Ole Rømer’s method still on the stage: the study of two bound eclipsing binaries in quintuple system V994 Her

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ABSTRACT

More than three hundred years ago, Ole Rømer measured the speed of light purely by observing the periodic shift of the observed eclipse arrival times of Jupiter’s moons arising from the varying Earth–Jupiter distance. The same method of measuring the periodic modulation of delays is still used in astrophysics. The ideal laboratories for this effect are eclipsing binaries. The unique system V994 Her consists of two eclipsing binaries orbiting each other. However, until now it was not certain whether these were gravitationally bound and what their orbital period was. We show that the system is in fact quintuple and the two eclipsing binaries are orbiting each other with a period of about 6.3 yr. This analysis was performed only through studying the periodic modulation of the two periods: during the periastron passage one binary has an apparently shorter period, while the other one is longer, exactly as required by theory. Additionally, it was found that both inner eclipsing pairs orbit with slightly eccentric orbits, undergoing slow apsidal motion with a period of the order of centuries.

Key words: binaries: eclipsing – binaries: visual – stars: fundamental parameters – stars: individual: V994 Her.

1 INTRODUCTION

Eclipsing binaries are ideal astrophysical laboratories, and even after more than a century of intensive photometric and spectroscopic monitoring, they still represent the best method by which to determine the masses, radii and luminosities of stars. Thanks to modern ground- (and space-) based telescopes we are able to discover these objects in other galaxies and to apply the same methods as used in our Solar neighbourhood. One very specific method is the analysis of their orbital periods. Using the precise times of minima (centres of eclipses of the components), we can determine whether a system’s period is constant, accelerating, decelerating or periodically alternating. If we detect a periodic shifting of the times of minima, we determine that there is an additional component in the system, which is orbiting around the barycentre with the eclipsing pair. If the system is moderately inclined to the observer, the light from the eclipsing binary needs alternately more and less time to reach us as it moves away from and closer to the observer as it orbits the unseen component. This method is in fact the same as was used in the 17th century by Ole Rømer when measuring the finite speed of light using the eclipse times of Jupiter’s moons (see e.g. Cohen 1940).

2 THE SYSTEM V994 HER

When dealing with eclipsing binaries, we have a few advantages. First of all, there are currently thousands of eclipsing binaries known. Moreover, the time baseline of observations for some eclipsing binaries is more than a century long. Importantly, the observations are very easy to obtain, even with small telescopes.

This is the case for one very interesting eclipsing system, V994 Her (HD 170314, ADS 11373 AB; $V$ = 7.00 mag). In 2008 it was discovered (Lee et al. 2008) that V994 Her was the first (at that time) system consisting of two eclipsing binaries. From one point on the sky we can see two different sets of eclipses, one with a period of $P_A = 2.08$ d while the other has a period of $P_B = 1.42$ d. The star was also observed with the Hipparcos satellite (Perryman et al. 1997), however the strange eclipsing behaviour was missed for about 15 years. A complete study of this interesting system was made (Lee et al. 2008), also on the basis of new spectroscopic observations, yielding a set of physical parameters of all four eclipsing components. This study showed that the system consists of two pairs: A (B8V + A0V) and B (A2V + A4V). All components are well-detached and still located on the main sequence. Both orbits are slightly eccentric.

On the other hand, one important question arises: whether the two eclipsing components comprise one gravitationally bounded system or whether the system is only an optical binary. The mutual orbital period of the two pairs can be very long and long-time monitoring is rather time-consuming. The system V994 Her also
contains one more distant component observed interferometrically (Mason et al. 2001), the period of which was estimated at about a few thousand years. Therefore, the authors (Lee et al. 2008) speculated that the two eclipsing pairs could be identified with these two visual components. For a brief review of quadruple systems with two eclipsing binaries, see Cagaš & Pejcha (2012). Currently we know only six such systems: BV + BW Dra, V994 Her, CzeV343 (Cagaš & Pejcha 2012), KIC 4247791 (Lehmann et al. 2012), TYC 3807-759-1 (Lohr et al. 2013) and OGLE LMC-ECL-16549 (Graczyk et al. 2011); see Table 1 for details.

### Table 1. List of currently known double eclipsing systems.

| System Name | Other designation | RA J2000.0 | Dec. J2000.0 | V (mag) | Period A (d) | Period B (d) | Type  |
|-------------|------------------|------------|-------------|--------|--------------|--------------|-------|
| OGLE LMC-ECL-16549 | OGLE LMC-SC3 179761 | 05 28 09.41 | −69 45 28.60 | 18.216 | 0.818 033 | 0.818 033 | EA + EW |
| CzeV343 | GSC 02405-01886 | 05 48 24.01 | +30 57 03.60 | 13.679 | 1.209 373 | 0.806 931 | EA + EA |
| TYC 3807-759-1 | GSC 03807-00759 | 09 30 10.75 | +53 38 59.80 | 9.538 | 1.305 545 | 0.227 715 | EA + EW |
| BV Dra | HIP 74370 | 15 11 50.36 | +61 51 25.25 | 8.040 | 0.350 067 | 0.292 165 | EW + |
| BW Dra | HIP 74368 | 15 11 50.09 | +61 51 41.16 | 8.334 | 0.292 165 | 0.292 165 | + |
| V994 Her | GSC 02110-01170 | 18 27 45.89 | +24 41 50.66 | 7.001 | 2.083 269 | 1.420 038 | EA + EA |
| KIC 4247791 | TYC 3124-1500-1 | 19 08 39.57 | +39 22 36.96 | 11.645 | 4.100 871 | 4.049 732 | EA + EA |

3 ANALYSIS

Here we introduce an original approach of delay-time variations of both eclipsing pairs, showing that the system is in fact quintuple and the two inner pairs are orbiting around each other with a much shorter period. We obtained many new observations of both pairs, as well as re-analysing Hipparcos and All-Sky Automated Survey (ASAS: Pojmanski 2002) photometry. The individual times of minima are presented in the Appendix (Table A1). These data were analysed simultaneously in a combined approach consisting of fitting both orbits together using a well-known method usually called the ‘light-time effect’ or ‘light-travel-time effect’ (hereafter LTTE), described elsewhere (e.g. Irwin 1959; Mayer 1990).

This method has been used for dozens of binaries in the past; however, V994 Her is the first eclipsing binary system in which the method can be applied to both binaries. The main advantage of this approach is that both eclipsing pairs serve as strictly periodic ‘stellar lighthouses’, the apparent period changes of which can be studied.

We used our new code for computing this combined approach of deriving both inner orbits (their periods and apsidal motion), together with the long orbit of mutual motion of the two pairs. Altogether 15 parameters were fitted, using all available times-of-minima observations (for A and B pairs: (25 + 36) published minima together with (18 + 17) new unpublished data points).

In Fig. 1 we plot the observed minus calculated (O − C) diagrams for A and B pairs, showing their period changes (the y-axis) with respect to time (the x-axis). In these plots, positive y values indicate that the detected signal occurs later while negative values indicate earlier detection than predicted from strictly periodic linear behaviour. As one can see, rapid period changes near periastron passage are clearly visible for both pairs. Most of the parameters for the LTTE fits for A and B are mainly the same. The exceptions are the omega angles (the argument of periastron, $\omega_A = \omega_B + 180^\circ$) and the $(O - C)$ amplitudes ($A_A$ and $A_B$, see below). The long-term modulation arises from the apsidal motion of the inner orbits, because both are slightly eccentric. For the final parameters of the fit see Table 2.

### Table 2. V994 Her: final parameters of the fits for A and B pairs.

| Parameter | Unit | Pair A | Value | Error | Value | Error |
|-----------|------|--------|-------|-------|-------|-------|
| JD$_{D_0}$ | HJD  | 2448501.1302 | 0.0110 | 2455375.4555 | 0.0062 |
| $P$ | Day  | 2.0832691 | 0.0000038 | 1.4200381 | 0.0000051 |
| $e$ | 0.0311 | 0.0074 | 0.1258 | 0.0032 |
| $\omega$ | Deg  | 16.0 | 4.2 | 313.8 | 2.8 |
| $\dot{\omega}/d\tau$ | Deg/Cycle | 0.0032 | 0.0013 | 0.0124 | 0.0010 |
| $\rho_3$ | Year | 6.33 | 0.56 | 6.33 | 0.56 |
| $T_0$ | HJD  | 2456067 | 199 | 0.0102 | 0.0042 |
| $A$ | Day  | 256.2 | 24.1 | 76.2 | 24.1 |
| $\omega_3$ | Deg  | 0.747 | 0.182 | 0.747 | 0.182 |

4 RESULTS

The main result of our analysis is the discovery that the two eclipsing pairs orbit around each other and also show detectable period modulation, together with slow apsidal motion. The period of motion of the apsides for pair A resulted in about (627 ± 439) yr, while for pair B the period is about (113 ± 10) yr.

![Figure 1. Plot of the O–C diagrams of both pairs. The dots stand for primary, the open circles for the secondary minima; the bigger the symbol, the higher the weight. The dash–dotted lines (red in the online article) indicate the LTTE fit, while the lower and upper curves (black and blue in the online article, respectively) represent the final fit (LTTE plus apsidal motion).](https://academic.oup.com/mnras/article-abstract/429/4/3472/1019545/for-29July2018)
From the parameters of LTTE we determine the semi-major axis of the LTTE orbit and, using the distance from the *Hipparcos* satellite (Perryman et al. 1997) of $r = (3.90 \pm 0.74)$ mas, we also derive the angular separation of the two eclipsing binaries on the sky. This resulted in an angular separation of $\Delta \alpha_{12} = (27.6 \pm 6.8)$ mas, which is well within the limits for modern stellar interferometers; hence its discovery is expected soon. Moreover, this indicates that the previously mentioned star at $\sim 1$ arcsec away is another star and not the eclipsing one as suggested by Lee et al. (2008). Membership of this distant component to the eclipsing pairs was suggested via similar proper motions: see e.g. the Washington Double Star (WDS) catalogue (Mason et al. 2001). Thus we have a quintuple star system. We currently know only 20 quintuples (Eggleton & Tokovinin 2008).

From the parameters of LTTE one can also calculate the mass function of the distant body:

$$f(m_3) = \frac{(m_3 \sin i)^3}{(m_1 + m_2 + m_3)^2} = \frac{1}{p_3^2} \left[ \frac{173.15 A}{\sqrt{1 - e_3^2 \cos^2 \omega}} \right]^3,$$

see e.g. Mayer (1990). Using the masses of both pairs as determined by Lee et al. (2008), we can also calculate the inclination between the eclipsing binary and the LTTE orbit. If we label the inclination between the orbit of pair A and the LTTE orbit as $i_A$ and vice versa for B, then one can derive

$$\frac{m_A}{\sin i_A} = \frac{m_B}{\sin i_B}.$$

From this equation and the mass function found from the LTTE, we can directly determine the inclination between the orbits. This results in $i_A = 37.1^\circ \pm 7.3^\circ$, while $i_B = 36.8^\circ \pm 6.8^\circ$. Evidently the inclinations derived from both A and B pairs are comparable and hence we know the absolute orientation of the orbit in space (see Fig. 2). This is the first time that the mutual inclination between the orbits of the eclipsing pairs has been measured. Only about twenty other systems with unambiguous mutual inclinations between the eclipsing and outer orbits are known; see e.g. O’Brien et al. (2011).

5 DISCUSSION AND CONCLUSIONS

V994 Her is an interesting target for a future study. However, there still remain some open questions. These include, for example, detection of the distant component in the spectra and determination of its orbital period. Additionally, some of the orbital elements of the 6.3-yr orbit are still unknown, for instance the longitude of the ascending node $\Omega$. The long-term evolution of outer and inner orbits should be studied over longer time-scales. However, detecting the mutual motion of the two eclipsing pairs is a unique discovery and we still hope to find similar configurations in other multiple systems also.

Surprisingly, for this analysis there was no need of spectroscopic observations of the radial velocities of the long-period system, which would be rather complicated given the current observing-time allocations on larger telescopes needed for such studies. It is noteworthy that all of our new observations were carried out with telescopes of 20-cm aperture or smaller by an amateur astronomer. As clearly demonstrated by this study, scientifically valuable results can be secured with small telescopes by amateur observers.

ACKNOWLEDGMENTS

The data used for the analysis are presented in the Appendix section in Table A1. We thank the ASAS team for making all of the observations easily available to the public. We also thank Associate Professor Marek Wolf for sending us his photometric data. Professor Ed Guinan is also gratefully acknowledged for his refereeing comments, which significantly improved the manuscript. This work was supported by the Czech Science Foundation grant no. P209/10/0715, by the research programme MSM0021620860 of the Czech Ministry of Education and by the grant UNCE 12 of the Charles University in Prague. This research has made use of the Washington Double Star Catalog maintained at the US Naval Observatory, the SIMBAD data base, operated at CDS, Strasbourg, France and NASA’s Astrophysics Data System Bibliographic Services.

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1 http://ad.usno.navy.mil/wds/
### Table A1. Heliocentric minima of V994 Her.

| HJD – 240 0000 | Error | Pair | Type | Filter | Observer/Reference |
|----------------|-------|------|------|--------|--------------------|
| 48480.29371    | 0.00125 | A    | p    | Hp     | Hipparcos – this paper |
| 48481.36885    | 0.00169 | A    | s    | Hp     | Hipparcos – this paper |
| 52488.4984     | 0.0006  | A    | p    | R      | Borkovits et al. (2002) |
| 52488.4994     | 0.0001  | A    | p    | V      | Borkovits et al. (2002) |
| 52488.4997     | 0.0003  | A    | p    | B      | Borkovits et al. (2002) |
| 52748.9041     | 0.0010  | A    | p    | V      | San Pedro Martir, M.Wolf – this paper |
| 52836.4002     | 0.0002  | A    | p    | R      | Borkovits et al. (2004) |
| 52937.4701     | 0.0001  | A    | s    | R      | Biro et al. (2006) |
| 53319.71928    | 0.00239 | A    | p    | V      | ASAS – this paper |
| 53320.80295    | 0.00542 | A    | s    | V      | ASAS – this paper |
| 53904.99882    | 0.00169 | A    | s    | V      | Lee et al. (2008) |
| 53909.26748    | 0.00089 | A    | p    | B      | Lee et al. (2008) |
| 53909.26932    | 0.00072 | A    | p    | V      | Lee et al. (2008) |
| 54290.517      | 0.0010  | A    | p    | V      | Borkovits et al. (2011) |
| 54314.5204     | 0.0008  | A    | s    | V      | Borkovits et al. (2011) |
| 54315.522      | 0.0010  | A    | p    | V      | Borkovits et al. (2011) |
| 54360.3524     | 0.0004  | A    | s    | V      | Borkovits et al. (2011) |
| 54361.3570     | 0.0002  | A    | p    | V      | Borkovits et al. (2011) |
| 54383.2729     | 0.0003  | A    | s    | V      | Borkovits et al. (2011) |
| 54610.3494     | 0.0008  | A    | s    | BVR    | Borkovits et al. (2011) |
| 54654.08476    | 0.00256 | A    | s    | V      | ASAS – this paper |
| 54713.4349     | 0.0014  | A    | p    | BVR    | Borkovits et al. (2011) |
| 55131.4026     | 0.00068 | A    | p    | R      | Zasche et al. (2011) |
| 55314.4827     | 0.00046 | A    | s    | I      | Zasche et al. (2011) |
| 55315.4896     | 0.00042 | A    | p    | I      | Zasche et al. (2011) |
| 55399.48381    | 0.00225 | A    | s    | I      | Zasche et al. (2011) |
| 55413.40450    | 0.0010  | A    | p    | VRI    | Brat et al. (2011) |
| 55641.55985    | 0.00012 | A    | s    | R      | Zasche et al. (2011) |
| 55642.56748    | 0.00042 | A    | p    | R      | Zasche et al. (2011) |
| 55688.39802    | 0.00029 | A    | p    | R      | Zasche et al. (2011) |
| 55691.56016    | 0.00011 | A    | s    | I      | Zasche et al. (2011) |
| 55740.47826    | 0.00135 | A    | p    | BVRI   | J.Tmka – var.astro.cz |
| 55993.62195    | 0.00007 | A    | s    | I      | R.Uhlaf – this paper |
| 56041.52826    | 0.00101 | A    | s    | I      | R.Uhlaf – this paper |
| 56064.44435    | 0.00049 | A    | s    | C      | R.Uhlaf – this paper |
| 56065.45050    | 0.00159 | A    | p    | R      | R.Uhlaf – this paper |
| 56138.36968    | 0.00059 | A    | p    | I      | R.Uhlaf – this paper |
| 56162.36395    | 0.00040 | A    | s    | R      | R.Uhlaf – this paper |
| 56163.36806    | 0.00026 | A    | p    | R      | R.Uhlaf – this paper |
| 56187.36470    | 0.00076 | A    | s    | IC     | R.Uhlaf – this paper |
| 56188.37316    | 0.00054 | A    | p    | I      | R.Uhlaf – this paper |
| 56210.28311    | 0.00180 | A    | s    | C      | R.Uhlaf – this paper |
| 56211.28403    | 0.00107 | A    | p    | C      | R.Uhlaf – this paper |
| 56234.20460    | 0.00183 | A    | p    | R      | R.Uhlaf – this paper |
| HJD – 240 0000 | Error | Pair | Type | Filter | Observer/Reference |
|---------------|-------|------|------|--------|-------------------|
| 54283.4131    | 0.0001| B    | p    | V      | Borkovits et al. (2011) |
| 54290.515     | 0.003 | B    | p    | V      | Borkovits et al. (2011) |
| 54298.3787    | 0.0002| B    | s    | V      | Borkovits et al. (2011) |
| 54300.4457    | 0.0004| B    | p    | V      | Borkovits et al. (2011) |
| 54307.5424    | 0.0005| B    | p    | V      | Borkovits et al. (2011) |
| 54332.457     | 0.001 | B    | s    | V      | Borkovits et al. (2011) |
| 54334.523     |       | B    | p    | V      | Borkovits et al. (2011) |
| 54347.3084    | 0.0003| B    | p    | V      | Borkovits et al. (2011) |
| 54364.3439    | 0.0003| B    | p    | V      | Borkovits et al. (2011) |
| 54374.2829    | 0.0007| B    | p    | V      | Borkovits et al. (2011) |
| 54618.5160    | 0.0013| B    | p    | V      | Borkovits et al. (2011) |
| 54650.5478    | 0.0030| B    | s    | V      | Borkovits et al. (2011) |
| 54652.6262    | 0.0068| B    | p    | V      | ASAS – this paper |
| 54653.3886    | 0.0013| B    | s    | V      | Borkovits et al. (2011) |
| 54699.4777    | 0.0014| B    | p    | V      | Borkovits et al. (2011) |
| 55375.40806   | 0.00037| B   | p    | I      | Zasche et al. (2011) |
| 55392.44365   | 0.0009| B    | p    | RI     | Brat et al. (2011) |
| 55392.44779   | 0.00055| B   | p    | I      | Zasche et al. (2011) |
| 55397.49810   | 0.00032| B   | s    | I      | Zasche et al. (2011) |
| 55424.47871   | 0.00079| B   | s    | R      | Zasche et al. (2011) |
| 55654.51845   | 0.00097| B   | s    | C      | Zasche et al. (2011) |
| 55681.50533   | 0.00036| B   | s    | R      | Zasche et al. (2011) |
| 55683.15108   | 0.00024| B   | p    | R      | Zasche et al. (2011) |
| 55691.44530   | 0.00013| B   | s    | I      | Zasche et al. (2011) |
| 55779.48535   | 0.00125| B   | s    | R      | Zasche et al. (2011) |
| 55799.36956   | 0.00033| B   | s    | I      | Zasche et al. (2011) |
| 55821.29667   | 0.00095| B   | p    | RV     | L.Šmelcer – var.astro.cz |
| 56026.60079   | 0.00063| B   | s    | C      | R.Uhlař – this paper |
| 56048.52317   | 0.00028| B   | p    | R      | R.Uhlař – this paper |
| 56058.46317   | 0.00020| B   | p    | I      | R.Uhlař – this paper |
| 56073.46347   | 0.00029| B   | s    | R      | R.Uhlař – this paper |
| 56102.48296   | 0.00058| B   | p    | R      | R.Uhlař – this paper |
| 56127.42060   | 0.00062| B   | s    | R      | R.Uhlař – this paper |
| 56136.55813   | 0.00106| B   | p    | R      | R.Uhlař – this paper |
| 56154.40165   | 0.00039| B   | s    | C      | R.Uhlař – this paper |
| 56156.44467   | 0.00159| B   | p    | C      | R.Uhlař – this paper |
| 56181.37945   | 0.00018| B   | s    | R      | R.Uhlař – this paper |
| 56230.28075   | 0.00063| B   | p    | C      | R.Uhlař – this paper |

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