Analysis of eight binaries in Lyncis constellation: RV Lyn, AA Lyn, AH Lyn, CD Lyn, CF Lyn, DR Lyn, EK Lyn, and FS Lyn.

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Abstract

The available photometry mainly from the WASP database was used for the first light curve analysis of eight eclipsing binary systems located in the Lyncis constellation: RV Lyn, AA Lyn, AH Lyn, CD Lyn, CF Lyn, DR Lyn, EK Lyn, and FS Lyn. Most of these eclipsing stars are detached ones, having the orbital periods from 0.54 to 2.3 days. For the systems AA Lyn and CF Lyn a non-negligible third light was detected during the light curve solution. Moreover, 284 new times of minima for these binaries were derived, trying to identify the period variations. For the system CD Lyn a hypothetical third body was detected with the period of about 59 yr.

Key words: stars: binaries: eclipsing, stars: fundamental parameters

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1 Introduction

The crucial role of the eclipsing binaries in the nowadays astrophysics is evident. The eclipsing binary systems (hereafter EB) are being used for the most accurate determination of the basic parameters such as stellar masses and radii, as distance indicators, or can serve as classical celestial mechanics laboratories. Nowadays, we can even test the stellar structure models outside of our Galaxy, see e.g. Ribas (2004). Additionally, also the hidden components can be studied via the long term observations of the binaries as well as study the dynamical effects in such multiple systems (Rappaport et al., 2013). Due
to all of these reasons the photometric monitoring and analysis of the light
curves of selected eclipsing binaries still presents a fruitful contribution to the
stellar astrophysics.

However, the available photometry for many interesting eclipsing binaries ex-
ists, but some of these EBs were still not analysed. Therefore, we decided to
use mainly the Super WASP photometry ([Pollacco et al., 2006]) for a light
curve analysis and derivation of new minima times for such systems, which
were not studied before and their light curve solution is missing.

2 Analysis

The selection criteria for the binaries included in our study were rather straight-
forward. We focused on the unstudied systems in the constellation Lyncis.
Only such binaries with known orbital periods were chosen, having no light
curve solution published up to now, have enough data points for the analy-
sis and also have several published times of minima. The last point was
checked via an online archive of minima times observations, a so-called $O-C$
gateway\footnote{http://var.astro.cz/ocgate/}, see Paschke & Bráť (2006). Due to the very good time coverage
provided by the Super WASP survey we used this database for the whole
analysis of the light curve. All of the studied systems are located in the Lyncis
constellations and are of moderate brightness ($9.3 \text{ mag} < V < 14.2 \text{ mag}$ in
maximum) and with the orbital periods ranging from 0.54 to 2.3 days.

For the analysis of the light curve we used the PHOEBE program, ver. 0.31
([Prša & Zwitter, 2003]), which is based on the algorithm by Wilson & Devinney
(1971) and its later modifications. Due to having rather limited informa-
tion about the stars, some of the parameters have to be fixed for the light curve
(hereafter LC) solution. At first, the "Detached binary" mode (in Wilson
& Devinney mode 2) was assumed for computing. If some of the compon-
ents overfills its Roche lobe, we switched to some other configuration. The
limb-darkening coefficients were interpolated from tables by van Hamme (see
van Hamme 1993), and the linear cosine law was used. The values of the grav-
ity brightening and bolometric albedo coefficients were set at their suggested
values for convective or radiative atmospheres (see Lucy 1968). Therefore, the
quantities which could be directly calculated from the LC are the following:
the relative luminosities $L_i$, the temperature of the secondary $T_2$, the incli-
nation $i$, and the Kopal’s modified potentials $\Omega_1$ and $\Omega_2$. The synchronicity
parameters $F_1$ and $F_2$ were also fixed at values of 1. The value of the additional
third light contribution $l_3$ was also computed as a free parameter, which some-
times resulted in a non-negligible value. Its value cannot be directly compared
with the two luminosities $L_1$ and $L_2$, but it is being compared with the output fluxes $l_1$ and $l_2$ near the quadratures. And finally, the linear ephemerides were calculated using the available minima times for a particular system. For the LC modelling, the number of grid points on the components’ surfaces were set to (40,30).

The problem with the mass ratio derivation arose in most of the studied systems. We started our analysis assuming the mass ratio $q = 1$, because no spectroscopy for these selected systems exists, and for detached EBs the LC solution is almost insensitive to the photometric mass ratio (see, e.g. Terrell & Wilson [2005]). However, because for some systems this approach led to incorrect results, hence we used an alternative method of deriving the mass ratio following the method e.g. by Graczyk (2003). It uses the assumption that both components are located on the main sequence (which is necessarily not true) and the computed mass ratio is being directly derived from the individual luminosities. Therefore, having only limited information in photometry (one filter), some of the individual fitted parameters suffer from strong correlations between each other. Hence, we have to emphasize once again that the presented solution is still only very preliminary yet and only further spectroscopic observations of these systems will be able to reveal their true nature and the physical parameters with higher conclusiveness.

There also arises the problem with the primary temperature $T_1$. This value has to be fixed during the whole computing process. When the spectral type is not available, the photometric indices were used for the rough estimation of the primary temperature (using the tables from Pecaut & Mamajek (2013) and the online web site[2]). However, for some of the systems this approach was not so straightforward due to the fact that for one star many different photometric indices exist, and moreover their interstellar reddening is not known. For the systems CD Lyn, CF Lyn, DR Lyn, EK Lyn, and FS Lyn some spectral estimations exist in the literature, while for RV Lyn, AA Lyn, and AH Lyn only the photometric indices are available. Hence, we collected all available indices and derived the particular spectral estimations. From these spectral types we eliminated the higher and lower outliers and from the rest some best value was estimated (or its upper value due to the unknown interstellar extinction).

With the final LC analysis, we also derived many times of minima for a particular system, using a method as presented in Zasche et al (2014). The template of the LC was used to fit the photometric data from the Super WASP survey. This set of minima times was then combined with the already published minima mostly taken from the $O - C$ gateway (Paschke & Brád, 2006).

[2] http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt
Table 1
The light-curve parameters as derived from our analysis.

| Parameter | RV Lyn | AA Lyn | AH Lyn | CD Lyn |
|-----------|--------|--------|--------|--------|
| JD<sub>0</sub> − 240000 | 54409.5592 ± 0.0005 | 54056.6671 ± 0.0008 | 54091.5447 ± 0.0010 | 54504.5198 ± 0.0004 |
| P [d] | 2.307640 ± 0.0000004 | 0.5613884 ± 0.0000003 | 1.01641142 ± 0.000008 | 2.2747194 ± 0.000008 |
| i [deg] | 84.91 ± 0.40 | 72.82 ± 0.46 | 88.75 ± 0.20 | 81.93 ± 0.70 |
| Type | Detached | Semidetached | Detached | Detached |
| T<sub>1</sub> [K] | 6700 (fixed) | 5600 (fixed) | 6500 (fixed) | 6800 (fixed) |
| T<sub>2</sub> [K] | 4287 ± 80 | 3760 ± 120 | 6074 ± 52 | 450 ± 48 |
| Ω<sub>1</sub> | 5.243 ± 0.081 | 4.984 ± 0.118 | 5.455 ± 0.037 | 4.946 ± 0.016 |
| Ω<sub>2</sub> | 3.785 ± 0.024 | 3.535<sup>b</sup> | 5.588 ± 0.035 | 4.502 ± 0.013 |
| L<sub>1</sub>/(L<sub>1</sub> + L<sub>2</sub>) [%] | 88.8 ± 1.3 | 86.3 ± 4.5 | 64.3 ± 1.3 | 94.4 ± 2.7 |
| L<sub>2</sub>/(L<sub>1</sub> + L<sub>2</sub>) [%] | 11.2 ± 0.8 | 13.7 ± 1.3 | 35.7 ± 1.1 | 5.6 ± 2.1 |
| f<sub>3</sub> [%]<sup>a</sup> | 0.0 | 7.6 ± 2.1 | 0.0 | 0.0 |
| R<sub>1</sub>/a | 0.210 ± 0.011 | 0.253 ± 0.021 | 0.219 ± 0.008 | 0.228 ± 0.040 |
| R<sub>2</sub>/a | 0.268 ± 0.010 | 0.376 ± 0.018 | 0.191 ± 0.007 | 0.163 ± 0.031 |

Note 1<sup>a</sup> - given at the orbital phase of 0.25, <sup>b</sup> - not fitted during computation.

3 The individual systems

3.1 RV Lyn

The system RV Lyn (also 2MASS J06561142+5051455) is a typical system in our sample of stars. There were published only a few times of minima for this eclipsing binary and its orbital period of about 2.3 days is known. Nothing more about this system was published, no analysis of its light curve as well as no spectroscopic study can be found in published papers. We can only roughly estimate its spectral type from the color indices, hence we fixed the primary temperature at a value of 6700 K for the whole fitting process.

The Super WASP photometry revealed that it is a detached system, having very deep primary minimum (of about 2 magnitudes) and very shallow secondary one. Therefore, the PHOEBE code was used to fit the WASP data and the LC is presented in Fig. 1 while the LC parameters are given in Table 1. As one can see, both components are rather different from each other and the primary dominates with its luminosity in the system. No third light was detected in the LC solution.

Due to very shallow secondary minima, we used only the primary ones for the period analysis. Despite quite a lot WASP data points only three primary minima have been derived. The resulting O − C diagram is shown in Fig. 2. We can see there that some long-period modulation of the orbital period is probably present in the system. This can naturally be explained by the mass transfer between the components, but only further investigation would be able
to prove this hypothesis.

3.2 AA Lyn

The eclipsing binary AA Lyn (also 2MASS J07504631+4134065) is rather faint star, which was also not studied before. Kinman et al. (1982) included the star into their survey of RR Lyrae stars, but with the note that it is an eclipsing binary with the period of about 0.56 days. Since then no analysis of AA Lyn was carried out.

For the LC fitting we assumed the primary temperature to be of 5600 K (it is the coolest star in our sample) and used the WASP photometry for the LC analysis. The result is plotted in Fig. 3 and the LC parameters as resulted from PHOEBE are given in Table 1. This is the only system which resulted in semidetached configuration. One can see that the primary is the dominant source in the system, but there also arose a non-negligible contribution of the third light. However, its origin is still questionable because there are two close companions to AA Lyn (see Bonnarel et al. 2000) at the distances of a few arcseconds only.

Because of shallow secondary minimum, only the primary ones were used for a period analysis. In our Fig. 4 there are plotted the new times of minima together with the already published ones. Obviously, there is no variation in the times of minima, or our dataset is still too poor for any such detection.

3.3 AH Lyn

The system AH Lyn (also 2MASS J08421824+3711051) is the binary which was also not studied before, therefore we included it into our sample of stars. AH Lyn was included into the study of RR Lyrae stars (Kinman et al. 1982) like AA Lyn and the authors correctly derived its orbital period to be of about 1.016 days. Since then only several publications with the times of minima were published.

For the light curve analysis we fixed the primary temperature to $T_1 = 6500$ K in agreement with the photometric indices of the star. The WASP photometry shows us that both the eclipses are rather deep and symmetrically shaped. The final parameters of the LC fitting are given in Table 1 while the LC plot is shown in Fig. 5. The system is well detached, both components are rather similar to each other, and no third light was detected in the LC solution.

For the period analysis we derived 60 new minima times (both primary and
secondary) from the WASP data covering almost 500 days. With the already published ones the complete dataset is plotted in Fig. 6, but no visible variation can be seen there.

3.4 CD Lyn

The star named CD Lyn (also HIP 37615) is relatively bright star, and it is also the most frequently studied one. There exist two dedicated studies on CD Lynics, Baldwin et al. (2000) and Meyer (2002), but these are only remarks on their observations of CD Lyn photometrically, with no LC analysis. Moreover, Baldwin et al. (2000) presented the orbital period of 4.549 days, abandoning the original 2.27 days period, arguing that there is no curvature near the quadrature. But as we can see from our analysis, the correct period is 2.27 days for sure.

The LC fitting of the Super WASP data using the PHOEBE programme was using the assumption of $T_1 = 6800$ K, because its spectral type was derived as F2 by Hill & Schilt (1952). The final fit of the LC is given in Fig. 7, and the LC parameters are written in Table 1. As one can see, the secondary minima have much less depth, but definitely cannot be taken as a noise. Hence, the main finding as published by Baldwin et al. (2000) has to be reconsidered. Another interesting finding about this star is the asymmetric shape of its light curve, hence we have to use a hypothesis of a star spot on the surface of primary (see Fig. 9). However, it seems like the shape of the LC is changing in time, maybe due to the moving spot or some other photospheric activity of the star(s).

The period analysis of CD Lyn was done using the already published data as well as our new data points (altogether eight new primary minima from the WASP survey). The result is shown in Fig. 8 where we also used the hypothesis of the third body orbiting around a common barycenter with the eclipsing pair (see e.g. Irwin 1959 or Mayer 1990). This approach was used because it produces much better result than the linear or quadratic ephemerides term for description of the period variation. The variation of such a component has the period of about 59 years and the amplitude of about 0.03 days in the O – C diagram. From our LITE fit we also predicted that such a body should present at least of about 2.5% of the total luminosity, but our LC solution results in zero value. Therefore, for a final confirmation of any such body in the system one needs much more data, so our presented solution is still just a hypothesis yet.
Table 2
The light-curve parameters as derived from our analysis.

| Parameter | CF Lyn | DR Lyn | EK Lyn | FS Lyn |
|-----------|--------|--------|--------|--------|
| JD - 2400000 | 54069.6974 ± 0.0007 | 54502.5720 ± 0.0026 | 54068.6844 ± 0.0005 | 54142.4354 ± 0.0003 |
| P [d] | 1.3853727 ± 0.0000029 | 1.7808806 ± 0.0000011 | 2.2355353 ± 0.000093 | 0.5400052 ± 0.0000030 |
| i [deg] | 86.31 ± 0.79 | 85.96 ± 0.69 | 83.13 ± 0.98 | 63.50 ± 0.94 |
| q = M2/M1 | 0.85 ± 0.06 | 0.74 ± 0.02 | 0.42 ± 0.03 | 0.71 ± 0.09 |
| T1 [K] | 6150 (fixed) | 6690 (fixed) | 8840 (fixed) | 7100 (fixed) |
| T2 [K] | 5100 ± 72 | 4370 ± 72 | 5325 ± 110 | 5019 ± 66 |
| Ω1 | 4.209 ± 0.022 | 5.100 ± 0.027 | 4.828 ± 0.040 | 3.292 ± 0.025 |
| Ω2 | 7.269 ± 0.046 | 3.580 ± 0.010 | 4.533 ± 0.027 | 3.297 ± 0.029 |
| L1/(L1 + L2) [%] | 92.5 ± 0.8 | 84.6 ± 0.8 | 96.9 ± 3.7 | 87.2 ± 1.7 |
| L2/(L1 + L2) [%] | 7.5 ± 0.3 | 15.4 ± 0.4 | 3.1 ± 1.2 | 12.8 ± 0.9 |
| l3 [%] a | 18.1 ± 1.0 | 0.0 | 3.7 ± 0.7 | 0.0 |
| R1/a | 0.305 ± 0.012 | 0.231 ± 0.011 | 0.228 ± 0.021 | 0.402 ± 0.027 |
| R2/a | 0.140 ± 0.009 | 0.310 ± 0.008 | 0.127 ± 0.034 | 0.342 ± 0.024 |

Note 2 a - given at the orbital phase of 0.25

3.5 CF Lyn

Another rather bright target is CF Lyn (also HIP 37748), which has the orbital period of about 1.4 days, but was also not studied in detail neither photometrically, nor spectroscopically. Only its spectral type was classified as F8 by Heckmann (1975).

We used the WASP photometry for the light curve modelling and the assumption of the 6150 K for the primary temperature. As we can see from Fig. 10, the star has relatively shallow total eclipses, which could indicate large fraction of the third light and inclination close to 90°. For this system we also tried a different approach for the analysis. Due to its significant curvature outside of eclipses we also tried to fit the mass ratio q as a free parameter despite its detached configuration. This result was then compared with the result as obtained via a standard method of q estimation by a Graczyk’s method. And both q parameters resulted in rather similar values of about 0.85 and 0.83, respectively. All the parameters of our LC fitting are given in Table 2 (a solution with fitted q is presented). Rather significant value of the third light resulted, indicating possible presence of the third component in the system. Noticeable is also some light curve variability over the Super WASP data period.

Concerning the period analysis we collected only the three minima as presented in the O—C gateway [Paschke & Bráž, 2006] and together with our 33 new times of minima, we have the coverage over almost 20 years of data. However, even on this dataset there is no evident variation of the period, see Fig. 11.
3.6 DR Lyn

The star DR Lyn (also TYC 3421-2216-1) is another Algol-type eclipsing binary in our sample of stars. No detailed study about this star was found in the published papers, only three times of minima were published till yet. These minima gave the orbital period of about 1.78 days. The star was also included into the survey of LAMOST (Luo et al., 2015), yielding its spectral type of about F3 and the primary temperature to be 6690 K.

With this assumed temperature we performed the light curve analysis of the WASP data. The light curve shape plotted in Fig. 12 shows very deep primary minimum (more than 2 magnitudes) and rather shallow secondary one. It indicates quite different components in the eclipsing pair. The results of the LC modelling are given in Table 2. The components are well detached, but rather different from each other.

For the period analysis we collected the already published data points (i.e. only three times of minima) together with our new ones from the WASP survey (i.e. 19 new minima). With this dataset we carried out the analysis, but no periodic signal was found, see our Fig. 13.

3.7 EK Lyn

The star EK Lyn (also TYC 2973-339-1) is the brightest target in our sample, having the orbital period of about 2.23 days. Despite its high luminosity, only very little is known about this star. The only relevant information is that one by Heckmann (1975) that the spectral type is of A2, hence it is the system of the earliest spectral type in our sample of stars.

For the light curve analysis we fixed the primary temperature to 8840 K (in agreement with Pecaut & Mamajek 2013). The shape of the LC is changing in time, hence its modelling was not straightforward. The parameters of our LC fit are given in Table 2, where we can see that the primary component dominates the system and no third light was detected. The fit is also plotted in Fig. 14.

Analysis of the period changes was done using the two published minima together with our new 13 data points. The result is shown in Fig. 15. No visible variation can be seen there, but the data set is still rather limited yet. The most recent minima deviate a bit from the linear ephemerides, but only further investigation would prove any such variation. What is quite surprising is the fact that the time of minimum published by Diethelm (2012) deviates of about 0.5 days from our ephemerides and is probably incorrect (we have
not plotted this one data point in our Fig. [15].

3.8 FS Lyn

The eclipsing system FS Lyn (also TYC 2986-534-1) is the only one system in our study, which was classified as a β-Lyrae type star (Maciejewski & Niedzielski, 2005). However, despite its short period (0.54 days) and relatively high brightness (11 mag) it was not studied before.

For the LC modelling we used the assumption that the star is of about F2 spectral type, i.e. the primary temperature was fixed at a value of 7100 K, see Ammons et al. (2006). Performing the LC modelling, we obtained a solution with a detached configuration (near contact, but both semidetached and contact configurations were tested but produced slightly worse fits). Due to its shape of the light curve, we also tried to compute the mass ratio as a free parameter. There resulted that the q values from the classical approach of Graczyk and that one fitted are not so different from each other (0.71 fitted, while 0.64 estimated from the mass-luminosity relation method by Graczyk 2003). The resulting parameters are given in Table 2 while the fit itself is plotted in Fig. 16.

For the analysis of its orbital period we derived from the WASP data 107 minima in total. With the two already published ones the complete data set covers about 8 years, see Fig. 17. However, no variation is visible on these data and the linear ephemerides are sufficient for prospective future observations.

4 Discussion and conclusions

The very first LC solution for eight Algol-type eclipsing binaries (based on the Super WASP photometry) led to several findings:

- The photometry based on the Super WASP survey data can be used for a fruitful analysis for the eclipsing binaries never studied before.
- Second-order effects such as the third light or the spots, are also detectable in these data.
- For two of the systems (AA Lyn, and CF Lyn) the amount of the third light is large enough that these cannot easily be considered as pure binaries in any future more detailed study.
- The method of using the light curve templates for deriving the times of minima provides us with reliable and sufficiently precise times of minima suitable for a period analysis.
For the system RV Lyn we found a steady period increase (probably due to mass transfer), while for the system CD Lyn there was detected some period modulation in the $O-C$ diagram. This variation with the period of about 59 years can be attributed to a prospective third body in the system.

All of the presented systems have not been studied before concerning their light curves, hence we can consider this study as a good starting point for a future more detailed analysis. Particularly, a special focus should be take to these systems, where a larger fraction of the third light was detected and the system, where a third body variation in the $O-C$ diagram was found.

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Fig. 1. Light curve analysis of RV Lyn, based on the Super WASP photometry.

Fig. 2. O-C diagram of times of minima for RV Lyn. The black points stand for the primary minima, the larger the symbol, the higher the weight. The red line represents the quadratic term in the ephemerides.

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Fig. 3. Light curve analysis of AA Lyn, based on the Super WASP photometry.

Fig. 4. O-C diagram of times of minima for AA Lyn.

Fig. 5. Light curve analysis of AH Lyn, based on the Super WASP photometry.
Fig. 6. O-C diagram of times of minima for AH Lyn. The secondary minima are plotted as open circles.

Fig. 7. Light curve analysis of CD Lyn, based on the Super WASP photometry.

Fig. 8. O-C diagram of times of minima for CD Lyn.
Fig. 9. 3D plot of CD Lyn, cross stands for the barycenter of the system.

Fig. 10. Light curve analysis of CF Lyn, based on the Super WASP photometry.

Fig. 11. O-C diagram of times of minima for CF Lyn.
Fig. 12. Light curve analysis of DR Lyn, based on the Super WASP photometry.

Fig. 13. O-C diagram of times of minima for DR Lyn.

Fig. 14. Light curve analysis of EK Lyn, based on the Super WASP photometry.
Fig. 15. O-C diagram of times of minima for EK Lyn.

Fig. 16. Light curve analysis of FS Lyn, based on the Super WASP photometry.

Fig. 17. O-C diagram of times of minima for FS Lyn.
| Star | HJD 2400000+ | Error Type | [days] | HJD 2400000+ | Error Type | [days] |
|------|---------------|------------|--------|---------------|------------|--------|
| FS Lyn 54099.52084 | 0.00057 | Pri | FS Lyn 54100.43072 | 0.00033 | Pri | FS Lyn 54101.34981 | 0.00051 |
| FS Lyn 54100.54971 | 0.00079 | Pri | FS Lyn 54101.45859 | 0.00045 | Pri | FS Lyn 54102.37277 | 0.00059 |
| FS Lyn 54101.56968 | 0.00081 | Pri | FS Lyn 54102.47756 | 0.00033 | Pri | FS Lyn 54103.39174 | 0.00050 |
| FS Lyn 54102.58964 | 0.00082 | Pri | FS Lyn 54103.49442 | 0.00035 | Pri | FS Lyn 54104.40910 | 0.00052 |
| FS Lyn 54103.60972 | 0.00083 | Pri | FS Lyn 54104.51288 | 0.00038 | Pri | FS Lyn 54105.42746 | 0.00056 |
| FS Lyn 54104.72071 | 0.00085 | Pri | FS Lyn 54105.53314 | 0.00040 | Pri | FS Lyn 54106.44802 | 0.00061 |
| FS Lyn 54105.83171 | 0.00087 | Pri | FS Lyn 54106.54280 | 0.00042 | Pri | FS Lyn 54107.45449 | 0.00067 |
| FS Lyn 54106.94276 | 0.00089 | Pri | FS Lyn 54107.54857 | 0.00045 | Pri | FS Lyn 54108.46415 | 0.00072 |
| FS Lyn 54107.10582 | 0.00092 | Pri | FS Lyn 54108.56013 | 0.00050 | Pri | FS Lyn 54109.47077 | 0.00080 |
| FS Lyn 54108.11684 | 0.00094 | Pri | FS Lyn 54109.65575 | 0.00055 | Pri | FS Lyn 54110.47739 | 0.00088 |
| FS Lyn 54109.12787 | 0.00096 | Pri | FS Lyn 54110.76137 | 0.00060 | Pri | FS Lyn 54111.48401 | 0.00098 |

**Table 3**

New Super WASP heliocentric minima times for the studied systems.

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The table above provides heliocentric minima times for the studied systems. The columns include the star name, heliocentric Julian date (HJD), error type, and error in [days]. The table is sorted by HJD in ascending order.