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Role of the Rossiter-McLaughlin effect in the study of close binaries

Galina N. Dryomova and Vladimir V. Dryomov

Russian Federal Nuclear Centre, Snezhinsk 456770, Russia; *G.N.Dryomova@mail.ru*

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Abstract This paper is devoted to binary stars belonging to the class of eclipsing-variable systems. Photometric and spectroscopic analysis of eclipses allows us to determine geometric parameters of the orbit and physical characteristics of stellar components as well as inclinations of stellar equators to the orbital plane. Estimations of inclinations can be obtained from measurement of the Rossiter-McLaughlin effect, which is discussed using examples of some eccentric binaries with an anomalous apsidal effect. Our task is to find the complete spectrum of solutions of the equation of apsidal motion, depending on the inclinations of the polar axes of the components to the orbital one for these systems, based on their individual spectroscopic and photometric observational data. The matrix of solutions allows us to select those pairs of polar inclinations that provide agreement with the observational apsidal period.

Key words: Rossiter-McLaughlin effect: eclipsing-variable stars — apsidal effect; individual binaries: AI Hya, NY Cep, EW Ori, DI Her, AS Cam

1 INTRODUCTION

With the invention of the telescope (1609), it became possible to observe double stars, which are called visual binaries. It is known that Benedetto Castelli, a disciple of the famous Galileo Galileo, in 1617, first discovered the duality of Mizar (Mizar A and Mizar B). In the following years, duality was noticed in Castor, 61 Cyg, α Cen, etc. By 1782, William Herschel had already published his first catalog of visual binaries, including 269 objects.

Even in ancient times, changes in the brightness of some stars were observed, the study of which eventually developed into the category of variable stars. The reasons for the variability remained unclear for a long time, until one brilliant idea flashed through the head of the young talented astronomer John Goodricke, who in 1783 observed a change in the brightness of β Per and understood that the cause of variability is periodic eclipses. When the orbit of a double star "lies" almost along the line of sight, the stellar components alternately become close to each other, weakening the overall brightness of the system.

In addition, Goodricke found the period of brightness variability of β Per, $2.86731^{\rm d}$, which turned out to be close to the modern value. Thus the category of eclipsing variable stars appeared. Today it is known that β Per, a triple system for which, using the 3D-tomography method, evidence of mass transfer (gas stream, circumprimary emission, localized region, absorption zone) between the components of the internal double has been obtained and confirmed by very long baseline interferometry (VLBI) radio images (Richards et al. 2012) and Center for High Angular Resolution Astronomy (CHARA) images (Baron et al. 2012).

Returning to the history of observations, it should be said that only from the 1820s, thanks to the initiative of Wilhelm Struve, the photometric study of binary stars became systematic. But, as it turned out, not only photometric methods can reveal the duality of a star. In 1889, Edward Pickering first discovered the spectral duality of Mizar A from variability of the radial velocity of the lines in the spectrum of the star. Around the same time, Hermann Vogel and Julius Scheiner found, from spectroscopic observations, variability in Spica and β Per.

In addition, although the methods of spectroscopic measurements had only just appeared, as early as 1893 Holt (Holt 1893) devised a method of how one can "extract" useful information about a star from spectroscopic analysis of the eclipse. To do this, one needs a spectrograph with high spatial resolution, which allows us to separate the absorption lines of both components in the spectrum and estimate the rotational velocity and angle between the vectors of axial and orbital rotation for each component.

The idea of Holt was simple and was reduced to finding a rotational anomaly in the spectrum of the binary. The nature of this anomaly is eclipses, that is, the main thing is that the binary system is an eclipsing variable, and it does not matter what its components are — early or late spectral types, young stars or old ones, in circular orbits or elongated ones.

Holt thought that, out of eclipses we have a trivial demonstration of the Doppler effect leading to a symmetrical broadening of the line wings: light emitted by the stellar hemisphere approaching us is blue-shifted, and light emitted from the hemisphere moving away from us is red-shifted. But during the eclipse, the segments of the hemispheres are gradually screened, which leads to a distortion in the absorption lines, and, consequently, to a weakening of the corresponding velocity component. Analysis of the distorted line profile could help to reveal projections of the rotation velocity of the star and the angle between the orbital and spin axes onto the plane of the sky. The idea was simple, but it took a long time to set up measurements.

2 MEASUREMENT OF ROTATIONAL ANOMALY DURING ECLIPSES

The first attempts to quantify the rotational anomaly imprinted in spectral lines were undertaken by Schlesinger in 1910, but were fruitless. More confident measurements were made in 1924 by Rossiter for β Lyr (Rossiter 1924) and by McLaughlin for β Per (McLaughlin 1924), which only revealed the displacement of the first moment of the absorption line that was described as "...rotational effect unmistakably real and measurable" (Rossiter 1924). However, a quantitative estimation of the velocity of rotation had not yet been made.

In 1931, Struve and Elvey (Struve & Elvey 1931) reported a change in the shape of the absorption line Mg II during eclipses in β Per and for the first time called it the Rossiter-McLaughlin effect (R-M effect). Spectral analysis showed that the theoretical contour of the Mg II line corresponds to the velocity of equatorial rotation of $67\,\mathrm{km\,s^{-1}}$, while the broadening of the observed line is assumed to be $60\,\mathrm{km\,s^{-1}}$. The authors (Struve & Elvey 1931) also found a rotational anomaly imprinted in the radial velocity curve, but could not find the rotation velocity on it, because they did not have new orbital elements for their epoch of observations.

Interest in "deciphering" the rotational anomaly was not lost, because the amplitude of the R-M effect does not depend on the line broadening mechanisms, and therefore could provide reliability in measuring the star's own rotation. Indeed, the broadening of the absorption line can be caused by a number of other reasons not at all related to the rotation of the star, for example, surface convection (blue convective shift), pressure, anisotropic macroturbulence, velocity fields on the stellar surface, point spread function of the spectrograph and others.

All these reasons stimulated modeling of the R-M effect, and the first steps here were taken in 1938 by Petrie (Petrie 1938) for the eclipsing binary RZ Cas. Petrie first introduced a new parameter – "rotation factor" which is a ratio of two quantities: the rotational velocity averaged over the visible part of a stellar disk and the equatorial velocity. The first quantity may be estimated from the radial velocity curve as the rotational deviation from the orbital motion for a particular phase of the observation. The rotation factor itself can be estimated as a purely geometric coefficient through variation of the radial velocity over the visible part of the stellar disk. In addition, it was shown that the R-M effect makes it possible to obtain an independent estimate of the size of the star.

As for the rotation factor, the theoretical aspects of the rotational anomaly were formulated and deduced by Kopal in 1942 (Kopal 1942). He considered the case of an absolutely collinear configuration when the axes of spin rotation of components and their orbital revolution are parallel, and took into account distortions of the components due to rotation and tidal gravity as well as limb- and gravity-darkening effects. In 1953, Hosokawa made a generalization to the case of an arbitrary spatial configuration of the binary and presented an analytical derivation of the formula for estimating the rotational effect of velocity curves in an eclipsing binary assuming that the angular velocity varies with the latitude of the stellar disk (Hosokawa 1953).

In 1979, Kopal in his fundamental monograph entitled "The Language of Stars" (Kopal 1979) gave a complete description of the rotational anomaly imprinted in the radial velocity curve. He introduced α-functions (Legendre polynomials) for integrating over the visible surface of stars. These functions can capture multiple distortions in surface brightness distribution. Such approach proved to be a very flexible method, but also labor-intensive for numerical implementation, especially if one takes into account the relatively weak computer capabilities in the 1980s. So, interest in calculation of the R-M effect was somewhat diminished.

However, the situation changed radically when, starting from the 1990s, a massive discovery of exoplanets and even exomoons began, which stimulated new attempts to model the R-M effect (Hirano et al. 2011, Boué et al. 2013). The discovery of "hot Jupiters" on orbits close to stars challenged the theory of planet formation, requiring the migration of giant planets. Here the R-M effect turned out to be useful (Triaud 2017). It allowed estimation of the angle of inclination of spin axis of a star (planet) to the orbital pole projected onto the picture plane. It is the inclination of these vectors that could serve as good evidence in favor of the migration of planets after their formation.

As for the stars, almost 95 yr have passed since the discovery of the R-M effect, and we have very few examples of a quantitative analysis of the rotational anomaly in eclipsing binaries.

A laborious procedure involved in the measurement of R-M effect during an eclipse phase faces the problem of light contamination from the occulting foreground star (there is no such difficulty when observing the passage of planets). This led to the tacit spread of the "coplanar standard" in binary stars. That is, by default it was assumed that since the component stars in a binary were formed simultaneously from the same protostellar cloud, their spin axes should be collinear with each other and with the axis of orbital revolution. This greatly simplified the calculations until one day which led to a "relativistic paradox" in apsidal motion.

3 RELATIVISTIC PARADOX IN APSIDAL MOTION OF AN ECCENTRIC BINARY

Apsidal motion is rotation of the elliptic orbit of a binary. The nature of the phenomenon is caused by two reasons. The first is the finite size of stars, and hence the action of mutual tidal-rotary deformation of stellar components, leading to a redistribution of angular momentum between the spin and orbital rotation of the stars and, as a consequence, to a breaking of classical Keplerian orbits of components. This is called the *classical* apsidal effect. The second reason is related to the curvature of space-time, considered within the framework of the General Theory of Relativity (GTR). Even if the components are assumed to be point-like bodies, the rotation of the orbit would still occur and this contribution to the rotation is known as the *relativistic* apsidal effect.

This phenomenon leads to secular changes in the periastron position, which may be estimated both from observations and from the dynamical theory of apsidal motion developed by Russell in 1928 and his followers (Russell 1928; Chandrasekhar 1933; Cowling 1938; Sterne 1939; Kopal 1959; Kopal 1978; Martynov & Khaliullin 1980; Moffat 1984; Moffat 1989). In this theory, the rate of apsidal motion is inseparably linked with the internal structure of stars which in turn is characterized by a series of internal structure constants describing the layer-density distribution.

These constants are derived from theoretical stellar evolutionary models and used for theoretical evaluation of the apsidal period which then may be compared with its observed value. Just the second-order constants give the dominant contribution to the determination of the rate of apsidal motion. This circumstance as well as the assumption about parallelism of spin and orbital angular momenta allows us to simplify mathematical manipulations for the evaluation of apsidal motion period.

To date, about fifty eccentric eclipsing binaries are known for which the theoretical evaluation of apsidal period was performed, and for 90% of these binaries the agreement with the observed value of apsidal period was found to be very good (Dremova & Svechnikov 2011). But for several systems, the difference between the observed and theoretical estimates of the apsidal period reached a factor of three or more. This has sown doubt about the GTR, which has happened before. This problem, called the "relativistic paradox" in apsidal motion, was sharply raised in the 1980s, when modifications of non-symmetric theories of gravitation began to occur, which corrected the situation in each individual case of the binary, but could not provide a unified formalism.

The claims about GTR were justified by the fact that discrepancies were found exactly for those binaries that have a considerable contribution of relativistic correction to the apsidal motion: AS Cam, NY Cep, V 1765 Cep, AI Hya, DI Her and EW Ori. For the remaining systems, the relativistic contribution was minor and formalism of the dynamic theory of apsidal motion, developed by Kopal for the absolutely collinear case, gave a good agreement between theory and observations.

However, subsequently four eclipsing binaries were discovered with almost 100% relativistic contribution to the apsidal movement. These were GG Ori, V541 Cas, V1143 Cyg and V1147 Cyg, and for them there was no discrepancy between the theoretically calculated and observed apsidal period. It turns out these cases confirm GTR.

4 FIVE REMARKABLE BINARIES, OR ABOUT THE NON-COLLINEARITY FACTOR

Back in 1985, Shakura showed with numerical calculations that for AS Cam and DI Her the assumption of an almost perpendicular orientation (87°) of spin axes for the components to the orbital axis eliminates the discrepancy between the observed and predicted rates for the turn of apside line (Shakura 1985).

We examined five eclipsing variables with eccentric orbits, for which the relativistic paradox was noted before. These binaries are AI Hya, NY Cep, EW Ori, AS Cam and DI Her. Our task is to find solutions to the equation of apsidal motion that would match the observed and theoretical rates of secular change in the longitude of periastron, w. It is a well-known equation of the form

$$(dw/dt)_{\rm total} = (dw/dt)_{\rm class} + (dw/dt)_{\rm GTR} \ . \tag{1}$$

The classical part due to rotary-tidal distortions of the components is written as follows

$$(dw/dt)_{\rm class} = 360^\circ \cdot P/U \ , \tag{2}$$

$$P/U = c_1 k_{21} + c_2 k_{22} \ . \tag{3}$$

where P and U correspond to orbital and apsidal periods of the binary, respectively; k_{21} and k_{22} mean internal structure constants of second-order, or, equivalently, the parameters of apsidal motion; c_1 and c_2 are coefficients representing the combination of physical and orbital parameters of an eclipsing binary

$$\begin{aligned} c_j = \left(\frac{R_j}{A}\right)^5 \times \Bigg[& \frac{M_{3-j}}{M_j} 15 f(e) - \frac{1}{2}\left(\frac{w_{{\rm spin},j}}{w_{\rm obs}}\right)^2 \\ & \times (1 - 3\cos^2\lambda_j)\left(1 + \frac{M_{3-j}}{M_j} g(e)\right)\Bigg] \ , \end{aligned} \tag{4}$$

where $f(e)$ and $g(e)$ are given as

$$f(e) = \left(1 + \frac{3}{2}e^2 + \frac{1}{8}e^4\right) \cdot (1 - e^2)^{-5} \ , \tag{5}$$

$$g(e) = (1 - e^2)^{-2} \ . \tag{6}$$

Index j indicates the component number. Such parameters as orbital period P, masses and radii of the components (M, R), semi-major axis A, eccentricity e and inclination of the orbit plane to the picture plane i are known as the rule from star catalogs. For example, we used the "Catalogue of orbital elements, masses and luminosities of close eclipsing variables with detached components" by Svechnikov & Perevozkina (2004). Values of k_{21} and k_{22} were calculated for each binary individually on the basis of evolutionary stellar model tracks by Claret (2004).

As for the determination of spin angular velocity of the components, we used data about their equatorial velocities projected onto the picture plane, related to each other by a simple formula

$$w_{{\rm spin},j} = V_j / (R_j \cdot \sin\phi_j) \ , \tag{7}$$

where ϕ_j is the angle between the axis of the component's spin rotation and the picture plane. Since from observations we do not know the equatorial velocity itself, only its projection $V_j \sin\phi_j$, we individually sorted out possible values of the angle ϕ_j for each component. Other angles, whose values were also chosen arbitrarily are designated as $\lambda_j (j = 1, 2)$ and characterize misalignment of the axes of spin and orbital rotation for each component.

The second term in square brackets in Equation (4) is responsible for the rotational deformation of the components themselves and their orbits. This term is written in a general form for the case of non-parallel spin and orbital axes. A more rigorous derivation of this term requires taking into account the evolution of orbital inclination to the picture plane, as has been shown by Company et al. (1988). However, the advance of periastron does not depend on the angle of the observer, so we assume the angle to be 90° to simplify the original formula (see Company et al. 1988).

Relativistic term of the apsidal motion is determined by Levi-Civita's formula (Levi-Civita 1937)

$$(dw/dt)_{\rm GTR} = 5.449 \times 10^{-4} \frac{(M_1 + M_2)^{2/3}}{P^{2/3}(1 - e^2)} \ . \tag{8}$$

Using the above equations, we can analyze solutions for the case of non-collinear spin and orbital axes in a binary. Fixing the inclination of the spin axis of the main component to the orbital axis and causing the satellite's inclination "to run through" all possible values in the range, we can calculate the rate of apsidal motion for each pair of angles (λ_1, λ_2). Thus, we obtain a spectrum of solutions from which one should choose only those ones that are consistent with the observed value of apsidal period.

We carried out such calculations for the five binaries AI Hya, NY Cep, EW Ori, DI Her and AS Cam with a noticeable discrepancy between the theoretical and observed rate of secular advance of the periastron.

The initial data for the selected binaries taken from Svechnikov & Perevozkina (2004) are given in Table 1, which also shows values of apsidal period predicted with the assumption of parallelism of the axes of spin and orbital rotation as well as their observed values.

4.1 Eclipsing Binary AI Hya

The first system we considered is AI Hya. It is a young binary belonging to the main sequence, whose age is estimated to be a billion years. The components have not yet synchronized their spin rotation with the orbital revolution (Dryomova & Svechnikov 2012), and its eccentricity is quite large, 0.23. The apsidal period for this system was

Table 1 Initial data for five remarkable binaries with the problem apsidal period taken from Svechnikov & Perevozkina (2004).

Name Binary	P (d)	M_1 $(M_\odot)$ M_2 $(M_\odot)$	R_1 $(R_\odot)$ R_2 $(R_\odot)$	A $R_\odot$	e	i (°)	k_{21} k_{22}	$U_{\rm obs}$ (yr)	$U_{\rm th,\|\|}$ (yr)
AI Hya	8.2899676	2.15 1.98	3.92 2.77	27.64	0.23	89.98	–2.6469 –2.5947	12 400	4500
NY Cep	15.27566	12.9 9.4	6.86 5.7	72.89	0.48	77.39	–2.2131 –2.2357	1300	4730
EW Ori	6.9368515	1.19 1.155	1.14 1.09	20.33	0.079	89.65	–1.9461 –1.8775	160 000	19 740
DI Her	10.550185	5.16 4.53	2.72 2.47	43.14	0.489	89.3	–2.1063 –2.1063	22 600	8630
AS Cam	3.4309714	3.3 2.5	2.55 1.95	17.19	0.16	88.1	–2.3215 –2.3148	2400	830

first determined in Khaliullin & Kozyreva (1989). The discrepancy between the observed and predicted apsidal motion period under the assumption of collinearity of the axes is three times. The relativistic contribution to the apsidal motion is not very large, slightly more than 20 percent of its predicted theoretical value. It should be noted that according to the analysis carried out by Petrova and Orlov, these estimates are highly unreliable, because "... this is the only determination of the apsidal period; the error is larger than the value by a factor of 1.7" (Petrova & Orlov 1999).

The rejection of collinearity of the rotation axes allows us to find a whole family of possible solutions for the motion equation. For example, with the prograde rotation of components, the inclinations of the spin axes of the main and secondary components to the orbital axis may have the following combinations: (90°, 33°), (80°, 39°), (70°, 52°), (60°, 85°), as can be seen from Figure 1. These calculations were carried out for the angles $\phi_1 = \phi_2 = 90°$. If the angles ϕ are fixed at 45°, the solutions change: (90°, 10°), (90°, 43°), (80°, 20°), (80°, 48°), (70°, 36°), (70°, 63°), (60°, 58°) (Fig. 2). These values can be easily seen in Figures 1 and 2 as the points of intersection of curves with a dashed line corresponding to the observed value of the apsidal period for AI Her, $U_{\rm obs} = 12\,400\,{\rm yr}$. Obviously, there is one solution, but we can choose it only based on the results of measurements of the R-M effect.

4.2 Eclipsing Binary NY Cep

Another eclipsing variable binary is NY Cep. The first observations of this system refer to Heard & Fernie (1968). A comparison of the longitude of periastron taken from the first observations and from spectrophotometric study performed in Holmgren et al. (1990) allowed estimation of its apsidal period that proved to be equal to 1300±800 yr, which is three times shorter than its observed value. The relativistic contribution to apsidal motion is 28 percent. The main feature of this system is an incomplete light curve with only one eclipse, which is associated with a very large eccentricity (0.48), on the one hand, and a low inclination angle of the orbital plane to the image one, 78°. It is known that this is a young system, whose age is not older than 10 million years, with components belonging to the main sequence which have not yet synchronized their spin rotation with the orbital one.

In addition, although the reliability of the computed orbital elements from the incomplete light curve of NY Cep is very low, nevertheless variants from matching the theoretical and observed apsidal periods were found. Practically on the whole range of the inclination of spin axis of the main component to the orbital axis ($30° - 90°$) and tilting the spin axis of the satellite to the orbital one that varies in the interval ($70° - 20°$), it is possible to obtain consistent solutions for the apsidal period with the ϕ being 15° for the case of prograde motion (Fig. 3).

4.3 Eclipsing Binary EW Ori

The next system is EW Ori which belongs to the main sequence. Its age is not older than 1 billion years, and the components have already synchronized their spin rotation with the orbital motion (Dryomova & Svechnikov 2012). Although it has been regularly observed since the 1930s, the first report on the evaluation of apsidal movement was made by Wolf et al. (1997). This is an eclipsing variable with a very large relativistic contribution to the apsidal motion, reaching almost 80 percent. The $(O - C)$ diagram analysis gives the rate of apsidal motion $0.0023°\,{\rm yr}^{-1}$, which is only 16 percent of the rate predicted by the GTR. The EW Ori system showed a discrepancy in the estimates of apsidal period by almost an order of magnitude, which

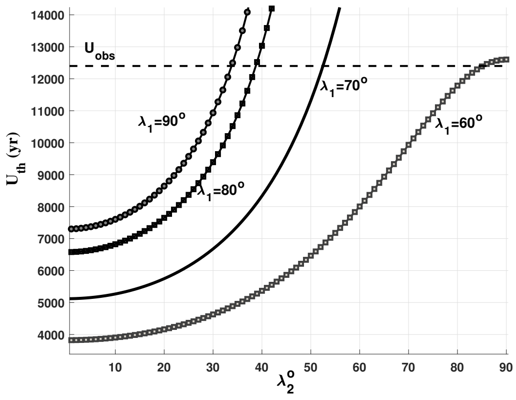

Fig. 1 Spectrum of apsidal motion solutions for AI Her, $\phi_{1,2} = 90°$.

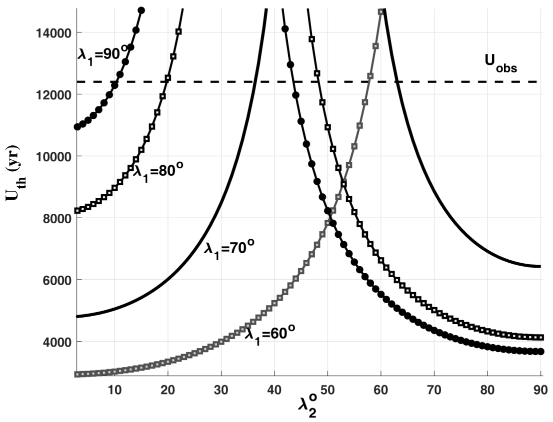

Fig. 2 The same for the case of $\phi_{1,2} = 45°$.

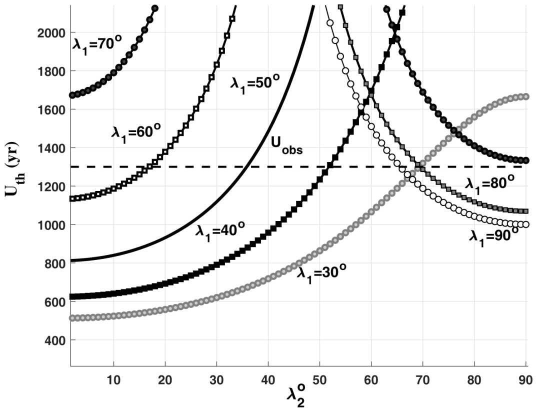

Fig. 3 Spectrum of apsidal motion solutions for NY Cep, $\phi_{1,2} = 15°$.

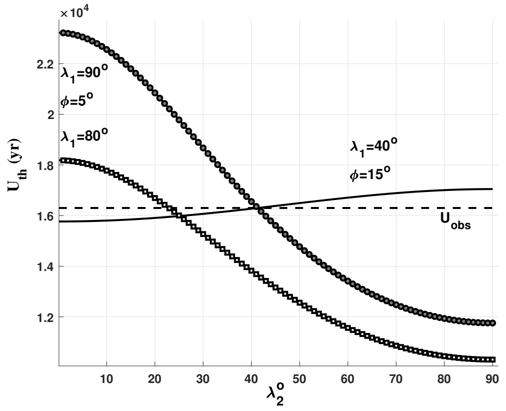

Fig. 4 Spectrum of apsidal motion solutions for EW Ori, prograde rotation.

can be eliminated on the assumption that the component axes are misaligned, with respect to both their prograde and retrograde rotations. With prograde rotation, the inclinations of the spin axes of main and secondary components may be ($\lambda_1 = 90°$, $\lambda_2 = 41°$) and ($\lambda_1 = 80°$, $\lambda_2 = 23°$), respectively, when $\phi_{1,2} = 5°$ as well as ($\lambda_1 = \lambda_2 = 40°$) when $\phi_{1,2} = 15°$ (Fig. 4). For the retrograde rotation of components, the corresponding solutions may be ($\lambda_1 = 70°$, $\lambda_2 = 55°$) and ($\lambda_1 = 50°$, $\lambda_2 = 70°$) for the case of $\phi_1 = \phi_2 = 5°$ (Fig. 5).

It should be noted that regarding the discrepancy between the observed and theoretically predicted apsidal period for EW Ori, a point was set in 2010 thanks to new $ubvy$ photometric data and high-resolution spectra that allowed Clausen and co-authors (Clausen et al. 2010) to refine the observed period of apsidal motion, 16 300 yr, which proved to be close to its theoretically predicted value of 19 700 yr.

4.4 Eclipsing Binary DI Her

A special place in the history of studying the apsidal period is occupied by the DI Her system. This is a young system that recently arrived at the zero age main sequence, and is an eclipsing binary. This system has a large eccentricity (0.489), and it shows a discrepancy between the calculated and observed values of apsidal period by a factor of four, and by some estimates, even more. For a long time the DI Her system was considered as a binary with anomalously low observed rate of secular advance of periastron which challenged our understanding of stellar physics. The problem of the discrepancy could be solved if its spin axes are tilted relative to the orbital axis, as Shakura suggested and showed in his calculations (Shakura 1985).

In 2009, these calculations were confirmed by Albrecht and co-authors who directly measured the R-M for DI Her (Albrecht et al. 2009). Thus the binary DI Her

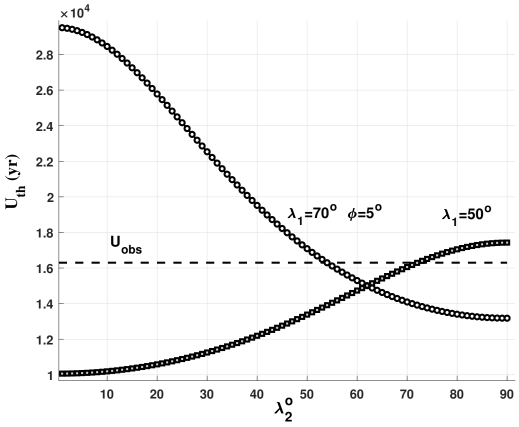

Fig. 5 The same for the case of retrograde rotation of the components.

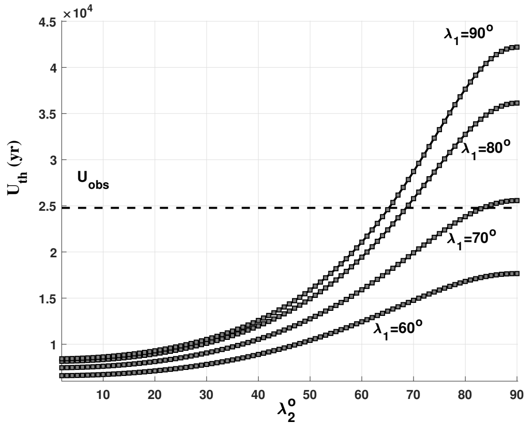

Fig. 6 Spectrum of apsidal motion solutions for DI Her, $\phi_{1,2} = 73^\circ$.

became the first eclipsing variable for which the relativistic paradox in apsidal motion was resolved. The angles of inclination of spin axes for both components to the orbital axis in the projection onto the sky sphere were evaluated from observations. Values of these angles are $+72^\circ \pm 4^\circ$ and $-84^\circ \pm 8^\circ$ for the primary and secondary components, respectively. The misalignment proved to be responsible for the retrograde component in apsidal motion which allowed Albrecht et al. to agree with the theoretically predicted rate of periastron advance ($\approx$1.52 arcsec cycle^{-1}) with the observed precession rate ($\approx$1.08 arcsec cycle^{-1}) within 40 percent (Albrecht et al. 2009). Using formula (2) and assuming anomalistic orbital period of DI Her equal 10.550185^{d}, these rates can be converted into the timescale of the apsidal motion: 24 645 yr and 34 685 yr, for theoretical and observational values, respectively.

In 2010, Claret and co-authors (Claret et al., 2010), using new times of minimum and new stellar evolutionary models, redefined apsidal motion constants for the components. Their results showed excellent agreement of total predicted rate of +0.00046 deg cycle^{-1} ($U_{\mathrm{th}} = 22\,620$ yr) with the newly measured value of +0.00042 deg cycle^{-1} ($U_{\mathrm{obs}} = 24\,775$ yr). The formal difference is now reduced to 10% and the case of DI Her is no longer an issue.

Although the problems with the system have been removed, we have formally shown that for this system there are several solutions under the assumption of prograde rotation of the components in which the inclinations of spin axes of both the main and secondary components vary in the range from 60° to 90°, taking into account the angle of the projection of the component spin axes onto the sky sphere set at 73° (Fig. 6).

4.5 Eclipsing Binary AS Cam

Finally the fifth system is AS Cam. Its apsidal motion was discovered by Khaliullin & Kozyreva (1983). This system immediately attracted attention, showing a discrepancy between the observed and theoretical estimates of the apsidal period by a factor of three. The relativistic contribution to the apsidal motion is quite high and amounts to about 70 percent. Pavlovski and co-authors (Pavlovski et al. 2011) presented the first high-resolution spectroscopy of AS Cam, from which they found that the projected spin velocities of the stars are much lower than expected and that their spin axes are likely misaligned with the orbital axis. But back in 1985, Shakura (1985) showed that the apsidal line may undergo retrograde motion if the spin axes of the components are oriented almost perpendicular to the orbital axis. For the case of AS Cam, Shakura found that the spin axis of the primary component should be inclined at 87°, and that for the secondary component is 82° (Shakura 1985).

The set of solutions which we obtained for AS Cam also includes similar orientations of the axes. For example, the inclinations of the spin axis of the primary component to the orbital axis at an angle of 80° and that for the secondary component at an angle of 20° give one of the possible solutions, provided that the axis of rotation of the main component is inclined to the picture plane at an angle of 5°. Also, a solution can be found on the assumption of retrograde motion of the components. For example, if the spin axis of the main component is tilted to the orbital axis by an angle of 80°, and the inclination of spin axis of the secondary component is 40° and $\phi_{1,2} = 15^\circ$, a correspondence is also achieved (Fig. 7).

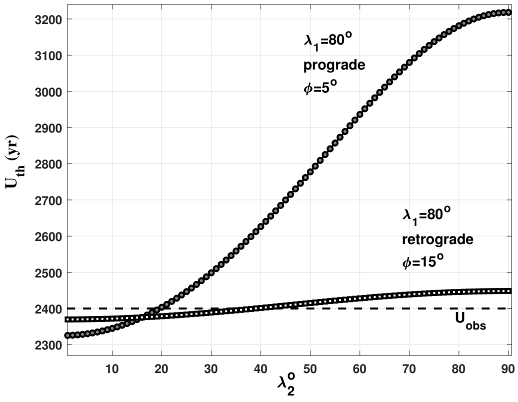

Fig. 7 Spectrum of apsidal motion solutions for AS Cam.

5 PROSPECTS FOR MEASURING THE R-M EFFECT IN BINARY SYSTEMS

Knowledge of inclinations is very important for testing the theory of star formation. There are not many methods for determining stellar inclinations, and these methods are also laborious like the measurement of the R-M effect. For example, tracing stellar spots (Sanchis-Ojeda & Winn 2011) or analyzing gravitational darkening to the edge of a disk (Szabó et al. 2011) can be useful for estimating the inclinations of polar axes, but it should be noted that this is applicable to binary systems in which one of the components is a substellar object (for example, a planet).

As one can see, the assumption of axial misalignment of both components "saves" the situation regarding the issue of agreement between theory and observations for the apsidal motion. But is the misalignment justified, especially for young systems? For a long time it was believed that the components of a binary are born from the same region of a molecular cloud, therefore the stellar spins must be well-aligned. According to the results of numerical simulation, star formation is a very chaotic process, accompanied by failures in the accretion regime, changing directions and even stopping, which certainly affect the redistribution of orbital and angular momenta in a binary (Bate et al. 2010, Bonnell et al. 1992).

To answer this question, we need statistics on measurements of the R-M effect in binaries. For this purpose, the BANANA project was launched, headed by Albrecht and his team (Albrecht et al. 2011). One of the incentives for organization of this project was connected with results of the R-M effect measurement for two eclipsing variables that did not fit into the previously accepted correlation "age-axis inclination" for the cases V 1143 Cyg and DI Her. One should emphasize that V 1143 Cyg became the first eclipsing variable for which inclinations of the component spin axes to the orbital pole were estimated from direct measurement of the R-M effect (Albrecht et al. 2007), from which follows that the configuration of the system is very close to collinear ($\lambda_1 = 7° \pm 6°$, $\lambda_2 = -2° \pm 3°$). This would seem logical: the age of the system is about half a billion years, the components have synchronized axial rotation well (Dryomova & Svechnikov 2012), and is it surprising that the axes are collinear? Even if the axes were not collinear at birth, they had a long time to align due to tidal friction.

Then measurements of the R-M effect were performed for another system, DI Her (Albrecht et al. 2009). This is a young binary that has just emerged on the main sequence (Dryomova & Svechnikov 2012), and the factor of axial misalignment is maximal: spin axes of stars are almost perpendicular to the orbital axis ($\lambda_1 = 72° \pm 4°$, $\lambda_2 = -84° \pm 8°$) (Albrecht et al. 2009). This is the case for a binary, the stellar components of which were misaligned from the very beginning, so binaries are not always neatly aligned (as found by the BANANA project, Albrecht et al. 2011).

As for DI Her, measurement of the axial inclinations helped to remove the problem of apsidal motion. For the case of V 1143 Cyg, the discrepancy between theoretical and observed apsidal periods remained within 25%, and the misalignment cannot be responsible for it. This discrepancy can be explained by the effect of a remote third body which is typical for binary systems. So, for example, according to Tokovinin's statistical estimates, the multiplicity of close spectroscopic binaries (SB) is a strong function of orbital period, for example, 96% of all short-period ($P < 3^{\mathrm{d}}$) SB are actually multiple systems while for long-period SB ($P > 12^{\mathrm{d}}$) the frequency drops to 34% (Tokovinin et al. 2006).

While the tidal friction between star components or the effect of a third body, being on a wide, inclined orbit and able to force Kozai cycles (Kozai 1962) in a close binary with primordial misalignment, results gradually in alignment of spin and orbital momenta, the occasional passages of single or even binary stars near the close binary with primordial collinear axes as well as arbitrary star encounters may lead to swinging of the axes and cause orbital precession. Numerous calculations confirm these effects (Eggleton & Kiseleva-Eggleton 2001; Gualandris et al. 2004).

The third system of the BANANA project is NY Cep, a young system not older than 10 million years (Dryomova & Svechnikov 2012), similar to DI Her in many physical aspects, but unlike it because the spin axes of the components are almost collinear with the orbital axis ($\lambda_{1,2} =$

$-2 \pm 4°$) (Albrecht et al. 2011). The discrepancy between the theoretical and observed apsidal period is associated with an incomplete light curve, and new more accurate photometric data are needed. Here are two young similar binary systems, and what different orbital histories they have.

EP Cru was the next system in the series of measurements of spin-orbit angles in eclipsing binaries performed in the framework of the BANANA project (Albrecht et al. 2013). EP Cru, also known as NSV 5783, was discovered by Strohmeier (1972). For the first time, a combined solution of photometric and spectroscopic observational data was replenished by Clausen and co-authors in 2007 who found the given system is a “twin” of the DI Her binary (Clausen et al. 2007), except that EP Cru is slightly older (its age is estimated at about 60 million years). Measurements of the R-M effect showed that EP Cru is nearly coaxial ($\lambda_1 = -1.8° \pm 1.6°$, $\lambda_2 < 17°$) (Albrecht et al. 2013) in contrast to DI Her (Albrecht et al. 2009). One would conclude that EP Cru has already completed the dynamic phase of aligning the axes, but then another puzzle arises. If the work of tidal forces has almost eliminated the misalignment why then have the components of EP Cru not yet synchronized? Since the components undergo spin rotation nine times faster than the orbital rotation, we can conclude that the dynamic evolution continues, so that EP Cru most likely formed immediately with an almost collinear axial configuration. It is not yet possible to verify the apsidal period, since there are still very few photometric data on this system, and the rate of periastron advance is poorly constrained (something about 20 min in 20 yr).

The fifth system for which the R-M effect was measured is CV Vel (Albrecht et al. 2014). CV Vel is a young system (its age is about 40 million years (Dryomova & Svechnikov 2012)) similar to NY Cep in age, but more like DI Her in axial configuration. It has a rich history of observations, in which the mismatch of component spin velocities was immediately noticed (Andersen 1975; Yakut et al. 2007). It was interpreted as evidence of axial misalignment, which was subsequently confirmed by direct measurements of the effect of rotation. From analysis of the R-M effect, the sky-projected spin-orbit angles were estimated as $\lambda_1 = -52° \pm 6°$ and $\lambda_2 = 3° \pm 6°$ (Albrecht et al. 2014) for the primary and secondary components of CV Vel, respectively. Thus the projected rotation velocities of the components of CV Vel are indeed changing on a timescale of decades. Also, Albrecht et al. (2014) found by integrating the secular tidal evolution equations backward in time that the CV Vel system could have evolved from a state with a much more pronounced axial misalignment compared to DI Her. Correlation of the axial inclinations of components and their rotational velocities, which are lower than synchronization values, suggests that CV Vel is in the state of equalization of orbital and spin axes due to tidal friction. The problem of the apsidal period does not stand for this system, since the eccentricity of the orbit is zero in contrast to DI Her ($e = 0.489$). It is interesting to note that until now no third body confirmations have been found for either DI Her or CV Vel.

We would like to say “the following system in the BANANA project is ...”, but so far the series of eclipsing variables with measured R-M effect discontinues. A “critical mass” of riddles for these five remarkable binaries (V 1143 Cyg, DI Her, NY Cep, EP Cru and CV Vel) motivates increasing the statistics of observations and measurements of the rotational anomaly imprinted in the spectrum of eccentric binaries when components eclipse each other.

Of course, the problem of stellar spectral disentanglement requires special technologies and techniques, but it is a matter of time before these become available. So, in future star catalogs, new columns with data about inclinations of the stellar axes should become as common as the orbital period, spectral types of components, eccentricity of the orbit, relative radii of components, orbital inclination to the picture plane, etc.

Analysis of the R-M effect has gone far beyond the apsidal problem, and its modern purpose is to shed light on the theory of star formation, to answer questions about why the axial configuration is so different in binaries since the moment of their birth.

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