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EVIDENCE FOR A THIRD BODY IN THE ECLIPSING BINARY DI HERCULIS

KHODYKIN, S. A.

Volgograd Pedagogical University, 12, Academicheskaja St., Volgograd 400001, Russia; khodykin@avtlg.ru

The detached eclipsing binary DI Herculis (HD 175227, B3V+B4V, $P = 10\overset{\mathrm{d}}{.}55$) exhibits a significant discrepancy between the theoretically expected apsidal motion rate and the rate measured based on observations of the difference between the primary and secondary eclipse periods ΔP.

The hypotheses of a third star in a highly inclined orbit can explain the observed apsidal motion (Martynov, and Khaliullin, 1980; Guinan, and Maloney, 1985; Khaliullin, Khodykin, and Zakharov, 1991). However, observational evidence of a third body in DI Her has hitherto escaped detection. We collected observed times of photo-visual and photoelectric minima spanning an interval of 75 years (Semeniuk, 1968; Martynov, and Khaliullin, 1980; Guinan, and Maloney, 1985; Khodykin, and Volkov, 1989; Guinan, Marshall, and Maloney, 1994; Dariush, Afroozeh, and Riazi, 2001; Smith, and Caton, 2007). Cyclic variations in $O-C$ residuals can provide indirect evidence for an invisible third companion as in the case of AS Cam (Kozyreva, and Khaliullin, 1999).

This bulletin reports the discovery of cyclic variations in $O-C$ residuals, consistent with the light-time effect on eclipse timing, for DI Her. These variations provide the first indirect evidence of a third body presence in DI Herculis.

The linear ephemerides were calculated according to Khodykin and Volkov (1989):

$$\text{Min I} \quad \mathrm{JD_{hel}} = 2447371.27914(8) + 10\overset{\mathrm{d}}{.}5501680(2) \times N$$

$$\text{Min II} \quad \mathrm{JD_{hel}} = 2447379.39548(9) + 10\overset{\mathrm{d}}{.}5501749(2) \times N$$

The primary (17) and secondary (20) minima (available electronically as `5788-t1.txt`) were analyzed separately to eliminate the small phase variation caused by the apsidal motion $\dot{\omega}$ and/or possible secular decreasing of orbital eccentricity $\dot{e}$ due to third body perturbations. Several photoelectric timings were removed because of unreasonably large residuals: 5 determined by Koch, 4 - by Biro and Hegedus, 2 secondary minima found by Battistini and Scarfe (the errors $0\overset{\mathrm{d}}{.}003$ are too large). We rejected two low accuracy timings obtained with the Fine-Error Sensor on board the IUE satellite, and 3 dubious timings determined by Guinan and Maloney from UBV data of Martynov and Khaliullin, which based on 12, 11, and 24 points only.

Plots of $O-C$ residuals versus orbital phase of the third body were examined for various trial values of the third body period. Generally, the points in the $(O-C)_{I,II}$ diagrams appeared chaotically, indicating random phases relative to the hypothetical orbital period of a third body.

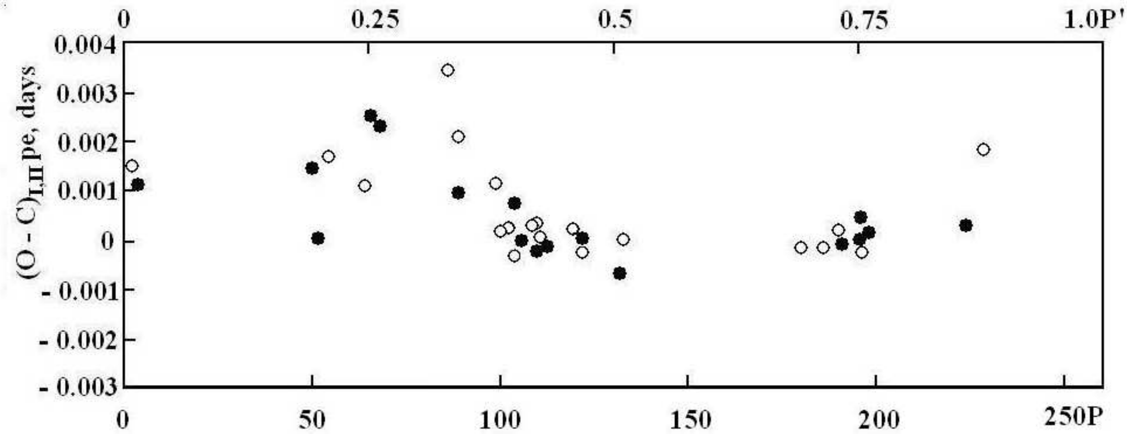

Figure 1. Photoelectric $O - C$ residuals for primary (•) and secondary (○) timings of minima of DI Her convolved with period $P' = 260P$ (7.51 yr).

A unique solution, shown in Fig. 1, was found that provided synchronous deviations for both primary and secondary photoelectric timings of minima with respect to phase: $P' = 260\ P = 2743^{\rm d} = 7.51\,{\rm yr}$. This periodic signal seems to be a light term caused by orbit of a third body. It is interesting to note that the low-precision photographic and visual timing tend to vary with the same period, albeit with more scatter (Fig. 2).

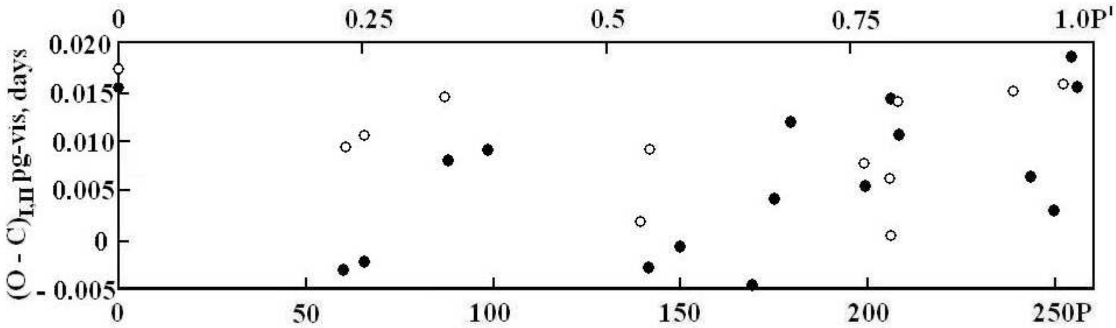

Figure 2. The symbols are the same as in Fig. 1, but for low-precision visual and photographic $O - C$ residuals. A weak tendency for $(O - C)$s to vary with the same period as in Fig. 1 occurs, although the deviations are large.

The asymmetric non-sinusoidal shape of the points (narrow peak, with an abrupt slope change and shallow extended bottom) indicates a large eccentricity e'. The curve corresponding to approximate values of the eccentricity $e' = 0.7$ and the longitude of periastron $\omega' = 330°$ is shown in Fig. 3.

The $O - C$ residuals of the primary and secondary minima vary synchronously with an amplitude about $0\overset{\rm d}{.}0028$, or $240^{\rm s}$, consistent with displacement of the binary along the line of sight at 0.485 AU

The perturbations in the orbital elements of a close binary were found by Khaliullin, Khodykin, and Zakharov (1991) to vary at twice the frequency of the third body orbit. As a result, additional $O - C$ variations of twice the orbiting frequency should occur; moreover, they must be in opposite phase for primary and secondary minima. The residuals between photoelectric $O - C$ residuals and the theoretical curve describing the effect

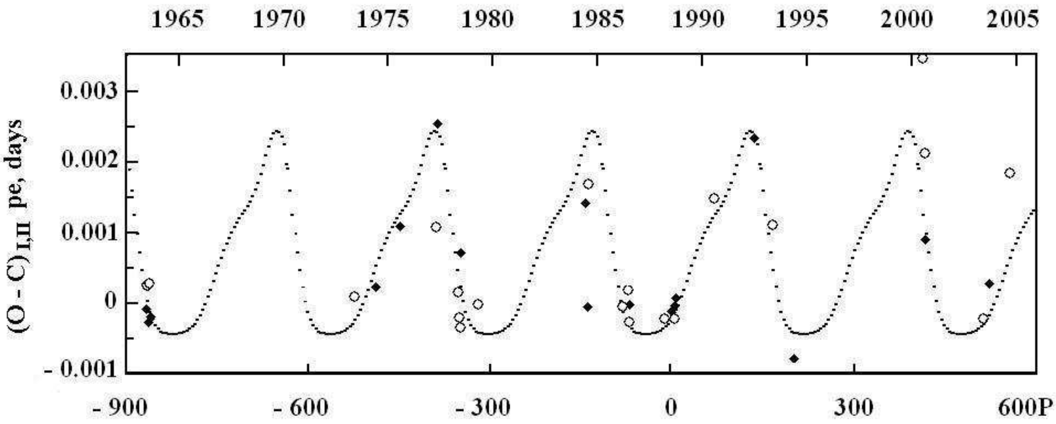

Figure 3. Photoelectric $O-C$ residuals, computed by linear ephemerides from Khodykin and Volkov (1989), versus minima numbers and years. The theoretical light-term curve (dotted) for third body period $P' = 7.51$ yr, eccentricity $e' = 0.7$ and argument of periastron $\omega' = 330°$ is shown.

of the third body $\Delta_{I,II} = (O-C)_{I,II} - LT$ (as shown in Fig. 3) were plotted versus phase assuming a period $0.5P' = 130P = 3.76$ yr (Fig. 4).

There is a weak evidence of approximately sinusoidal oscillations of $(O-C)_I$ and $(O-C)_{II}$ in opposing phase. Altogether, these anomalies in the $O-C$ curve seem to provide convincing evidence of the presence of a third body in DI Her.

Consider now the properties of the third companion. Assuming the total mass of the close binary system (CBS) is $m_1 + m_2 = 9.67 M_\odot$ and a partial luminosity of a third body $L' \leq 0.03$, Guinan and Maloney (1985) obtained the restrictions to its mass: $0.8 M_\odot \leq m' \leq 2.5 M_\odot$. Let D^+ and D^- are the maximal distances of CBS to the visual plane. Then the light-term effect is $LT = (D^+ + D^-)/c$, where c is a light velocity. The projection of an elliptical orbit of the binary onto the line of sight is given by formula (Kopal, 1978)

$$D^+ + D^- = a'(1 - e'^2) \sin i' \frac{m'}{m_1 + m_2 + m'} \sqrt{1 - e'^2 \cos 2\omega'}.$$

Substituting the amplitude of a theoretical curve $0\overset{d}{.}0028$ (Fig. 3), and using the third Kepler's law we obtained the relation:

$$\frac{a' m' \sin i'}{m_1 + m_2 + m'} = \frac{P'^{2/3} m' \sin i'}{(m_1 + m_2 + m')^{2/3}} = 0.3045, \quad \text{or} \quad \sin i' = \frac{0.0794 (9.67 + m')^{2/3}}{m'}.$$

For minimal mass $m' = 0.8 M_\odot$ the semimajor axis $a' = 8.39$ AU and $i' = 28\overset{\circ}{.}4$, then the mutual inclination of orbits is $\varepsilon \geq 90° - i' = 61\overset{\circ}{.}6$. For maximal mass $m' = 2.5 M_\odot$ we have $a' = 8.82$ AU, $i' = 9\overset{\circ}{.}6$, and $\varepsilon \geq 80°$. The space orientation of the third body orbits with masses mentioned above providing observed period difference $\Delta P = P_2 - P_1$ consistent with Khaliullin, Khodykin, and Zakharov (1991). All stellar and orbital parameters presented above are in a good accord with those considered in the numerical predictions of a hierarchical triple model of DI Her. It should be noted that the hypothetical third body perturbs all the orbital elements of close binary, and because of the orientation of its highly inclined orbit with relative to the line of apsides the perturbations in ω are positive

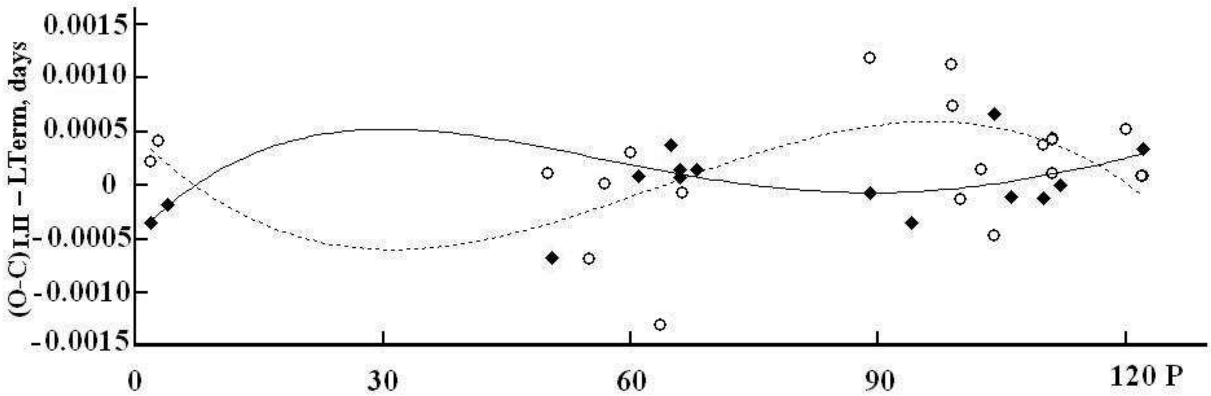

Figure 4. Differences between the observed photoelectric residuals $(O-C)$s and theoretical light-term curve (see Fig. 3.) convolved with a half-period of a third body. The symbols are the same as in the previous figures. The primary and secondary timings of minima seem to vary in opposing phase with double frequency of the third body, in agreement with theoretical predictions for third body perturbations in the framework of the once-averaged three-body problem.

or are close to zero: $(\mathrm{d}\omega/\mathrm{d}t)_{tb} \geq 0$. The third body seems not to affect considerably to the apsidal motion of the close pair. It turns out that the secondary minima phase's shift in DI Her is provided mainly by slow decreasing of the orbital eccentricity: $(\mathrm{d}e/\mathrm{d}t)_{tb} < 0$, as it was determined by Khodykin and Vedeneyev (1997) on the basis of comparison of two light curve solutions. Therefore, further observations of this unique eclipsing system are needed to improve both the values of the orbital elements and their possible long-term or secular perturbations.

The most reliable and direct confirmation of a third body presence in DI Herculis would be the observations of a faint companion. As it was noted in Khodykin, Zakharov and Andersen (2004), interferometric observations in the infrared range (H and K bands) are more preferable in this case.

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