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Stars and planets at high spatial and spectral resolution

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Citation

Albrecht, S. (2008, December 17). *Stars and planets at high spatial and spectral resolution*. Retrieved from <https://hdl.handle.net/1887/13359>

Version: Corrected Publisher's Version

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Chapter 5

Misaligned spin axes in the DI Herculis system

DI Herculis is one of the most interesting young eclipsing binary systems known. Its apsidal motion, the rotation of the orbit in its own plane, has been measured to be significantly lower ($2.9 \times 10^{-4} \pm 0.4 \cdot 10^{-4} \text{ }^\circ/\text{cycle}$) than the expected value ($1.25 \cdot 10^{-3} \text{ }^\circ/\text{cycle}$). Until now the reason why its apsidal motion is much slower than theoretically expected escapes a solid explanation. A number of theories have been put forward to explain this apparent discrepancy, including a revision of general relativity.

However the underlying calculations are based on the premise of co-aligned stellar rotation axes. To test this assumption we observed the DI Herculis system during both primary and secondary eclipse with the high resolution Echelle spectrograph Sophie of the Observatoire de Haute Provence.

Using our newly developed analysis tools (Chapter 4) we find a strong misalignment between the projections of the stellar spin axes and the orbital spin axis on the sky. The angle between, the projected stellar spin axes and the projected orbital spin axis is ($71 \pm 4^\circ$) for the primary and ($93 \pm 8^\circ$) for the secondary. This is the first time that such a strong degree of misalignment between the different spin axes in a close binary system has been demonstrated.

The observed misalignment has two immediate consequences. 1) The expected apsidal motion for this system is reduced to ($4.9 \cdot 10^{-4} \text{ }^\circ/\text{cycle}$). As we are not sensitive to a possible inclination of the stellar spin axes, the calculated value represents an upper limit for the expected apsidal motion. Allowing for a moderate amount of inclination ($\sim 30^\circ$), with respect to the line of sight, of both stellar axes the measured and expected apsidal motion are in perfect agreement. 2) So far most studies of binary formation and evolution, theoretical and observational, assume co-aligned spin axes in close systems. This assumption might not always be true, and as demonstrated for DI Herculis, can have important consequences for the evolution of the system. Finally, we shortly discuss possible ways towards strong misalignment of stellar spin axes.

5.1 Introduction

DI Herculis (spectral type B4 V and B5 V, $P = 10.55$ d, $e = 0.49$) is one of the most fascinating eclipsing binaries systems known. The most striking feature of the DI Herculis system is the much lower measured apsidal motion rate than expected and the lack of a convincing explanation for this (Guinan & Maloney 1985; Claret 1998). The apsidal motion describes the precession of the orbit in its own plane, i.e. the change of the argument of the periastron (ω) over time. It is caused by both a general relativistic effect and a Newtonian contribution, the latter consisting of two terms which are due to the deformation of the two stars by tidal forces and stellar rotation. The expected apsidal motion for DI Herculis is $0.00125^\circ/\text{cycle}$ (Claret 1998), including the apsidal motion due to the Newtonian term ($0.00056^\circ/\text{cycle}$) and that caused by the general relativity term ($0.000676^\circ/\text{cycle}$; Company et al. 1988). This value for the expected apsidal motion is in strong contrast to the measured value of the apsidal motion ($0.00029 \pm 0.000043^\circ/\text{cycle}$) found by Guinan et al. (1994). Even the relativistic term alone is greater than the measured value.

Historically, also for a number of other eclipsing binary systems a discrepancy between the theoretical and measured apsidal motion has existed, but thanks to new observations and new stellar evolution codes, these discrepancies have been reduced and the expected and measured apsidal motion rates for these systems are now in good agreement (Claret & Gimenez 1993; Claret & Willems 2002). However, for DI Herculis this is not the case. A number of different scenarios have been suggested to explain this discrepancy (See Guinan & Maloney 1985; Claret 1998, for a summary.). For example a modification to the theory of gravity was suggested. Also a third companion of smaller mass could alter the apsidal motion rate. However none of the explanations are satisfactory as they are, at the moment, very difficult to prove or reject. For example searches for a low mass star or massive planetary object around the bright early type stars are very difficult to conduct and so far have neither excluded this possibility nor found candidates (Guinan & Maloney 1985; Marshall et al. 1995).

There is however one suggested mechanism which could reduce the apsidal motion that we can test. A misalignment between the stellar rotation axes and the orbital spin axis would reduce the apsidal motion. The impact of misaligned stellar spin axes on apsidal motion has been studied for different systems by different authors (e.g. Kopal 1978; Shakura 1985; Company et al. 1988; Petrova & Orlov 2003). For the case of DI Herculis it was found that a strong misalignment could indeed be sufficient to account for the difference between the expected and measured apsidal motion rates. As every close binary system, also DI Herculis experiences synchronization forces. DI Herculis is however a very young system ($5 \cdot 10^6$ years) and the time scale for alignment is 20 time greater than its age (Claret 1998). Therefore one would find inclined rotation axes, if they were initially inclined.

Unfortunately, it is not straight forward to measure the orientation of the stellar rotation axes for all but a few stars, as nearly all stars are unresolved and the telescope integrates the light from the complete stellar surface. Thus only the radially-projected rotational velocity $v \sin i$ can be measured. During eclipses, however varying parts of the stellar disk are obscured, allowing the observer to gather spatially resolved information. The crossing of a companion in front of a rotating star causes a change in the line profile of the eclipsed star. This rotation or Rossiter-

Table 5.1 — Parameters for [DI Herculis](#) DI Herculis taken from [Hipparcos \(1997\)](#)‡ and [Guinan & Maloney \(1985\)](#)†. Radius_p denotes the radius of the primary component and Radius_s the radius of the secondary component. The masses and effective temperatures of the components are denoted by Mass_i and T_{eff*i*}, respectively.

HIP	92708	
HD	175227	
R.A. _{J2000}	18 ^h 53 ^m 26 ^s	‡
Dec. _{J2000}	24°16′41″	‡
V _{max}	8.45 mag	‡
Sp. Type	B 4/5 V	†
Period	10 ^d 550164(1)	†
Radius _p	2.68(5) $R_{\odot}$	†
Radius _s	2.48(5) $R_{\odot}$	†
Mass _p	5.15(10) $M_{\odot}$	†
Mass _s	4.52(6) $M_{\odot}$	†
T _{eff }	17 000(800) K	†
T _{eff }	15 100(800) K	†

McLaughlin (RM) effect was first observed by [Rossiter \(1924\)](#) in β Lyrae, and by [McLaughlin \(1924\)](#) in the Algol system. Due to the Doppler effect, light emitted from the side of the stellar disk that moves towards the observer is blue-shifted and light emitted from the receding side is red-shifted. When the red-shifted (receding) part of the disk is blocked, the net starlight looks slightly blue-shifted, and vice versa. If the spin axis of the eclipsed star is aligned with the orbital axis, first blue-shifted light and later, to the same amount, red-shifted light is blocked. For a misaligned axis this is not true, and red-shifted and blue-shifted light is blocked at different times and to different amounts. We developed two methods to accurately determine the alignment of stellar rotation axes in double lined eclipsing binaries. (See Chapter 4). Recently the RM-effect has been used to determine the relative orientation of the spin axes of exoplanet host stars (see for example [Winn et al. 2005](#)). The RM-effect might also be used to probe atmospheres of transiting exoplanets [Snellen \(2004\)](#).

We observed DI Herculis at the Observatoire de Haute Provence (OHP) during the primary and secondary eclipses and out of eclipse to measure the relative orientation of the stellar spin axes. This way we either confirm that tilted rotation axes are responsible for the difference between the theoretical and measured apsidal motion or to exclude this possibility from the list of possible explanations. In the next section we present our data. This is followed by the description of our analysis and results in Section 5.3. In Section 5.4 we describe the implications of our results followed by our conclusion.

5.2 Data

We observed the DI Herculis system using the high resolution Echelle spectrograph Sophie at the 1.93 m telescope of the OHP during the secondary eclipse in the night 30.06 – 01.07.2008 where mid-eclipse occurs at $\sim 23 : 00$ UT. The total duration of the secondary eclipse is ~ 7 hours. Unfortunately, we lost the first few hours of the night due to technical problems. We therefore covered only the mid to second half of the secondary eclipse. The primary eclipse

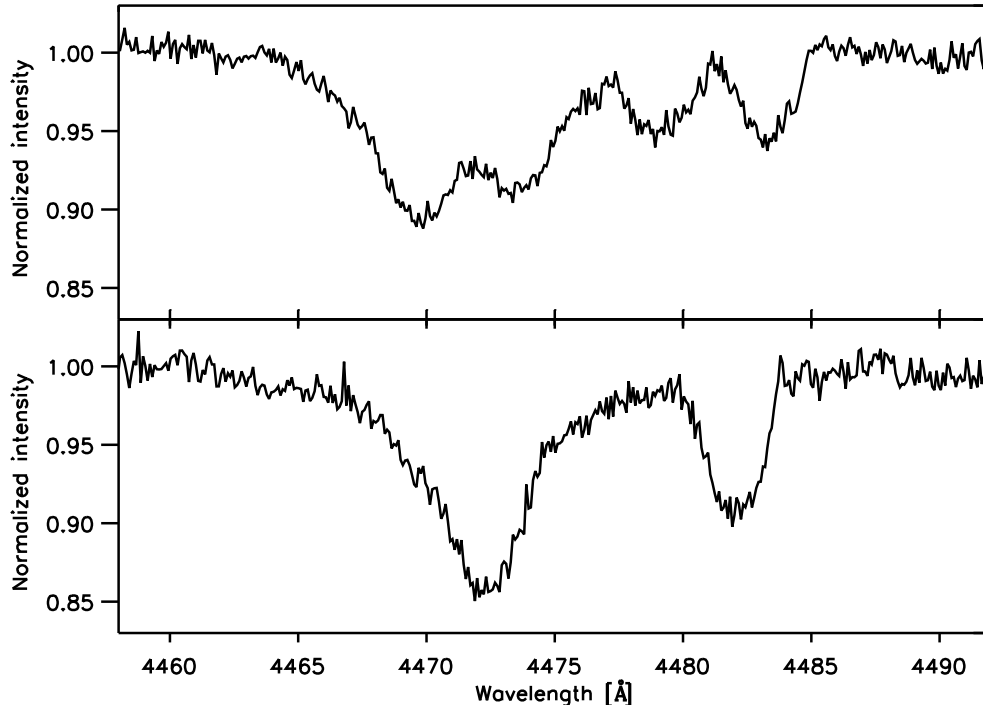


Figure 5.1 — The upper panel displays a normalized spectrum around the He I and Mg II lines of DI Herculis. It was obtained at a orbital phase (0.07) when the components have high radial-velocities relative to each other. The absorption lines of the two stars are well separated. Note the broad ‘wings’ of the He I line (~ 4471 Å), which is due to pressure broadening. The lower panel displays a spectrum obtained 0.1 hours before mid-point of the secondary eclipse. The received light originated nearly completely from the foreground primary.

was observed in the night 13 – 14.07.2008. Mid-eclipse occurred at $\sim 22 : 40$ UT. As the primary eclipse has a total duration of 11 1/2 hours, it can therefore not be covered in one night. We therefore had additional observations planned for the night of the 20.05.2006. Due to bad weather only one observation directly before the beginning and two in the first half of the primary eclipse were conducted. In addition eight observations out of eclipse have been obtained.

We used the High Efficiency (HE) mode of Sophie which offers a high throughput and a spectral resolution of $R \sim 40000$. One fibre was pointed towards DI Herculis while the second fibre was exposed to the sky. We chose an integration time of 20 min for observations during eclipses, and 15 min integration time for observations outside the eclipses. Less than one minute after the shutter was closed science grade spectra had been produced by the instrument and its software. For our further analysis we used the 2D-spectra delivered by the software.

5.3 Results

For our analysis of the RM-effect we focused on the Mg II line at 4481 Å. We chose this line as it is relatively deep in the spectra of both stars, and it is mainly broadened by stellar rotation. It

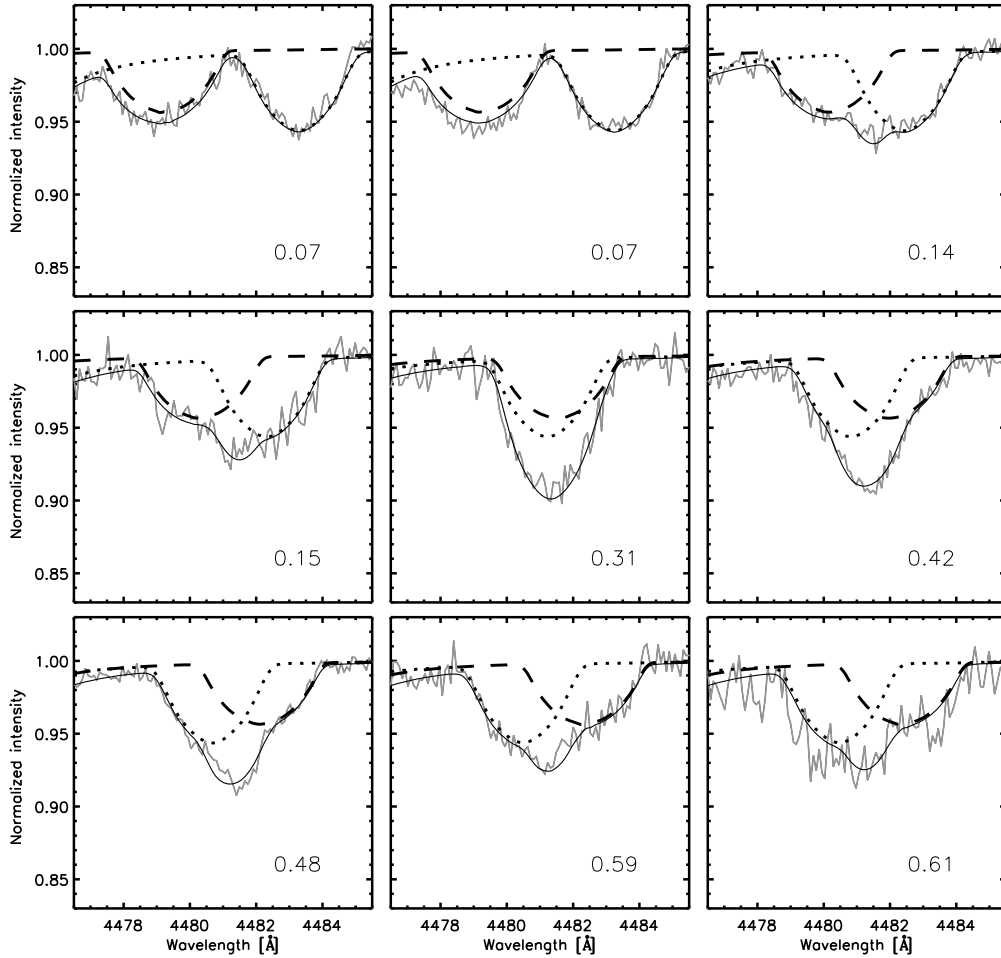


Figure 5.2 — Normalized spectra around the Mg II line at $4481 \text{ \AA}$ of DI Herculis obtained out of eclipses. Each panel shows one observation. The gray line represents the measured spectrum, while the solid line shows our best fit. The dotted line shows the contribution of the primary and the dashed line the contribution of the secondary. The numbers in the lower right corner of each panel indicate the phase of the system at the time of the observation. Note that the two observations at an orbital phase of 0.07 have been obtained at different nights.

is located in the ‘red’ wing of the He I line at $4471 \text{ \AA}$. We therefore also included this, mainly pressure broadened line, into our analysis. Both lines are, in our setup, located approximately in the middle of order nr. 11 on the Sophie CCD. See Figure 5.1 for two spectra centered on these two lines.

Normalization is the first, and at the same time, one of the most critical parts of our analysis. We used, for initial normalization, the flat-fields delivered by the software of the instrument. In a second step we corrected for the residuals by fitting a third order polynomial to the remaining curvature in the science spectra. Here we excluded the wavelength regions influenced by the He I and Mg II lines. Finally we divided the science spectra by this polynomial, extrapolated over the wavelength region of the two lines of interest. In addition we corrected for bad-pixels.

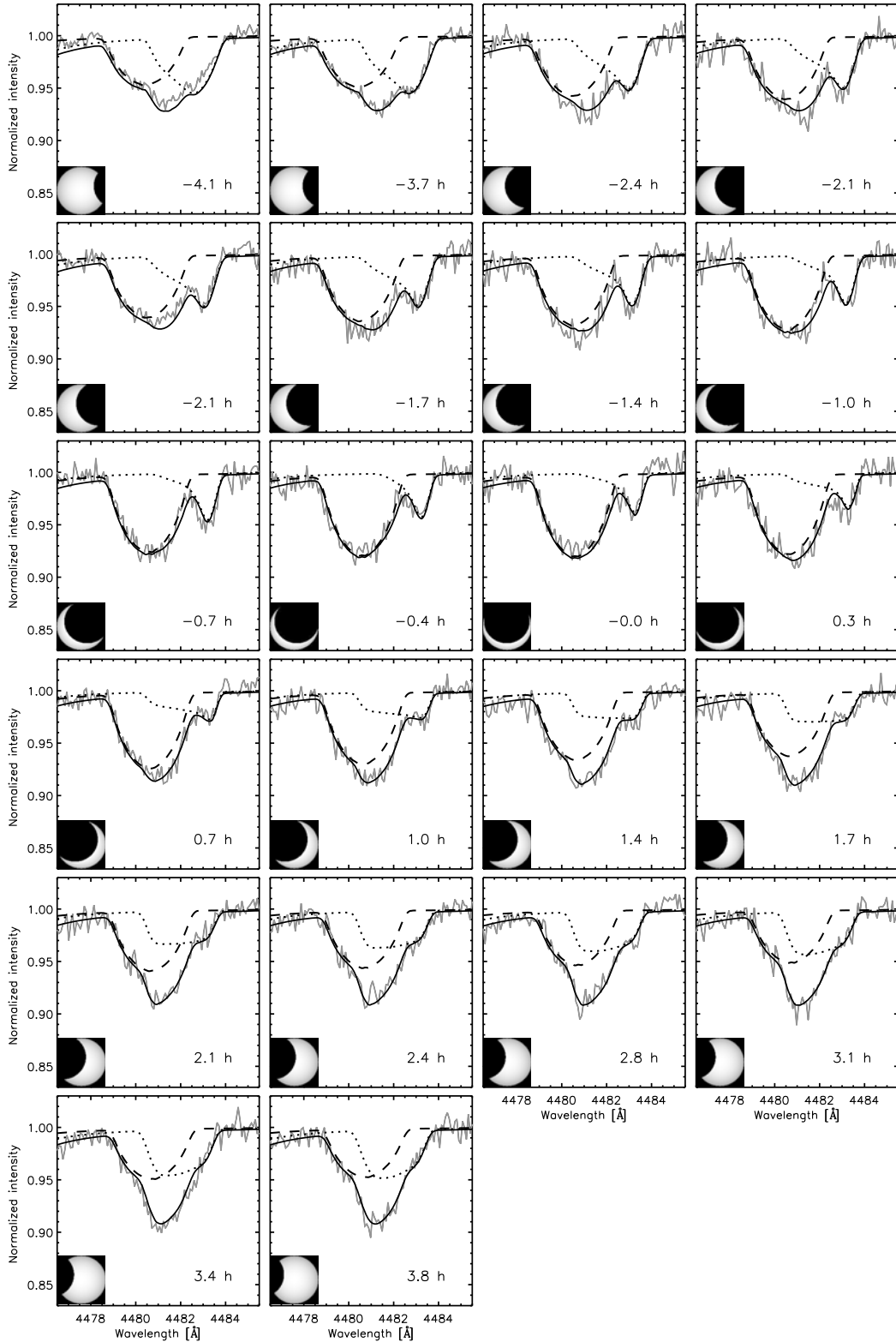


Figure 5.3 — The same as for Figure 5.2, but this time for observations during the primary eclipse. The numbers in the lower right corner of each panel indicate the time difference between the midpoint of the observation and the midpoint of the primary eclipse in hours. In the lower left corner one can see the uncovered part of the primary half-sphere for the midpoint of that measurement. The projected angle between the spin axis of the primary and the orbital axis is 71° for our best fitting model shown here.

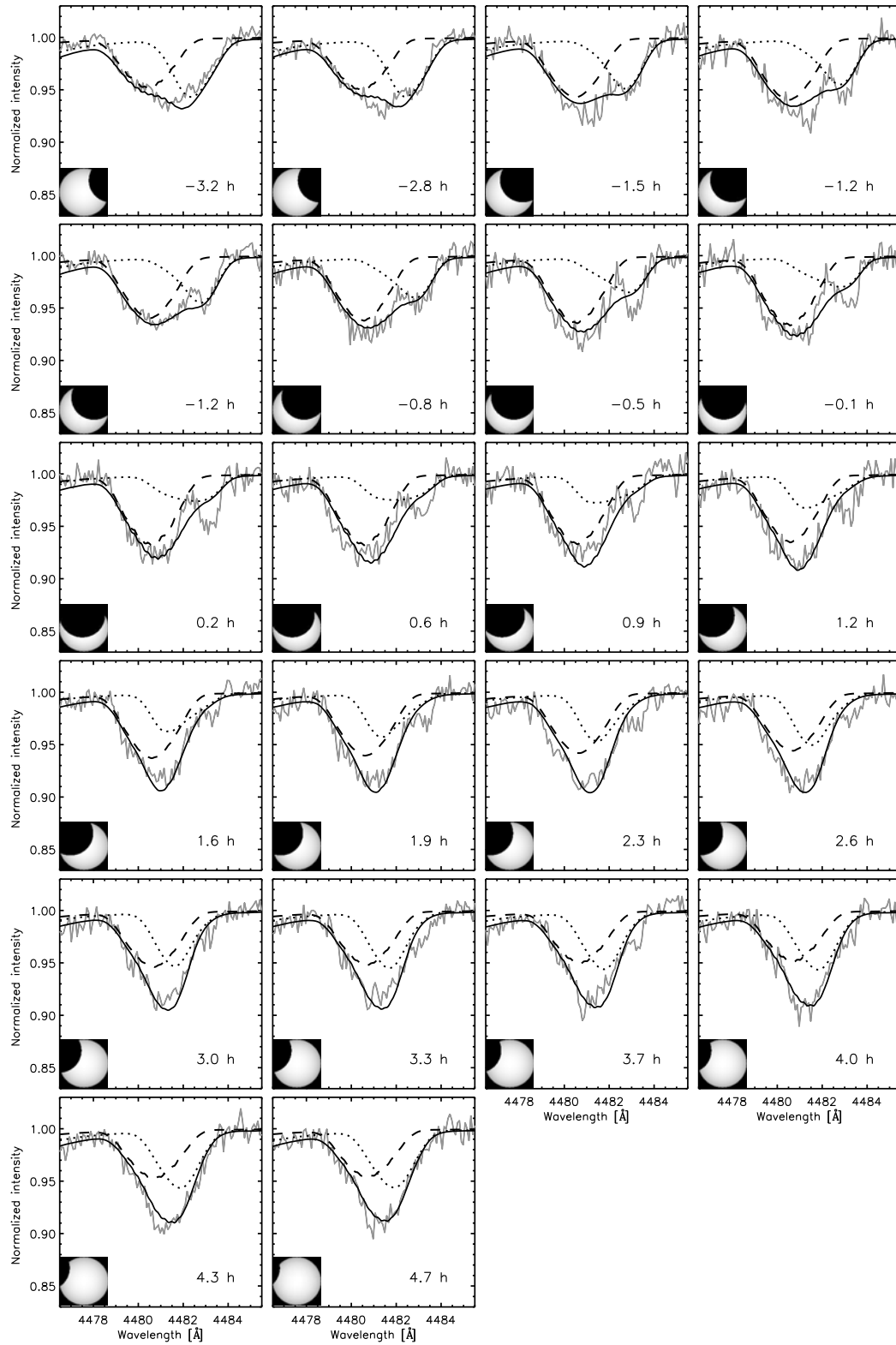


Figure 5.4 — The same as for Figure 5.3, but this time for our best fitting model with parallel spin axes in the DI Herculis system ($\beta \equiv 0^\circ$). Note the disagreement between the model and the measured spectra in the spectral region which is dominated by the primary.

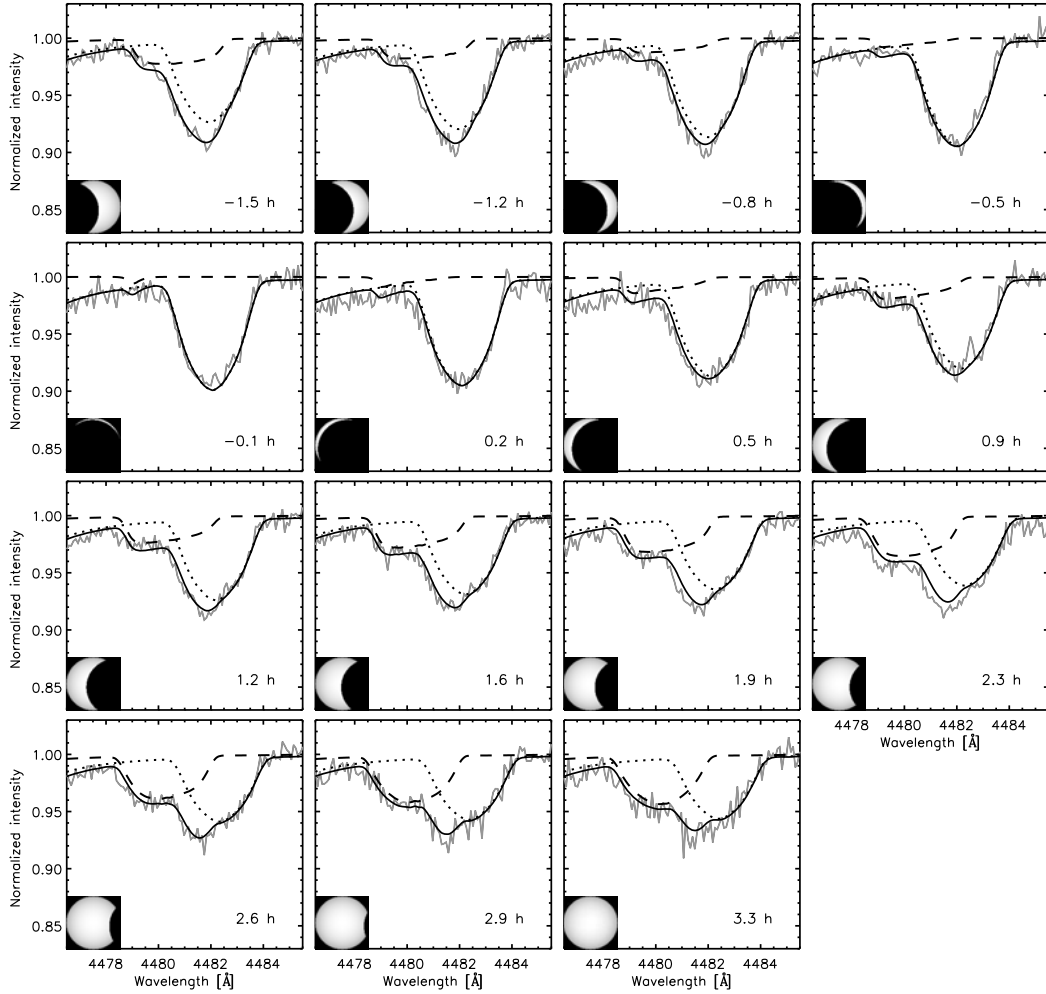


Figure 5.5 — The same as for Figure 5.3, but this time for observations during the secondary eclipse. The projected angle between the spin axis of the secondary and the orbital axis is 93° for the best model while a degeneracy exists with a second minimum at -88° (See Section 5.4.1).

The uncertainty in the wavelength solution of the spectrograph is very low and negligible for our purposes.

For the analysis of the RM-effect we use our approach developed in Chapter 4, which we shortly summarize here. The main difficulty in the interpretation of the RM-effect in double star systems is in the fact, that one does not only receive light from the eclipsed background star, which is the light one is interested in, but also from the eclipsing foreground star. For a double star system consisting of components of the same spectral type that means that one actually receives more light from the foreground star than from the eclipsed background star. In Chapter 4 we developed two methods to analyze the RM-effect despite this difficulty. In our first approach (Section 4.3.1) we extract from each obtained spectrum during its eclipse the contribution of the foreground star. To do this we first disentangle the spectra of the two components by using the tomography algorithm developed by [Bagnuolo & Gies \(1991\)](#), all observations obtained out of eclipse, and an orbital model of the binary system. We then derive

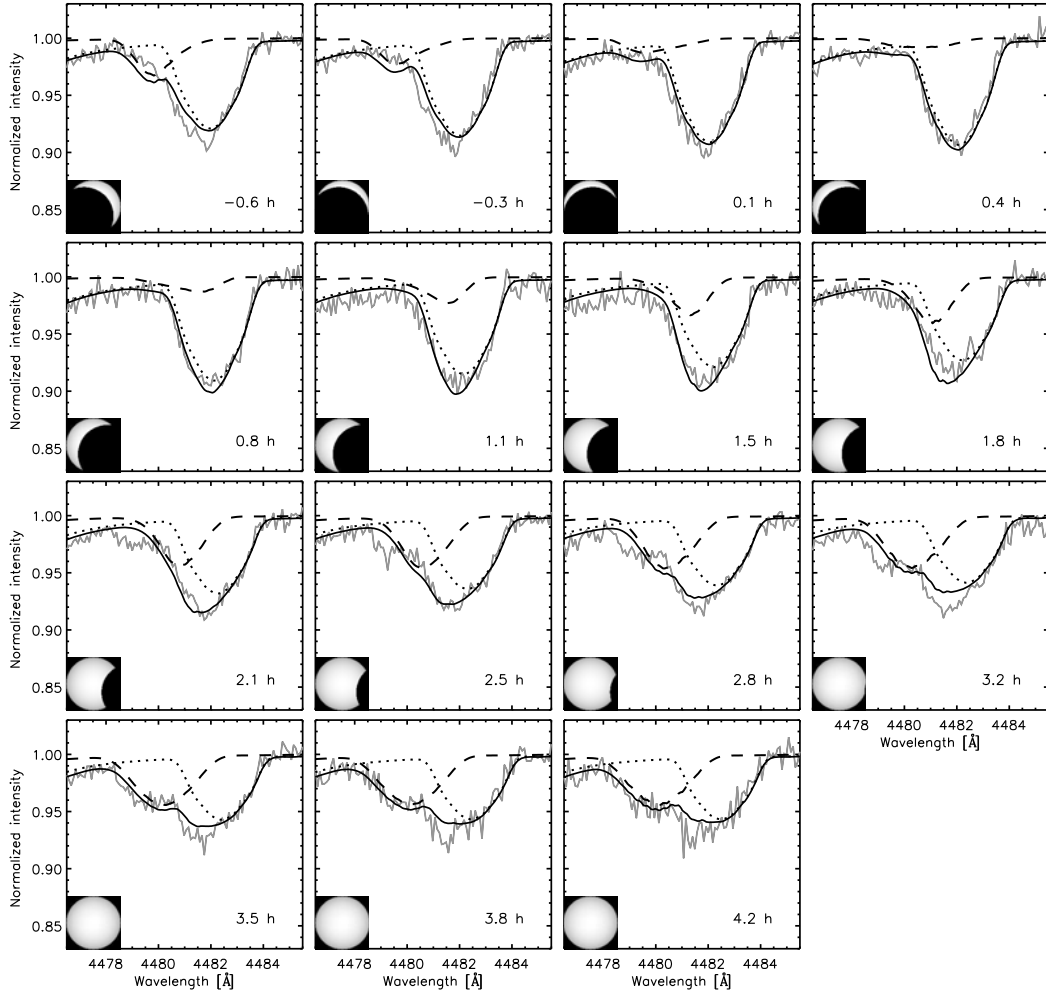


Figure 5.6 — The same as for Figure 5.4. Our best fitting model with parallel spin axes in the DI Herculis system ($\beta \equiv 0^\circ$) is displayed along the observed spectra, but this time for the secondary eclipse.

the parameters which governs the RM-effect by measuring the shift of the center of gravity of the absorption lines of the eclipsed star. In our second approach (section 4.3.2) we simulate the absorption lines of both stars – out of the eclipses and during both eclipses – and derive the best fitting orbital and stellar parameters by comparing our model to the measured spectra. As it turned out, our second method delivers more accurate and precise results (see section 4.4) and since we have only a relative small number of out of eclipse observations of the DI Herculis system, we use only the second method in this chapter.

We fitted the spectra of the two stars in the DI Herculis system during and out of eclipses leaving the following orbital parameters free: the period (P), the time of primary minimum (T_{minI}), the eccentricity (e), the argument of periastron (ω), the orbital inclination (i), and the semi-amplitudes of the two stars (K_i). Furthermore the luminosity ratio at $\sim 4500 \text{ \AA}$ between the two stars enters the fit as a free parameter (L_s/L_p). For each star we have four additional free parameters: The first parameter describes the projected rotational velocity ($v \sin i$). The second parameter, the Gaussian width of the macro-turbulence (ζ_{RT}), describes the strength

of velocity fields on the stellar surface (Gray 2005). We kept the σ of the Gaussians for the tangential and radial velocity fields and their covered surface fraction equal. Another stellar parameter describes the degree of pressure broadening for the He I lines. The angle between the stellar spin axis and the orbital spin axis, projected onto the plane of the sky, β , is the fourth parameter. A projected rotation axis perpendicular to the orbital plane would mean $\beta = 0^\circ$, whereas $\beta = 90^\circ$ would indicate that the rotation axis lies in the orbital plane. The longitude of the ascending node of the orbit (Ω) is not known, resulting in an ambiguity in the sign of the angle β . In our definition, a positive β indicates that the RM-effect, integrated over the complete eclipse, would give a positive residual in radial-velocity, for an exactly edge-on orbit. The companion passes over a larger stellar surface area which is moving towards the observer than over surface area which is moving away from us. Two additional free parameters are needed, one which weights the relative depth of the simulated He I and Mg II lines, and another which describes the total depth of the stellar lines in the spectrum.

Next to these 18 free parameters we adopted a number of parameters from the literature for our model and kept these fixed: We describe the limb darkening of both stars using a linear limb darkening law and with the limb darkening coefficient $u = 0.4$ at $\sim 4500 \text{ \AA}$ (Gray 2005). We further adapted the radii of the two stars from Guinan & Maloney (1985) displayed in Table 5.1. Finally we did not allow for solar-like differential rotation $\alpha = 0$.

We used the Levenberg-Marquardt least-squares minimization algorithm to derive the best fitting parameters and the bootstrap method (Press et al. 1992) to derive the $1 - \sigma$ uncertainties in the parameters. Our best fitting parameters are displayed in the first column of Table 5.2, along with literature values for the orbital and some stellar parameters in the second column. Note that we find that the rotation-axes of both stars are tilted against each other and with respect to the orbital spin (i.e. $\beta_i \neq 0$). Note that the literature value for ω (329.9°) obtained from Popper (1982) is brought forward to the year 2008 including an apsidal motion rate of $1.04^\circ/100$ years as determined by Guinan et al. (1994). Figure 5.2 displays the spectra around the Mg II line at $4481 \text{ \AA}$ for all observations out of eclipse (gray lines). Furthermore we indicate our best fitting model for absorption lines of the primary (dotted lines) and secondary (dashed lines) and their combined contribution (solid lines). Figure 5.3 shows the same for our observations during primary eclipse, and Figure 5.5 displays data obtained during secondary eclipse along with the model. All figures show spectra which for clarity have been spectrally binned by four pixels. The fits, however, have been performed with the original resolution. The radial velocities of our orbital model and the orbital plane of DI Herculis are displayed in Figure 5.8.

We further tried to fit our data using the same model but this time with the β_i for both stars set to 0. This would mean that the projections of all axes in this system are parallel. The results of this fit are displayed in the third column of Table 5.2 and in Figure 5.4 and Figure 5.6.

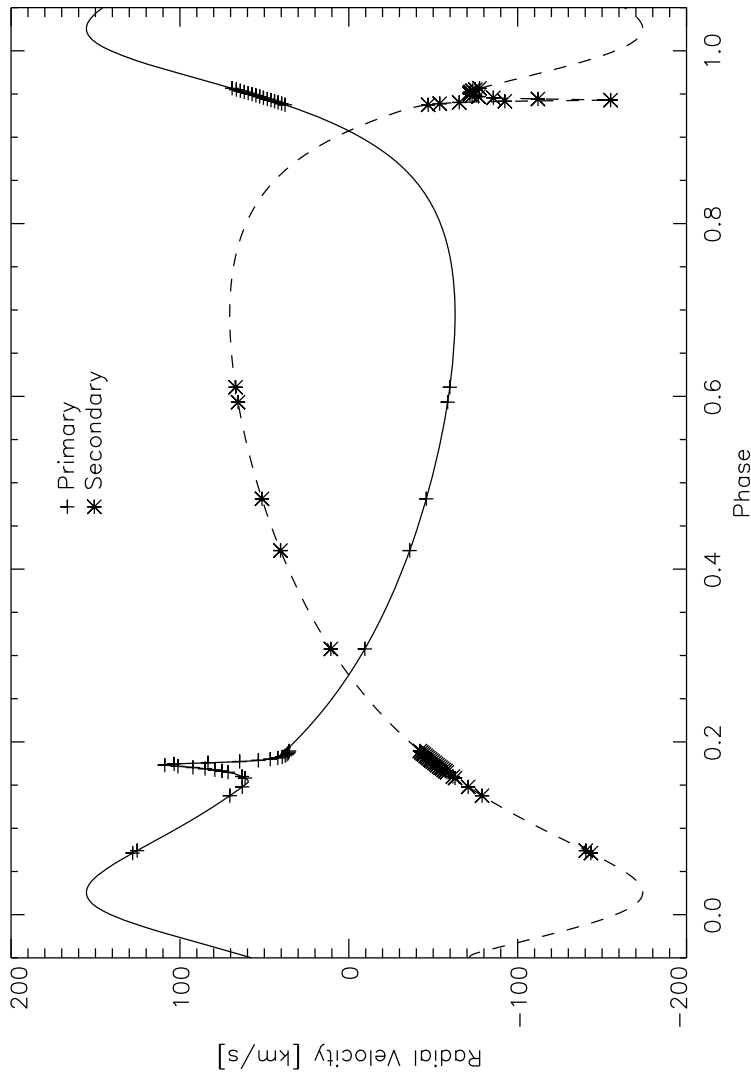


Figure 5.7 — The radial-velocity solution for the primary (solid line) and secondary (dashed line) components of DI Herculis is plotted against orbital phase. The crosses and stars indicate the radial-velocities of the stars at the times of the observations according to our best fitting model (they do not indicate radial-velocity measurements). The midpoint of the primary eclipse occurs at a phase of ~ 0.17 , and the midpoint of the secondary eclipse occurs at a phase of ~ 0.94 . Note that the systemic velocity is not shown in this graph.

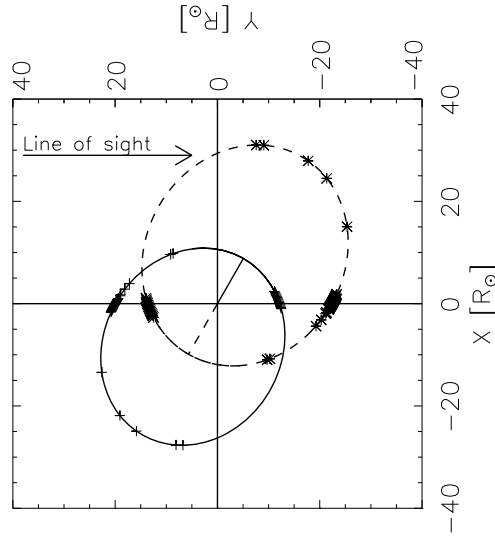


Figure 5.8 — A polar view of the orbit of the binary system DI Herculis. The solid line represents the orbit of the primary component and the dashed line the orbit of the secondary. The lines from the center of gravity towards the orbits indicate the periastron. The crosses and stars indicate the positions of the stars during observations.

Table 5.2 — Derived parameters for the DI Herculis system and its components are shown together with their formal errors derived using the bootstrap method. The second column shows our best fit parameters. For comparison, values given by [Popper \(1982\)](#) and [Guinan & Maloney \(1985\)](#) are shown in the third column, while the fourth column shows the derived parameters with the assumption of aligned spin axes $\beta_i \equiv 0^\circ$. See Section 5.4 for a further discussion about the uncertainties of the best fitting parameters.

Parameter	Best fit	Popper (1982) [†] Guinan & Maloney (1985) [★]	Parallel axes $\beta_i \equiv 0^\circ$
T_{mid} [JD-2400000]	42233.36 $\pm$ 0.05	42233.3481 $\pm$ 0.0007 [★]	42233.36 $\pm$ 0.05
P [days]	10.55017 $\pm$ 0.00004	10.550164 $\pm$ 0.000001 [★]	10.55015 $\pm$ 0.00005
e	0.487 $\pm$ 0.003	0.489 $\pm$ 0.003 [†]	0.487 $\pm$ 0.004
ω [°]	330.6 $\pm$ 0.6	330.2 $\pm$ 0.6 [†]	330.4 $\pm$ 0.9
i [°]	89.28 $\pm$ 0.05	89.3 $\pm$ 0.03 [★]	88.16 $\pm$ 0.14
$a \sin i$ [$R_\odot$]	42.3 $\pm$ 0.6	43.18 $\pm$ 0.24 [†]	43.7 $\pm$ 1.0
K_p [km/s]	109.6 $\pm$ 2.1	110.7 $\pm$ 0.5 [†]	114.2 $\pm$ 3.4
K_s [km/s]	123.0 $\pm$ 2.0	126.6 $\pm$ 1.2 [†]	126.9 $\pm$ 3.5
γ_1 [km/s]	9.1 $\pm$ 2.5	8.5 $\pm$ 0.3	9.2 $\pm$ 2.3
γ_2 [km/s]	$= \gamma_1$	9.1 $\pm$ 0.3	$= \gamma_1$
$v \sin i_p$ [km/s]	105 $\pm$ 1		102.7 $\pm$ 2.2
$v \sin i_s$ [km/s]	116 $\pm$ 2		111.8 $\pm$ 2.5
ζ_{RP} [km/s]	13 $\pm$ 2		12 $\pm$ 2
ζ_{RS} [km/s]	10 $\pm$ 1		23 $\pm$ 2
β_p [°]	71 $\pm$ 2		0 (fixed)
β_s [°]	93 $\pm$ 4		0 (fixed)

5.4 Discussion

5.4.1 Robustness of the results

How robust are the derived parameters for the stars in the DI Herculis system? The biggest uncertainty in our results comes from the imperfection of the normalization of the spectra. This can be seen in the panels displaying the observations obtained during the primary eclipse (Figure 5.3). The two left panels in the two top rows have been obtained during different nights than the rest of the observations during the primary eclipse. One can see that there is an offset between the model and the spectra. It is difficult to quantify the error introduced by this imperfection in the normalization as most observations during primary eclipse, and all observations during the secondary eclipse, have been obtained during one night each. Under this condition it is not possible for the bootstrap method to derive reliable uncertainties. We estimate that the stated uncertainties listed in Table 5.2 underestimate the real uncertainties by a factor ~ 2 for each parameter. There are a few methods with which the normalization of the spectra can be improved. One of these is used, in a different context, in Chapter 6 of this thesis and applying it here will be an immediate improvement to our analysis.

A second challenge lies in our incomplete coverage of the orbit (see Figure 5.8). In particular we miss, due to bad weather, observations at orbital phases where the components have high radial velocities. One can expect that this influences the derived values for the semi-amplitudes of the radial-velocities most. Indeed for our best fit we derive orbital parameters which are, with the exception of the semi-amplitude of the secondary K_s , consistent with values found over 20 years ago by Popper (1982) and Guinan & Maloney (1985). We estimate that our real uncertainties in the semi-amplitudes is $\sim 5 \text{ km s}^{-1}$. The other orbital parameters are however not as much affected by this problem of orbital coverage, as their uncertainty is more a function of the coverage of the eclipses which actually have been covered fairly well.

How do the reduced accuracies in the semi-amplitudes of the radial-velocities influence our results for the relative orientations of the stellar spin axes, β_i ? The case for the DI Herculis system is in this respect more fortunate than that for the V1143 Cyg system, where the orbital velocity of the components was an order of magnitude greater than the projected rotational velocities, and changed rapidly during eclipses, compared to the $v \sin i$ of the components. Therefore small systematics in the orbital solution would have strongly influenced the derived values for the spin axes in the V1143 Cyg. This is not the case for DI Herculis. The nearly edge-on orientation of the DI Herculis system does however introduce a degeneracy in the derived values for β of the secondary as we find that its axis is nearly in the orbital plane. It is therefore very difficult to decide if the angle of β is $\sim 90^\circ$ or $\sim -90^\circ$. This has no consequences for our conclusion on the apsidal motion (section 5.4.2), but it might suggest a different route to misalignment (section 5.4.2). We find that $\sim 10\%$ of our bootstrap runs find a minimum at $\sim -88^\circ$ and $\sim 90\%$ a minimum at 93° . (Each run starts with parallel axes of both stars.) The latter is therefore our preferred value for β_s .

Furthermore our model does not include the fact that the shape of the stellar line changes

from the center towards the limb of the star. This can in particular introduce systematics in the parameters for $v \sin i$ and ζ_{RT} (See also Chapter 4.4.2 for a discussion on this subject). However in the same chapter we show, using a much higher S/N ratio mean stellar absorption profile (Broadening function), albeit for slower rotating F stars, that this does not have any significant influence on β , the parameter we wish to determine with the work in this chapter. We are therefore confident that this does not constitute a major additional source of systematics for the fitted values of β .

In addition, our program oversimplifies the velocity fields on the stellar surface, as it assumes that the same surface area is covered by material moving tangentially and by material moving radially. This is not true for early type stars like the ones in the DI Herculis system as can be seen in bisector analysis (Gray 2005). However, changing the ratio of the surface areas covered by the different velocity fields does not significantly change the values for the fitted stellar parameters. The stellar rotation is simply the dominant broadening mechanism for these two stars. However, as our understanding of the velocity-fields on stellar surfaces of early type stars is not complete, it would be interesting to observe the RM-effect in a system for which the components have a lower $v \sin i$.

A set of parameters for which disagreement with the literature values exists, and which are important to derive the expected apsidal motion rate, are the projected rotational velocities of the stars. We derive for $v \sin i_p$ and $v \sin i_s$ values of 108 km s^{-1} and 119 km s^{-1} respectively. Guinan & Maloney (1985) estimated the $v \sin i$ for both components to be $\sim 45 \text{ km s}^{-1}$. This value is a conservative estimate as a higher $v \sin i$ would have increased the disagreement between expected and measured apsidal motion even more (see Section 5.4.2). We are, given our experience with V1143 Cyg and including the systematics discussed in these paragraphs, confident that the derived parameters have an uncertainty not greater than 10 km s^{-1} .

Note that our results for the stellar parameters, and in particular for β , are reproduced if we use literature values for the orbital parameter of DI Herculis (not shown here). While this is not surprising, as our orbital parameters are similar to the literature values, this gives us extra confidence that our approach is not dominated by systematic errors. Finally, one should note that the fit for which we used parallel rotation axes produces a significantly worse fit to the data during eclipses as can be seen in the Figures 5.4 and 5.6. Furthermore this fit finds an orbital inclination (i) far outside of the 1σ interval given for this value in the literature, as can be seen in Table 5.2. Keeping the orbital inclination fixed to its literature value, other orbital parameters (especially T_0 , P , e , and ω) are found to be outside of the error-margins of the literature values (not shown here). We therefore conclude that our conclusion that the rotation axes in the DI Herculis system are misaligned is solid.

We will now focus on the discussion about the consequences of this result for the expected apsidal motion rate in the next section and then shortly mention possible causes of misalignment in Section 5.4.2.

5.4.2 Implications of the misaligned rotation axes

Apsidal motion

How does a misalignment of the stellar rotation axes influence the expected apsidal motion? The effect of a misalignment between the stellar rotation axes and the orbital spin axis on the apsidal motion has been studied by [Kopal \(1978\)](#); [Shakura \(1985\)](#); [Company et al. \(1988\)](#) and [Petrova & Orlov \(2003\)](#). The contribution of the stellar rotation to the advance of the longitude of the periastron is reduced if the stellar rotation axis is tilted with respect to the orbital spin axis until, finally, when the axis of stellar rotation lies in the orbital plane, its contribution is half as large, and with the opposite sign, compared to when the stellar and orbital axes would be parallel. In this situation, it contributes to a retrograde rotation of the periastron. The contribution of the stellar rotation to the apsidal motion depends not only on the orientation of the axis, but also on the square of the angular stellar rotation rate. As one measures only $v \sin i$, a greater inclination towards the observer would mean a higher angular stellar rotation rate, and therefore a greater contribution of the rotation term to the overall apsidal motion. In this study we derive only the angle between the projection of orbital spin axis and the stellar spin axes. We therefore have only limited information on the geometry.

Table 5.3 — Expected apsidal motion of the orbit of the DI Herculis system for a few different orientations of the stellar spin axes, and rotational speeds of the components.

V_p km s ⁻¹	V_s km s ⁻¹	β_p [°]	β_s [°]	$incl_p$ [°]	$incl_s$ [°]	$d\omega/dt$ [° /cycle]
45	45	0	0	0	0	0.00127
105	116	0	0	0	0	0.00238
105	116	71	93	0	0	0.00049
120	133	71	93	30	30	0.00031
measured						0.00029 ± 0.000041

In Table 5.3 we show a few expected apsidal motion rates ($d\omega/dt$) for the DI Herculis system for different degrees of misalignment between the axes. The first column is a reproduction of the results obtained by [Guinan & Maloney \(1985\)](#) who estimated a $v \sin i$ of 45 km s⁻¹ and assumed aligned axes. The second row shows ω for the observed $v \sin i$ with the rotation axes aligned. For this case the difference between the measured and expected apsidal motion amounts to nearly a factor of 10. The next row shows the expected apsidal motion for the case that the components have no inclination towards us – rotational speed (V) is equal to the projected rotational speed ($v \sin i$). For this case the disagreement is reduced to a factor of 2. The next row shows our calculations for a moderate amount of inclination of 30° for both stellar spin axes. For this case the expected and measured values for ($d\omega/dt$) agree with each other. From a statistical point of view it is expected that the stars show a certain degree of inclination, the position of the Earth does not constitute a preferred reference frame for the stars in DI Herculis and it also appears from the measurements of β that the orbital frame of DI Herculis does not constitute such a

system. We therefore conclude that a misalignment of the different spin axes in DI Herculis is responsible for the low observed apsidal motion rate in this system.

Star formation and evolution

An interesting question is how the stars in the DI Herculis system end up having a completely different angular momentum vector than their orbit. Have they formed with their formation axes misaligned, and if so, how was it possible to maintain the misalignment during subsequent phases? There are a number of ways stars can acquire tilted rotation axes in binary systems, see for example [Monin et al. \(2007\)](#) for a discussion on this subject. A interesting mechanism for DI Herculis would be the mechanism suggested by [Bonnell et al. \(1992\)](#). According to these authors a situation like in DI Herculis can arise if the initial cloud, out of which the binary forms, is elongated and its rotation axis is misaligned to the cloud axis. However, if the stars have formed with misaligned axes, it is not clear how they can remain having misaligned axes, as it is thought that during the pre-main-sequence phase, when the stars are more extended, tidal forces are strong and align the axes.

The spin axes of the stars could also get misaligned after their formation. One mechanism would be Kozai migration which might be responsible for the existence of a number of close binaries (e.g. [Fabrycky & Tremaine 2007](#)). For $i > 39.2^\circ$ between the orbits, the torque from the outer body causes the inner orbit's orientation to librate, while i and e oscillate. During the phases of high eccentricity, tidal forces dissipate energy and ultimately shrink and circularize the orbit. So far no third body has been found. If a third body exists, the Kozai migration might have helped to shrink the orbit of an originally already misaligned binary system, which would also help to explain the existence of DI Herculis as for a wider system tidal forces during the pre-main-sequence phase might not have aligned the system. As DI Herculis is a very young system it would be interesting to model how long the Kozai migration would have needed to work as this might constrain the parameters of the potential third body. Also other 3-body mechanisms, like a close encounter, might have influenced the relative orientations of the spin axes. Another possible cause for the misalignment could be the ejection of the binary out of a cluster which might have changed the orientation of the orbital and stellar axes.

Here we cannot answer how the axes in the DI Herculis system ended up being misaligned. In the future we will attempt to exclude at least a number of scenarios, of which we did only list a few in the above paragraphs, by carrying out further observations and more detailed modelling.

5.5 Conclusion

We observed the DI Herculis system during and out of its eclipses with the high resolution Echelle spectrograph Sophie at the OHP. We have shown that the stellar rotation axes are neither aligned with each other nor with the orbital angular momentum. The projections between the stellar spin axes and the orbital spin axis span angles of $71 \pm 4^\circ$ and $93 \pm 8^\circ$, respectively. This is the first clear demonstration of such a strong misalignment. It further solves a 20-year-old mystery about this system: the observed orbital precession is too slow to be in agreement with the predictions made by Newtonian mechanics and general relativity. This prediction was based on the premise of co-aligned stars. When this assumption is relaxed, as shown

by our observations, the paradox disappears. The results of these measurements contain new challenges for binary formation and evolution theories. systems like DI Herculis.

Acknowledgments

We would like to thank the team which designed and build the amazing Sophie spectrograph and its software. We are also grateful for the support from the complete team at the OHP observatoire. Also thanks to Yuri Levin for enlightening discussions.

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