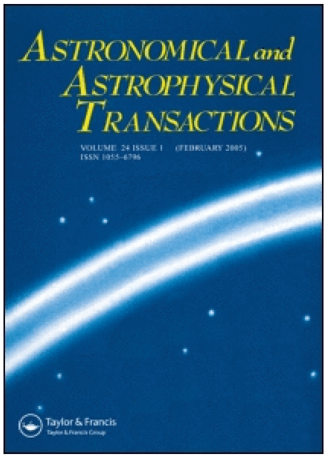

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Apsidal motion of U Oph

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Apsidal motion of U Oph

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The $O - C$ diagram of U Oph, based on photoelectric and charge-coupled device data on the times of minimum light, was analysed. The traditional analysis method was used because of the clear sinusoidal shape of the $O - C$ diagram (with a constant period). Thus, possible apsidal motion and a light time effect were considered. Moreover, taking into account the early visual and photographic data it was found to be consistent with our findings, within the error limits. Our results are in good agreement with those from previous analyses.

Keywords: Binary star; Eclipsing star; Apsidal motion; U Oph

1. Introduction

The bright eclipsing binary U Ophiuchi (HD 156247, BD + 1°3408) is a well-studied detached system, whose variability has been known since 1871, discovered by Gould. It has similar components of spectral type B5V and an orbital period of 1.6773 days, which is relatively short for a detached system. Parenago [1] suggested a periodic term with $P' \approx 46$ years and explained it as being due to the light time effect. Kamper [2], from a more detailed analysis of the system, found an apsidal motion and a third body. More recently, the analysis by Wolf *et al.* [3] was in agreement with Kamper's findings. Adding the most recent times of minima, we made a new analysis, testing the hypothesis of the apsidal motion and the third body.

2. $O - C$ analysis

We collected all times of minima to date and divided them in two sets: early, mostly visual data (1881–1940); recent, mostly photoelectric data (1940–2004). To trace a possible apsidal motion, we decided to carry out our investigation using the recent data set only, because of the large scatter of the other data. Nevertheless, we used all data to compare their agreement with

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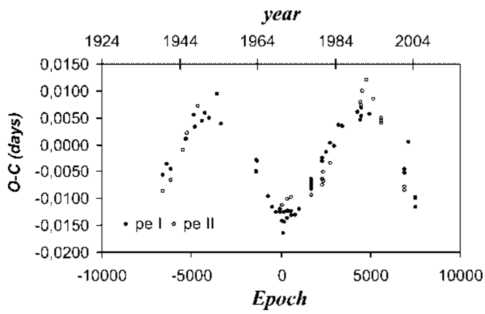

Figure 1. The $O - C$ diagram of U Oph based on the recent data set. The full and open symbols represent the primary and secondary minima, respectively.

the acquired parameters. The $O - C$ residuals were computed from the ephemeris formula [4]

$$\text{Min I} = \text{HJD}\, 2\,440\,484.6890 + 1.677\,345\,98E$$

(where HJD means the heliocentric Julian date), while the respective diagram (of the recent data set) can be seen in figure 1.

3. Apsidal motion

In a close binary system, the apsidal motion is apparent as a sinusoidal time variation in the displacement of the secondary eclipse relative to the midprimary. So, in the limit of small eccentricity e, we have [5]

$$t_{\mathrm{II}} - t_{\mathrm{I}} - \frac{P}{2} = \frac{eP}{\pi}\left(1 + \frac{1}{\sin^2 i}\right)\cos(\omega_0 + \dot{\omega}E), \tag{1}$$

where P represents the orbital period, i the inclination, ω_0 the longitude of the periastron at the epoch $E = 0$, and $\dot{\omega}$ the periastron advance. We computed the respective values of the above quantity for the observed times of the secondary minima. The cosine fit to these data can be seen in figure 2. The acquired function is

$$0.002\,651\,(\pm\,0.0002)\text{ days} \times \cos[0.001\,424\,(\pm\,0.000\,03)\text{ rad} \times E + 5.741\,(\pm\,0.1)\text{ rad}]. \tag{2}$$

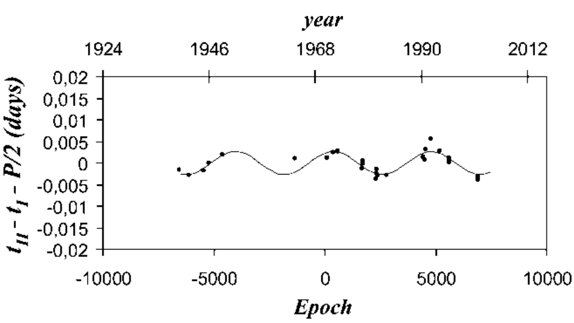

Figure 2. Time variation in the displacement of the secondary eclipse relative to the midprimary. The solid curve is the function (2).

Taking the inclination $i = 87.7°$ [6], we calculated the parameters of the apsidal motion as follows: the eccentricity is $e = 0.002\,479$ and the ratio of the period of apsidal revolution to the orbital period is $U/P = 4413.552$.

4. Third body

Given that the amplitude of the apsidal motion effect on the $O - C$ diagram is very small, an additional physical mechanism is necessary to explain the observed period variation of U Oph. This mechanism is a possible third body in the system. So, we corrected the $O - C$ value for the apsidal motion and in the resulting data we made a search for a sinusoidal fit (figure 3).

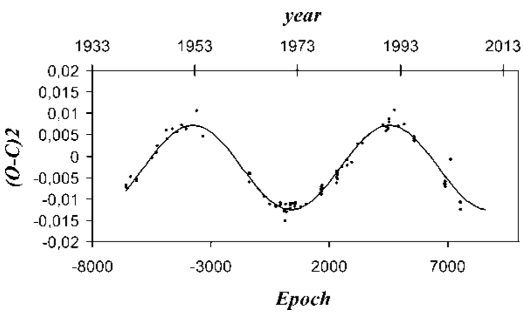

Figure 3. The $O - C$ residuals of the recent set corrected for the apsidal motion. The solid curve is the sinusoidal fit (function (3)) due to the light time effect.

Table 1. Acquired parameters.

Apsidal motion	Third body
$a = 0.002\,651$ days	$a' = 0.0098$ days
$e = 0.002\,479$	$P' = 38.1$ years
$U/P = 4413.552$	$f(m) = 0.0036$†
$U = 20.3$ years	$a' \sin i = 1.74$ AU†
	$M_3 = 0.72\,M_{\odot}$†

†Assuming a coplanar orbit and $e' = 0.2$.

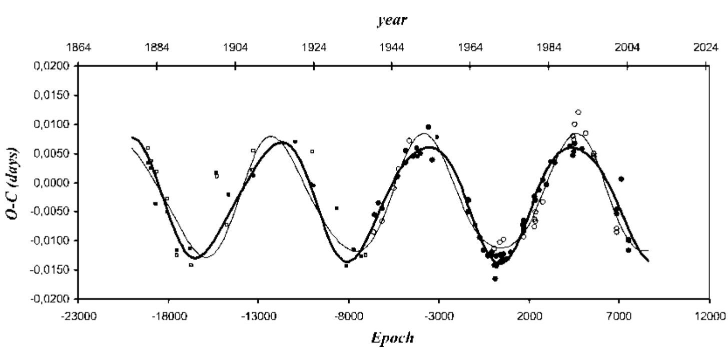

Figure 4. The total of $O - C$ residuals. The two curves represent the apsidal motion combined with the presence of a third body: the bold curve represents the primary minima, and the thin curve the secondary minima.

The best-fitted function is

$$0.009\,846\ (\pm\ 0.0002)\ \text{days} \times \sin[0.000\,757\ (\pm\ 0.000\,006)\ \text{rad} \times E + 4.41\ (\pm\ 0.02)\ \text{rad}] - 0.002\,69\ (\pm\ 0.0002)\ \text{days}. \tag{3}$$

The resulting parameters of the combined mechanisms can be found in table 1 and are represented in figure 4.

5. Discussion

In the present study the traditional analysis method was used because of the clear sinusoidal shape of the $O - C$ diagram (with a constant period), which is also obvious in the early data in spite of their large scattering. It was found that the amplitude of the apsidal motion is about a quarter of that due to the presence of a third body in the system. Concerning the eccentricity of the third body, the value of $e' = 0.2$ was preferred instead of the typical zero value, because of the better fit to the data. The resulting parameters of our analysis are in very good agreement with those found by Kamper [2] and Wolf *et al.* [3].

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