightcurve of 90 Antiope in October–November 2001.

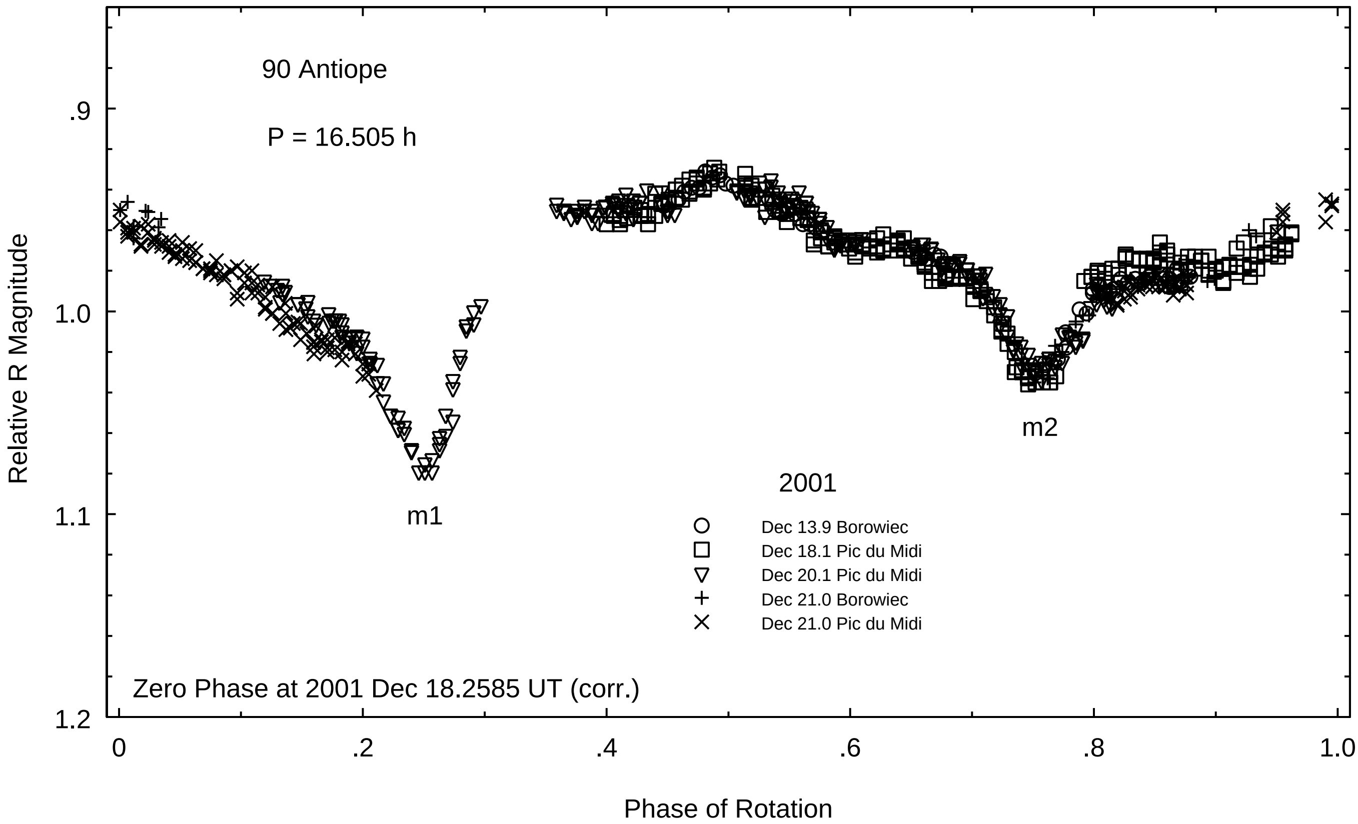

Fig. 2. Composite lightcurve of 90 Antiope in December 2001.

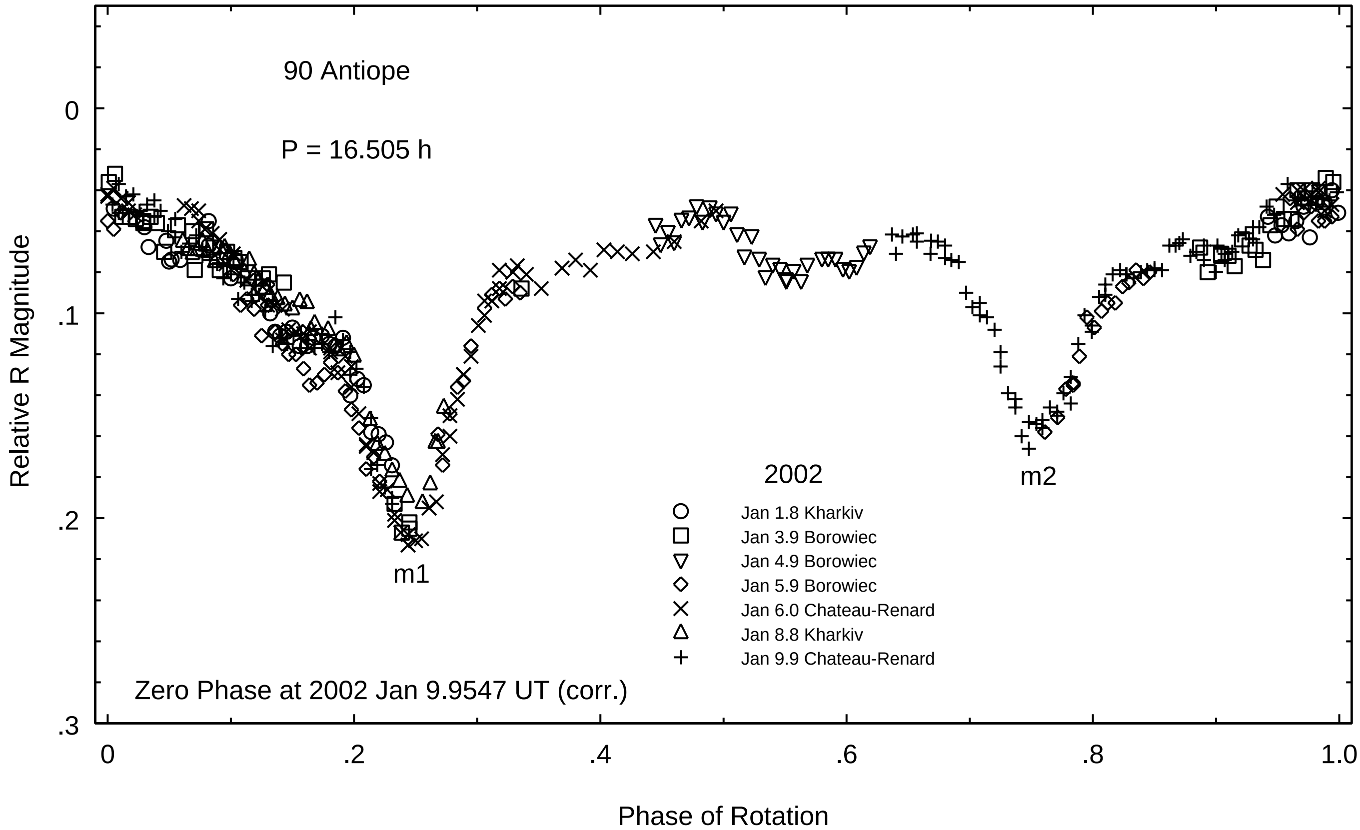

Fig. 3. Composite lightcurve of 90 Antiope in January 2002.

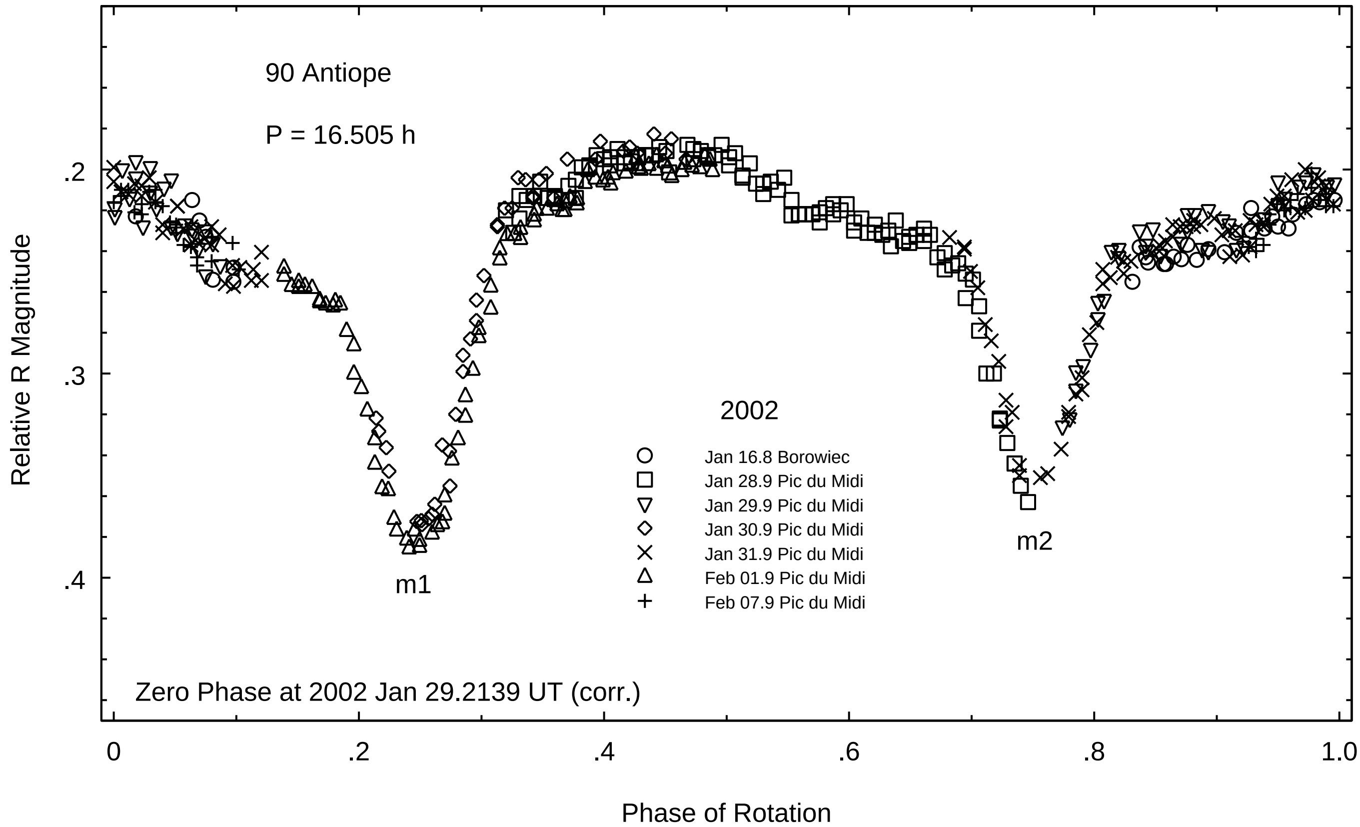

Fig. 4. Composite lightcurve of 90 Antiope in January–February 2002.

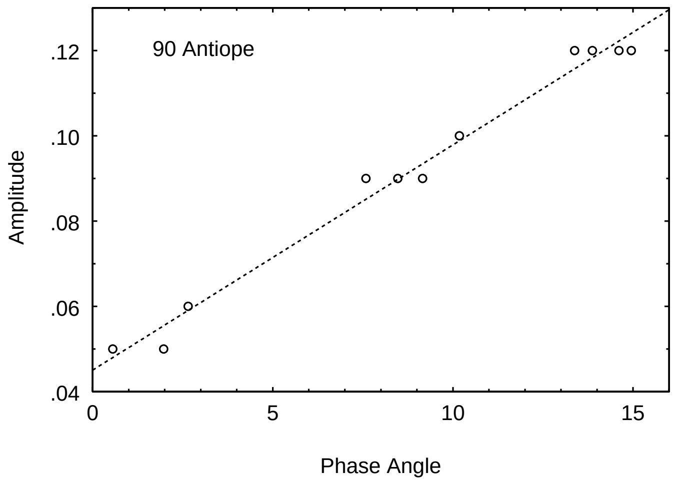

Fig. 5. *Eclipsing* amplitude versus phase angle for 90 Antiope in 2001/02 opposition.

which suggested that the Earth was nearly exactly in the orbital plane of the Antiope system (the inclination i of the orbit was almost 90°). We will use this assumption but we have to realize that it might not be true. Careful examination of the whole 1996 amplitude of 0.70 mag showed that it consisted of the *rotational* one of 0.14 mag and the *eclipsing* one of only 0.56 mag. This observed *eclipsing* amplitude was smaller than the 0.75 mag required for the total occultation.

Antiope is always visible close to the Ecliptic plane (see Table 2 for comparison) and Michałowski et al. (2001a) showed that the inclination i (an angle between the normal to the orbital system and direction to the Earth) can be calculated from the simple formula

$$\cos(i) = -\cos(\beta_n)\cos(\lambda - \lambda_n), \tag{1}$$

where (λ_n,β_n) are the ecliptic coordinates of the pole of the orbital system, and λ – geocentric ecliptic longitude of the asteroid. They also showed that for the Antiope system a partial occultation occured for $i > 60°$. For the 1996 opposition we have $\lambda = 120°$ and $i \approx 90°$ (assuming the total occultation), which gives us $\lambda_n = 30°$ (or 210°) for any value of β_n.

Careful examination of the 1996 observations (Hansen et al. 1997) gives the total duration of the eclipse to be 2^h50^m. Knowing the separation of the components and the orbital period we have obtained a diameter of 86 km for each body, which is consistent with the IRAS determination. Of course, the eclipse in 2001/02 was shorter and equal to 2^h10^m. This implies 68 km for a length of a chord formed by an intersection of the projections (onto the plane perpendicular to the line of sight) of two equal bodies. Geometric analysis of these two eclipsing events (1996 and 2001/02) gives $i = 72°$ for the inclination of the system orbit in the 2001/02 apparitions. Using Eq. (1) for $\lambda = 80°$ (see Table 2) and $\lambda_n = 30°$ (or 210°) we have obtained $\beta_n = 62°$.

The ecliptic coordinates (λ_n, β_n) could mean that we have fully determined the orientation of the orbit of the binary system of Antiope. If yes, we can predict the inclinations i for the past and future apparitions. Table 2 gives the dates of the oppositions, the asteroid ecliptic coordinates (λ,β). The next

Table 2. Oppositions of 90 Antiope and results for two methods.

Opposition	λ [°]	β [°]	Timing method i [°]	Timing method ampl. [mag]	Amplitude method i [°]	Amplitude method ampl. [mag]	Obs. ampl. [mag]
1996 Dec.	120	2	90	0.75	90	0.75	0.56
2000 Nov.	355	−3	67	0.07	58	0	0
2001 Dec.	80	1	72	0.16	66	0.05	0.05
2003 Feb.	137	3	82	0.43	79	0.34	
2004 Apr.	197	3	63	0.02	51	0	
2005 Jul.	287	−2	84	0.50	82	0.43	
2006 Oct.	35	−2	62	0.01	50	0	
2008 Jan.	103	2	82	0.43	79	0.34	

two columns, denoted as *Timing model*, give the expected inclination i of the orbital plane as well as brightness drops due to the eclipses. For three apparitions (Dec. 1996, Nov. 2000, Dec. 2001) we also give the values of the observed *eclipsing* amplitude.

Results displayed in Table 2 for the *timing method* indicate that the inclination i is always greater than 60°, so we should expect the eclipsing events during all apparitions mentioned. It is not true, if we compare the expected *eclipsing* amplitude in Nov. 2000 (0.07 mag) with the observed one (0 mag). We also observed a drop in brightness in December 2001 (0.05 mag) smaller than the predicted one (0.16 mag).

In this situation we can conclude that the orbit of the Antiope system has been wrongly determined by the *timing method*. It is probably due to the assuption that the total eclipse was observed in December 1996.

4.2. Amplitude method

On the basis of the amplitudes observed, it is also possible to determine the orientation of the system orbit. Again, we have assumed the total eclipse in December 1996 and obtained $\lambda_n = 30°$ (or 210°). For the 2001/02 apparition we have the amplitude 0.05 mag for the smallest phase angle. For this value we can easily obtain the inclination $i = 66°$. From Eq. (1) we have obtained $\beta_n = 50°$. Again, it is possible to predict the inclination i and the expected *eclipsing* amplitude for the oppositions mentioned in Table 2. They are displayed in the columns denoted as *Amplitude method*.

The results, especially for November 2000 and December 2001, seem to better reproduce observations. However, we have to remember that they were obtained with the assumption of a total eclipse in 1996, which might not be true. So, only future observations will help us obtain correct results.

5. Future work

Although the future eclipsing events are not predicted precisely, we should be able to observe them in 2003, 2005, and 2008. We think that the amplitudes might be different to those shown in Table 2. The oppositions in 2004 and 2006 will probably not reveal any eclipses.

The opposition in February 2003 seems to be very promising. Antiope will be in good observational circumstances between December 2002 and April 2003. We should expect an *eclipsing* amplitude larger than in 2001/02 apparition. Thus, we will have data from three apparitions with eclipsing events. These observations will allow us to determine the orientation of the binary system without the assumption $i = 90°$ in 1996. Moreover, we we will be able to determine not only (λ_n, β_n) but the diameter of the asteroid as well. These results will be obtained by using the two methods: *timing* and *amplitude*.

It should be mentioned that the situation with orbit determination can be very different if the orbital plane of the system precesses. However, we hope that the observations from December 2002 to April 2003 will resolve this problem as well.

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