



universität
wien

DISSERTATION

Titel der Dissertation

„RR Lyrae stars in the space age:

New insights from high-precision photometry and high-
resolution spectroscopy“

Verfasserin

Mag. Elisabeth Guggenberger

angestrebter akademischer Grad

Doktorin der Naturwissenschaften (Dr. rer. nat)

Wien, 2014

Studienkennzahl lt. Studienblatt:

A 091 413

Dissertationsgebiet lt. Studienblatt:

Astronomie

Betreuerin / Betreuer:

Em. O . Univ. Prof. Dr. Michel Breger

Contents

List of Papers	iii
Introduction	1
1 Known facts and open questions	5
1.1 A short history of the study of RR Lyrae stars	5
1.2 Basic properties of RR Lyrae stars	7
1.3 Structure and evolution of an RR Lyrae star	12
1.4 The Blazhko effect (before the space age)	17
1.5 Models for the Blazhko effect (before the satellite age)	21
2 Testing the magnetic model (Paper I)	27
2.1 Previous studies on magnetic fields in RR Lyrae stars	28
2.2 Some basic definitions	30
2.3 Instrumentation	32
2.3.1 SemPol	32
2.3.2 AAT and the UCLES spectrograph	38
2.4 Data Reduction and Analysis	38
2.5 Targets and Results	41
3 Towards a complex Blazhko effect (Papers II and III)	51
3.1 Analysis of the CoRoT photometry	52
3.2 Kepler photometry of V445 Lyrae	66
4 A bisector analysis of the prototype RR Lyrae (Paper IV)	85
4.1 Work preceding the bisector study	86
4.1.1 The “quiet” phase	87
4.1.2 Consistent analysis: parameters of all phases	88
4.2 The Basics of Bisector analysis	91
4.2.1 Methods of constructing the bisectors	91
4.2.2 Applications of line bisectors	92
4.3 Line selection for the bisector analysis	95
4.3.1 Shifts between different ions	97
4.4 The bisector in atmospheric depth	100

4.5	Comparison to pulsation models	116
4.6	The Van Hoof effect	120
4.6.1	The Van Hoof effect in our spectra	121
5	Discussion and Outlook	125
	Abstract	131
	Zusammenfassung	133
	Bibliography	135
	List of Publications	143
	Curriculum Vitae	147

List of Papers

This thesis is based on the following papers:

1. **Guggenberger, E.**; Kolenberg, K.; Marsden, S. C.; Waite, I. A.; Henrichs, H. F.; Lüftinger, T. *High-Resolution Magnetic Field Measurements of RR Lyrae Stars with SemPol*, published in “Stellar Pulsation: Challenges for theory and evolution”, Proceedings of the International Conference. AIP Conference Proceedings, Volume 1170, pp. 278-280 (2009)
2. **Guggenberger, E.**; Kolenberg, K.; Chapellier, E.; Poretti, E.; Szabó, R.; Benkő, J. M.; Paparó, M.: *The CoRoT star 105288363: strong cycle-to-cycle changes of the Blazhko modulation*, published in the Monthly Notices of the Royal Astronomical Society, 415, 1577 (2011)
3. **Guggenberger, E.**; Kolenberg, K.; Nemec, J. M.; Smolec, R.; Benkő, J. M.; Ngeow, C.-C.; Cohen, J. G.; Sesar, B.; Szabó, R.; Catelan, M.; Moskalik, P.; Kinemuchi, K.; Seader, S. E.; Smith, J. C.; Tenenbaum, P.; Kjeldsen, H.: *The complex case of V445 Lyr observed with Kepler: two Blazhko modulations, a non-radial mode, possible triple mode RR Lyrae pulsation, and more*, published in the Monthly Notices of the Royal Astronomical Society, 424, 649 (2012)
4. **Guggenberger, E.**; Shulyak, D.; Tsymbal, V.; Kolenberg, K.: *Bisector analysis of RR Lyrae: atmosphere dynamics at different phases*, published in “Precision Asteroseismology”, Proceedings of the International Astronomical Union, IAU Symposium, Volume 301, pp. 261-264 (2014)

The papers were included with the permission of the publishers.

Introduction

Since their discovery more than a hundred years ago, much has been found out about the class of RR Lyrae stars. Nowadays we know about their evolutionary stage, we can estimate their age, we know their source of energy, the structure of their interior, and the mechanism that causes their pulsation. Evolutionary models can calculate their probable evolution in the future, and with hydrodynamical models it is possible for theorists to reproduce their light and velocity curves. RR Lyrae stars have also served as important tools in many astrophysical fields, from distance determination based on their known absolute magnitude and their period-luminosity-color relation to tracing the chemical history of our Galaxy through abundance analysis of those old objects.

There are, however, still some crucial unsolved questions that need to be answered. Without the answer to these, one cannot claim that we truly understand these important astrophysical objects. The most intriguing one among the unsolved puzzles is the so-called Blazhko effect – a phenomenon that affects a very large fraction of the fundamental mode RR Lyrae stars and manifests itself as a modulation of the pulsation amplitude and/or phase on timescales of weeks or months. The percentage of stars known to be affected by this phenomenon has been increasing continuously with the availability of increasingly precise photometry, from 20-30% estimated by Szeidl (1988) to around 50% after dedicated ground-based surveys had been conducted (Jurcsik et al. 2009) and when satellite data became available (Benkő et al. 2010).

It is not only the frequency of occurrence of this effect that makes it so important, but it is also its strength that makes it impossible to dismiss. There are stars in which the modulation decreases the amplitude of the pulsation to its half, and for one case, during the minimum of the modulation, the pulsation is even barely recognizable as that of an RR Lyrae star. An effect of this strength needs an explanation before we can say that we understand stellar pulsation.

Through their evolutionary stage, RR Lyrae stars also connect to other important types of stars. During their main sequence life time, they most probably had masses similar to (and slightly less than) the sun, and there is a small chance that the sun itself evolves into an RR Lyrae star, provided that the mass loss is large enough. After their main sequence life, they evolve up the red giant branch, becoming similar to those objects which are at the moment studied intensely with the help of asteroseismology through their stochastic oscillations. Only after they

have lived through all those stages of evolution, they will finally experience the helium flash and settle on the horizontal branch. Provided they will then have the correct combination of mass and metallicity, they might then end up between the borders of the instability strip and commence pulsations as new-born RR Lyrae stars.

Satellites have now enormously improved our possibilities to study the Blazhko effect, and the CoRoT and *Kepler* missions have initiated a golden age of variable star research. While the best ground-based photometry usually had a precision of a few millimagnitudes, the space photometry suddenly supplied asteroseismologists with data sets with an unbelievable precision in the micromagnitude range, making it possible to observe details that had remained hidden during the century of RR Lyrae observations that preceded the space age.

But it was not only the precision that made those data sets so valuable, it was also the length of the time base of the observations, as well as the uninterrupted sequences of measurements. Unlike ground-based data, space photometry is not interrupted by gaps caused by bad weather, daylight, or seasons in which the star is not visible. For Blazhko RR Lyrae stars this meant that for the first time, continuous measurements over several modulation cycles became available which allowed to study long-term effects, and provided an unprecedented frequency resolution. Detailed studies of two very peculiar Blazhko stars observed by the CoRoT and *Kepler* satellites, respectively, making use of continuous data sets covering several subsequent cycles are presented in Section 3 of this thesis.

In addition to the long-term stability of the Blazhko effect, another question could be tackled with the help of satellite data, namely whether additional pulsation modes beyond the classical radial pulsations are present in RR Lyrae stars. Overtone (so-called RRc stars) and double mode pulsators (RRd stars) had been known for decades. Other pulsation features, especially non-radial modes had not been unambiguously found in ground-based data, even though they were predicted by theory (e.g, Cox 1993; Van Hoolst et al. 1998), and their existence would be plausible. There was a time when the peaks in the frequency spectrum caused by the Blazhko effect were suspected to be non-radial modes, with the other components of the multiplets being combination frequencies of those. This approach is mathematically still widely used in the Fourier analysis of Blazhko RR Lyraes. The highest multiplet component is then considered an independent frequency, and the other peaks are fixed to the frequency values of calculated combinations.

While this is a mathematically valid method of fitting the light curve, the presence of those peaks in the Fourier spectrum is by itself no proof that those frequencies are indeed pulsation modes inside the star. In spite of some claims (Olech et al. 1999, for example assumed those multiplet peaks were non-radial modes), no confirmed detection of non-radial modes had been made before the space age. Gruberbauer et al. (2007) were the first to unambiguously find non-radial modes in the RRd star AQ Leo observed with data from the MOST satellite. This was the first thorough study of the pulsation of an RR Lyrae star with space

photometry. Unfortunately, AQ Leo remained the only RR Lyrae star observed by MOST so far, so the community had to wait for CoRoT and *Kepler* to continue to use the extremely high precision of space photometry for the study of RR Lyraes. In this thesis, I present a detailed analyses of two stars observed from space which show a zoo of additional frequencies well away from the classical multiplet typical for modulated stars.

But new insight is not only gained from satellite data, also from the ground it was possible to obtain measurements that in this form had not been available previously for RR Lyrae stars, and which help to study the nature of the Blazhko effect. For example, the question about the cause for the Blazhko effect was closely related to the question whether RR Lyrae stars in general (and Blazhko stars in particular) have strong magnetic fields. Among many other models (which will be discussed in more detail in Section 1.5), one very promising explanation for the Blazhko effect suggested a strong dipole magnetic field as the cause for the modulation, similar to the mechanism that has been proposed as an explanation of the behaviour of the group of rapidly oscillating Ap (roAp) stars.

Such a field would introduce a non-radial component to the pulsation. Assuming that the magnetic field is then inclined to the rotation axis, one would observe a modulation with the period of the rotation. Of course, magnetic fields can be measured through spectropolarimetry, but the history of magnetic field measurements in RR Lyrae has been controversial with several detections as well as non-detections reported in the literature. Also for a long time, the measurements were restricted to the brightest member of the class, RR Lyrae itself. Only a few years ago (at the starting point of this thesis), Kolenberg & Bagnulo (2009) extended the measurements to a larger sample of stars using low-resolution spectroscopy. In this thesis, we use high-resolution spectroscopy instead, extending the sample and verifying that the low resolution was not the reason for the non-detections of Kolenberg & Bagnulo (2009), and ultimately exclude the magnetic model as a cause for the Blazhko effect.

The thesis is structured as follows: the introductory Chapter 1 provides information on the basic characteristics of RR Lyrae stars, their evolutionary path, the previous knowledge about the Blazhko effect, both from photometry and from spectroscopy, and the models trying to explain the phenomenon. Some results obtained with the help of high-resolution ground-based data can be found in Chapter 2, in which I present magnetic field measurements of RR Lyrae stars. It is followed by the analysis of the satellite photometry in which I describe how the space observations changed our view of the Blazhko effect as a simple and periodic phenomenon, and present the findings on irregular modulations and additional frequencies in two Blazhko stars observed by CoRoT and *Kepler*, respectively (Chapter 3). Chapter 4 describes the analysis of the spectral line bisectors of the prototype RR Lyrae, which was used to study the dynamic atmosphere of RR Lyrae.

Even though in the framework of this thesis we were able to gain some more insight into RR Lyrae stars, there remain many other exciting mysteries about this class of stars, and a lot of work is still to do. The outlook in Chapter 5 of this thesis will provide an overview of some of the open questions, and of work that should and hopefully will be done in the future to bring even more light into the mechanisms operating inside these important stars.

Chapter 1

Known facts and open questions

RR Lyrae stars are rather well-studied objects, with the history of their observations starting already at the end of the nineteenth century. This chapter is intended to give a short overview of the basic facts about them, starting with a stroll through the history of the studies of RR Lyrae stars, then describing their basic and their pulsational characteristics and evolution, concluding with a description of the Blazhko effect, which is the most stubborn unsolved problem in the study of RR Lyrae stars. Of course, such an introduction can never be complete, especially not when it is about such extensively studied objects, but can give the reader a rough idea about the objects studied in this thesis and highlight a few selected milestones in their history.

1.1 A short history of the study of RR Lyrae stars

The old name for what is now called the class of RR Lyrae stars was *cluster variables*, owing to the fact that at the end of the nineteenth century many of them were first discovered in globular clusters. One of the most important works of that time, among others, is the survey initiated by Solon Irvin Bailey, an extensive program of photographic observations of globular clusters. Dozens of variable stars with amplitudes between half a magnitude and two magnitudes were found in the course of this survey (Pickering & Bailey 1895).

Only much later, after many stars with the same characteristics had also been found in the field, and long after Willamina Fleming (Pickering et al. 1901) discovered a bright star of the same type in Lyrae (now called RR Lyrae), the whole class was renamed to RR Lyrae stars. Because of its brightness, the star discovered by Fleming became the eponym of the group. This was decided at the 1948 meeting of the International Astronomical Union.

Of course, at the time of the discovery, the mechanism that causes the variation in brightness was not yet known. Bailey also introduced his famous classification

(RRa, RRb, and RRc type stars, Bailey 1902) solely based on the light curve shape and the typical period of the stars, and without the knowledge that RRc stars are indeed physically different from the other subgroups, now united to the group RRab. Decades passed until Schwarzschild (1946) unveiled on the basis of theoretical models what must be the reason behind the difference of the groups, namely that RRc stars are overtone pulsators while RRab stars are pulsating in the fundamental mode.

Also in the 1940s, peculiarities were for the first time detected in the spectra of RR Lyrae during rising light: Struve (1947) found hydrogen emission, and Sanford (1949) for the first time detected the hydrogen line doubling that we also see in the data used for this thesis. Both phenomena were later attributed to the passage of a shock front through the stellar atmosphere.

Several groundbreaking results concerning the three-dimensional structure of our Galaxy were obtained in the 1950s. RR Lyrae stars were used extensively in these studies to determine the distances to the Galactic center, to bulge components and to halo objects. However, efforts to refine our maps of the Galaxy are still ongoing today, and RR Lyrae stars are nowadays still used for this purpose (see for example Sesar 2010).

The study of RR Lyrae stars was soon extended to systems outside the Milky Way. The first extragalactic system in which RR Lyrae stars were studied extensively with 133 RR Lyrae stars detected was the Draco dwarf galaxy (Baade & Swope 1961), in a study performed by Baade shortly before his death. Comparing the characteristics of the variables, the study allowed to determine an approximate distance to the Draco galaxy, and to find differences between other systems and our own Galaxy.

In 1977, Jerzykiewicz & Wenzel (1977) found the first star that pulsates in both the radial fundamental as well as the first overtone mode simultaneously: AQ Leo. This class of stars was named RRd, extending the scheme of Bailey. However, developing a hydrodynamical model that could reproduce a stable RRd pulsation posed a significant challenge. The problem was only solved about 20 years later by Feuchtinger (1998).

The number of known RR Lyrae stars increased significantly in the 1990s and in the beginning of the twenty-first century when the results of microlensing surveys became available which, as a by-product, detected numerous variable stars. Suddenly, instead of roughly one thousand RR Lyrae stars in the Galactic bulge, tens of thousands were known thanks to the OGLE survey (e.g., Mizerski 2003; Soszyński et al. 2011) and the MACHO survey (e.g., Alcock et al. 1998). Also the Magellanic Clouds were extensively observed in the framework of microlensing surveys, again resulting in the detection of tens of thousands of RR Lyrae stars (Alcock et al. 1996; Soszyński et al. 2009; Soszyński et al. 2010). These homogeneous data sets allowed to create large statistics of the pulsational behaviour and to systematically study the Blazhko effect.

It was the MOST satellite, a joint mission of Austria and Canada, that for the first time delivered a long and uninterrupted light curve of an RR Lyrae star observed from space. This unique data set was analysed in detail by Gruberbauer et al. (2007).

With the launch of CoRoT and *Kepler*, for the first time a large sample of such impressive uninterrupted high-precision light curves became available, starting a golden age in the research of RR Lyrae stars and of variable stars in general. Chapter 3 of this thesis deals with the photometry obtained by this satellite and presents some findings that would have been undetectable in ground-based data.

1.2 Basic properties of RR Lyrae stars

Together with the Cepheids, which show a similar light curve shape to that of RR Lyrae stars, but with longer periods, they form the group of the so-called *classical pulsators*. Because of their high amplitudes the variability of those two classes of stars had been identified quite early, in contrast to the many other types of stars that joined the "zoo" of variable stars later. Those classical pulsators, because of their presumed pure radial pulsation, have often been considered simple objects. However, the Blazhko effect is one example of behavior that is not so simple to interpret, and space photometry showed that there is much more to RR Lyrae stars than single-mode radial pulsation.

RR Lyrae stars are evolved objects that burn helium in their core and that are located on the so-called horizontal branch of the HRD (more details on their evolution will be provided in the next subsection). Their spectral types range from A-F, and their absolute magnitudes are roughly in the range of $0 \leq M_V \leq 1$.

Metallicity: RR Lyrae stars usually are population II stars, which means that they are old and have a low content of heavy elements. For this reason, they are sometimes used as tracers of the chemistry of the galaxy and to study the element composition that prevailed in the past. This is possible as the observable element abundances at their surface are not expected to change much during their evolution. They are however, not a totally uniform group. RR Lyrae stars near the galactic plane typically show higher metallicities than their halo or globular cluster counterparts. This was first shown by Preston (1959) who studied over 100 RR Lyrae stars. In his extensive spectroscopic survey, he also found a period-metallicity dependence which was in agreement with previous observations that short-period RRab stars were only present at low galactic latitudes, exactly where Preston (1959) found the stars to be more metal-rich. The observed metallicities in RR Lyrae stars now range approximately from $Z=0.0001$ to $Z=0.01$ (Aerts et al. 2010).

Bailey types and pulsation modes: As already mentioned in the historical overview, RR Lyrae stars are grouped into the subclasses RRab, RRc and RRd. The two groups differ in many aspects. RRab stars have high amplitudes, periods of about half a day, very asymmetric light curves, and they pulsate in the radial fundamental mode (see Figure 1.1). RRc stars on the other hand, have smaller amplitudes, periods of about 0.3 d, rather sinusoidal light curves, and pulsate in the first radial overtone. The two groups also have different effective temperatures, with the RRab stars being cooler, and the RRc stars populating the hotter side of the instability strip.

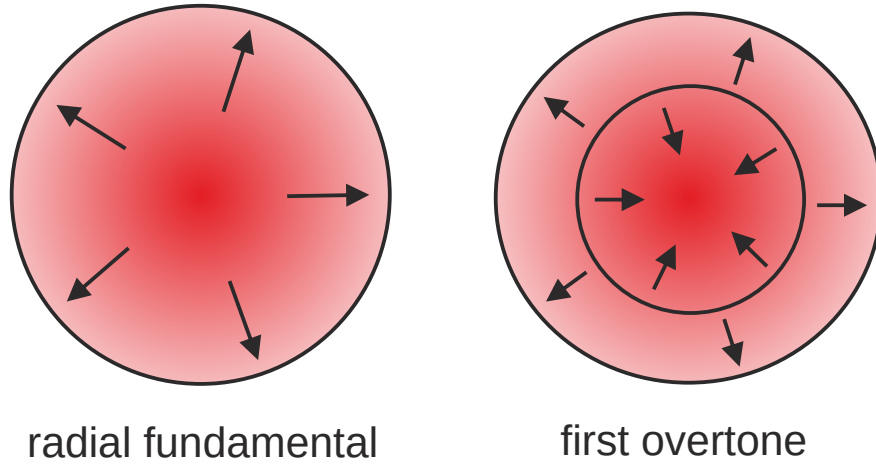


Figure 1.1: Simplified schematic illustration of radial pulsation. Please note that as the pulsation of RR Lyrae stars is highly nonlinear, the motion of the atmosphere is not quite as simple as that, and different layers can have differing velocities (see also Chapter 4).

There is, however, an overlap of the two instability regions of the fundamental and the first overtone mode, meaning that the blue edge of the fundamental instability strip is farther to the blue than the red edge of the first overtone instability strip. This was shown theoretically for example by Christy (1966). Therefore, there is a region where both modes can be unstable at small amplitude. The models indicate that it might depend on the initial situation whether a star in this region shows overtone or fundamental mode pulsation, depending for example on its evolutionary direction (the star tends to keep its mode of pulsation). This is also the region where double mode pulsation may occur. Such a double mode pulsation was first observed in 1977, as was already mentioned in the section about the history of RR Lyrae star studies.

A different nomenclature that would have the potential to replace the Bailey types was later introduced by Alcock et al. (2000). It relies on numbers rather than on letters and therefore would easily allow an extension of the set of types

for higher overtone pulsation and various combination of modes. In their scheme, fundamental stars are called RR0, first overtone stars RR1, and so on. Double mode stars are called RR01, and stars that pulsate in the second overtone are named RR2 rather than RR_e. However, this classification scheme, although somehow more logical, is not widely used.

Mode switches of RR Lyrae stars have also been observed. Clement & Goranskij (1999) e.g., found that the variable V79 in the cluster M3 switched from fundamental mode to double mode pulsation with a dominant first overtone. There have also been reports on changes in the relative amplitude of the modes in RRd stars: Clementini et al. (2004) observed that the star V200 in the globular cluster M3 changed its dominant mode from fundamental to first overtone, while the star V251, also in M3, did the opposite.

Fundamental parameters: RR Lyrae stars generally are observed to have average effective temperatures between 6000 and 7200 K (see Figure 1.2), radii between about 4 to 6 $R_{\odot}$ and an absolute brightness around $M_V = +0.6$. Their luminosities are approximately 50 $L_{\odot}$, and their masses range from about 0.5 to 0.8 $M_{\odot}$. The masses, however, are difficult to determine and almost no RR Lyrae stars have been found in binary systems which would allow to determine their masses more precisely.

On the theoretical side, many important characteristics of RR Lyrae stars were first determined by Christy (1966), who carried out nonlinear calculations for not only one but one hundred RR Lyrae models to investigate the stability of their pulsation. For his model survey he used many different combinations of composition, mass, luminosity, and effective temperature with the goal to find the location of the borders of the instability strip and to explore their dependence on parameters like composition, mass and luminosity.

One of his most important findings was that under certain circumstances the hydrogen ionization zone is, in addition to the HeII ionization region, also of significance for the driving of the pulsation. The importance of the HeII ionization for the driving through the κ mechanism had already been noticed before. Additionally, Christy was able to conclude from his results that the masses of RR Lyrae stars must be near 0.5 $M_{\odot}$, which implies a significant mass loss during their evolution.

While it was already possible quite early for theorists to determine the blue edge of the instability strip (which depends on various parameters such as the hydrogen mass fraction, luminosity, and mass), the red edge evaded the theorists for a while, because of convection that starts to set in at lower temperatures and which makes it difficult to treat the stellar energy transport. Nowadays, however, also the red edge has been calculated, and the typical temperatures of RR Lyrae stars have been found to be between 6000 and 7200 K. Because of the refined treatment of convection, also the light curve morphology can be reproduced well by the models (Feuchtinger 1999).

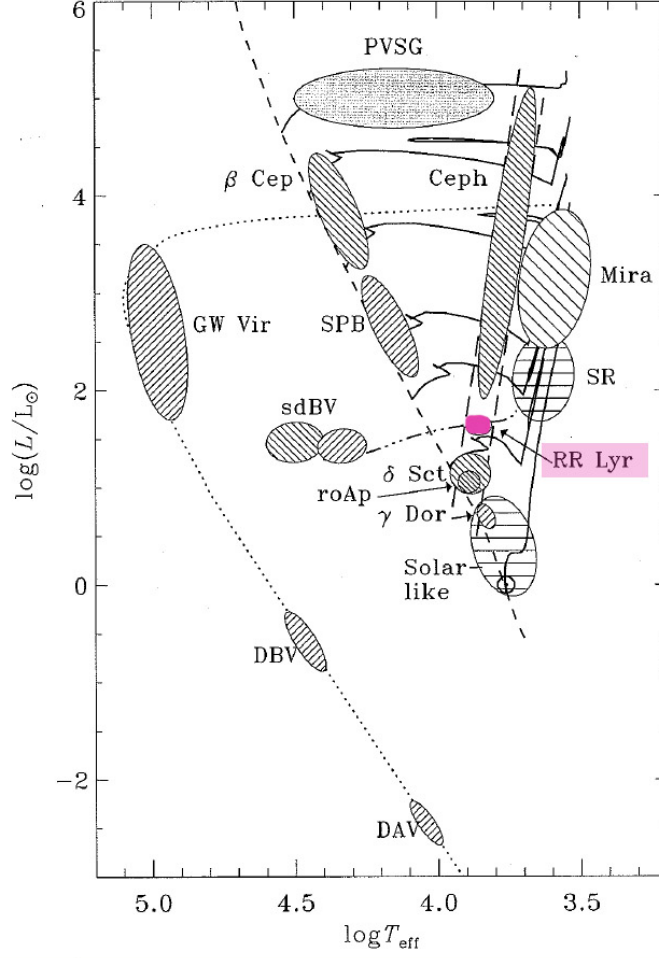


Figure 1.2: HR diagram showing RR Lyrae stars in context with the many other known classes of pulsating stars. Adopted from Aerts et al. (2010) with a modification by the author.

Features observed in spectroscopy: The change of the parameters during the pulsation cycle of an RR Lyrae star can be quite impressive. Already Preston (1959) noted that during one cycle, a spectral variation of one full spectral class is common for RR Lyrae stars. During a cycle of just half a day, those stars can also change their temperature by more than 1000 K. The amplitude of the radial velocity curve can amount to several tens of km/s, and the radius of the star is therefore expected to change by approximately 10 %.

Another aspect seen in spectroscopy is that RR Lyrae stars seem to be very slow rotators. Spectral lines are narrow in all studied stars (except during the phases when a shock passes through the atmosphere), and only upper limits for their rotation are usually given. Peterson et al. (1996), for example, studied 27 RR Lyrae stars and gave an upper limit of $v \sin(i) \leq 10$ km/s for all of them.

In contrast, much higher rotational velocities are known for the blue horizontal branch stars which are adjacent to the RR Lyrae stars in the HRD.

Light curve features: The observed periods of RR Lyrae stars of course depend on their mode of pulsation. Generally, the range of possible pulsation periods is 0.2 to 1 d, with RRC stars having the shorter periods typically around 0.3 d, and RRab stars having periods of about half a day. Photometric amplitudes in V range from about 0.3 mag in RRC stars to over a magnitude in RRab stars. Amplitudes on the B filter are higher than in V.

In the light curves of RRab stars, peculiar features can sometimes be observed. During the steep rising branch of the curve, a stillstand can occur, which is sometimes called a *shoulder* or the *hump*. During this phase, a UV excess can be observed, and in some cases spectroscopy reveals an emission in the hydrogen lines (Preston et al. 1965). Line doubling in the spectra indicates that a shock wave is most probably the reason for this phenomenon.

A similar feature is the so-called *bump* which occurs just before minimum light at a phase of about 0.7 (with zero set to maximum light). Also during this phase an emission is sometimes observed, but less strong than during the *hump* phase. A second shock front is suspected to be the reason for this feature. Shock waves in RR Lyrae stars were studied in detail for example by Hill (1972) and Fokin (1992).

The bump was also observed to vary strongly depending on Blazhko phase (Guggenberger & Kolenberg 2006), indicating that the shock travel time or the shock formation region changes during the Blazhko cycle. The variation can be so strong that in certain Blazhko phases the bump appears about 20 % of the pulsation period earlier than in other phases. In other stars the variation is less strong but has the same direction. Studying the bump progression in Blazhko stars and comparing it to theoretical models might give an additional clue about the phenomenon. Therefore, in Chapter 3 the corresponding bump phases of the studied stars are determined as well.

During the finalization of this thesis, a new model for the Blazhko effect was proposed which makes use of these observations of changing bump phases and explains the modulation via interacting shock fronts (Gillet 2013). This and other new models developed during the satellite age will briefly be discussed in the outlook section.

Fourier spectra of RR Lyrae stars: During a Fourier analysis of RR Lyrae light curves, the skewness of the curve in RRab stars causes many harmonics to appear. Those are found at integer multiples of the fundamental frequency and are important for a correct fitting of the light curve. In Blazhko stars, the modulation causes multiplet features in the Fourier space that are not only found around the frequency of the fundamental mode but around all harmonics.

For non-modulated stars, a strong correlation between some Fourier parameters (i.e., amplitude ratios and phase differences of those peaks which describe the light

curve shape) and the observed metallicity has been found (Jurcsik & Kovacs 1996). Therefore it seems possible to obtain a quite reliable estimate of an RR Lyrae star's metallicity solely from a photometric data set. This is very practical because photometry can be much easier obtained and analyzed than spectra, especially for such faint objects.

1.3 Structure and evolution of an RR Lyrae star

Even though during one human generation we can usually observe only snapshots of a stellar life, every star has a history. The study of a certain type of stars therefore should not only focus on that particular group of stars, but should also consider the progenitors of the stars in question, and at their successors. Any finding on a certain class of stars might also influence our understanding of the stars they have once been or which they will once become. How did a star get to the place in the Hertzsprung-Russell Diagram (HRD) where we observe it now? Especially for the asteroseismologist, this question can be of great interest, considering that an object, during its path through the HRD, might experience different types of pulsation. In the case of RR Lyrae stars, looking at their history means putting them into context with the now intensely studied group of solar-like pulsators on the red giant branch, and with solar-like pulsators on the main sequence. We know from the previous section that RR Lyrae stars are evolved stars in the location where the so-called horizontal branch intersects with the classical instability strip, but how did they evolve to this point? What is their structure now and how did it change during their evolution to arrive at its current state? This section intends to give a basic general introduction to the structure and evolution of RR Lyrae stars. Of course in this context we can only give a brief overview, as a detailed description would go beyond the scope of this thesis. For the detailed picture the reader is referred to the classical textbooks on stellar structure and evolution like those by Kippenhahn & Weigert (1994), Iben (2012) and Prialnik (2000).

The main sequence (MS) phase: RR Lyrae stars, like all other stars, begin their life at the zero age main sequence (ZAMS), which is characterized by hydrogen burning in the core and which is generally considered the starting point of stellar evolution. Even though we have some knowledge on the current masses of RR Lyrae stars, their initial masses, i.e., the masses they had on the main sequence, are not exactly known. The cause for this is the extent of mass loss on the red giant branch, which cannot be predicted precisely and is still a problem in stellar evolution theory. Many different mass loss formulae exist, and the mass loss rate depends on a lot of parameters. It is sure, however, that RR Lyrae stars belong to the so-called low-mass stars (stars with masses below about $2 M_{\odot}$), characterized by the degenerate conditions in their core that occur before helium ignites. The main sequence masses of RR Lyrae stars are assumed to have been somewhere near one solar mass. As we cannot reconstruct the exact masses, also the other

parameters like temperature and luminosity - and hence the position in the HRD - are not exactly known. An HRD diagram showing the evolutionary tracks of stars with 3 different masses (but the same metallicity and with the same treatment of mass loss) is given in Figure 1.3. Models in the figure were computed by the author with the MESA star code (Paxton et al. 2011).

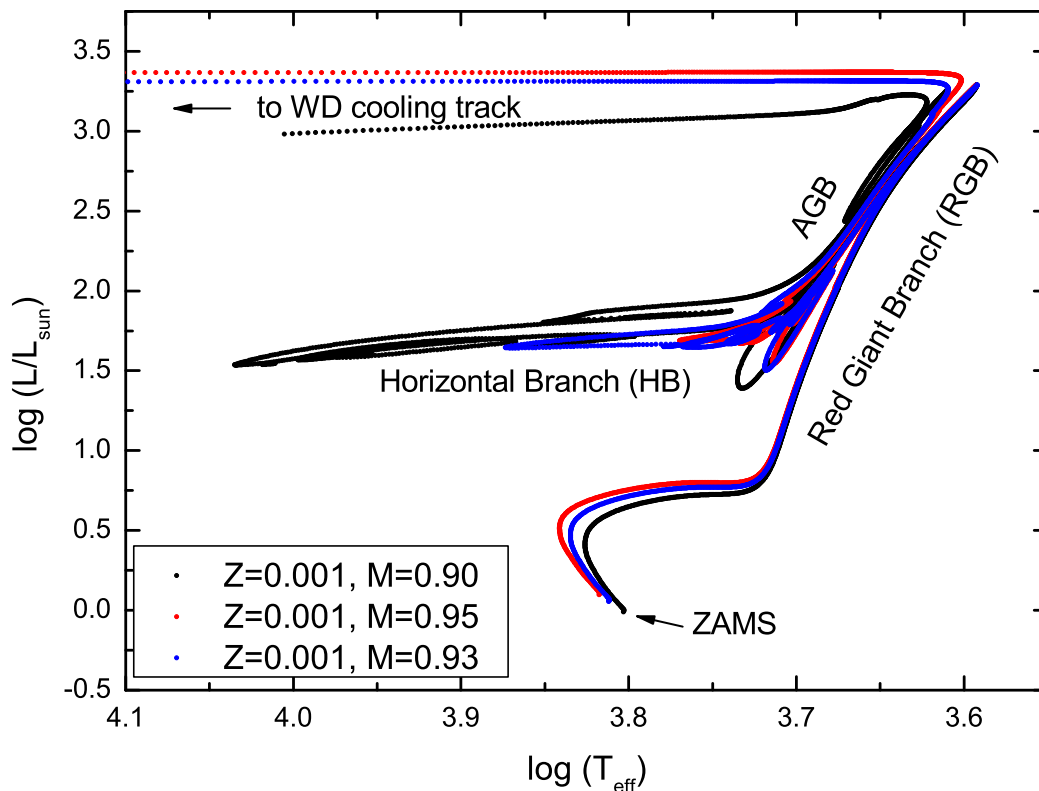


Figure 1.3: Evolution of three low-mass low-metallicity models from the zero age main sequence (ZAMS) through the Red Giant Branch (RGB), the Horizontal Branch (HB), and the Asymptotic Giant Branch (AGB) phase. Note the difference in position on the HB depending on mass.

On the main sequence, it depends on stellar mass (and therefore temperature) whether a star has a convective zone, and where it is located. Convective zones can be in the outer envelope or in the core. Massive MS stars usually have a convective core (where the hydrogen burning takes place via the CNO-cycle), and no, or a very thin, outer convection zone. Low mass stars on the other hand have radiative cores and convective envelopes. The extent of the convective zone in the envelope increases with decreasing stellar mass, with the lowest mass stars ($M \leq 0.3M_{\odot}$) being fully convective. RR Lyrae precursors on the MS probably had some convection in their envelopes.

The main sequence is the longest phase in the life of a star, and a star typically spends about 80 % of its life in this stage. As a consequence it is much more likely to observe a star at this stage than at one of the shorter evolutionary stages. Helium core burning which occurs on the horizontal branch later in the life of a star is the second longest phase. The main sequence life times of stars vary enormously - from 6×10^{12} yr for stars with masses around $0.1 M_{\odot}$ to 6×10^6 yr for masses of $25 M_{\odot}$ (Prialnik 2000). At the lower end of the main sequence, the expected life time drastically exceeds the current age of the universe. Low metallicity stars, however, tend to have hotter main sequence temperatures and shorter life times than higher metallicity stars of the same mass. The model stars in Figure 1.3, for example, leave the main sequence already after 5.5-7.5 Gyr even though they are less massive than the sun.

As soon as the main sequence phase is over, hydrogen burning proceeds in a shell that surrounds the core and which separates it from the stellar envelope. A model star remains near the ZAMS burning hydrogen in a shell until it has been exhausted over about 13 % of the stellar mass (Iben 1971). During the shell burning phase the core which now mostly consists of helium continues to grow in mass. As it is free of an energy source it has to contract, which is accompanied by an expansion of the envelope. The star therefore evolves rapidly to the right in the HRD (towards lower surface temperatures), and convection begins to extend more and more into the interior. The star is now approaching the red giant branch. This process advances rather quickly, especially for higher mass stars, therefore it is unlikely to observe a star in this phase. The empty region in the HRD that is caused by this fast evolution is called the Hertzsprung gap. Low mass stars, however, approach the red giant branch more slowly and gradually.

The red giant phase: The red giant phase is characterized by a drastic increase in luminosity and a slight decrease in effective temperature, resulting in an almost vertical, but only slightly tilted red giant branch in the HRD which the star “climbs up” during its evolution. The star now consists of an inert helium core, surrounded by a hydrogen burning shell and an envelope around it. Due to the low temperatures the envelope now becomes convective down to just outside the burning shell. Eventually, the base of the convective zone can reach regions where nuclear processes have taken place earlier. The convective motions can then transport the processed material to the surface making it observable in the spectra. This phenomenon is called the first dredge-up.

The huge convective envelope is also the reason why solar-like (stochastic) oscillations are observed in red giants. These oscillations provide many possibilities to study the interior of this type of stars through asteroseismology. For example, they allow to determine the masses and radii of the stars to unprecedented accuracy (typical uncertainties of a few percent), providing valuable information for the study of the planets hosted by those stars (see for example, Huber et al. 2013). Additionally, it was possible to measure the rotation of the core and its spin-down

during evolution (Mosser et al. 2012). A good overview summarizing all the recent developments and results is given by Hekker (2013).

At the tip of the red giant branch, the core temperature has become sufficiently high (10^8K) to ignite the triple- α process which turns helium into carbon and oxygen. There are some red giants, however, that do not reach helium burning. They are the ones that lost too much mass during the red giant evolution before the temperatures in the core became sufficiently high. Their helium cores continue their contraction and become so-called helium white dwarfs. For the remaining stars - those which did not lose their envelope - there are two ways to start helium burning.

Intermediate mass stars ignite helium quiescently, as their cores are not degenerate. Low mass stars ($M \leq 2M_{\odot}$), and therefore also the progenitors of RR Lyrae stars, develop a degenerate core in which degenerate electrons provide a large part of the pressure that is necessary to counteract gravity. In those stars, helium burning sets in as a violent explosion, the so-called helium-flash. Because of strong neutrino losses that happen in the center of the star and act as a heat sink, the hottest point is not in the center of the star but in a shell surrounding it. This is logically also the place where the helium flash takes place. The local luminosity during the flash can reach the luminosity of a whole galaxy ($\sim 10^{11}L_{\odot}$). Nevertheless, the helium flash is not observable on the surface of the star, as the energy that is produced is absorbed by the stellar envelope. During a series of secondary flashes, the degeneracy is then lifted throughout the core, and via a series of small loops in the HRD the star settles on the horizontal branch where helium burning is stable.

During this phase of helium ignition the star has moved down and to the left in the HRD, now having a higher temperature than on the red giant branch. This is the phase where an RR Lyrae progenitor probably loses its ability to produce stochastic pulsations in the envelope, as temperatures are now too high for convection. Depending on its mass and metallicity, the newly created horizontal branch star might settle either within the borders of the classical instability strip, or at the hotter (bluer) or the cooler (redder) side of it. The stars that settle at cooler temperatures on the horizontal branch - very close to the red giant branch - can still have convective envelopes and therefore still show solar-like pulsation similar to those during the red giant stage. Those oscillations are indeed observed by space telescopes, and methods have been developed to distinguish via asteroseismology whether a star at this position in the HRD has already ignited helium or whether it is still ascending the red giant branch (Bedding et al. 2011).

The stars on the other hand that settle at a temperature bluewards of the instability strip (and therefore are too hot for RR Lyrae pulsation) have to cross the instability strip to reach their position in the HRD. It has recently been suggested by Silva Aguirre et al. (2010) that RR Lyrae stars evolving towards the zero age horizontal branch (ZAHB) could be identified via their anomalously large period

changes that result from their quick evolutionary pace. They identified several stars in M3 as probable pre-ZAHB pulsators.

The horizontal branch: The horizontal branch phase is characterized by quiescent core helium burning. As mentioned above, this is the phase in which stars can pulsate as RR Lyraes, provided that they settle in the correct temperature range where the instability strip is located.

The helium burning in the core takes place via the triple- α process which is extremely temperature sensitive ($\propto T^{40}$). During this process, two ${}^4\text{He}$ nuclei (i.e., α particles) are fused to form ${}^8\text{Be}$ which is very unstable with a life time in the order of only 10^{-16}s . This life time, however, is still longer than the collision times of ${}^4\text{He}$ at this temperature. Therefore, ${}^8\text{Be}$ can collide with another ${}^4\text{He}$ in time before it decays and form ${}^{12}\text{C}$. The ${}^{12}\text{C}$ might then collide with another α particle and form ${}^{16}\text{O}$. In addition to the core helium burning, also hydrogen burning is still going on in a shell surrounding the core. Depending on the star's mass and temperature, the relative contribution of that shell to the total energy production can vary. The smaller the envelope mass, the weaker the contribution of the shell source.

The cores of the stars that have experienced a helium flash all have approximately the same mass of about $0.5 M_{\odot}$. The different positions they take on the horizontal branch therefore originate from other factors which are total mass as well as metallicity. For a given metal content Z , the higher mass stars can be found on the red side of the HB, while the less massive stars are bluer. For a given mass on the other hand, metal-rich stars are found to the right of (at lower temperatures than) the low-metallicity stars. The total mass, of course, depends not only on the initial mass but also on the mass loss during the red giant evolution, which is not exactly known.

The life time of a star on the horizontal branch is about 10^8 yr, which is much shorter than the duration of the main sequence phase. It is therefore possible, also thanks to the century-old observations that are meanwhile available for some RR Lyrae stars, to directly observe stellar evolution. This is due to the changes that the star undergoes during its evolution away from the ZAHB. Depending on, among other factors, initial helium content (Iben 1971) that motion can be redwards or bluewards in the HRD, leading to either a positive or a negative change in period. These period changes can be observed in the so-called O-C diagrams of the pulsation that compare the predicted times of maximum with the observed ones. Le Borgne et al. (2007) presented a large sample of RR Lyrae stars that show detectable period changes that are indicative of stellar evolution.

When the helium in the inner core is depleted, He burning continues in a shell surrounding the core that now consists mostly of C and O. Still farther out there is still a shell burning hydrogen to helium, so that the star now has two shells acting as energy sources - characteristic of an asymptotic giant branch (AGB) star.

Final stages: During the asymptotic giant branch (AGB) phase the situation is similar to the first ascent along the red giant branch: the core does not have an energy source and therefore contracts, while the envelope expands and cools. Again, the outer layers of the star become convective. Also, similar to the first dredge-up, the convective motions can reach down to material that has been processed by nuclear fusion, and might take this processed material to the surface. This is a second dredge-up. The star again climbs up in the HRD, reaching even higher luminosities and larger radii than during its red giant phase. Nuclear burning will take place in two shells which is an unstable situation that can lead to so-called thermal pulses.

The star will develop a strong wind, and as the envelope is not as gravitationally bound as before, it will lose a significant amount of mass, enriching its surroundings with stellar material. As the atmospheres of AGB stars are very cool, this stellar material also comprises molecules and dust.

Eventually, the star will expel its envelope as a planetary nebula, and the core will continue its evolution towards the white dwarf cooling track.

1.4 The Blazhko effect (before the space age)

It is now known that about half of the RRab stars are affected by a phenomenon called the Blazhko effect. This effect is usually defined as an amplitude and/or phase modulation of RR Lyrae stars. However, the term is now also used sometimes when amplitude or phase variation in other types of stars, such as Cepheids or Delta Scuti stars, are discussed. The timescale of that modulation in RR Lyrae stars is typically in the range of tens to hundreds of days, although extreme cases exist. This section gives an overview about the observed characteristics of the Blazhko effect before space data of modulated stars were available.

Discovery: The phenomenon was first described by Blažko (1907), who measured the times when maxima of the star RW Dra occurred. He noted that their behavior could not be described with one period alone, but that it was necessary to assume a periodic change of the period. The effect is now named after him.

Another important contribution was made by Shapley (1916) who noticed that not only the times of maximum light were modulated, but also the amplitude of the star and its light curve shape changed noticeably. Nowadays it is this amplitude modulation that is most likely to be noticed first in modern data sets before the phase variation is detected.

Percentage of affected stars: In the following decades, when more and more modulated RR Lyrae stars were discovered it became obvious that this phenomenon was not exceptional but rather wide-spread. Finding their exact modulation periods, however, required a lot of effort, as observations needed to be

performed over a long period of time. When Szeidl (1976) in his extensive review listed all RRab stars with known modulation period, there were 26 of them, and 3 RRC stars were suspected to be possible Blazhko stars at that time. Based on a well-studied sample of stars, he could also estimate the incidence rate of the Blazhko effect, which he gives as 15-20%. By examining his list, he also noted that the stars showing the Blazhko effect generally seemed to have lower metallicities. Later, an incidence rate of 20-30 % is given by Szeidl (1988).

Thanks to big surveys such as the MACHO (Massive Compact Halo Object) and OGLE (Optical Gravitational Lensing Experiment) projects, homogeneous data sets of large numbers of RR Lyrae stars later became available. In the course of these studies, thousands of RR Lyrae stars were observed and analyzed in a homogeneous way. The incidence rates these projects yielded for different stellar systems are the following: In the Large Magellanic Cloud (LMC), 11.9 % of the RRab stars were found to be modulated in the study of Alcock et al. (2003, MACHO), as well as 7.5 % of the RRC stars (Nagy & Kovács 2006). For our Galaxy, the numbers are different with 22.7 % of the RRab stars being modulated (Moskalik & Poretti 2003, OGLE-I), or 19.9 % according to the study of Mizerski (2003, OGLE-II), and 6.7 % modulated RRC stars (Mizerski 2003).

In the third phase of the OGLE survey, Soszyński et al. (2010) found 22 % of the RRab stars in the Small Magellanic cloud to have frequencies close to the main pulsation mode which could be caused by the Blazhko effect, and 14% of the stars pulsating in a single overtone. In the Large Magellanic Cloud, incidence rates were 20% for the RRab stars, 19% for the RRC stars, and 25% of the RRe stars. Concerning the Galactic Bulge, Soszyński et al. (2011) found that at least 30 % of the RRab stars and 8% of the RRC stars are modulated.

The observed differences between the incidence rates in the LMC and the Milky Way were originally suspected to be a consequence of a difference in metallicity. Smolec (2005), however, could demonstrate that the Blazhko effect occurs independently of metallicity.

Concerning the incidence rates from microlensing surveys one also has to note that the observed stars are mostly very faint. Consequently, the noise in the data is rather high and hampers the detection of low-amplitude modulation. This is the reason why dedicated surveys using high-precision photometry like the Konkoly Blazhko Survey (Jurcsik et al. 2009) could raise the percentage of modulated stars significantly. In this Hungarian survey, 14 out of 30 observed RRab stars were found to be modulated. In about half of them, the modulation had such a small amplitude that it would have been missed in previous surveys.

Typical modulation periods: Another success of the big microlensing surveys was that they did not only allow to get statistical information on the incidence rate, but also on the distribution of the modulation periods which could be studied in histograms.

What was found out is that the famous 40d modulation period of the prototype RR Lyrae itself is in the range of the most common values. The results found from MACHO and OGLE data agree very well in this respect in the sense that very short modulation periods are uncommon and periods of several tens of days are the most wide-spread. There is a slow decrease in the number of stars towards longer periods.

The shortest modulation period that has ever been discovered in an RRab star occurs in SS Cnc, which shows a modulation with a period of only 5.31 days (Jurcsik et al. 2006). RRC stars on the other hand tend to have shorter modulation periods than RRab stars, for example with a period of 3.6 d as observed for a star in M55 (Olech et al. 1999).

Giving an upper limit for the modulation periods is difficult as this value is strongly biased by the lengths of the available data sets. If the time base of the data is not long enough, it is impossible to distinguish between a slow period change and a periodic modulation of the period. The microlensing surveys, however, indicated that long Blazhko periods are indeed rarer than those in the range given above.

No direct correlation between the pulsation period and the modulation period of Blazhko stars had been found for a long time, but Jurcsik et al. (2005) were able to show that a correlation between the pulsation period and the upper limit of the modulation frequency exists. According to their study, only short period pulsators can have short modulation periods (as well as long modulation periods), while those with a long pulsation period are restricted to long modulation periods.

Characteristics of the Fourier spectra The Fourier spectra of Blazhko stars, of course, show some features that are not present in the power spectra of non-modulated stars. The peaks that are caused by the radial pulsation, i.e., the frequency of the fundamental mode and its numerous harmonics that are due to the skewness of the light curve, are surrounded by a multiplet of additional peaks. Usually the spacing of the multiplet components is rather regular. The amplitudes of those side peaks, however, are observed to differ significantly, which also leads to the fact that depending on data noise, different numbers of side peaks can be observed as some components might end up below the detection limit.

The amplitudes of the side peaks depend on the strength of the modulation, and their spacing in frequency to the radial mode equals the Blazhko period of the star.

When only ground-based data with rather high noise were available, for a long time only triplet structures (a side peak on each side of the fundamental frequency) and doublet structures (a side peak on only one side of the fundamental frequency) were observed in the power spectra of Blazhko stars. Initially, it was not known whether these two cases were caused by the same phenomenon or whether they were different types of modulated stars. In some publications, the two classes are treated separately, and sometimes only the cases with triplets were denoted Blazhko stars, while the others received a different designation. It was

then suggested, however, that it was probably mostly a question of data quality whether one or two additional peaks are seen.

Another point of discussion was whether instead of the triplet, there should be a quintuplet of peaks around the main frequencies. Also the theoretical models predicted different structures which made it important for observers to verify the presence of higher-order multiplets. Finally, the question whether quintuplets are present in the spectra could be resolved by Hurta et al. (2008) who found a quintuplet in ground-based data of RV UMa in the framework of the Konkoly survey. Subsequently, a quintuplet was also detected in high-precision photometry of the star SS For (Kolenberg et al. 2009).

There were also mathematical predictions that many more than 5 peaks should be present, and that a modulation would cause a long series of equidistant peaks with decreasing amplitudes at higher orders (Szeidl & Jurcsik 2009). As we will see in the chapter on the space photometry, these long series of peaks are indeed seen in ultra-high-precision data. In their interesting mathematical study, Szeidl & Jurcsik (2009) also discussed the amplitudes of the side peaks and came to the conclusion that the asymmetry which is often observed must be caused by a phase difference between the amplitude modulation and the phase modulation.

Concerning the observed asymmetry of the side peak amplitudes, again the large number of stars observed in the microlensing surveys could be used to take a look at the statistics. Alcock et al. (2003) investigated the MACHO data in detail and found that the right side peak (i.e. the one on the higher frequency side) is the higher peak in 74 % of the cases. For RRc stars, the opposite seems to be the case. There, the left peak is usually higher. In the study of Alcock et al. (2000), for example, the left side peak was found to be the higher one in 63% of the studied RRc stars.

Some features observed spectroscopically: Preston et al. (1965) first showed that many spectroscopic parameters of RR Lyrae were strongly variable with the Blazhko cycle. He observed that the radial velocity amplitude changed considerably, with both the minimum and the maximum value of the velocity being variable during the modulation.

He also found that the line doubling of the Balmer absorption lines correlates with the hydrogen emission which in turn is a function of the phase of the modulation. The emission was first detected by Struve (1947) who had already suggested that there might also be a variation with the 41-d cycle of RR Lyrae. Preston et al. (1965) showed that the emission was strongest at those Blazhko phases when the doubling was also detectable, and the light amplitude was highest. He estimated that the doubling of H lines is visible only when the velocity amplitude is above 60 km/s. Also in the metallic lines, he observed a broadening and even a doubling that occurs only in Blazhko phases with large amplitudes. This is interpreted as a shock wave in the layers where the lines are formed. Preston et al. (1965) suggests

that during the Blazhko effect the layer where the shock is formed moves up and down in the atmosphere.

His observations that the Blazhko effect was almost completely gone in 1963 and reoccurred in 1964 were of importance for the discovery of the additional 4-year cycle in RR Lyrae.

Kolenberg (2002) used 669 spectra of RR Lyrae spread over a time base of 433 d to study the presence and the geometry of non-radial modes. In the variation of the first moment of the line profile, clearly a multiplet structure was found with a separation equal to the Blazhko frequency, proving the presence of amplitude modulation in the spectra of RR Lyrae. The nonradial modes were identified as nonaxisymmetric (with respect to the rotation axis) modes of degree $\ell \leq 3$.

Regularity of the modulation: As the Blazhko effect was by its discoverer described as a “periodic change of the period” it was only natural that many researchers assumed that it is indeed a periodic effect. Some indications that in reality this was not the case date back rather far, with the earliest report on a change in the Blazhko modulation probably being the one by Balázs (1959).

Also the spectroscopic work of Preston et al. (1965) showed clear indication of differences between several years. Later this led to the now well-known 4-year cycle of RR Lyrae which causes the Blazhko effect to disappear and then to reappear with a phase shift of 0.5. This superimposed cycle, however, was also interpreted as a periodic phenomenon.

The historic indications that the Blazhko effect is probably not strictly periodic are summarized in Section 5 of Guggenberger et al. (2011), a paper which is also part of Chapter 3 of this thesis. There it will be shown that the Blazhko effect can be a very irregular phenomenon.

1.5 Models for the Blazhko effect (before the satellite age)

Explanations for the Blazhko effect have been sought for a long time, starting not long after the discovery of the effect. Therefore, at the onset of the asteroseismic space age, there existed a multitude of different models and scenarios that tried to explain the Blazhko effect. I will only briefly introduce a few of them here, focussing on those that were or are considered the most promising ones. This section is meant to describe the situation at the starting point of this thesis, and I will therefore not treat models which were developed after the satellite data became available (those will be discussed in the outlook in Chapter 5). A special emphasis will be given here to the model involving a strong magnetic field, as this is the model that will be tested observationally in Section 2. For a detailed discussion of many of the available models and their respective strengths and weaknesses I refer the reader to the excellent overview by Kovács (2009).

The magnetic oblique pulsator The idea that an oblique dipole magnetic field can influence the pulsation of a star dates back to the 1950s. Soon after the concept was proposed for A type stars (Deutsch 1956) it was also considered as a possible cause for the Blazhko effect (Balázs 1959; Balázs-Detre & Detre 1962). They assumed that RR Lyrae stars were eruptive variables as well as magnetic oblique rotators at the same time. Preston (1964) later noted that the part of the hypothesis that involves eruptions and which was considered quite unlikely is not necessary for the other part of the hypothesis to work. According to Balázs-Detre & Detre (1962), the variations of the amplitude should be aspect effects caused by the rotation of the star, and the rotation period would therefore be identical to the Blazhko period. This is plausible as the observed Blazhko periods are indeed of the same order as the expected rotation periods. At the time of the publications of Balázs-Detre & Detre (1962), however, the considerations did not go beyond a descriptive hypothesis, and no calculations whatsoever were presented.

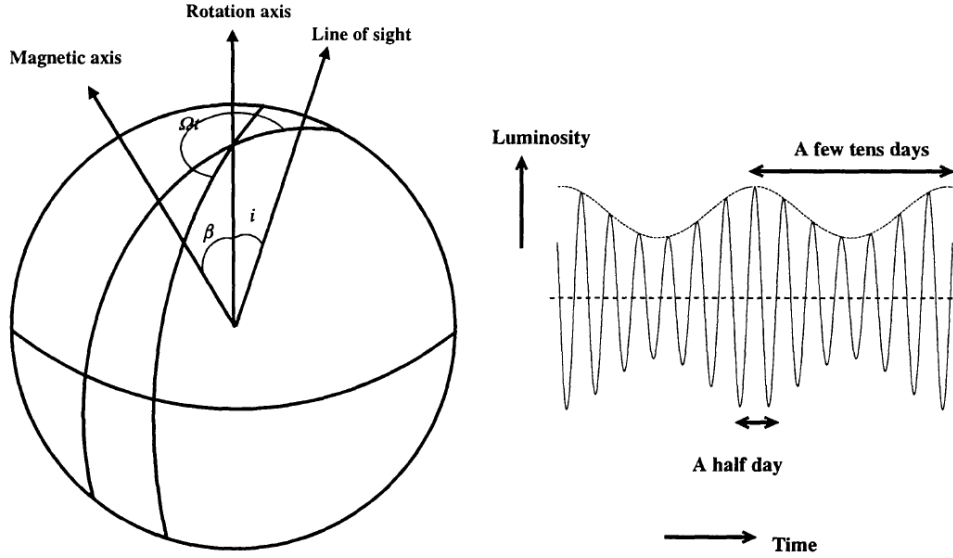


Figure 1.4: Schematic illustration of the oblique magnetic field causing amplitude modulation in a light curve, adopted from Shibahashi (2000).

Calculations and theoretical predictions concerning the influence of a magnetic field on the pulsation of RR Lyrae stars were published only decades later (Cousens 1983). Shibahashi & Takata (1995) and Shibahashi (2000) presented their calculation of the eigenfunctions of the spherical harmonics, and they also provided several valuable predictions. Their graphical illustration of the magnetic oblique pulsator model is reproduced here in Fig. 1.4.

In their model, they assume that the RR Lyrae star has a fairly strong dipole magnetic field, and that its axis is inclined to the rotation axis of the star. They find that the oscillation which would be purely radial ($\ell=0$) in the absence of

a magnetic field would then be altered by the magnetic field so that an additional quadrupole component ($\ell=2$) comes into play. The symmetry axis of that quadrupole component would have to be identical with the magnetic axis. For the case of a magnetic field whose axis passes through the center of the star (i.e., an on-axis field), they predict pure amplitude modulation. Phase modulation on the other hand would occur in the case of an off-axis field. Another prediction is that the effect would lead to a quintuplet structure in the Fourier spectrum, and that in some cases only a triplet structure would be observed. This was in good agreement with the observations, where usually triplet structures were seen in the data. Not much later, for the first time a quintuplet structure was detected in the Fourier spectrum of a Blazhko star (Hurta et al. 2008).

Also, because there are no additional oscillation modes added in this model, but instead the existing eigenmode is deformed, Shibahashi (2000) predicted that the highest amplitude that occurs during the modulation in a Blazhko star should fit into the general scheme that relates the periods and amplitudes of non-modulated stars. This is in agreement with what is found from observational data (Szeidl 1988).

The most important prediction for our purpose here, however, is the one on the field strength that is necessary to produce a modulation such as the one observed in RR Lyrae and other Blazhko stars. After testing several geometrical configurations, Shibahashi (2000) concluded that a field strength of the order of 1 kG is necessary to cause the observed strength of the Blazhko effect in RR Lyrae. The presence of this rather strong field is what will be tested in Section 2.

Resonances with non-radial modes In the models involving resonances with non-radial modes, the Blazhko effect is caused by a resonant interaction between the radial mode and a nearby non-radial mode. In most of the proposed models, it is a 1:1 resonance.

The possibility that non-radial modes can play a role in the observed amplitude modulation of RR Lyrae stars was first suggested by Cox (1993). In his model of an RR Lyrae star he found non-radial modes that are almost resonant with the fundamental mode period for many low ℓ values. He specifically pointed out that there is an $\ell = 1$ mode very close to the radial fundamental mode, which could produce a Blazhko effect via beating. However, this proposal did rely on a purely linear description.

Van Hoolst et al. (1998) performed numerical calculations using a model of an RR Lyrae star. In their study the stability was examined via non-adiabatic non-radial calculations and using amplitude equations. In agreement with Cox (1993) they also find many unstable $\ell = 1$ and $\ell = 2$ modes in the frequency range of the first three radial modes and based on their calculations they consider it plausible that the Blazhko effect could be caused by an interaction as proposed by Cox. However, they note that growth rates of such modes are considerably smaller than those of the radial modes.

Dziembowski & Cassisi (1999) performed similar calculations not only for one model as Van Hoolst et al. (1998) had done it, but for a large set of RR Lyrae models using two different heavy element abundances ($Z=0.0002$ and $Z=0.001$) and covering the whole temperature range possible for RR Lyrae stars. From their survey they could conclude that a large number of unstable low degree modes with frequencies close to unstable radial modes is always present. They noted that an amplitude modulation as it is observed in Blazhko stars could arise if the non-radial mode in question is of low degree and not symmetric about the rotation axis. Similarly to the magnetic model the change of the aspect angle would then cause the apparent modulation, and the Blazhko period would be identical to the rotation period.

Nowakowski & Dziembowski (2001) used amplitude equations describing resonant coupling between radial and nonradial modes and found that significant amplitude and phase modulation is predicted in the case of excitation of a $m = \pm 1$ pair, and that this might explain the Blazhko effect.

Attempts have been made to identify the possible non-radial modes in spectra of RR Lyrae by Kolenberg (2002), especially because the degree of the proposed non-radial modes is an important test for the models. The magnetic models predict the presence of a $\ell=2$ component, while in the models involving a resonance with non-radial modes, an $\ell=1$ mode is favored. Kolenberg (2002) could show that the modes with $(\ell, |m|) = (1,1), (2,1)$ and $(2,2)$ are the most probable candidates with a slightly higher probability for $(1,1)$, but it was impossible to definitely rule out quadrupole modes.

Resonances between radial modes Not only resonances with non-radial modes are possible in RR Lyrae stars, also radial mode resonances have been taken into consideration. For example, Moskalik (1986) has proposed a model in which a 2:1 resonance of the radial fundamental mode with the third overtone can cause a slow modulation of the amplitude and could therefore explain the Blazhko effect. For his work he used amplitude equations, and he also discusses a possible connection between double mode pulsation and the Blazhko effect. The obvious connection between Blazhko stars and RRd stars is that they form the two groups of RR Lyrae stars that deviate from strictly periodic pulsation. He found that it is possible to reproduce observed periods of the Blazhko effect with a reasonable choice of input parameters. According to his model, the same resonance can under slightly different conditions also lead to RRd-like double mode pulsation.

He found his results in good agreement with observations. One reason was that the resonance model predicted a bump in the ascending branch of the light curve similar to the one observed in bump cepheids, but modulated together with the modulation of the amplitude. This was confirmed by observational data. Secondly, his model predicted a certain relation between the growth rates of the modes and the ratio of pulsation and modulation period. The values derived from this relation were in agreement with the observed periods of the 26 Blazhko stars that had been

well enough studied at that time. Moskalik (1986) wrote that their model implies strictly periodic amplitude modulation.

However, it was argued later that overtone modes in RR Lyrae stars are too heavily damped and therefore could not disturb the steady pulsation of the strong fundamental mode, and that the required resonances cannot occur in RR Lyrae stars.

But in his review on models on the Blazhko effect, Kovács (2009) again attests the model some viability. He searched for the necessary input parameters that could bring one of the overtones and the fundamental mode into a 2:1 resonance. The desired parameters should also make the overtone mode less damped, or even excited. Finally he presented what he calls a “toy model” of an amplitude modulated star but notes at the same time that it “requires most probably unacceptable torture of the stellar structure”.

Variable turbulent convection The model involving a variation of the turbulent convection caused by a magnetic field was first introduced by Stothers (1980). It builds on the idea of Balazs-Detre that it could be an analog of the solar magnetic activity cycle that causes the Blazhko effect in RR Lyrae stars. In his first paper Stothers puts the focus on the observed period changes that are too rapid and too erratic to be caused by stellar evolution. Amplitude changes as they are also observed in Blazhko stars are not treated there. Stothers (1980) assumed that since the envelope of an RR Lyrae star is convectively unstable in the zones of hydrogen and helium ionization, the local turbulent motions might interfere directly with the otherwise periodic pulsation of the envelope. He also suggests that the apparent absence of the Blazhko effect in many RR Lyrae stars, and the cessation of the Blazhko effect in some cases might be the analog of the minima that have been observed in the cycle on the sun. Starting from a supposed destruction and rebuilding of a strong magnetic field below the convective regions, they find that period changes should be observed.

Later Stothers (2006) published a refined version of the model that does no longer require any dredge-up of a large amount of magnetic flux from deeper layers, but instead involves a magnetic field that is created in situ by either a turbulent or a rotational dynamo mechanism. According to this scenario, this transient magnetic field cyclically weakens and strengthens the turbulent convection inside the hydrogen and helium ionization zones. This new scenario also includes an effect on the pulsation amplitude. The author argues that disturbances of the convection region in the hydrogen and helium ionization zone should affect the amount of pulsational driving and consequently also the observable surface amplitudes, as these regions are the source of the pulsational driving. This connection relies on previous numerical studies that have shown that convection reduces the pulsational amplitudes of RR Lyrae stars and on the fact that strong magnetic fields might quench convection.

A strength of this scenario that sets it apart from the other models is that the process proposed by Stothers (2006) is partly stochastic, because the magnetic cycles do not necessarily occur with exactly the same period and same strength. Therefore the model is one of the few that would predict an irregular Blazhko effect. That this is of importance will be discussed further in Chapter 3. Also the fact that the Blazhko effect is much rarer in RRc stars than in RRab stars can, according to Stothers (2006), be explained by this scenario. They state that because hotter RR Lyrae stars such as the RRc stars automatically have smaller convective zones, one would expect that they become less modulated by a magnetic field. The author admits, however, that many of the ideas in his paper are still rather rough.

Exactly this lack of elaboration is something that has been criticized in the past, for example by Kovács (2009). Other points of criticism are that there are no predictions on the expected modulation periods and on the expected strength of the modulation, and that the unequal amplitudes of the side peaks in the power spectrum are not explained (Kovács 2009).

Chapter 2

Testing the magnetic model (Paper I)

Part of the work presented in this chapter has been published in the paper:

- **Guggenberger, E.**; Kolenberg, K.; Marsden, S. C.; Waite, I. A.; Henrichs, H. F.; Lüftinger, T. *High-Resolution Magnetic Field Measurements of RR Lyrae Stars with SemPol*, published in “Stellar Pulsation: Challenges for theory and evolution”, Proceedings of the International Conference. AIP Conference Proceedings, Volume 1170, pp. 278-280 (2009)

The contribution of the author of this thesis to the paper was the following:

- assembled the instrument for use at the telescope
- performed the observations together with Stephen Marsden and Ian Waite
- reduced and analyzed the data with the software package ESPrIT
- wrote the paper

As it was discussed in Section 1.5, the magnetic oblique rotator model is among the most promising and elaborate models to explain the Blazhko effect, and the presence of a strong magnetic field in RR Lyrae stars is an essential requirement for this model. Now of course, strong magnetic fields are a quantity that can be measured with modern instruments via spectropolarimetric data. Performing such measurements is clearly a logical step in clarifying the mystery of the Blazhko effect. In the last decades, several authors attempted measurements of RR Lyrae magnetic fields (six publications on the topic can be found in the literature), but their results were a more or less alternating series of clear detections and null detections, and the question whether RR Lyrae stars do indeed have strong magnetic fields or not was a disputed one. The following section will give an overview on the current status of magnetic field measurements in RR Lyrae stars before we turn to the observations obtained in the framework of this thesis.

2.1 Previous studies on magnetic fields in RR Lyrae stars

The first to attempt spectropolarimetric measurements on RR Lyrae was a pioneer of this method and of stellar magnetic field research in general: Horace W. Babcock. He took nine spectrograms of RR Lyrae in 1955 (Babcock 1956), analysed the circular polarization and reported that he found a magnetic field that was both strong and variable, with reversals of magnetic polarity. He reported the extreme values of his measurements to be +1170 gauss and -1580 gauss. In some additional observations, also taken with the 200-inch telescope on Mount Palomar and the 100-inch telescope on Mount Wilson, he detected strong variations from day to day which did not form a smooth curve when plotted against the pulsation phase. In an older spectrogram, however, he did not find any evidence of a field. Subsequently, Babcock also listed RR Lyrae in his catalogue of magnetic stars (Babcock 1958) in the category of stars in which a magnetic field is definitely present, and he noted that the field is highly variable.

While his findings on Ap stars are still valid today and can be considered groundbreaking, the results on RR Lyrae were severely challenged in 1967, when Preston (1967) reported in his review talk on stellar magnetism, that he had observed RR Lyrae some 50 times in the past years and never had found evidence of a magnetic field. All the small effects that he could find were buried in the probable errors of the observations.

Twenty years later, Romanov et al. (1987) again reported clear detections of strong magnetic fields in RR Lyrae. They had taken altogether 63 spectrograms with the 6 m telescope of the Special Astrophysical Observatory of the USSR Academy of Science and a circular polarisation analyser. Their measurements dated from 1978 to 1983 and were taken during several different pulsation cycles and in different Blazhko epochs. For each of their observing runs (one in 1978,

one in 1982 and one in 1983), they found a clear correlation of the magnetic field strength with the phase of the pulsation cycle. Amplitudes of the field variations were 1 kG, 1.5 kG and 1 kG, respectively. They found the field polarity, however, to be reversed from one run to the next. Finally, based on photometry they derived the Blazhko phases for their observing intervals, calculated average fields strengths for each interval, and combined their results with those of Babcock, for which they had also calculated the Blazhko phase and derived the mean field strength from the curves in his publication. Based on those combined data, they reported a clear variation of the mean magnetic field strength with the Blazhko phase.

Again almost two decades later, Chadid et al. (2004) presented spectropolarimetric observations of RR Lyrae in which no significant magnetic field was present. They obtained 27 measurements of circular polarization with the MuSi-CoS instrument at the 2 m Bernard Lyot telescope at the Pic du Midi Observatory, at different pulsation phases as well as Blazhko phase over a period of almost 4 years (and therefore covering also the 4-year-cycle of RR Lyrae). The magnetic field strengths calculated from their data never exceeded the significance limit, and they concluded that RR Lyrae is a bona-fide non-magnetic star. They suggested that a combination of underestimating the true errors and the rapid line profile changes that occur in RR Lyrae were the cause for the previous claims of detections of magnetic fields in RR Lyrae.

Another very recent polarimetric measurement of RR Lyrae can be found in the paper by Schnerr et al. (2008). These authors performed magnetic field strength measurements on a sample of 25 massive OB-type stars, a study in principle quite unrelated to RR Lyrae stars. Being aware, however, of the open question about the Blazhko effect in RR Lyrae stars and its possible magnetic explanation, they also added RR Lyrae to their observing schedule in 2003 and obtained 9 measurements. In none of their measurements they could detect a significant magnetic field, therefore confirming the results of Chadid et al. (2004).

So far, as the reader has certainly noted, all observations of RR Lyrae stars had been restricted to the brightest prototype of the class, RR Lyrae itself. But at the beginning of the 21st century, precise instruments and the availability of large telescopes had meanwhile brought also other RR Lyrae stars within reach. The first ones to make use of those new options and to perform spectropolarimetry on a larger sample of RR Lyrae stars were Kolenberg & Bagnulo (2009). Their goal was to answer the question whether RR Lyrae stars in general are characterized by magnetic fields on a large scale. They used the low-dispersion spectrograph FORS1 at the ESO VLT unit Kueyen to perform altogether 20 measurements on 17 different stars. Among their targets were both Blazhko and non-modulated stars, of both R Rab and R Rc type, to find out which of those groups (if any) has a detectable field. In accordance with the other recent measurements of Schnerr et al. (2008) and Chadid et al. (2004) they reported that all their measurements resulted in null detection within the significance limit of 3σ . From the available photometry of the targets they determined the pulsation phases for each of their

measurements and plotted the field strength as a function of phase. Even though all are null detections, a slight tendency for higher field strengths at the pulsation phase around zero (i.e., at light maximum), which would be expected from the conservation of magnetic flux, is discernible in their diagram. Having a rather large sample of different stars at hand, a statistical analysis was possible, assuming a random distribution of the orientation of the field axes. This led to the conclusion that the dipole field strength must be below 130G at the 95% confidence level. Their measurements however, were taken at a very low resolution of only $R=1400$ and $R=2800$, respectively, depending on the slit that was used. The question still remained whether a higher resolution would make a difference, i.e. whether magnetic fields of RR Lyrae stars could be detected when also the metallic lines were resolved. This is where the work in this thesis comes into play.

In the following sections, after a short introduction to the methods applied and the instruments that were used, we present results based on high-resolution ($R=70000$) spectropolarimetry of a sample of RR Lyrae stars which builds upon the work of Kolenberg & Bagnulo (2009), extending their sample as well as testing on some stars whether the results differ from those obtained from the low resolution spectra.

2.2 Some basic definitions

Zeeman effect: In the presence of a magnetic field, the degeneracy of the levels of an atom is removed, and a level with the angular momentum quantum number J splits up into $(2J+1)$ equally spaced sublevels. Their splitting is proportional to the strength of the acting magnetic field, as well as to the Landé factor g . This factor is usually known from laboratory experiments or from theoretical calculations. In the case of a weak field, a line broadening is present, while only in strong fields an actual splitting is observed. The frequencies of the lines can be calculated by

$$\nu = \nu_0 + \frac{B\mu_0}{h}(g'M' - gM)$$

where ν is the frequency resulting from the transition between a level with the quantum numbers J and M to a level with the quantum numbers J' and M' , μ_0 is the Bohr magneton, B is the magnetic field strength, h is the Planck constant, ν_0 is the frequency in the absence of a magnetic field, and g and g' are the respective Landé factors of the upper and lower level.

Due to selection rules, not all of the possible Zeeman signatures can be observed. The change in the magnetic quantum number M cannot be larger than one unit. Therefore, only transitions with $\Delta M = (M' - M) = \pm 1, 0$ are allowed, resulting in three distinct components. M' and M are the magnetic quantum numbers of the upper and lower level, respectively. The components with $\Delta M = -1$ and $\Delta M = +1$ are called the σ_r and σ_b component, respectively, as they are observed on the red and blue side of the unperturbed line. The designation σ historically

originated from the German word *senkrecht* (perpendicular), as those components are linearly polarized when observing perpendicularly to the magnetic field. When observing along the magnetic field, they are circularly polarized. The central component, on the other hand, is called π component, its name being derived from the word *parallel*. It is linearly polarized when observing in the direction parallel to the magnetic field. The σ components are the ones that cause the typical Stokes V profile (see next paragraph) when observing the line-of-sight (longitudinal) magnetic field, and this is the method used in our study. Many more details on the Zeeman effect and the mathematics behind it can be found in the comprehensive textbook of Landi Degl'Innocenti & Landolfi (2004).

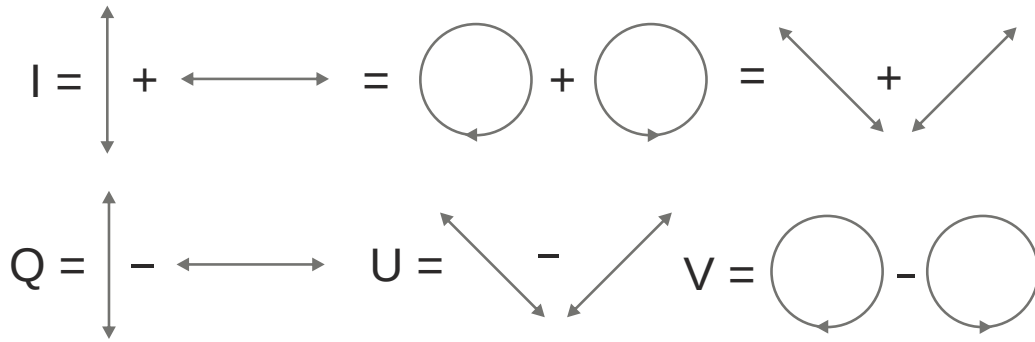


Figure 2.1: Operational definition of the Stokes parameters.

The Stokes parameters: The Stokes vector is a set of four parameters - the Stokes parameters (usually designated I, Q, U and V) which can be used to describe the polarization state of light. They were introduced by Sir Georg Stokes in 1852 who, with his work, made the description of polarized radiation fully consistent. To connect the polarization characteristics to actual measurements, an operational definition is needed. This definition for the Stokes parameters goes as follows: an ideal polarizer (i.e. a polarizer that fully transmits the electric field component that is aligned with its transmission axis and fully blocks the perpendicular components) is placed in a beam which propagates perpendicular to the polarizer. As a reference axis we select the vertical direction. When the polarizer's transmission axis is aligned with the reference axis, the measured intensity is I_0 . When the polarizer is rotated by 45° , the measured intensity is I_{45} , a rotation by 90° gives I_{90} , and one of 135° gives I_{135} . The intensity measured through an ideal filter for right-handed or left-handed circular polarization gives I_+ and I_- , respectively. The Stokes parameters are then given as:

$$I = I_0 + I_{90} = I_{45} + I_{135} = I_+ + I_-$$

$$\begin{aligned} Q &= I_0 - I_{90}, \\ U &= I_{45} - I_{135}, \\ V &= I_+ - I_-. \end{aligned}$$

This is also illustrated schematically in Figure 2.1. One can see that Stokes I is the total intensity, Stokes Q and U describe linear polarization, and Stokes V describes circular polarization. For the data in this thesis, we observed circular polarization, i.e., the Stokes V profile in our spectra. An extensive description of polarization in spectral lines, its measurement and its application in astronomy can be found, among others, in the textbook of Landi Degl’Innocenti & Landolfi (2004) as well in the proceedings edited by Trujillo-Bueno et al. (2002).

2.3 Instrumentation

In the optical wavelength range, there are no detectors that can directly measure the polarization of the radiation. They are only sensitive to the intensity of the light. Therefore, polarization measurements are performed by measuring the intensity of linear combinations of Stokes parameters, for example $I \pm Q$ or $I \pm V$. The task of creating those combinations is done by the polarimeter. Two orthogonal states of polarization are compared, for example left- and right-handed circular polarization. Those two orthogonal states are either detected successively or simultaneously by double beam optics (Semel et al. 1993). The polarimeter used for this work (SemPol) is described in the subsequent section. It has double beam optics and offers the possibility to interchange the polarization states of the beams to minimize instrumental effects on the polarization measurements.

2.3.1 SemPol

The Semel polarimeter (SemPol) was designed by Dr. Meir Semel and built at the Observatory in Paris Meudon and can be attached to the AAT as a visitor instrument. To be able to obtain the observations used for this thesis, the author visited Dr. Meir Semel’s working group in Paris to learn how to assemble the image slicer which needs to be shipped in pieces, and how to install and calibrate the polarimeter. The instrument was then shipped from France to Australia, and there it was prepared for the observing run by Dr. Stephen Marsden and myself. This section provides some information on how the instrument works and of which constituents it consists.

The main parts of SemPol are: the calibration wheel, the two wave retarders, the beam splitter (all in one unit), and the image slicer (which is separate from the other components). Some very useful and detailed notes have been written by Martinez-Gonzalez & Semel (2008), and a description of the setup of an earlier version of the instrument, together with some technical considerations has been published by Semel et al. (1993).

The wave retarders Among the most crucial parts of SemPol are the two wave retarders (or phase shifters). These are devices that can convert one polarization state into another, for example circular polarization into linear polarization. They do so by resolving the beam into two components, retarding the phase of one component with respect to the other, and reuniting the components into one beam. An ideal retarder does not alter the amplitudes of the components in the process. When the phase delay between the two states of polarization is $\pi/2$ then the retarder is called a *quarter wave plate*, if the retardation is π , then it is a *half-wave plate*. The retardance can be achieved either by using a birefringent material or by using reflections. The retarders used in SemPol are of reflection type: they are Fresnel rhombs (Martinez-Gonzalez & Semel 2008). An illustration of the Fresnel rhombs (parallelepipeds made of crystal) used in Sempol can be seen in panels b and c of Figure 2.2.

The light enters one of the small faces and is then reflected twice (in the case of a quarter wave plate) on the longer, tilted sides before it exits the parallelepiped through the other small face. Each of these reflections cause a 45° phase delay of one component with respect to the other, resulting in a delay of $\pi/2$ in the case of two reflections, and π in the case of four reflections (as it is the case for the half wave plate). It is important to note that the analysis of the polarimetry is not done in the retarders, but will happen later in the beam splitter. The retarder only converts the polarization form. It is also important to note that - as can be seen in Figure 2.2, the quarter wave Fresnel rhomb causes a lateral displacement of the beam. Therefore, in the current setup of SemPol, it is not possible to rotate the quarter-wave plate, as this would require a shift of all the optics behind it. The other components (i.e., the half-wave plate and the beam splitter can be rotated) to switch between observation modes. It is also obvious from Figure 2.2 that the half-wave plate does not displace the light beam.

The beam splitter The beam splitter is the most important part in the sense that it performs the actual analysis of the polarization. It divides the incident light into two beams with their polarizations orthogonal to each other, deviates them into different directions, and transmits both. The beam splitter installed in the SemPol polarimeter is a Wollaston prism (Martinez-Gonzalez & Semel 2008) consisting of two magnesium fluoride (MgF_2) prisms whose optical axes lie perpendicular to each other, and also perpendicular to the direction of the light. The two prisms are optically contacted. When the light crosses the first prism, it is separated into an ordinary and an extraordinary ray which both continue to propagate in the same direction. A small phase shift occurs, but this is not relevant for the future analysis as the beams will be treated separately from here on.

At the interface between the two prisms, the two beams will be refracted differently because the refraction indices change due to the different orientation of the birefringent prism. They are refracted into different directions. A detailed drawing is given in panel d of Figure 2.2. It can be shown that a quarter-wave plate

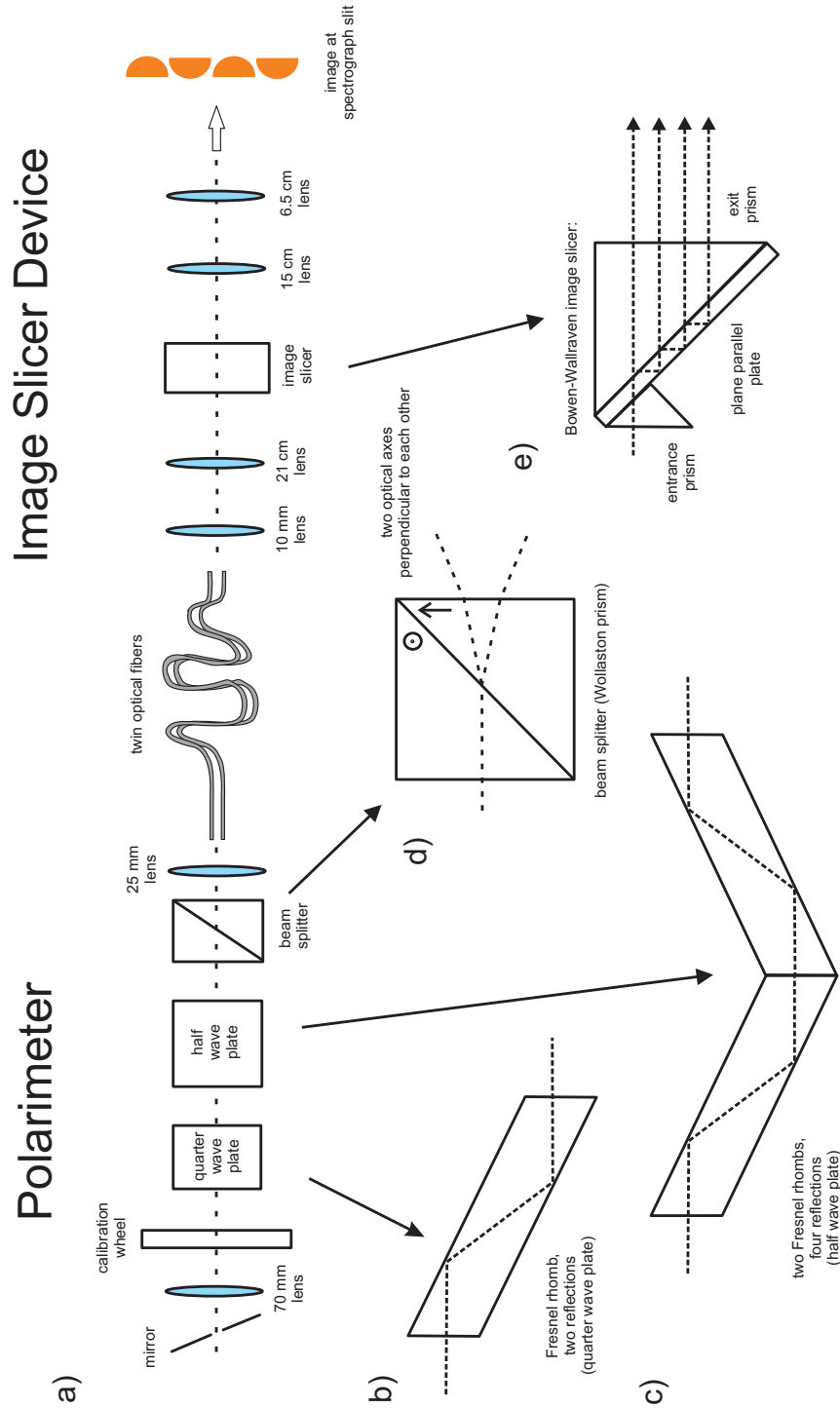


Figure 2.2: Panel a shows the overall setup of the Sempol polarimeter with its image slicer device. Panels b and c show detailed drawings of the Fresnel rhombs that serve as quarter and half wave plate, respectively. Panel d illustrates the beam splitter, and panel e shows a drawing of the image slicer.

that is aligned with the reference axis, combined with a beam splitter that has an inclination of 45° with respect to the quarter-wave plate act as an ideal filter for circular polarization. In this case, the half-wave plate also needs to be aligned with the reference axis. This is the setup that was used for the study in this thesis.

Overall setup of SemPol The essential constituents of SemPol have already been described in detail in the previous paragraphs. They are embedded, however, in a series of other optical elements that are necessary for the full functionality of the polarimeter and which shall be described here and are illustrated in panel a of Fig. 2.2.

At first, the light coming from the telescope enters the polarimeter through a hole in a tilted mirror. It is very important that the star image is focused exactly within this so-called exploration hole, otherwise light will be lost. Via the tilted mirror, light can be directed sideways for inspection (to center and to focus the star). The diameter of the hole corresponds to about 1.8", as required by the typical seeing conditions at the AAT. The next part after the entrance hole is a 70 mm lens that puts the focus of the image to the infinite. This is useful since the subsequent optics will not change the focus. After the lens, there is a calibration wheel which contains several optical elements that can be selected according to the needs: a Fabry-perot interferometer, a linear polarizer, a mirror that reflects the incoming light to the eyepiece of the instrument, a hole, and an additional quarter-wave plate. For our purpose, what was needed was the observation hole in the calibration wheel, as for the circular polarization observed by us, the half-wave plate and the quarter-wave plate were sufficient. For observation of linear polarisation, however, the effect of the built-in quarter-wave plate needs to be cancelled, which is done with the additional plate in the calibration wheel. The next parts in the path of the light are the Fresnel rhombs: first the quarter-wave plate, then the half-wave plate, and then the beam splitter. Afterwards, the two beams emerging from the beam splitter need to be sent into the fibers, which is done by a 25 mm lens. During the adjustment of the instrument before an observing run, it is necessary to adjust this lens with the two calibration screws in vertical and horizontal directions so that all the light is directed into the optical fibers.

All the above mentioned components are in the main body of the instrument that can also be seen in Figure 2.3, and which is indicated in the left part of the schematic drawing in Figure 2.2. From this main part of the polarimeter, two long optical fibers (33 m long, one for each beam) lead down two floors to the spectrograph where the last part of SemPol (the image slicer) is installed directly in front of the spectrograph slit.

The image slicer The purpose of the image slicer is to maximize the throughput through the spectrograph slit and to optimize the resolution. In principle, the light coming from the optical fibers could be sent directly to the spectrograph, but to obtain a higher resolution, a thinner slit is necessary. Sending the two beams

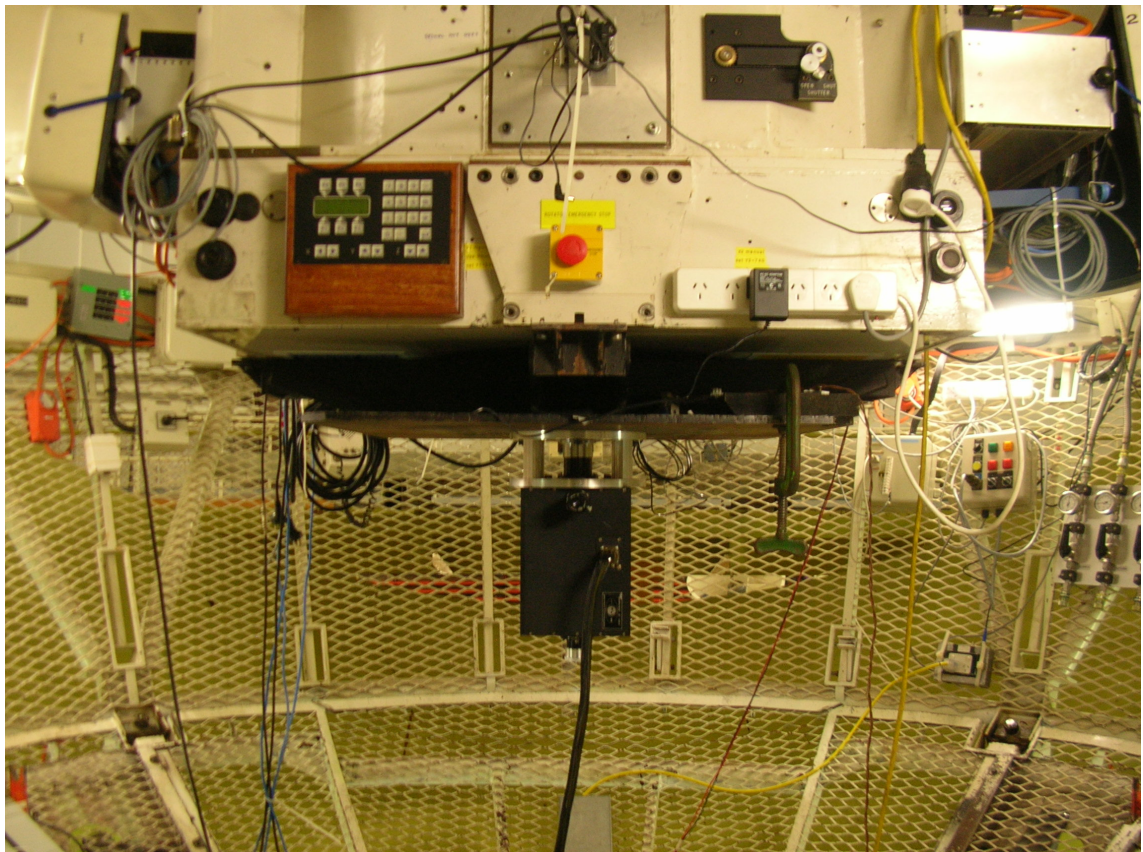


Figure 2.3: The Semel polarimeter (SemPol) attached to the base of the AAT in the Cassegrain cage with the eyepiece facing the entrance door. The fibers leading to the spectrograph are not yet installed.

through a narrow slit, however, would lead to a dramatic loss of light. The solution that was found for this problem was to “chop” the beams into narrower slices which are aligned above each other to form an artificial slit by themselves (see Figure 2.2). This task is performed by the *Bowen-Wallraven* image slicer which constitutes an important part of SemPol. The slicer consists of three optical components: a small entrance prism, a plane-parallel plate, and a large exit prism. All components are optically connected to each other. A schematic drawing of the slicer is given in panel e of Figure 2.2. The secret of the slicer lies in the wedge that is missing in the large exit prism, which creates a so-called *slicing edge*. When light enters through the entrance prism, it is reflected several times within the borders of the plane-parallel plate, and it can only exit the optical system if behind the plate it encounters the exit prism. If instead of the prism, due to the missing wedge the light encounters air, it is totally reflected. Now the slicing edge is inclined to the path of the reflection, so that every time a part of the beam is transmitted, and the rest is internally reflected, which results in a series of slices. This always leads to an even number of internal reflections. The number of slices is dependent on

the rotation of the slicing edge, with a small angle resulting a large number of narrow slices, and a larger angle in a smaller number of slices. The optimal setup for the observations obtained in the framework of this thesis (using the 31.6 gr/mm grating) turned out to be two slices for each beam, and therefore 4 half circles. The appearance of the final image is illustrated in Figure 2.2. This slit shaped image contains all the star light that comes from the polarimeter, and can directly be used as a slit, meaning that the usual slit of the spectrograph remains in its fully opened position, and the image created by the image slicer itself forms the “slit”. The image slicer is therefore positioned directly in front of the spectrograph where normally the shutters of the slit would be. This special shape of the slit makes it necessary to use a dedicated software package for extraction of the spectra, as ordinary data reduction packages would fail. The data reduction will be described in Section 2.4.

Of course, the slicer device consists of some more optical elements than just the actual slicer (i.e., the prism/plate/prism combination described above). One issue that needs to be solved with the help of additional optics is the slit length. Because of the limited separation between orders on the chip, there is a maximum slit length that should not be exceeded in order to avoid inter-order contaminations. For the 79 grooves/mm grating the separation between the orders is 2.5 times larger than for the 31.6 grooves/mm grating, allowing for a much longer (and therefore narrower) slit composed of a larger number of slices. The polarimeter was initially optimized to be used with this grating. For our observations, however, we had to use the 31.6 gr/mm grating which requires a smaller image.

To achieve the suitable image size, first an afocal system consisting of a 10 mm and a 21 cm lens is put in between the fibers and the slicer, enlarging the images from 100 μm to 2.1 mm. This combination of lenses focuses the image onto the plate of the slicer and brings the pupil to the infinite. After the slicing took place, another system of two lenses is placed in the beam to reduce the image size to the suitable value and to focus the image on the plane of the slit of the UCLES spectrograph. The pupil is placed in the infinite, i.e. in this case, on the collimator of the spectrograph. For the 31.6 gr/mm grating, the pair of lenses consists of a 15 cm and a 6.5 cm lens. Unfortunately, as the product of the pupil and the image size is a constant, such a small image leads to a large pupil that overfills the collimator, and therefore leads to some loss of light. The resulting resolution with this setup is approximately $R=71000$.

Fine-tuning of the image slicer optics was a delicate and time consuming task, as the image slicer had to be shipped to Australia in several pieces that needed to be assembled before observations could start.

Observing strategy Many different things in the path of the light between the star and the detector can cause spurious polarimetric signals: seeing, instrumental drifts, detector sensitivity, the fact that the two polarization states are transported by two different fibers, etc. (Semel et al. 1993). Successively interchanging the po-

larization states of the two beams is a solution that can help to remove many of these instrumental effects. For example, different sensitivities of CCD pixels, crosstalk between linear and circular polarization that might happen in the polarimeter, and any effect in the optical system that causes the two spectra to be systematically different are cancelled out by the beam exchange when the resulting spectra are then divided by each other. This method was therefore applied in this work. To reduce flatfielding effects to a minimum, each polarization state was observed not only once but twice in the same configuration, resulting in a sequence of four spectra for each magnetic field measurement. Exchanging the polarization states of the beams was achieved by rotation the wave plate by 90° . The sequence of measurements was therefore taken with the positions alternating as -45° , $+45^\circ$, $+45^\circ$ and -45° . The error in the orientation is usually negligible (Semel et al. 1993).

2.3.2 AAT and the UCLES spectrograph

The SemPol instrument is always installed in the Cassegrain focus of the 3.9-m Anglo-Australian telescope (AAT). This helps to reduce the instrumental polarization effects to those of the telescope alone (Semel et al. 1993). Any oblique reflections that would introduce spurious polarization are avoided by this strategy (normally, four plane mirrors would be used to direct the light down to the spectrograph). In this setup, the effects of the telescope optics on the polarization analysis are the only ones that remain and they are expected to be small (Semel et al. 1993). A photograph of SemPol installed in the so-called Cassegrain cage at the base of the AAT during our observing run can be seen in Figure 2.3. Due to this installation, very long (33 m) fibers are needed to feed the light down to the University College London Echelle Spectrograph (UCLES) spectrograph where the Bowen-Wallraven image slicer is installed just in front of the spectrograph slit.

For our observations, we used the 31.6 grooves/mm grating. Our spectra cover 46 orders, ranging from order 84 to 129. The resolution obtained with this setup is $R=71000$, with a wavelength range from 4377 to 6810 Å and a central wavelength of 5268 Å. The detector used in this study was the EEV2 CCD with 2048×2746 pixels.

2.4 Data Reduction and Analysis

As already mentioned in Section 2.3.1, data obtained with the spectropolarimetric setup of UCLES + SemPol has a very peculiar format and therefore cannot efficiently be reduced with standard reduction packages. Therefore we made use of a dedicated software package developed by Donati et al. (1997): ESPrIT. Its name stands for "Echelle Spectra Reduction: an Interactive Tool" and it has been designed to optimally extract the spectra in the special format produced by the fiber-fed image slicer. I kindly thank J.-F. Donati for allowing me to use his software.

The challenges of spectropolarimetric observations are, among others, that every order contains 2 different spectra, one for right-handed and one for left-handed circular polarization. This can be seen from the illustration in Fig. 2.2, and also in the spectrum that is given in Fig. 2.4 as a dark line along the orders that separates the two spectra. ESPrIT offers the possibility to extract those spectra either together to get an ordinary unpolarized spectrum, or separately for spectropolarimetric analysis. Another speciality is that the image slicer can produce a tilt of the slit with respect to the CCD axis which could induce wavelength shifts, and, as a consequence, spurious polarization signatures, if not accounted for. This tilt as well as the complex order section profile are also taken into account by the extraction package.

To correct for instrumental errors, we followed the standard procedure of taking approximately 20 flat field images as well as 20 bias images in each night. A master bias and a master flat field were created from those files in the usual way. For the wavelength calibration spectra of a Thorium-Argon lamp were taken every night.

As the first step of the analysis with ESPrIT, the basic parameters of the geometry of the spectra on the chip need to be derived. For this purpose, information like the chip size (in our case 2048×2746), dispersion direction (in our case along columns), as well as the approximate position of the first order, etc need to be entered by the user. In our exposures, we have observed 46 orders ranging from order 84 to order 129. The geometrical information on order position, order curvature etc. is then stored for further use in the extraction of the spectra.

For the wavelength calibration, an initial estimate of the wavelength and dispersion for a given order needs to be provided. All orders are then calibrated simultaneously on the basis of the Thorium-Argon spectrum and a dedicated atlas.

Having two spectra in each exposure and four exposures for each star due to the observing strategy described in Section 2.3.1, in principal means that there are eight spectra available. These can be combined in such a way that instrumental errors are cancelled out and a polarization profile is obtained (by dividing spectra of different beam orientation by each other), and also in a way that cancels out the polarization signature to obtain a so-called *Null profile*. In this case, spectra with identical beam orientation are divided by each other. This Null profile gives an indication of the expected error and serves as a diagnostic profile that can reveal spurious signals. A polarization signature should only be considered real, if it is present in the Stokes V profile, but not in the Null profile. In the section on our results, all profiles are plotted for comparison.

To enhance the sensitivity in the last step of the data analysis, a so-called *least squares deconvolution* (LSD) is applied by ESPrIT, a technique similar to cross-correlation. As polarization signatures are very small, and spectra – especially of fainter stars – are usually far too noisy to detect them directly in a single spectral line, it is necessary to combine the information of as many spectral lines as possible. This is feasible because lines can be expected to show the same shape of their

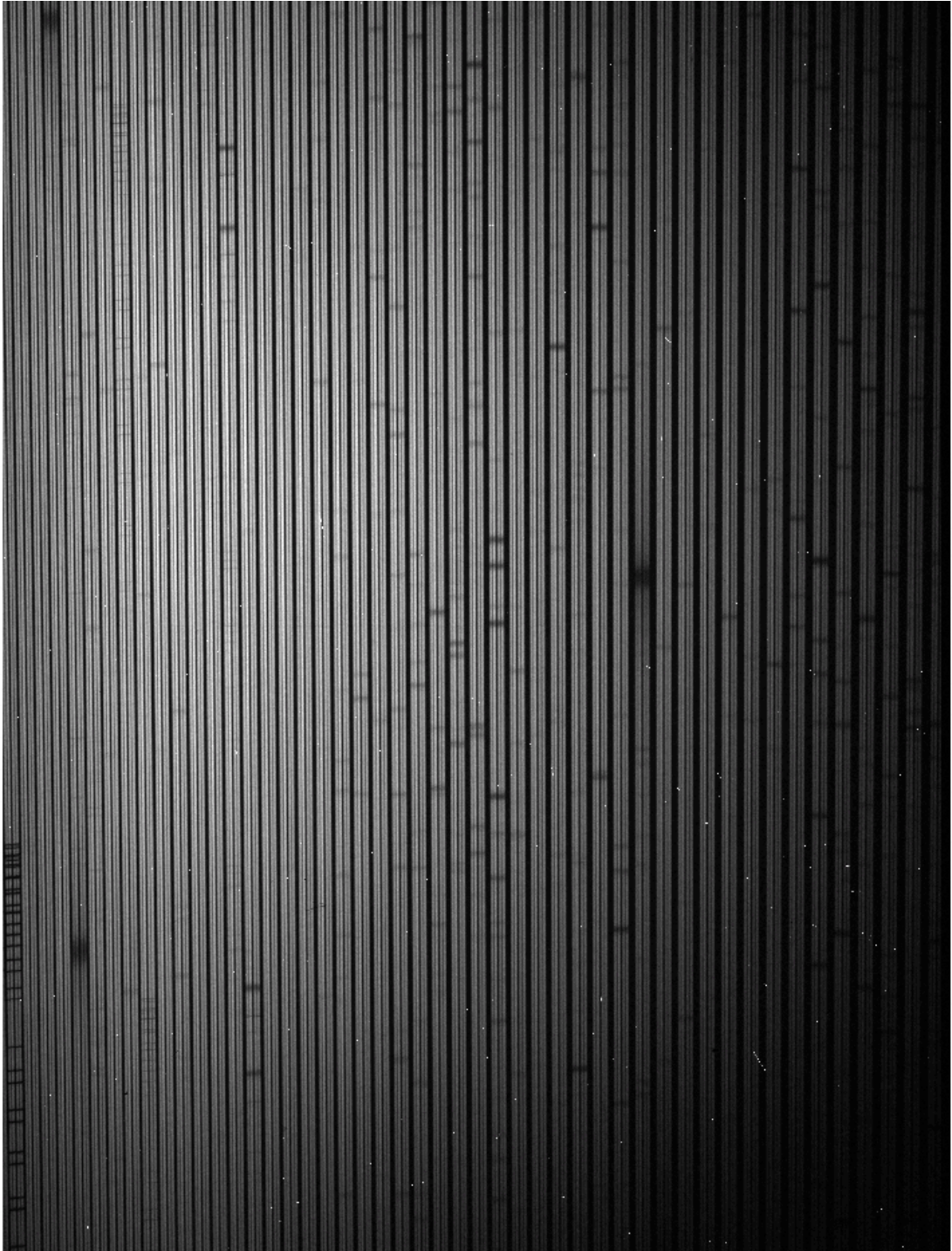


Figure 2.4: Example spectrum. RR Cet observed with the UCLES spectrograph. Orders are aligned along columns, and the complex order section caused by the image slicer is visible when having a close look at the orders.

circular polarization signature. This combination is done by the LSD procedure. Details on the mathematics used in this procedure can be found in Donati et al. (1997), who introduced this specific technique. To perform an LSD analysis, a so-called line mask, i.e., a list of spectral lines that are present in the star and their corresponding depths, needs to be provided. The spectrum is then cross-correlated with this line pattern. We performed the analysis both with previously available masks for the given spectral type of the stars, as well as (as a test) with a refined mask composed by us on the basis of Kurucz stellar atmosphere models and based on temperatures for the targets found in the literature, and using only lines with high Landé factors. The results turned out to be the same: no detectable magnetic field in both cases.

2.5 Targets and Results

Five different stars were observed in this project. One of them, SS For, is a well-studied Blazhko star that was analyzed photometrically by Kolenberg et al. (2009). Three other stars are non-modulated RRab stars (RX Eri, RR Cet and XZ Cet), and one is of RRc type (CS Eri). The observed stars therefore represent the most important subgroups of RR Lyrae stars (modulated RRc stars, as well as RRd stars, which are not represented by the sample, are comparatively small groups). Two of the targets (CS Eri and SS For) had already been observed in the polarimetric study of Kolenberg & Bagnulo (2009). The additional data obtained here served the purpose of comparing the results from low-resolution spectropolarimetry with those of high-resolution spectropolarimetry. It was considered possible that the increased resolution would make it possible to detect weaker fields. Also, the measurements were taken at different pulsation phases than the previous study, therefore providing additional information. Due to the conservation of magnetic flux, one would expect a change in the field strength in a radially pulsating star that changes its radius as dramatically as an RR Lyrae star. Kolenberg & Bagnulo (2009), even though the magnetic fields measured by them were below the significance limit, suspected a possible slight variation of the field strength with pulsation phase. Obtaining an additional measurement at a different phase is therefore also valuable. In the case of SS For, a Blazhko star, of course also the Blazhko phases of the two measurements are different. Checking the presence of a magnetic field at different Blazhko effect phases is important as a variation with the Blazhko effect had been suggested for RR Lyrae, and would, if present, reveal a lot about the mechanism behind the effect.

For the other three targets which had not been observed by Kolenberg & Bagnulo (2009) we present here the first spectropolarimetric measurements ever obtained. This increases the total number of RR Lyrae stars for which magnetic field measurements are available to 21.

Table 2.1 lists the targets with their basic properties, the date of observation, and the pulsation phase during the measurement. The stars will now be discussed

in detail. Final results (Stokes V profiles and Null profiles) of all five targets can be seen in Figures 2.7 and 2.8.

Table 2.1: Table of targets.

Name	other name	$\alpha(2000)$	$\delta(2000)$	V Brightness [mag]
CS Eri	HD 16456	02 37 05.76	-42 57 48.06	8.75-9.31
RX Eri	BD-15872	04 49 44.29	-15 44 28.25	9.25-10.18
SS For	HIC 9932	02 07 51.98	-26 51 57.72	9.45-10.60
RR Cet	HD 9356	01 32 08.17	+01 20 30.23	9.28-10.26
XZ Cet	HD 12293	02 00 16.63	-16 20 46.03	9.33-9.82
Name	Type	date (dd/mm/yyyy)	integration	pulsation phase
CS Eri	RRc	7/12/ 2008	4x1800 s	0.893 ± 0.02
RX Eri	RRab	8/12/2008	4x1800 s	0.0497 ± 0.0007
SS For	RRab-BL	9/12/2008	4x2400 s	0.1044 ± 0.0001
RR Cet	RRab	15/12/2008	4x2400 s	0.1703 ± 0.0008
XZ Cet	RRab	16/12/2008	4x2400 s	0.37 ± 0.48

CS Eri: This star was already part of the sample of Kolenberg & Bagnulo (2009), measured by them twice at the pulsation phases 0.41 and 0.10. According to the GCVS, its period is 0.311331d, typical for an RRc star. Other names of CS Eri are: HD 16456, HIC 12199.

CS Eri has a metallicity of $\text{Fe}/\text{H}=-1.41$ (Feast et al. 2008), and a parallax of $\pi = 2.70 \pm 1.10$ mas. According to Kinman et al. (2012), who studied the kinematics of horizontal branch stars, CS Eri belongs to the so-called H99 group - a group of stars that does not follow the typical kinematic behavior of its environment. CS Eri was studied by De Medeiros et al (2006) in their survey about rotation velocities of low metallicity stars. They determined a temperature of $T_{\text{eff}}=7700\text{K}$, $\log g = 2.8$, $v \sin(i) = 15.0$ km/s and metallicity of $[\text{Fe}/\text{H}]=-1.50$. Other observations (Kinman et al. 2000) at different phases yielded $T_{\text{eff}}=6750$ K and $T_{\text{eff}}=7500$ K, respectively.

Phases given in the table are based on the Hipparcos data and are therefore consistent with those given by Kolenberg & Bagnulo (2009). The accuracy of the phase given by Kolenberg & Bagnulo (2009) is ± 0.02 . As an independent check, we can also conclude from indicators in our spectra (line depth) that we probably have observed the star around its hottest phase, as the lines get shallower and wider (indicating an increase in temperature) in the second and third exposure, and deeper again in the last exposure, indicating that the hottest phase is over. This is in agreement with the phases calculated in this manner.

A challenge in the spectropolarimetry of RR Lyrae stars is their faintness which requires long exposure times. On the other hand, RR Lyrae stars have large radial velocity amplitudes during their pulsation, and therefore the lines move during the four sub-exposures. This is illustrated in Figure 2.5 for a Mg line of CS Eri, which has the shortest period among the stars in our sample.

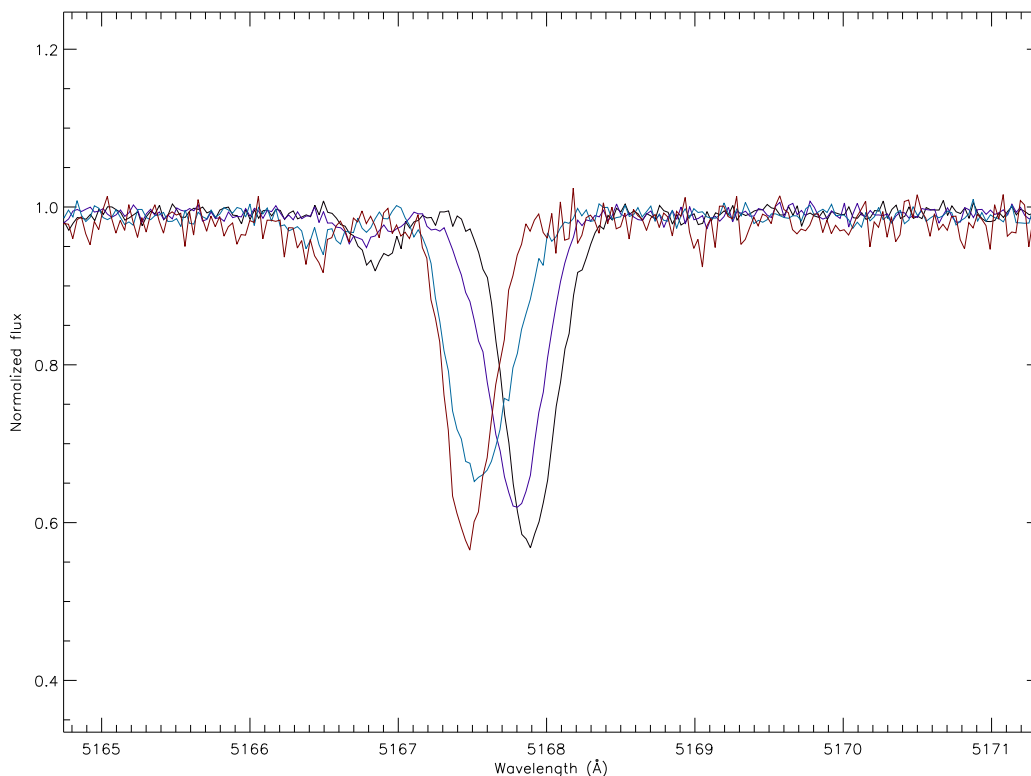


Figure 2.5: A Mg line in CS Eri illustrates the radial velocity changes of RR Lyrae stars during the four sub-exposures.

RX Eri: is one of the stars observed for the first time with spectropolarimetry, as it was not in the sample of Kolenberg & Bagnulo (2009). Alternative names of RX Eri are BD-15872, or HIP 22442. Very accurate and up-to-date elements are given by Berdnikov et al. (2012) who give the epoch as 2453626.3323 ± 0.0004 , and a pulsation period of $0.58724613 \pm 0.00000022$ d. Le Borgne et al. (2009) also observed a maximum of this star about two weeks before our spectra were taken. The phases obtained on the basis of this maximum agree quite well with those of Berdnikov et al. (2012) which we use for calculating the phases of our spectra. For the midpoint of the total exposures (corresponding to the time of the magnetic field measurement) we get a phase of $\varphi = 0.0497 \pm 0.0007$. According to Feast et al. (2008), the metallicity of RX Eri is $\text{Fe}/\text{H} = -1.33$, and its parallax $\pi = 1.31$. For et al. (2011) carefully determined the temperature variation of this and other stars with

Table 2.2: Times of observations and phases for CS Eri. Phases are for the time of mid-exposure, and are based on the closest epoch of maximum light that could be found in the literature.

JD start exposure	phase	RV (km/s)
2454807.933898	0.94	-138
2454807.955745	0.01	-144
2454807.977592	0.08	-159
2454807.999439	0.15	-163

phase, finding the temperature of RX Eri to range approximately from 5900 to 7100 K.

SS For: is a well-known Blazhko star that was also part of the sample of Kolenberg & Bagnulo (2009). It was measured via spectropolarimetry by them three times at pulsation phases 0.09, 0.61 and 0.90. Other designations of SS For are HIC 9932, and CD-27737. SS For was studied photometrically in great detail by Kolenberg et al. (2009), who based on their extensive photometric data give the ephemerides as: $\text{HJD } 2453296.440 + 0.495433 \times E$, and $2453298.914 + 34.94 \times E$ for the pulsation and the Blazhko cycle, respectively. The phases given in Table 2.3 were calculated from the ephemerides of Kolenberg et al. (2009). The phase of the midpoint of all combined four spectra (and therefore of the magnetic field measurement) is $\varphi=0.1044$. A light maximum of SS For was also measured with the Tarot telescope a few weeks before our spectra were taken. The time of phase zero (maximum light) was 2454793.6430 according to Le Borgne et al. (2009). Phases calculated on this basis agree quite well with those based on the data of Kolenberg et al. (2009). The Blazhko phase at the time of our spectropolarimetric measurements was $\psi=0.25$. During the observations of Kolenberg & Bagnulo (2009), its Blazhko phase was quite different: 0.43, 0.47 and 0.49, respectively for their three measurements.

SS For is much hotter than the other stars treated so far. Cacciari et al. (1989) determined the temperature curve of SS For and found it to vary roughly between 6200 and 8800 K. They also publish radial velocities in connection with pulsation phases. A comparison of their values with our results show a good agreement.

A special feature that we found to be present in our spectra of SS For is a line doubling in the $\text{H}\alpha$ line (see Figure 2.6), which is considered to be an indication of a shock wave travelling through the stellar atmosphere. Stellar material before and after the shock wave is then observed at two different, well-separated velocities which lead to a splitting in the observed spectral lines. This is usually referred to as the Schwarzschild effect (see also Chapter 4 for details on the violent atmospheres of RR Lyrae stars). The effect disappears as the shock wave moves on and leaves

Table 2.3: Times of observations and phases for SS For. Phases are for the time of mid-exposure. Values in column 2 were calculated based on the ephemerides given by Kolenberg et al. (2009).

JD start exposure	phase	RV (km/s)
2454809.982457	0.0172	-139
2454810.011249	0.0753	-135
2454810.040040	0.1334	-130
2454810.068832	0.1916	-123

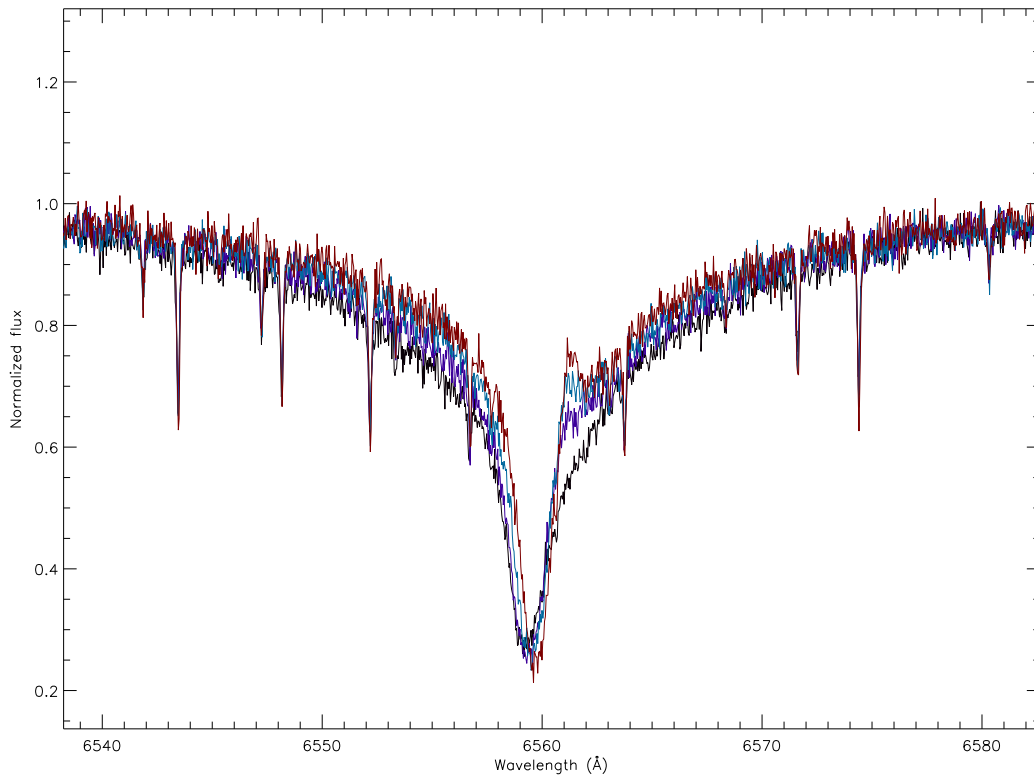


Figure 2.6: $H\alpha$ line of the star SS For in our four subexposures. The changing doubling of the line during the transient shock passage can be seen. The x axis is in observed wavelength.

the line forming region. We have captured this moment in two of the stars in our sample: SS For and RR Cet. While the effect is seen in $H\alpha$, it is not present in $H\beta$ or any of the metallic lines, due to the fact that those lines are formed at different depths in the atmosphere. The doubling therefore should not influence our spectropolarimetric measurements as they are based on a set of metallic lines. It is interesting to note that the typical “shock phase” of RR Lyrae stars is considered

the phase around $\varphi=0.9$ where a so-called *hump* is observed in the B and V light curves, and in some cases a UV excess is observed. Our observations of $H\alpha$ line doubling in SS For (as well as in RR Cet) were taken at a much later phase (after light maximum), which is consistent with the assumption that $H\alpha$ is formed in much higher layers and that the shock wave is traveling outwards.

RR Cet: is one of the stars for which spectropolarimetric observations are presented here for the first time as it was not in the sample of Kolenberg & Bagnulo (2009).

There are ephemerides for RR Cet provided by Berdnikov et al. (2012) who regularly observed 81 RR Lyrae stars photometrically. The epoch according to them is 2453805.4870 ± 0.0004 , and the pulsation period is $0.55302938 \pm 0.00000023$. RR Cet was also monitored in the framework of the GEOS survey with the automated Tarot telescopes (Le Borgne et al. 2009). They measured a maximum at JD 2454820.2950, only five days after our spectra were taken, resulting in a phase of $\varphi=0.067$ for our first spectrum, roughly in agreement with the ephemerides of Berdnikov et al. (2012). The pulsation phase at the midpoint of the four spectra (and therefore corresponding to the time of the magnetic field measurement) is $\varphi=0.169$.

Table 2.4: Times of observations for RR Cet. Phases are for the time of mid-exposure and were calculated based on the ephemerides given by Berdnikov et al. (2012).

JD start exposure	phase	RV (km/s)
2454815.907886	0.065	-104
2454815.936677	0.118	-98
2454815.965468	0.170	-93
2454815.994260	0.222	-88

RR Cet was also investigated by For et al. (2011), who found the temperature to vary between approximately 6100-7300K. Butler et al. (1982) also measured the star spectroscopically near light maximum and found a temperature of 7340K. We therefore adopt a temperature of about 7200K for our line list to fit our observations taken shortly after light maximum.

Note that in RR Cet we also detect a line doubling in $H\alpha$ as in SS For. For a discussion of this phenomenon we refer to the paragraph on SS For.

XZ Cet (other names: HD 12293 and BD-17366) was not in the sample of Kolenberg & Bagnulo (2009), and we therefore present the first spectropolarimetric observations of this object. The classification of XZ Cet was disputed in the past,

with Teays & Simon (1985) classifying it as anomalous cepheid, which is questioned by other authors. Wallerstein et al. (2009) include it into their study of carbon-rich RR Lyrae stars.

Because of the long period, the radial velocity changes during our four sub exposures are smaller than for the other stars. Its elements are: 2448500.799 + 0.82314 E (Hipparcos, 1997).

Table 2.5: Times of observations and phases for XZ Cet.

JD start exposure	phase	RV (km/s)
2454816.933721	0.221	+188.5
2454816.962512	0.256	+190.5
2454816.991304	0.291	+192.0
2454817.020095	0.325	+193.0

Conclusions The observations of all our stars resulted in null detections, consistent with the findings of Kolenberg & Bagnulo (2009). In order to test the functionality of the instrumental setup we also observed a magnetic standard star (HD 94660) which showed a clear signature of a strong field in our spectra (see Figure 2.8), indicating that our non-detections in the RR Lyrae stars did not stem from any instrumental failure.

With our data we have shown that even with high-resolution spectroscopy it is not possible to detect a magnetic field in the selected RR Lyrae stars. The model for the Blazhko effect that requires a strong magnetic field is therefore most probably not the correct explanation for the modulation.

With our sample of stars we have increased the total number of RR Lyrae stars observed with spectropolarimetry to 21. With such a high number, it can safely be assumed that it was not an unfavorable geometrical configuration (i.e., one with an inclination so that the line-of-sight component of the magnetic field is small) or an unfavorable timing (observations during a minimum in a magnetic cycle) that caused the non-detections. In none of the represented groups of RR Lyrae stars, RRab, RRc and RRab-Blazhko stars, a field was detectable.

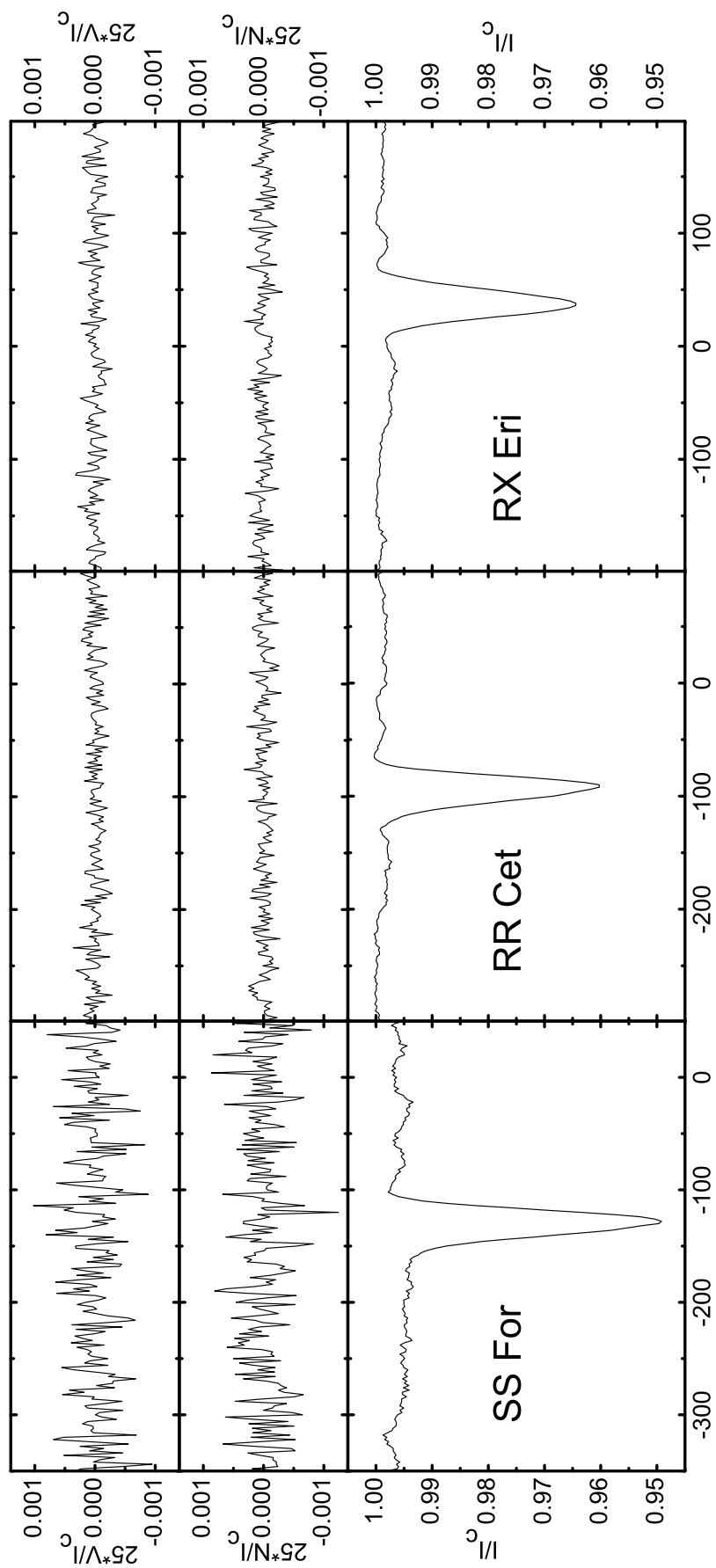


Figure 2.7: LSD Stokes profiles of three of our target stars: SS For, RR Cet and RX Eri. The top panel shows the Stokes V profile, the middle panel the Null profile that indicates the errors, and the bottom panel shows the LSD line profile in intensity.

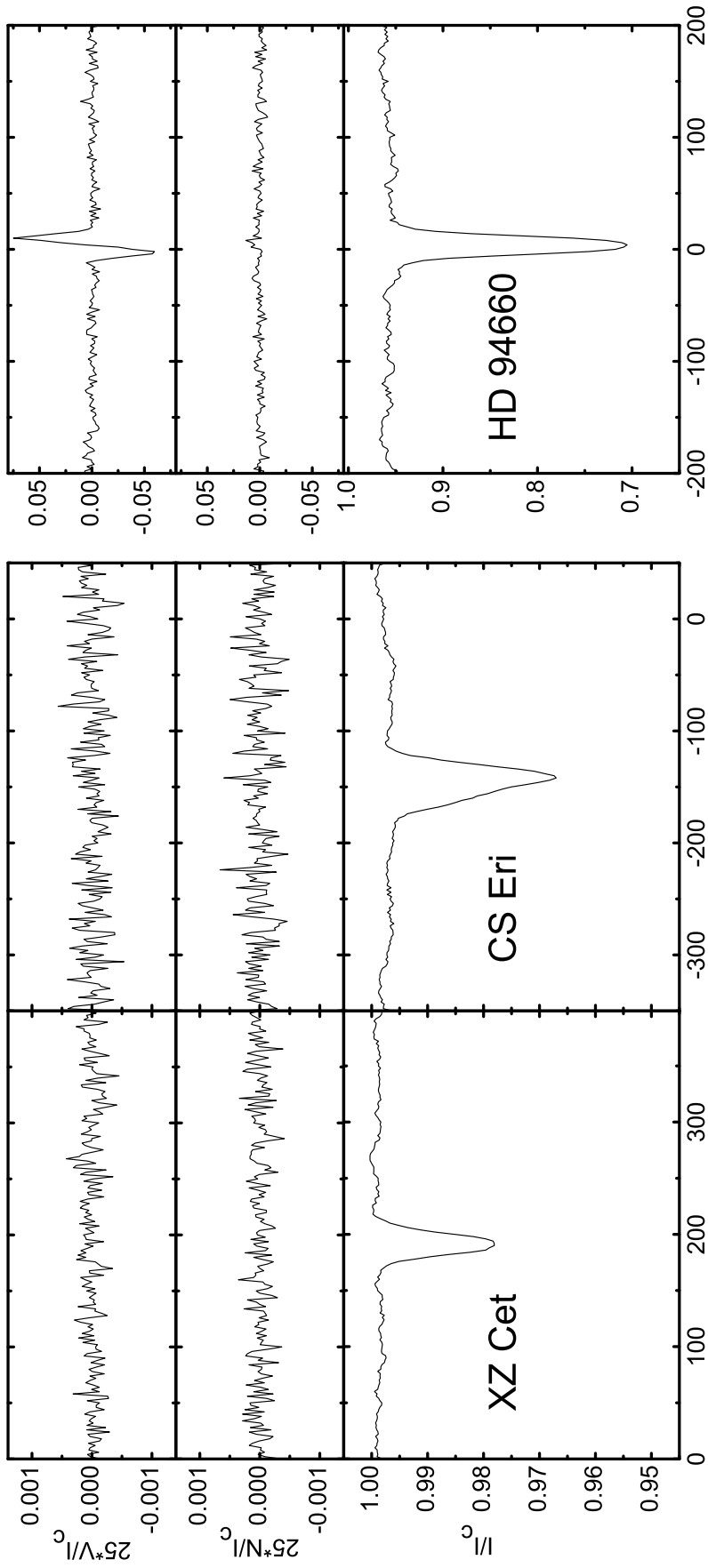


Figure 2.8: Same as Figure 2.7 but for the remaining two target stars (XZ Cet and CS Eri) plus a magnetic standard star to test the instrument functionality.

Chapter 3

Towards a complex Blazhko effect (Papers II and III)

Blazhko stars had before only been observed from the ground, and the data sets suffered from large gaps due to bad weather and interruptions between observing seasons. Therefore, also all previous indications that the Blazhko effect might be not strictly periodic were based on sparse data with large gaps, often obtained with different instruments in different filters and by different observers. From such inhomogenous data sets it was hardly possible to tell whether the changes were caused either by evolution (slow ceasing or appearing of the Blazhko effect as the star gradually changes its parameters) or caused by a superimposed long-term modulation. Continuous and homogeneous space photometry allows for the first time to have a look at those changes taking place.

Also, of course the precision of space photometry was much better than that of ground-based data. This allowed to search for low amplitude components in the Fourier spectra of RR Lyrae stars.

In the following, the analyses of two peculiar RR Lyrae stars are presented. The first one was observed with CoRoT and the second one with the *Kepler* space telescope.

3.1 Analysis of the CoRoT photometry

This section consists of the publication:

- **Guggenberger, E.**; Kolenberg, K.; Chapellier, E.; Poretti, E.; Szabó, R.; Benkő, J. M.; Paparó, M.: *The CoRoT star 105288363: strong cycle-to-cycle changes of the Blazhko modulation*, published in the Monthly Notices of the Royal Astronomical Society, 415, 1577 (2011)

The contribution of the author of the thesis to the paper was the following:

- prepared the data for analysis by removing instrumental effects
- performed all analyses
- wrote the paper



The *CoRoT* star 105288363: strong cycle-to-cycle changes of the Blazhko modulation

E. Guggenberger,¹★ K. Kolenberg,^{1,2} E. Chapellier,³ E. Poretti,⁴ R. Szabó,⁵
J. M. Benkő⁵ and M. Paparó⁵

¹Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, A-1180 Vienna, Austria

²Harvard-Smithsonian Center for Astrophysics, 60 Garden street, Cambridge, MA 02138, USA

³Observatoire de la Côte d'Azur, Université Nice Sophia-Antipolis, UMR 6525, Parc Valrose, 06108 Nice Cedex 02, France

⁴INAF - Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate (LC), Italy

⁵Konkoly Observatory of the Hungarian Academy of Sciences, PO Box 67, H-1525 Budapest, Hungary

Accepted 2011 March 28. Received 2011 March 25; in original form 2011 March 11

ABSTRACT

We present an analysis of the *CONvection, ROTation and planetary Transits (CoRoT)* star 105288363, a new Blazhko RR Lyrae star of type RRab ($f_0 = 1.7623 \text{ d}^{-1}$), observed with the *CoRoT* spacecraft during the second long run in the direction of the Galactic Centre (LRc02, time-base 145 d). The *CoRoT* data are characterized by an excellent time-sampling and a low noise amplitude of 0.07 mmag in the 2–12 d^{-1} range and allow us to study not only the fine details of the variability of the star, but also long-term changes in the pulsation behaviour and the stability of the Blazhko cycle. We use, among other methods, standard Fourier analysis techniques and O–C diagrams to investigate the pulsational behaviour of the Blazhko star 105288363. In addition to the frequency pattern expected for a Blazhko RR Lyrae star, we find an independent mode ($f_1 = 2.984 \text{ d}^{-1}$) showing a f_0/f_1 ratio of 0.59 which is similar to that observed in other Blazhko RR Lyrae stars. The bump and hump phenomena are also analysed, with their variations over the Blazhko cycle. We carefully investigated the strong cycle-to-cycle changes in the Blazhko modulation ($P_B = 35.6 \text{ d}$), which seem to happen independently and partly diametrically in the amplitude and phase modulations. Furthermore, the phasing between the two types of modulations is found to change during the course of the observations.

Key words: techniques: photometric – stars: individual: CoRoT ID 105288363 – stars: variables: RR Lyrae.

1 INTRODUCTION

RR Lyrae stars are low-mass stars on the horizontal branch that burn helium in their core. They have contributed to the progress in many fields of modern astronomy. With their large amplitudes of up to 1.5 mag, they have been known since the end of the 19th century and offer the opportunity to study stellar evolution in real time (Le Borgne et al. 2007). They obey a period–luminosity–colour relation which makes them important standard candles. Also, their evolutionary status makes them useful for the study of Galactic evolution. RR Lyrae stars can pulsate in the radial fundamental mode (RRab stars), in the first radial overtone (RRc stars) or in both modes simultaneously (RRd stars). Some RR Lyrae stars are candidates for possible higher radial overtone pulsation.

One of the remaining unsolved questions on those seemingly well-studied stars is the century-old Blazhko enigma, a modulation

of the amplitude and/or phase of the main pulsation period on time-scales of typically weeks to months. With the availability of new and precise data, the estimated incidence rate of this phenomenon has recently increased dramatically, making it even more important to understand the effect. While until some years ago a value of 20–30 per cent was assumed for RRab stars, Kolenberg et al. (2010a) find at least 40 per cent of the stars observed by the *Kepler* satellite to be modulated, and Jurcsik et al. (2009c) give a lower limit of 50 per cent of modulated stars in their sample and even raise the suspicion that the modulation might be a universal property of RRab stars.

Several promising models have been proposed to explain the Blazhko phenomenon, among those are the magnetic oblique pulsator–rotator model (e.g. Shibahashi 2000) that works similarly to the mechanism that causes the typical patterns of roAp variation, as well as models involving resonances between the main pulsation and either higher order radial modes or non-radial modes (e.g. Dziembowski & Mizerski 2004, and references therein). None of these models, however, succeeds in explaining the full spectrum of

★E-mail: elisabeth.guggenberger@univie.ac.at

1578 *E. Guggenberger et al.*

observed features of Blazhko stars. The repeated non-detection of the required strong dipole magnetic fields in RR Lyrae stars in recent studies (Chadid et al. 2004; Schnerr et al. 2008; Guggenberger et al. 2009; Kolenberg & Bagnulo 2009) poses a significant problem for the magnetic models, and the changes that have been reported to occur in the Blazhko phenomenon of several stars, especially variations in its period, are a big challenge for any model that links the Blazhko effect directly to rotation and therefore predicts an almost clock-work-like behaviour.

A scenario that explicitly favours irregular or stochastic Blazhko cycles was published by Stothers (2006). It connects the amplitude and phase modulations of Blazhko stars to a cyclic weakening and strengthening of the turbulent convection inside the helium and hydrogen ionization zones due to the presence of local transient magnetic fields.

Most recently, the detection of period doubling in several RR Lyrae stars in the high-precision data delivered by the *Kepler* mission (Kolenberg et al. 2010a; Szabó, Kolláth & Molnár 2010) triggered the exploration of radial resonances in Blazhko RR Lyrae stars. While hydrodynamical simulations successfully reproduced period doubling (Szabó, Kolláth & Molnár 2010; Kolláth, Molnár & Szabó 2011) and found a 9:2 resonance between the ninth overtone which appears as a surface mode and the fundamental pulsation to be responsible for the phenomenon, they were not able to yield modulated light curves. It was an alternative approach by Buchler & Kolláth (2011), using the amplitude equation formalism, that succeeded in producing amplitude modulation of both regular and irregular types. In their simulations, chaos occurs because of the presence of a strange attractor in the dynamics, causing irregular behaviour.

Changes in both the amplitude and/or the length of the Blazhko cycles, irregularities in the Blazhko phenomenon, sometimes also accompanied by a change in the main pulsation period, have been reported for a sample of RR Lyrae stars. A detailed look at the known changes in Blazhko cycles of different stars will be taken in Section 5.1. One has to note, however, that previous studies of changing Blazhko phenomena usually relied on ground-based data only, suffering from small or sometimes large gaps due to daylight and/or weather and therefore also often from incomplete coverage of the pulsation and especially the Blazhko period. Reports on long-term variations in the Blazhko effect in specific stars also often compare publications of different authors using different methods with varying precisions. It was therefore often impossible to say when the changes took place and whether they happened abruptly or continuously. In this study, we have, for the first time, investigated strong cycle-to-cycle changes of the Blazhko effect in a continuous and homogeneous data set that covers 255 pulsation and more than four full Blazhko cycles.

Section 3 will present the data used for analysis, as well as data-processing methods. Section 4 explains the analysis methods and presents the results, while their implications are discussed in Section 5. At the final stages of preparing our manuscript, we were informed that another group had analysed the same data set and published their results in Chadid et al. (2011). The main differences between the results of the two manuscripts are briefly summarized in Appendix A.

2 THE TARGET

The *CO*nvection, *RO*tation and planetary *TR*ansits (*CoRoT*) star 105288363 (hereinafter CoRoT ID 105288363, $\alpha = 18^{\text{h}}39^{\text{m}}30^{\text{s}}.8$, $\delta = +7^{\circ}26'53''.9$, J2000) is a 15.3-mag star

(V) in the constellation Ophiuchus. Before the *CoRoT* mission, it was not known to be variable. CoRoT ID 105288363 was classified as an RR Lyrae variable with the ‘CoRoT Variability Classifier’, using two different automated supervised classification methods (Debosscher et al. 2009), and was then confirmed by human inspection. The ExoDat data base (Deleuil et al. 2009), which provides important information on the parameters of the stars observed in the *CoRoT* exoplanet field, lists a contamination of the CoRoT ID 105288363 data of 0.177, meaning that 17.7 per cent of the measured flux might originate from background stars. The nearest background stars also included in the photometric mask of CoRoT ID 105288363 are also listed in the ExoDat data base and are all 2 mag or more fainter than the target star.

3 OBSERVATIONS AND DATA TREATMENT

The data used in this study were obtained in the framework of the Additional Programmes of the exoplanetary field during the second long run in the direction of the Galactic Centre (LR02). Observations were carried out during a time-span of 145 d from 2008 April 15 to 2008 September 7, or *CoRoT* JD 3027.47 to 3172.46. Note that the zero-point of the *CoRoT* JD corresponds to HJD 245 1545.0, which is 2000 January 1 at 12:00:00 UT. The nominal exposure time in the exoplanet field is 512 s, as 16 measurements with a sampling of 32 s are averaged onboard (Debosscher et al. 2009). For this study, we used the calibrated light curves of N2 level.

The *CoRoT* space telescope is dedicated to stellar seismology and the search for extrasolar planets. It was launched successfully on 2006 December 27 into a polar low-Earth orbit with an apogee of 911 km and a perigee of 888 km (Auvergne et al. 2009). With its unprecedented photometric precision, its continuous time-sampling and its capability to observe a target for up to 150 d, it provides an excellent opportunity to study variable stars and especially the long-term behaviour and stability of their pulsation.

As the *CoRoT* spacecraft is in a low-Earth orbit, the Earth has an influence on the satellite and causes perturbations. The most important of these perturbations are temperature variations due to light/penumbra/shadow transitions and changes in the Earth’s albedo, cosmic-ray hits during the passage through the South Atlantic Anomaly and satellite attitude variations because of the Earth’s gravity field (Auvergne et al. 2009). These result in instrumental jumps and trends in the data, as well as some strongly deviating points.

Due to the above-mentioned effects, the data of CoRoT ID 105288363 were affected by one significant jump and a slight trend. As the high amplitudes typical for RR Lyrae stars hamper a profound trend correction, and the data sampling would strongly affect the linear fit to the original data, a frequency fit had to be subtracted before the slope of the trend could be determined. The frequency fit contained the main pulsation frequency, its first 10 harmonics and the classical triplet solution around those peaks which describe the mean Blazhko effect of the star. From the residuals we then found the parameters for the jump and trend correction and applied it to the original data. Note that an instrumental trend in the flux data, if not removed, would lead to a spurious change in amplitude due to the conversion to the magnitude scale. This would be fatal for any investigation of the Blazhko effect and its stability, as the amplitudes and their changes are of great interest. Special attention was therefore paid to a correct trend removal, and both the jumps and trends were removed from the flux data before converting it to magnitudes. Luckily, the trend in the data of CoRoT ID 105288363 was only marginal and could easily be removed with a linear

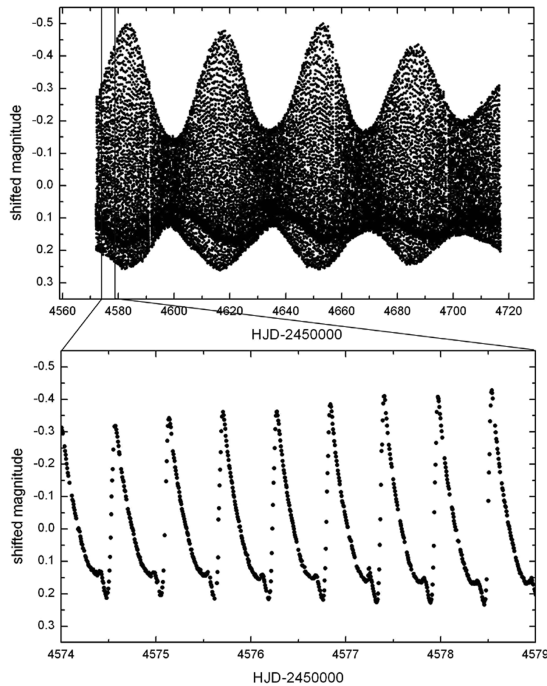


Figure 1. The complete data set of CoRoT ID 105288363 covering more than four Blazhko cycles is shown in the top panel. In the bottom panel, a zoom-in is given to illustrate the continuous sampling of the light curve which is typical for satellite missions, like *CoRoT*.

correction. The fact that the trend was very small in this case rules out the possibility that the observed amplitude changes could originate from the contamination with background stars. Fig. 1 shows the corrected full data set used in this paper, illustrating the full coverage and giving an example of the excellent data quality by zooming-in to a smaller region. A phase diagram, showing the data folded with the main period, is given in Fig. 2.

In the framework of the standard *CoRoT* data reduction pipeline, a ‘flag’ is attributed to every data point, indicating the quality and

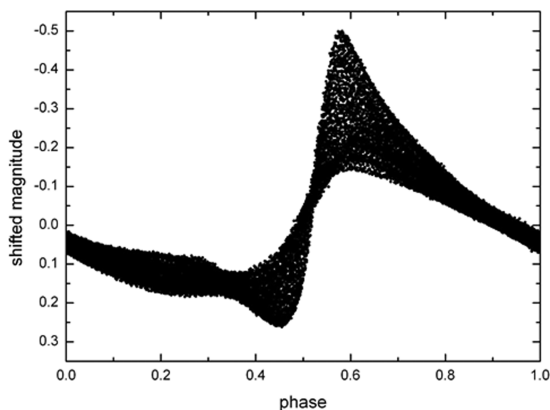


Figure 2. Data of CoRoT ID 105288363 folded with the main period of 0.567 d.

reliability of the measurement as well as the nature of the effect that might have affected the measurement in question. As only measurements with flag = 0 are considered fully reliable, an analysis is usually only performed using those data points. For RR Lyrae stars, however, it turned out that the rapid brightness changes that occur during rising light caused a lot of measurements to be spuriously classified as non-zero, even though they are high-quality measurements. This would result in incomplete coverage and regular gaps in the light curve when only flag = 0 points are used. The flag algorithm was therefore not used to exclude measurements, and the light curve was instead cleaned manually off outlying points. The final data set is composed of 20 983 useful points, yielding the very high duty cycle of 86 per cent.

4 ANALYSIS AND RESULTS

4.1 Fourier analysis

A Fourier analysis of the data was performed using the PERIOD04 software package developed by Lenz & Breger (2005). It provides simultaneous sine-wave fitting and least-squares fitting algorithms. The results were thereafter cross-checked with an analysis performed with the iterative sine-wave fitting method (Vaniček 1971) and found to agree within the errors.

The spectral window of the data shows the typical features of high-precision satellite data: alias peaks have low amplitudes (smaller than 0.1 normalized amplitude, see the upper panel of Fig. 3) and are centred around the orbital frequency and its multiples. The orbital period of *CoRoT* is 6184 s (Auvergne et al. 2009), corresponding to a frequency of $f_{\text{orb}} = 13.97 \text{ d}^{-1}$. In addition to f_{orb} , we also find the term $2f_{\text{sid}} = 2.0054 \text{ d}^{-1}$, which is caused by two passages over the South Atlantic Anomaly per day, and its harmonic $4f_{\text{sid}}$. The term $f_{\text{sid}} = 1.0027 \text{ d}^{-1}$ itself is not visible in the spectral window, but its combinations with f_{orb} are present. In summary, we find peaks at

$$f_{0,s} = kf_{\text{orb}} \pm nf_{\text{sid}}$$

with $0 \leq k \leq 6$ and $1 \leq n \leq 7$. The highest peaks are at $(k, n) = (1, \pm 1)$, $(2, 0)$ and $(0, 2)$.

The dominant features in the Fourier spectrum of CoRoT ID 105288363 are the radial fundamental pulsation frequency of $1.762 2967 \text{ d}^{-1}$ and its numerous harmonics describing the asymmetric light curve shape that is typical for RRab stars. The harmonics were significant up to the 22nd order, when applying a significance criterion of a signal-to-noise ratio of 3.5 for combination frequencies. The noise amplitude calculated in the $2\text{--}12 \text{ d}^{-1}$ range is 0.07 mmag and is probably still affected by the long-term instrumental drift. Indeed, it is lower (0.04 mmag) in the $50\text{--}90 \text{ d}^{-1}$ region. The well-known triplet structure with a spacing of the Blazhko frequency (in this case 0.028 d^{-1}), which is usually observed in Blazhko stars, is also clearly visible. The triplet could either be caused by a non-radial mode close to the main pulsation mode and its many combinations (Breger & Kolenberg 2006) or simply result from the modulation of purely radial pulsation as was recently mathematically described by Szeidl & Jurscik (2009) and, using a different approach, by Benkő, Paparó & Szabó (2009). The middle panels of Fig. 3 show the Fourier spectrum of the original data, after the subtraction of f_0 and its first nine harmonics, and of a fit including the triplet components. The insets show a zoom into the vicinity of the fourth harmonic to illustrate the fine structure of the remaining signal.

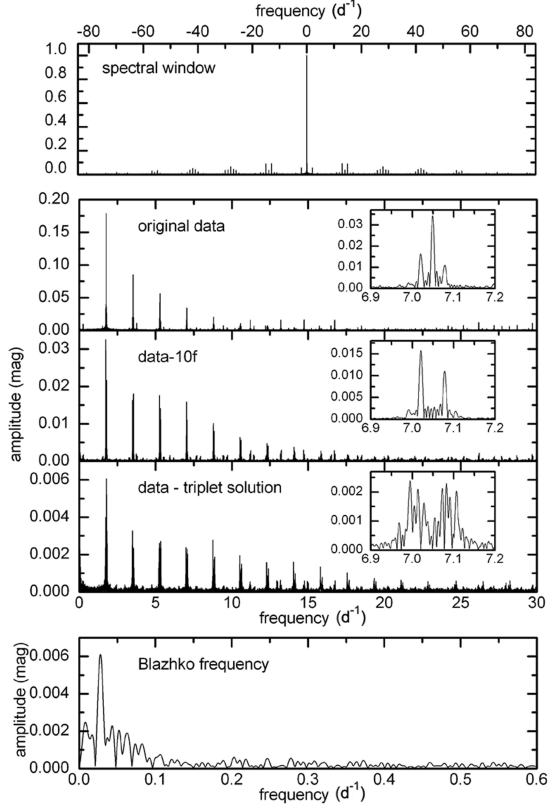
1580 *E. Guggenberger et al.*

Figure 3. Consecutive steps of pre-whitening. The top panel shows the spectral window and the middle panels (top to bottom) give the Fourier spectrum of the original data, the spectrum of the data after pre-whitening the main pulsation component and nine harmonics, and the spectrum after subtraction of the triplet solution, respectively. The insets show an enlargement of the region around $4f_0$ to illustrate the triplet structure and the remaining signal. The bottom panel shows the low-frequency region where the Blazhko frequency is directly detected.

The ephemerides of the maximum pulsation light and maximum pulsation amplitude (i.e. the Blazhko maximum) found from a classical Fourier analysis of the complete data set are

$$\text{HJD}(T_{\max}) = 245\,4572.8037 + 0.567\,44122 \times E_{\text{pulsation}},$$

$$\text{HJD}(T_{\text{Blazhkomax}}) = 245\,4583.5768 + 35.6 \times E_{\text{Blazhko}}.$$

Note that the Blazhko effect undergoes strong changes in CoRoT ID 105288363 (as can already be guessed after a close inspection of the raw data shown in Fig. 1). Hence, the values above should be understood as mean values of the complete data set. A detailed investigation of the Blazhko period and changes of the Blazhko effect using different approaches will be performed in the subsequent sections.

4.1.1 Multiplet components

In the past few years, it was debated whether only triplet structures occur in Blazhko stars or whether higher order multiplets are also

present, but hidden in the noise of the available data sets. The question was resolved when Hurta et al. (2008) reported the first detection of quintuplets in the RRab star RV UMa using high-precision ground-based data obtained during a dedicated campaign. Meanwhile, quintuplets have been found in other RR Lyrae stars as well, for example, in the southern star SS For by Kolenberg et al. (2009) and, thanks to high-precision satellite photometry, even higher order multiplets are known today, with the record held by a septet component that has been found in the *CoRoT* data of V1127 Aql (Chadid et al. 2010).

In CoRoT ID 105288363, however, the situation is a bit more complicated. In a Fourier analysis, the strongly changing Blazhko effect and, especially, its seemingly irregular nature cause peaks of high amplitude to appear around the dominant peaks. Therefore, most multiplet components are hidden, not in the noise, but in an irregular pattern of unresolved peaks that are caused by the cycle-to-cycle changes of the Blazhko modulation. Residual peaks like these were also detected in two other Blazhko stars observed by *CoRoT* so far: V1127 Aql (Chadid et al. 2010) and CoRoT ID 101128793 (Poretti et al. 2010). In these cases, the amplitudes of the peaks were small, indicating slight changes of the Blazhko cycle. In CoRoT ID 105288363, however, the amplitudes of the residual peaks are very high, complicating the analysis of the full data set. As a result, the quintuplet peaks become unambiguously detectable only at higher harmonic orders, as their amplitudes do not decrease as rapidly with increasing order as those of the main pulsation components (see also Section 4.1.4). It is a valid assumption that if the quintuplets can be detected at higher orders, they are also present at lower orders. Therefore the quintuplet peaks around low orders were included into our fit to the data, even if they lie very close to high-amplitude peaks caused by the varying Blazhko effect. The frequencies included in the final fit to the data of CoRoT ID 105288363, including the triplet and quintuplet peaks, are given in Table 1. For obtaining this fit, a Fourier sum of the form

$$f(t) = A_0 + \sum_{k=1}^n \left\{ A_k \sin(2\pi(kf_0 t + \varphi_k)) \right. \\ + A_k^+ \sin(2\pi[(kf_0 + f_B)t + \varphi_k^+]) \\ + A_k^- \sin(2\pi[(kf_0 - f_B)t + \varphi_k^-]) \\ + A_k^{++} \sin(2\pi[(kf_0 + 2f_B)t + \varphi_k^{++}]) \\ + A_k^{--} \sin(2\pi[(kf_0 - 2f_B)t + \varphi_k^{--}]) \left. \right\} \\ + B_0 \sin(2\pi(f_B t + \varphi_B))$$

was used, with f_B being the Blazhko frequency, A^+ and A^- denoting the amplitudes of the triplet components, and A^{++} and A^{--} denoting the amplitudes of the quintuplet peaks on the higher and lower sides of the main pulsation component, and B_0 is the amplitude of the Blazhko frequency itself. This is the standard method of fitting the light curves of Blazhko RR Lyrae stars, assuming equidistant triplets, extended here to include also equidistant quintuplets and the Blazhko frequency itself, which has only in rare cases been detectable in ground-based data. The Fourier spectrum of the vicinity of the Blazhko frequency is displayed in the bottom panel of Fig. 3.

4.1.2 Additional modes

We also carefully investigated the amplitude spectra to search for additional modes, that is, frequencies not related to f_0 and f_B . As

1582 *E. Guggenberger et al.***Table 2.** Parameters describing the multiplets as explained in the text.

Order k	R_k	$\sigma(R_k)$	$\Delta\phi$	$\sigma(\Delta\phi)$	Q_k	$\sigma(Q_k)$	ΔA^2	$\sigma(\Delta A^2)$
Triplet components								
1	0.67	0.01	-0.460	0.002	-0.199	0.007	-6.01E-04	1.57E-05
2	1.12	0.03	0.622	0.003	0.056	0.012	6.50E-05	9.58E-06
3	0.80	0.02	0.641	0.004	-0.113	0.013	-1.11E-04	8.84E-06
4	0.68	0.02	-0.379	0.005	-0.191	0.015	-1.33E-04	7.53E-06
5	0.78	0.04	-0.378	0.007	-0.126	0.023	-3.81E-05	4.91E-06
6	0.85	0.06	-0.353	0.010	-0.082	0.036	-1.03E-05	3.14E-06
7	0.81	0.08	-0.318	0.014	-0.106	0.050	-6.84E-06	2.26E-06
8	0.73	0.10	0.711	0.021	-0.154	0.068	-5.34E-06	1.67E-06
9	0.72	0.15	0.728	0.029	-0.163	0.101	-2.58E-06	1.13E-06
10	0.78	0.25	-0.233	0.049	-0.122	0.158	-7.72E-07	7.10E-07
11	0.91	0.40	-0.180	0.066	-0.050	0.223	-1.58E-07	4.99E-07
12	1.08	0.68	-0.124	0.099	0.038	0.316	5.91E-08	3.52E-07
13	2.09	2.47	-0.071	0.204	0.354	0.516	2.34E-07	2.42E-07
Quintuplet components								
1	0.9	0.2	-0.19	0.03	-0.07	0.10	-1.10E-06	1.08E-06
2	0.4	0.1	-0.34	0.04	-0.40	0.12	-5.39E-06	1.10E-06
3	3.0	1.1	0.10	0.06	0.50	0.14	4.75E-06	9.65E-07
4	1.0	0.2	0.11	0.03	-0.01	0.10	-1.64E-07	1.08E-06
5	0.7	0.1	0.05	0.03	-0.20	0.09	-3.95E-06	1.26E-06
6	0.8	0.2	-0.95	0.04	-0.10	0.13	-9.13E-07	8.59E-07
7	0.9	0.3	0.14	0.05	-0.07	0.16	-4.44E-07	6.88E-07
8	0.6	0.2	0.16	0.06	-0.25	0.18	-1.23E-06	6.43E-07
9	0.6	0.3	0.15	0.08	-0.28	0.23	-8.86E-07	5.18E-07
10	0.8	0.5	0.17	0.09	-0.12	0.31	-2.03E-07	3.62E-07
11	0.9	0.8	-0.79	0.13	-0.04	0.41	-3.60E-08	2.74E-07
12	0.9	0.9	-0.79	0.16	-0.05	0.48	-3.07E-08	2.31E-07
13	1.0	1.1	0.24	0.20	-0.01	0.56	-6.85E-09	1.98E-07

harmonic order and are listed in Table 2. It is known that about three-fourths of all RRab Blazhko stars in the MACHO data base show a triplet with the higher component on the higher frequency side (Alcock et al. 2003), that is, $R_k > 1$. CoRoT ID 105288363 seems to be part of the rarer class, with the left-hand side component having a higher amplitude, and hence R_k values significantly smaller than 1 in most orders. Also in the quintuplets, the left-hand side peak is usually higher in CoRoT ID 105288363. The asymmetry parameter $Q = (A_+ - A_-)/(A_+ + A_-)$, which is similar to R_k , was introduced by Alcock et al. (2003) who find that in their large sample of stars observed in the MACHO project, Q usually lies between 0.1 and 0.6, with a peak at 0.3. In our data, the mostly negative values of Q again indicate the dominance of the left-hand side peak. Finally, we include the power difference of the modulation components $\Delta A_k^2 = A_+^2 - A_-^2$. According to Szeidl & Jursik (2009), this is the more physically meaningful quantity to measure the asymmetry of the multiplet, as it is connected to the phase difference between the amplitude modulation and the phase modulation, with the triplet being symmetrical if both types of modulations are in phase or if one of the two types occurs in its pure form.

4.1.4 Decrease in amplitudes

It was first shown by Jursik et al. (2005) that the amplitudes of the harmonics and those of the triplet components behave in different ways with increasing harmonic order. While the main pulsation components (i.e. f_0 and its harmonics) decrease exponentially, the triplet components show a much less steep decrease. This was, since then, confirmed for several RR Lyrae stars. In CoRoT ID

105288363, the result is the same and can be seen in Fig. 4. Note that due to the high precision of the satellite data, we are able to show not only the triplet components, but additionally also the amplitudes of the quintuplet components in this diagram. This has so far only been done for one star (the prototype RR Lyrae itself) using the data of the *Kepler* satellite (Kolenberg et al. 2010b). Their decrease is more or less linear and even less steep than that of the triplet components. This phenomenon also leads to the effect that at higher harmonic orders, the quintuplet components become the dominant feature after subtracting a fit with the triplet solution, while they are hardly discernible in the disturbing irregular peaks at lower orders. In order 1, the peaks associated with the quintuplet were not visible among the high and numerous other peaks, in orders 2 and 3 only one of the two components was detectable, but with a very low amplitude, in orders 4–6, both peaks are clearly present but not the highest feature, and from order 7 onwards, the quintuplet peaks became the dominant signal after subtracting the triplet fit. An example can be seen in the insets of Fig. 3 where the region around $4f_0$ is shown at different steps of pre-whitening. After removal of the triplet solution, the ‘forest’ of peaks caused by the non-repetitive nature of the Blazhko cycles is visible.

4.1.5 Separate analysis of the Blazhko cycles

As changes in the amplitudes, like they occur in CoRoT ID 105288363, as well as frequency changes, are known to cause unresolved peaks to appear in the frequency spectrum of the full data set, a classical Fourier analysis using the complete time-string at once is obviously not the best method. We therefore decided to

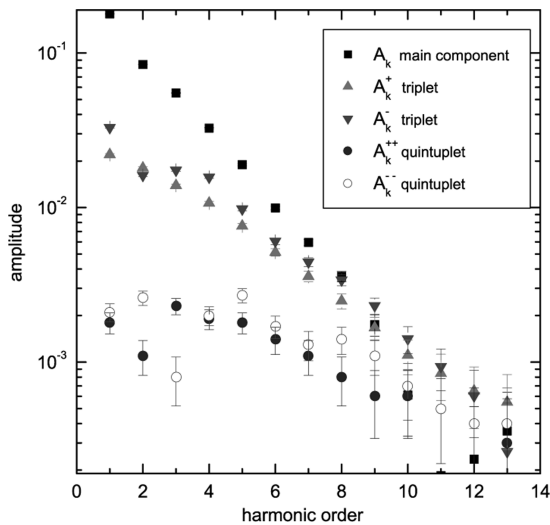


Figure 4. Amplitudes of the main pulsation component (squares), the triplet components (triangles) and the quintuplet components (circles) with increasing harmonic order. It is obvious that the amplitudes of the main pulsation components decrease exponentially, while the amplitudes of the triplet and quintuplet components show a less steep, more or less linear decrease. The error bars have been calculated using MC simulations and are smaller than the symbols.

perform a separate analysis of each Blazhko cycle to be able to study the properties of the classical Blazhko multiplets without the presence of dominant disturbing peaks. It was found in this analysis that the amplitudes of the main frequency and its harmonics hardly change from one cycle to the next (they remain within 2 per cent), while the amplitudes of the triplets and quintuplets change by up to 25 per cent. We also observed that, especially in the last Blazhko cycle, the amplitudes of the multiplet features decrease dramatically. The overall picture (i.e. whether the left-hand or the right-hand side peak is higher), on the other hand, remains constant over all the cycles. Also, higher order multiplet components could be detected in the analysis of the separate cycles while they were hidden under disturbing peaks when analysing the full data set. Depending on the cycle, most or even all septuplet peaks ($nf_0 \pm 3f_B$) up to order $n = 18$ were detectable as well as some or most nonuplet ($nf_0 \pm 4f_B$) and some undecaplet ($nf_0 \pm 5f_B$) peaks. Triplet and quintuplet peaks emerged clearer at low orders than they did in the full data set, and they were significant up to much higher orders.

The frequency analysis of the full data set was therefore only used to find a *mean* pulsation and Blazhko period for the data and to determine the overall properties of the modulation components.

4.1.6 Fourier parameters

Another approach to avoid the residual peaks caused by the changes in the modulation is to subdivide the light curve into small bins which are hardly affected by the Blazhko modulation and then calculate the amplitudes and phases of f_0 and its harmonics for each of them. This method is used to investigate the time-dependent behaviour of the star on a time-scale of a few days, reflected by the Fourier parameters.

We divided the data set into 73 bins of 2 d duration each (i.e. about 3.5 pulsation cycles), and calculated the Fourier parameters

The CoRoT star 105288363 1583

A_k and φ_k (with k denoting the harmonic order), as well as their amplitude ratios $R_{k1} = A_k/A_1$ and epoch-independent phase differences $\varphi_{k1} = \varphi_k - k\varphi_1$ in each bin. These Fourier parameters are useful in many aspects. First of all, they describe the shape of the light curve, which for RRab stars is known to change dramatically during the Blazhko cycle. Furthermore, they are a practical tool to compare the properties of synthetic light curves from hydrodynamical models to real data (e.g. Dorfi & Feuchtinger 1999; Smolec et al. 2011), and Kovacs & Zsoldos (1995) showed that – for non-modulated stars – it is possible to derive fundamental stellar parameters, like metallicity, from the Fourier parameters of RR Lyrae stars. Moreover, Jurcsik, Benkő & Szeidl (2002) used the Fourier parameters and their interrelations to test at which Blazhko phase, if at all, the light curves of Blazhko stars resemble those of non-modulated RR Lyrae stars. Also, in the case of a changing Blazhko effect like in CoRoT ID 105288363, they are useful to compare the different observed cycles in the context of the light-curve shape which is given by the parameters.

The Fourier parameters of CoRoT ID 105288363 are displayed in Fig. 5. Some interesting features can immediately be seen: while A_1 shows a definite decrease in its variation, indicating the weakening of the Blazhko effect during the duration of the observations, the variation in φ_1 is getting stronger and sometimes shows double maxima. The other phases also show distinct differences from one cycle to the next, with the fourth observed Blazhko cycle being very weak in all of them. The amplitude ratio R_{21} increases its variation, with flat maxima in the beginning of the observations and a sharper maximum in the last cycle, and also for the phase differences, none of the Blazhko cycles resembles the other ones exactly.

4.2 O–C diagrams

The O–C analysis is the most classical way to analyse RR Lyrae stars and has nowadays mostly been replaced by Fourier analysis as the preferred method of investigation. In the case of strong changes in the pulsation behaviour, however, when the Fourier spectrum shows a large number of unresolved peaks that hamper the analysis, an O–C diagram might still be a valuable tool to have a closer look at the Blazhko effect. As CoRoT provides continuous time-sampling and therefore complete light curves, it is possible to plot an O–C diagram not only for the times of maximum light, but also for the minima. As CoRoT ID 105288363 also shows dramatic changes in the light-curve shape, the O–C of minima might hold some additional information. The O–C values of both the maxima and minima are shown in Fig. 6. Additionally, the brightness values of the extrema are shown for comparison.

The first obvious observation is that O–C of maxima and minima shows diametrical behaviour, with the minima occurring latest when the maxima are earliest and vice versa. This reflects the fact that CoRoT ID 105288363 has a skewer light curve during the Blazhko maximum than during the Blazhko minimum. The next observation is that O–C of maxima shows an increase in amplitude from one cycle to the next, starting from a value of 0.011 d (i.e. about 16 min) peak-to-peak amplitude in the first observed cycle and then increasing to 0.016 and 0.021 and finally to 0.023 d (i.e. 33 min) in the fourth cycle, resulting in an increase to about twice the starting value. To obtain these values, five measured light maxima were averaged per Blazhko extremum to balance the scatter. We see definite strengthening of the Blazhko effect here. Compared to the brightness variations (see the left-hand panels of Fig. 6 and also the Fourier parameter A_1 in Fig. 5), this is paradoxical, as the brightness variation indicates weakening of the Blazhko effect of

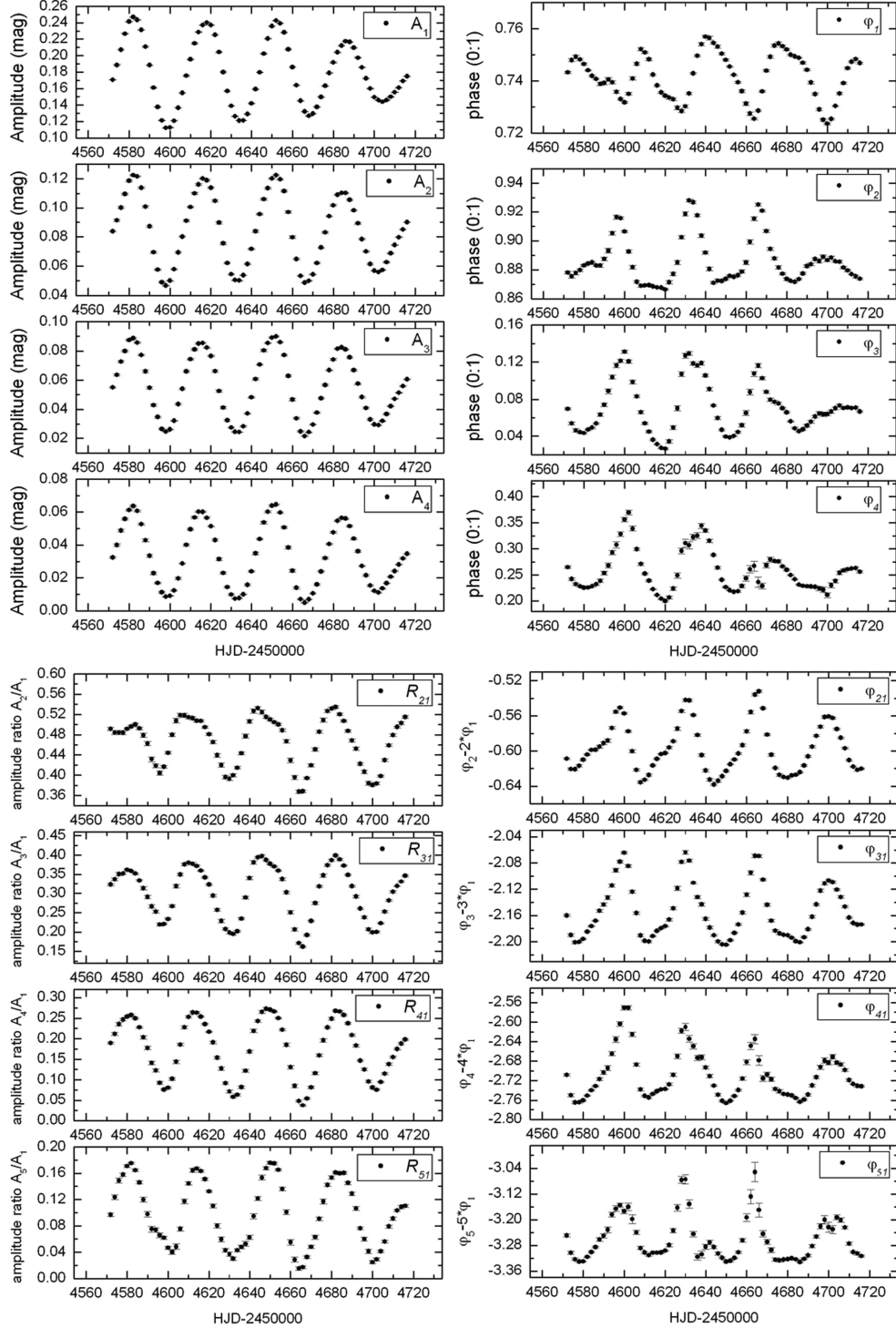
1584 *E. Guggenberger et al.*

Figure 5. Amplitudes, phases, amplitude ratios and phase differences for all 73 bins are shown. Note the error bars barely exceeding the symbol size.

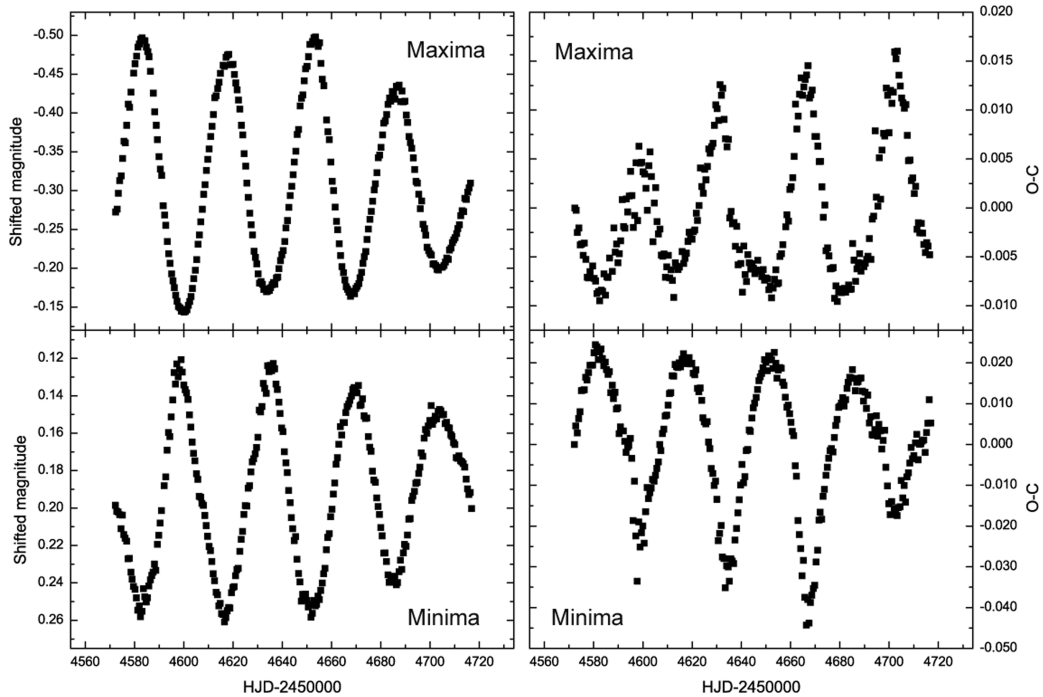


Figure 6. Magnitudes of maximum and minimum light (left-hand panels) and the O–C values of the maxima and minima, respectively (right-hand panels). The strong changes in the Blazhko modulation, both in brightness and O–C variations, are obvious.

CoRoT ID 105288363 with peak-to-peak amplitudes of the maxima (upper left-hand panel of Fig. 6) starting from 0.35 mag and dropping to 0.31, 0.32 and finally to 0.23 mag in the last cycle (with three observed light extrema averaged in each Blazhko extremum to compensate for scatter). This diametrical behaviour gives the impression that the energy of the Blazhko modulation might have gradually been converted from amplitude into frequency modulation.

The O–C diagram of minimum light offers another intriguing feature: during the first three cycles, the variation gets stronger like for the maxima, from a peak-to-peak amplitude of 0.050 d in the first to 0.051 in the second to 0.062 d in the third cycle, but the last Blazhko cycle shows only a very weak variation with an amplitude of only 0.035 d, indicating again that also the light-curve shape does not repeat exactly. Like it was noted in the Fourier phases φ_3 and φ_4 in Fig. 5, the fourth cycle seems to deviate strongly from the others. Table 3 lists the times of maximum light, their magnitude and their O–C values. The full table is available online only (see Supporting Information).

4.3 Loop diagrams

An important method of diagnosis for the Blazhko effect is the O–C versus brightness or, simply, ‘loop’ diagrams. They represent the contributions of the phase and amplitude modulations and the relation between the two. The results for CoRoT ID 105288363 are given in Fig. 7 for the four observed cycles separately for better visibility. In the upper left-hand panel, which shows the first cycle, the points lie almost on a single line which indicates that the amplitude and frequency modulations are taking place in phase, while

the bigger areas that are enclosed by the loops in the second and third cycles indicate that a large phase shift is present. The direction of motion through the diagram is given by the arrows. The fourth cycle appears more like the first one with only a small phase shift. An inspection of the scale of the axes reveals that not only does a phase shift occur and disappear again, but also the strength of the variations changes for both types of modulations, as we already noted in the previous section. A Blazhko cycle was, for the purpose of these plots, defined as from the beginning of the data set to the next time the same Blazhko phase is reached, resulting in four observed cycles. When using the definition that a Blazhko cycle starts at the Blazhko maximum, the shape of the loops would, of course, be different. However, the fact that the phasing of the amplitude and the phase modulations changes remains untouched.

4.4 Bump and hump features

RRab Lyrae stars are known to show a distinct brightness increase – the so-called bump – shortly before minimum light. Unlike in Cepheids, this bump does not show a progression with the pulsation period, but it has been noted that it changes its appearance with the Blazhko phase in modulated stars. The first detailed investigation on the bump behaviour during the Blazhko cycle has been published by Guggenberger & Kolenberg (2006) for the southern Blazhko star SS For, using an extended set of ground-based data. With the availability of satellite photometry and therefore uninterrupted observations, it became much easier to see how the bump moves back and forth during the Blazhko cycle. The phases of its maximum for all pulsation cycles observed in CoRoT ID 105288363 were calculated using the mean period given in Section 4.1 and are

Table 3. Observed maxima and minima of the pulsation of CoRoT ID 105288363. Columns are: epoch, time of maximum in HJD, relative magnitude, O–C (d), times of minimum, relative magnitude and O–C (d). The full table is available in the online version of the article only (see Supporting Information).

Epoch	Times of maximum	Magnitude	O–C (d)	Times of minimum	Magnitude	O–C (d)
0	4572.8037	−0.2726	0.0000	4572.7018	0.1985	0.0000
1	4573.3709	−0.2761	−0.0002	4573.2738	0.2017	0.0046
2	4573.9361	−0.2967	−0.0025	4573.8395	0.2020	0.0028
3	4574.5040	−0.3130	−0.0021	4574.4105	0.2035	0.0064
4	4575.0697	−0.3191	−0.0038	4574.9796	0.2110	0.0081
5	4575.6373	−0.3414	−0.0037	4575.5522	0.2038	0.0132
6	4576.2035	−0.3636	−0.0049	4576.1198	0.2141	0.0133
7	4576.7722	−0.3618	−0.0036	4576.6873	0.2161	0.0134
...	...	...	...	...	...	...

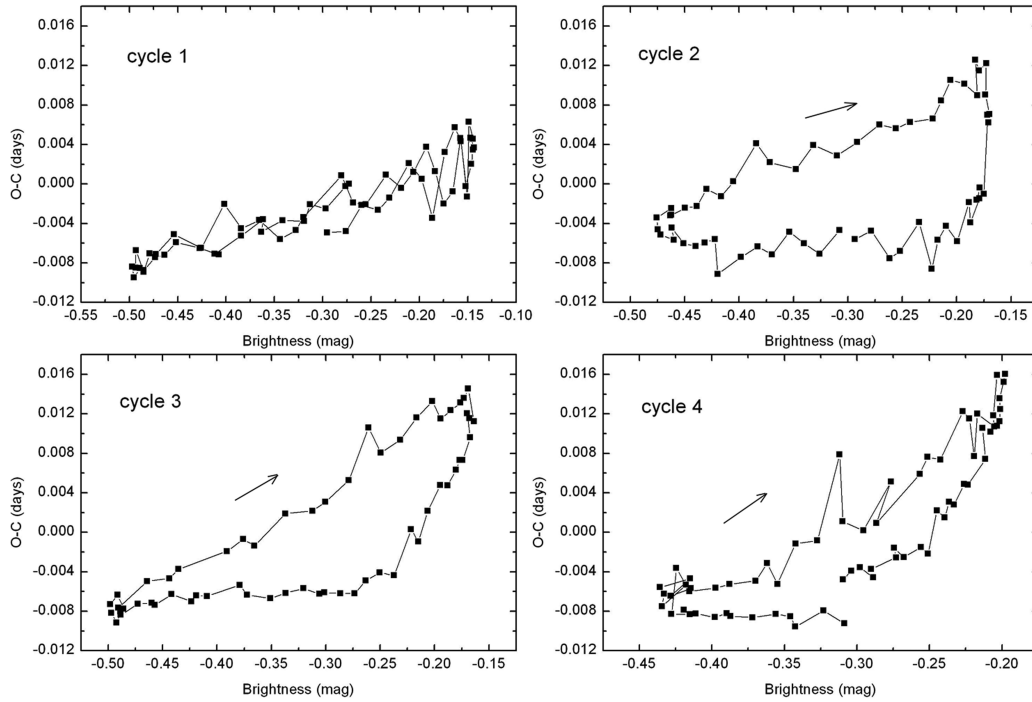


Figure 7. Magnitudes of light maximum versus O–C for the four observed Blazhko cycles.

plotted against time in Fig. 8. The bump occurs later (at a pulsation phase of about 0.72 when zero is set to maximum light) around the Blazhko maximum and significantly earlier (at $\phi = 0.56$) during the Blazhko minimum, with a rapid progression to higher phases which causes a very non-sinusoidal shape of the curve. To exclude the possibility that this effect is just a consequence of the phase modulation, that is, it is only caused by the light minima occurring sooner or later depending on the Blazhko phase; the position of the bump was also checked in relation to the adjacent light minimum. The results turned out to be comparable.

The other prominent feature that is often observed in RRab stars is the hump or still stand which occurs during the rising light shortly before maximum light. This feature, which is caused by the so-called main shock, was also investigated quantitatively, although it is not very pronounced in CoRoT ID 105288363 and only hardly discernible at some Blazhko phases. Four consecutive pulsation cycles

were combined to obtain a better coverage of the rising branch, and the phase value of the hump was determined by visual inspection. The result follows the same general course of variation as for the bump with later phases at the Blazhko maximum and earlier phases around the Blazhko minimum, although, of course, the variation is much smaller. This phase shift of the hump is certainly worth investigating in further studies.

5 DISCUSSIONS AND CONCLUSIONS

5.1 Changing Blazhko modulations

The fact that the Blazhko modulation in RR Lyrae stars can undergo changes of various types is not totally new. In the literature, several reports about phenomena like possible secondary cycles, ceasing and restarting Blazhko modulations, changing values of the

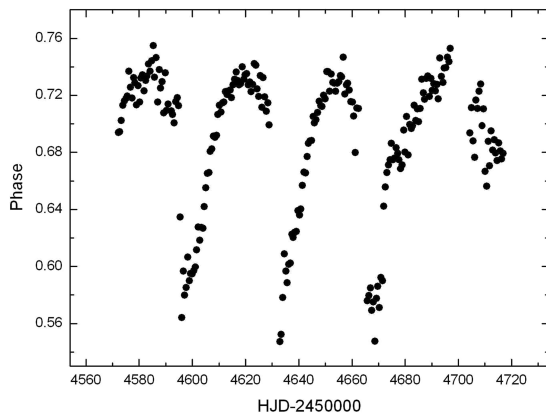


Figure 8. Phases of the bump feature.

Blazhko period, etc., can be found. The most prominent case certainly is the prototype RR Lyrae with its 4-yr cycle which affects the amplitude of the modulation. It was reported that the modulation was barely notable in 1963, 1967, 1971 and 1975 (Szeidl 1976), the years which obviously correspond to the minima of the secondary cycle. However, not only those changes in the amplitude of the modulation are known, but also variations of the Blazhko period have been reported. Based on data from the years 2003 and 2004, Kolenberg et al. (2006) find a Blazhko period for RR Lyrae that is notably shorter than previous values in the literature (38.8 d instead of 40.8 d), while the fundamental period remained roughly the same. It is not known when exactly the change took place.

Probably the oldest report about a changing Blazhko effect is the investigation of RW Dra by Balazs (1957). The author reports that in 1938, the amplitude of the variation in the O–C diagram caused by the Blazhko effect of RW Dra dropped to about half the value that was measured 3 months earlier (about 1 h instead of 2 h 17 m). This reminds us of Section 4.2 where we observed the opposite case for CoRoT ID 105288363: an increase to twice the starting value (33 min instead of 16 min). At the same time, they found that the amplitude modulation of RW Dra got dramatically weaker.

Another well-studied example is XZ Cyg. La Cluyzé et al. (2004) report that the Blazhko period of XZ Cyg has changed on a time-scale of decades and that these changes are anticorrelated with observed changes of the pulsation period. While in the first half of the 20th century (Blazhko 1922), the star was known to have a Blazhko period of 57.4 d, it increased to 58.5 d in the 1960s, while the pulsation period underwent a steep decline in several steps. There was an interval when the Blazhko modulation disappeared for a while, an additional modulation period of 41.6 d was reported to occur at the times when the period of the main modulation was low, and the presence of an overlying long modulation period of almost 10 yr was also suspected.

The only Blazhko star for which it was possible to unambiguously detect the two modulation frequencies that cause the complex multiperiodic modulation behaviour is CZ Lac (Sódor 2009; Sódor, Jurcsik & Szeidl 2010). The two periods have similar amplitudes, so that there is no dominant one, and a strong beating is the result. The periodic decrease in the modulation therefore resembles the cessation of the Blazhko effect in RR Lyrae, and the authors suggest that the cause of the 4-yr cycle of RR Lyrae might be the same as in CZ Lac, which would also explain why different Blazhko periods in the range 38.8–40.8 d have been reported.

Another one of the few stars which have observations available over a sufficiently long time-span to investigate the long-term changes of the modulation properties is RV UMa. It was known to show a regular large-amplitude modulation, but based on 90 yr of observation, Hurta et al. (2008) could find period changes in both the pulsation and modulation periods. The range of detected modulation periods was from 89.9 to 90.6 d. An anticorrelation of the changes of the two periods was reported with the relation $dP_{\text{BI}}/dP_0 = -8.6 \times 10^4$. This relation, however, does not seem to be very strict, as also an episode of parallel behaviour was observed. No change in the modulation amplitude has been reported.

An anticorrelation of the changing Blazhko and pulsation periods has also been reported for DM Cyg (Jurcsik et al. 2009b), with a value of $dP_{\text{BI}}/dP_0 = -1.32 \times 10^4$, based on almost 100 yr of observations, while a parallel behaviour of the two periods was found in XZ Dra (Jurcsik et al. 2002) with $dP_{\text{BI}}/dP_0 = 7.7 \times 10^4$. Again, no change in the modulation amplitude has been found. An example of a different type of change is the star RR Gem (Sódor, Szeidl & Jurcsik 2007), with both the amplitude and the period of the modulation undergoing changes. The modulation amplitude showed variations from the undetectable level (less than 0.04 mag) to about 0.2 mag, while parallel changes in P_{BI} and P_0 were found with $dP_{\text{BI}}/dP_0 = 1.6 \times 10^3$. Both steady and abrupt pulsation period changes were observed, as well as times when the period remained constant.

Recently, Jurcsik et al. (2011) investigated the RR Lyrae variables in the globular cluster M 5 and listed six Blazhko stars for which a change in the modulation period could be determined. Besides this, they also report that in the star V18, the light curve significantly changes from one season to the next, while the random period changes if the pulsation periods are detected. They state that in this case *the Blazhko effect manifests itself in strong, random, abrupt changes of the light curves, lacking any clear periodic behaviour*. A stochastic and/or chaotic behaviour was also suggested for the star MW Lyrae (Jurcsik et al. 2008), a star that, in principle, shows a high degree of regularity in its modulation, but nevertheless reveals significant and non-periodic deviations in the residual light curve. A complex behaviour of the modulation was also suspected by Sódor, Vida & Jurcsik (2006) for UZ UMa because of the unexpected high residuals which still remained even after a fit with two modulation periods was subtracted.

As we can see, there are reports about changes in both the amplitude of the Blazhko phenomenon and its period, but the investigations usually suffer from the gaps of ground-based data, larger scatter and from the incomplete coverage of the Blazhko cycle. In the homogeneous, uninterrupted and precise data delivered by the CoRoT satellite, we can, for the first time, perform a detailed study of the changes of the Blazhko modulation. Up to now, in most cases, it was unclear when exactly the changes happened or whether they took place abruptly or continuously, while in CoRoT ID 105288363 we can watch the details of variation taking place.

For CoRoT ID 105288363, an explanation involving two modulation periods that lead to a beating which strengthens and weakens the cycle as in CZ Lac (and maybe RR Lyrae itself) can be ruled out, as two modulation periods cannot describe the observed light variation. The variation in the Blazhko effect of CoRoT ID 105288363 seems to be of a complex, chaotic nature, like it was proposed for V18 in M 5, especially considering the fact that the O–C amplitude increases while the brightness modulation decreases (see Section 4.2), which is hard to describe with a combination of modulation frequencies.

1588 *E. Guggenberger et al.*

Models which connect the Blazhko effect to rotation and therefore predict clock-work-like behaviour face significant problems after the detection of the strong cycle-to-cycle variations in the Blazhko effect of CoRoT ID 105288363. The most promising approaches from the theoretical side are certainly the scenario proposed by Stothers (2006, 2010), as well as the 9:2 resonance with chaos occurring due to the presence of a strange attractor (Buchler & Kolláth 2011). The 9:2 resonance can yield the period doubling in some stars or some during specific Blazhko phases, but it seems to be unlikely that it is the sole explanation of the Blazhko effect.

On the other hand, the convective cycles proposed in the Stothers models are capable of producing irregular Blazhko cycles. If the light variability of RR Lyrae stars is as complicated as the complex behaviour exhibited by CoRoT ID 105288363 seems to suggest, then both phenomena could coexist. We also note that the Stothers model was critically investigated by Smolec et al. (2011) who concluded that a huge modulation of the mixing length was required to reproduce the amplitude changes in RR Lyrae.

In this context, it is relevant to note that the high-amplitude δ Scuti star CoRoT ID 101155310 shows small but very clear modulation of the fundamental radial mode (Poretti et al. 2011). Though it is still unclear if this is due to the star's rotation or an analogue of the Blazhko effect, the thin convective layer predicted by the physical model of CoRoT ID 101155310 is an intriguing similarity between RR Lyrae and high-amplitude δ Scuti stars.

5.2 Variations in the bump feature

Spectroscopically, signatures of emission have been detected during the bump phase (Gillet & Crowe 1988), strengthening the generally accepted explanation that the bump is caused by a shock wave (Hill 1972) that propagates through the atmosphere, resulting from a collision of layers in the deep atmosphere. A change in the mean radius of the star, as it has recently been reported by Jurcsik et al. (2009a) for the Blazhko star MW Lyrae, could explain different phases of the bump as the runtime of the shock wave through the atmosphere changes and the photosphere is therefore reached earlier or later. A displacement of the region of shock formation during the Blazhko cycle, like it was proposed by Preston, Smak & Paczynski (1965), would also offer an explanation for the changing bump phases.

5.3 Phasing of the modulation

The dramatic change not only in the strength but also in the appearance of the Blazhko effect certainly provides strong constraints for the models, as an explanation for the Blazhko effect would need to be able to account for strong changes in the phasing of the two types of modulations (amplitude as well as phase modulations) which can be present in a Blazhko star. As we have shown in Section 4.2, the phase variation is getting stronger in CoRoT ID 105288363, while at the same time the amplitude modulation is getting weaker. Also, we have seen in Section 4.3 that suddenly a phase shift between the two types of modulations appears and ceases again. Never before have such drastic changes in the Blazhko behaviour of an RR Lyrae star been documented. It is certainly a big challenge for the models to reproduce these phenomena.

5.4 Additional modes

The excitation of additional modes is an open issue in modelling the pulsation of RR Lyrae stars. Two frequencies not related to the

Blazhko modulation were convincingly found in the case of CoRoT ID 101128793 (Poretti et al. 2010). One of them is perhaps related to the period-doubling bifurcation, while the other supplies the ratio 0.582 with the main pulsation frequency (i.e. $2.119/3.630 = 0.582$). Moreover, the same authors found similar ratios when rediscussing the cases of V1127 Aql (Chadid et al. 2010) and MW Lyrae (Jurcsik et al. 2008), that is, $2.8090/4.8254 = 0.582$ and $2.5146/4.2738 = 0.588$, respectively.

In the case of CoRoT ID 105288363, we found a possible additional mode only, that is, 2.984 d^{-1} . The ratio $1.762/2.984 = 0.591$ is very similar to those reported above and this strengthens our confidence on the reliability of the detection of such small amplitude f_1 term. The identification of the additional mode as the second radial overtone, as in the case of CoRoT ID 101128793, is still the most plausible explanation.

A few similar stars in which frequencies close to the expected value of the overtones appear were also found in the sample of RR Lyrae stars observed by the *Kepler* satellite (Benkő et al. 2010).

ACKNOWLEDGMENTS

This research has made use of the ExoDat data base, operated at LAM-OAMP, Marseille, France, on behalf of the *CoRoT/Exoplanet* programme. KK and EG acknowledge support from the Austrian Fonds zur Förderung der wissenschaftlichen Forschung (FWF), project numbers T359-N16 and P19962-N16. EP acknowledges support from the PRIN-INAF 2010 'Asteroseismology: looking inside the stars'. MP, JMB and RS acknowledge the support of the ESA PECS projects Nos. 98022 and 98114. RS and JMB are supported by the Hungarian OTKA grant K83790.

REFERENCES

- Alcock C. et al., 2003, *ApJ*, 598, 597
- Auvergne M. et al., 2009, *A&A*, 506, 411
- Balazs J., 1957, *Commun. Konkoly Obs.*, 42, 99
- Benkő J. M., Paparó M., Szabó R., Chadid M., Kolenberg K., Poretti E., 2009, in Guzik J. A., Bradley P. A., eds, *AIP Conf. Proc. Vol. 1170, Stellar Pulsation: Challenges for Theory and Observation*. Am. Inst. Phys., New York, p. 273
- Benkő J. M. et al., 2010, *MNRAS*, 409, 1585
- Blazhko S., 1922, *Astron. Nachr.*, 216, 103
- Breger M., Kolenberg K., 2006, *A&A*, 460, 167
- Buchler R., Kolláth Z., 2011, *ApJ*, 731, 24
- Chadid M., Wade G. A., Shorlin S. L. S., Landstreet J. D., 2004, *A&A*, 413, 1087
- Chadid M. et al., 2010, *A&A*, 510, 39
- Chadid M., Perini C., Bono G., Auvergne M., Buglin A., Weiss W. W., Debosscher J., 2011, *A&A*, 527, 146
- Debosscher J. et al., 2009, *A&A*, 506, 519
- Deleuil M. et al., 2009, *AJ*, 138, 649
- Dorfi E., Feuchtinger M. U., 1999, *A&A*, 348, 815
- Dziembowski W., Mizerski T., 2004, *Acta Astron.*, 54, 363
- Gillet D., Crowe R. A., 1988, *A&A*, 199, 242
- Guggenberger E., Kolenberg K., 2006, *Commun. Asteroseismol.*, 148, 21
- Guggenberger E., Kolenberg K., Marsden S. C., Waite I. A., Henrichs H. F., Löffinger T., 2009, in Guzik J. A., Bradley P. A., eds, *AIP Conf. Proc.*, 1170, *Stellar Pulsation: Challenges for Theory and Observation*. Am. Inst. Phys., New York, p. 278
- Hill S. J., 1972, *ApJ*, 178, 793
- Hurta Zs., Jurcsik J., Szeidl B., Sódor A., 2008, *AJ*, 135, 957
- Jurcsik J., Benkő J. M., Szeidl B., 2002, *A&A*, 390, 133
- Jurcsik J. et al., 2005, *A&A*, 430, 1049
- Jurcsik J. et al., 2008, *MNRAS*, 391, 164
- Jurcsik J. et al., 2009a, *MNRAS*, 393, 1553

- Jurcsik J. et al., 2009b, MNRAS, 397, 350
 Jurcsik J. et al., 2009c, MNRAS, 400, 1006
 Jurcsik J., Szeidl B., Clement C., Hurta Zs., Lovas M., 2011, MNRAS, 411, 1763
 Kolenberg K., Bagnulo S., 2009, A&A, 498, 543
 Kolenberg K. et al., 2006, A&A, 459, 577
 Kolenberg K. et al., 2009, MNRAS, 396, 263
 Kolenberg K. et al., 2010a, ApJ, 713, 198
 Kolenberg K. et al., 2010b, MNRAS, 411, 878
 Kolláth Z., Molnár L., Szabó R., 2011, MNRAS, doi:10.1111/j.1365-2966.2011.18451.x
 Kovacs G., Zsoldos E., 1995, A&A, 293, 57
 LaCluyze A. et al., 2004, AJ, 127, 1653
 Le Borgne J. F. et al., 2007, A&A, 476, 307
 Lenz P., Breger M., 2005, Commun. Asteroseismol., 146, 53
 Loumos G., Deeming T., 1978, Ap&SS, 56, 285
 Poretti E. et al., 2010, A&A, 520, A108
 Poretti E. et al., 2011, A&A, 528, A147
 Preston G. W., Smak J., Paczynski B., 1965, ApJS, 12, 99
 Schnerr R. S. et al., 2008, A&A, 483, 857
 Shibahashi H., 2000, in Szabados L., Kurtz D., eds, ASP Conf. Ser. Vol. 203, The Impact of Large-Scale Surveys on Pulsating Star Research. Astron. Soc. Pac., San Francisco, p. 299
 Smolec R., Moskalik P., Kolenberg K., Bryson S., Cote M. T., Morris R. L., 2011, MNRAS, doi:10.1111/j.1365-2966.2011.18592.x
 Sódor A., 2009, Commun. Asteroseismol., 159, 55
 Sódor A., Vida K., Jurcsik J., 2006, Inf. Bull. Var. Stars, 5705, 1S
 Sódor A., Szeidl B., Jurcsik J., 2007, A&A, 469, 1033
 Sódor A., Jurcsik J., Szeidl B., 2010, MNRAS, 411, 1585
 Stothers R. B., 2006, ApJ, 652, 643
 Stothers R. B., 2010, PASP, 122, 536
 Szabó R., Kolláth Z., Molnár L., 2010, MNRAS, 409, 1244
 Szeidl B., 1976, in Fitch W. S., ed., Proc. IAU Colloq. 29, Multiple Periodic Variable Stars. D. Reidel, Dordrecht, p. 133
 Szeidl B., Jurcsik J., 2009, Commun. Asteroseismol., 160, 17
 Vaniček P., 1971, Ap&SS, 12, 10

APPENDIX A: COMPARISON WITH THE RESULTS OF CHADID ET AL. ON CoRoT ID 105288363

After finishing the final draft of this manuscript, we found out that Chadid et al. (2011) had just published the results of their analysis of the same public data set of CoRoT ID 105288363. While in some points, our results are in agreement with theirs, there are also some aspects which differ. Those aspects refer to the following items, discussed in a detailed way in the text.

A1 Conclusions for models

Chadid et al. (2011) state that the behaviour of CoRoT ID 105288363 is a strong support for the scenario described by Stothers (2006). We note, however, that a varying magnetic field modulating the convection is still an unproven hypothesis and that there is currently no model that can quantitatively describe the interaction between such a field and the turbulent convection.

Buchler & Kolláth (2011) use the amplitude equation formalism to study the interaction between the fundamental mode and the ninth overtone in a 9:2 resonance and find stochastic, chaotic behaviour. The low amplitudes of possible excited overtones and the fact that period doubling is not observed in all Blazhko stars, however, seem

to make the 9:2 resonance as the sole cause for the Blazhko effect unlikely. On the other hand, the resonance that was found in the simulations of Szabó et al. (2010) and Buchler & Kolláth (2011) was startlingly strong, and considering the fact that period doubling is a temporary phenomenon which is present only during certain phases, one might expect that the occurrence rate increases when more continuous and accurate satellite data become available.

It is, of course, possible that the two effects, the variable turbulent convection and the 9:2 resonance, coexist to explain the various observed phenomena. The observed behaviour of CoRoT ID 105288363 certainly poses a significant problem to all models which require a clock-work-like behaviour and favours explanations that are capable of producing irregular modulation.

A2 Long-term modulation

Chadid et al. (2011) report a long-term modulation period of 151 ± 7 d. We note that the detection of periods exceeding the time-base of the available data (145 d) has to be taken with great caution. Frequencies which are separated by a value of $\nu_1 - \nu_2 < 1/\Delta T$, with ΔT being the time-base of the data, are usually considered unresolved (Loumos & Deeming 1978). Also, it is well known that artefacts of the Fourier analysis might appear as peaks close to the exact value of $1/\Delta T$. Even though it might be possible under ideal circumstances to predict a long-term behaviour from a short data set, we do not think this is the case for CoRoT ID 105288363. Considering the irregular nature of its modulation which can be seen in both the Fourier parameter variation and the O–C variation, it is unlikely that a correct prediction of only partially observed long-term modulations is possible. The light curve shown in Fig. 1, top panel, the behaviour of the Fourier parameters in Fig. 5 and the changing shape of the Blazhko cycles in Fig. 7 suggest that a long-term modulation, if periodic, should have a time-scale much longer than the time-baseline.

A3 Additional mode

We find in our analysis an additional, independent mode which was not found by Chadid et al. (2011). The excitation of additional modes is a new observational result obtained from the careful analysis of *CoRoT* and *Kepler* time-series. The recurrence of the same ratio between additional modes and the main pulsational mode is also discussed in our paper.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 3. Observed maxima and minima of the pulsation of CoRoT ID 105288363.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.

3.2 Kepler photometry of V445 Lyrae

This section consists of the publication:

- **Guggenberger, E.**; Kolenberg, K.; Nemec, J. M.; Smolec, R.; Benkő, J. M.; Ngeow, C.-C.; Cohen, J. G.; Sesar, B.; Szabó, R.; Catelan, M.; Moskalik, P.; Kinemuchi, K.; Seader, S. E.; Smith, J. C.; Tenenbaum, P.; Kjeldsen, H.: *The complex case of V445 Lyr observed with Kepler: two Blazhko modulations, a non-radial mode, possible triple mode RR Lyrae pulsation, and more*, published in the Monthly Notices of the Royal Astronomical Society, 424, 649 (2012)

The contribution of the author of the thesis to the paper was the following:

- prepared the space data for analysis by removing instrumental effects
- performed all analyses on the space data, except the linear models used in Section 4.1.5 which were calculated by R. Smolec and except the analytic modulation analysis in Section 4.4 which was done by J. Benkő.
- wrote the paper (except Section 4.4 which was written by J. Benkő).



The complex case of V445 Lyr observed with *Kepler*: two Blazhko modulations, a non-radial mode, possible triple mode RR Lyrae pulsation, and more

E. Guggenberger,^{1*} K. Kolenberg,^{2,3} J. M. Nemec,⁴ R. Smolec,^{1,5} J. M. Benkő,⁶ C.-C. Ngeow,⁷ J. G. Cohen,⁸ B. Sesar,⁸ R. Szabó,⁶ M. Catelan,⁹ P. Moskalik,⁵ K. Kinemuchi,¹⁰ S. E. Seader,¹¹ J. C. Smith,¹¹ P. Tenenbaum¹¹ and H. Kjeldsen¹²

¹Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, A-1180 Vienna, Austria

²Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

³Instituut voor Sterrenkunde, Celestijnenlaan 200D, B-3001 Leuven, Belgium

⁴Department of Physics & Astronomy, Camosun College, Victoria, British Columbia V8P 5J2, Canada

⁵Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warszawa, Poland

⁶Konkoly Observatory, Research Center for Astronomy and Earth Sciences, PO Box 67, H-1525 Budapest, Hungary

⁷Graduate Institute of Astronomy, National Central University, Jhongli City, Taoyuan County 32001, Taiwan

⁸California Institute of Technology, Mail Stop 249-17, 1200 East California Boulevard, Pasadena, CA 91125, USA

⁹Departamento de Astronomía y Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile

¹⁰NASA Ames Research Center/Bay Area Environmental Research Institute, Mail Stop 244-30, Moffett Field, CA 94035, USA

¹¹SETI Institute/NASA Ames Research Center, Moffett Field, CA 94035, USA

¹²Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

Accepted 2012 May 4. Received 2012 April 30; in original form 2012 February 23

ABSTRACT

Rapid and strong changes in the Blazhko modulation of RR Lyrae stars, as have recently been detected in high-precision satellite data, have become a crucial topic in finding an explanation of the long-standing mystery of the Blazhko effect. We present here an analysis of the most extreme case detected so far, the RRab star V445 Lyr (KIC 6186029) which was observed with the *Kepler* space mission. V445 Lyr shows very strong cycle-to-cycle changes in its Blazhko modulation, which are caused by both a secondary long-term modulation period and irregular variations. In addition to the complex Blazhko modulation, V445 Lyr also shows a rich spectrum of additional peaks in the frequency range between the fundamental pulsation and the first harmonic. Among those peaks, the second radial overtone could be identified, which, combined with a metallicity estimate of $[\text{Fe}/\text{H}] = -2.0$ dex from spectroscopy, allowed us to constrain the mass ($0.55\text{--}0.65 M_{\odot}$) and luminosity ($40\text{--}50 L_{\odot}$) of V445 Lyr through theoretical Petersen diagrams. A non-radial mode and possibly the first overtone are also excited. Furthermore, V445 Lyr shows signs of the period-doubling phenomenon and a long-term period change. A detailed Fourier analysis along with a study of the O – C variation of V445 Lyr is presented, and the origin of the additional peaks and possible causes of the changes in the Blazhko modulation are discussed. The results are then put into context with those of the only other star with a variable Blazhko effect for which a long enough set of high-precision continuous satellite data has been published so far, the *CoRoT* star 105288363.

Key words: asteroseismology – methods: data analysis – techniques: photometric – stars: individual: KIC 6186029 (V445 Lyr) – stars: individual: CoRoT 105288363 – stars: variables: RR Lyrae.

1 INTRODUCTION

RR Lyrae stars, which are low-mass helium-burning stars on the horizontal branch, were long thought to be rather simple radial pulsators. They follow a period–luminosity–colour relation which makes them valuable distance indicators, and because of their age

*E-mail: elisabeth.guggenberger@univie.ac.at

650 *E. Guggenberger et al.*

and evolutionary status, they are also used to study the formation and evolution of the Galaxy (Catelan 2009). They can oscillate in the fundamental radial mode (type RRab), the first overtone (type RRe) or both modes simultaneously (type RRd), and their high amplitudes of up to 1.5 mag in *V* for RRab type stars made their variability easy to discover, so they have been known since the end of the 19th century.

Already more than a hundred years ago, however, it turned out that there is an aspect to RR Lyrae stars which is not understood at all: Blazhko (1907) found a ‘periodic change in the period’ of RW Dra, which he could not explain, and which still remains unexplained today. Shapley (1916) later found in his observations of RR Lyrae that the brightness of the maxima and the light-curve shape also show periodic changes. With increasing data quality in the recent past, the unsolved problem got even more severe, as it turned out that not just a rather small fraction of exceptional RR Lyrae stars were affected, but probably around 40–50 per cent of all RRab stars (Jurcsik et al. 2009; Benkő et al. 2010; Kolenberg et al. 2010). Also among RRe type stars, amplitude and phase modulation was found to be surprisingly widespread (Arellano Ferro et al. 2012).

This so-called Blazhko effect was long thought to be a periodic/regular phenomenon. Traditionally, only one Blazhko period was assigned to each modulated star, and the phenomenon was expected to repeat in every Blazhko cycle, agreeing with the widely used definition that ‘the Blazhko effect is a periodic amplitude and/or phase modulation with a period of several tens to hundreds of pulsation periods’. There were several reports about changes in the Blazhko modulation of various stars (see section 5 of Guggenberger et al. 2011 for a recent summary), but those reports usually had to rely on sparse data with large gaps, so that it was impossible to say when exactly a change took place and whether it happened continuously or abruptly. The Blazhko effect was therefore still considered to be a strictly repetitive phenomenon with only some rare exceptions showing secondary modulation periods (e.g. CZ Lac; Sódor et al. 2011) or changes on very long time-scales. It was not until the availability of ultraprecise data from space missions like *CoRoT* that strong and irregular cycle-to-cycle changes of a Blazhko star were documented and that it became obvious that seemingly chaotic phenomena need to be accounted for when modelling the Blazhko effect.

While the detection of cycle-to-cycle changes in the Blazhko modulation posed a significant challenge for all classical models that required a clock-work-like behaviour, some new ideas were published. Stothers (2006) suggested that transient small-scale magnetic fields modulate the turbulent convection inside the helium and hydrogen ionization zones, a mechanism which certainly could explain subsequent Blazhko cycles of different strengths. This scenario, however, was recently tested on the basis of hydrodynamical models by Smolec et al. (2011) who found that it was not possible to reproduce all observed properties of the light curve, even when allowing a huge modulation of the mixing length. On the other hand, Buchler & Kolláth (2011) successfully modelled both regular and irregular modulations by using the amplitude equation formalism. In their models, a strange attractor in the dynamics causes chaotic behaviour. The 9:2 resonance between the fundamental mode and the ninth overtone that was found by Kolláth, Molnár & Szabó (2011) to be the reason for the recently discovered phenomenon of period doubling (Szabó et al. 2010) seems to play an important role in causing a Blazhko modulation.

We present here a study of the most extreme case detected so far: V445 Lyr (KIC 6186029). This RRab star not only shows the strongest cycle-to-cycle change found up to now, but also shows

a rich spectrum of additional modes in the region between 2 and 4 d⁻¹. Both Fourier and O – C analyses are used to investigate the variability of the pulsation and the modulation (Section 4), and the results are compared to the case of CoRoT 105288363 in Section 6. Spectroscopy and theoretical Petersen diagrams are used to determine the fundamental parameters such as metallicity, luminosity and mass (Section 5). Additionally, the new *analytic modulation approach* for data analysis recently proposed by Benkő, Szabó & Paparó (2011) is applied to the data in Section 4.4.

2 BACKGROUND INFORMATION ON V445 LYR

V445 Lyr, with the coordinates RA 18^h58^m26^s and Dec. 41°35′49″ (J2000), is also known as KIC 6186029, or GR244, and has a *Kepler* magnitude of *Kp* = 17.4. Two publications from the pre-*Kepler* era exist for this target: Romano (1972) found it to be variable and classified it as an RR Lyrae, and Kukarkin et al. (1973) included it into his name list of variable stars. Romano (1972) also lists the photographic brightnesses of maximum and minimum to be 15.3 and 17.3 mag, respectively, indicating a surprisingly large amplitude of 2 mag, which is much higher than the amplitude observed even during extreme Blazhko maxima in the modern data. This might at least partly be explained, however, by the difference between the observed bandpasses. Unfortunately, no details of the observations and no light curves are given, and the forthcoming paper that was announced by the author could not be found. We therefore cannot know if the observed amplitude of 2 mag is real or it is possibly due to some observational errors. No error estimations of the observations were given by Romano (1972).

Since *Kepler* data have become available, two more publications have dealt with V445 Lyr, both presenting the *Kepler* data up to Q2: Szabó et al. (2010) listed V445 Lyr as a possible candidate for the period-doubling phenomenon, and Benkő et al. (2010) already noted changes in the Blazhko modulation of V445 Lyr and reported the presence of radial overtones.

3 KEPLER PHOTOMETRY

The *Kepler* space mission was launched on 2009 March 6 into an Earth-trailing heliocentric orbit (Koch et al. 2010). Its primary purpose is the detection of Earth-sized planets in the habitable zone of solar-like stars through the transit method, which requires continuous and ultraprecise photometry of over 150 000 stars for at least 3.5 years. This is also the duration of the primary mission. *Kepler* therefore not only provides the longest continuous data sets ever observed for RR Lyrae stars, but also does so with the highest photometric precision ever obtained, as a consequence greatly improving our knowledge about stellar pulsations.

The *Kepler* spacecraft carries a Schmidt telescope with an aperture of 0.95 m and 42 science CCDs which cover a field of view of about 115 deg² (Jenkins et al. 2010). The photometric bandpass ranges from 423 to 897 nm, thus avoiding the Ca II H&K lines in the blue, and fringing due to internal reflection in the red. The *Kepler* band is therefore slightly broader than a combination of Johnson *V* and *R*, and *Kepler* magnitudes are usually about 0.1 mag from *R* for most of the stars (Koch et al. 2010).

Every quarter orbit, the spacecraft is rotated in order to keep the solar panels oriented towards the Sun, and the radiator that cools the focal plane towards deep space (Haas et al. 2010). Data from different quarters are denominated Q1, Q2, etc. Each of the quarters which is used here has a time base of about 90 d, except Q1 which covers about 33 d.

Each measurement is based on a 6.02 s exposure plus a 0.52 s readout time. To obtain long cadence (LC) data (29.4 min), 270 measurements are co-added; for short cadence (SC) data (1 min) nine exposures are co-added (Christiansen et al. 2011).

The time of each measurement is given in truncated Barycentric Julian Date (HJD – 240 0000), and refers to the mid-point of the measurement.

3.1 The V445 Lyr data set

Fig. 1 illustrates the data obtained for V445 Lyr. In this paper, we present LC data obtained in quarters 1–7, with a total time base of 588 d. Because of the loss of module 3, which happened in 2010 January, there are no data available for this target in Q5. Some smaller gaps are also present in the data as can be seen in Fig. 1. Some of them are due to unplanned safe mode events or loss of fine point control, others are caused by the regular downlinks where the spacecraft’s antenna is pointed towards Earth for data transmission, and science data collection is interrupted.

Kepler provides light curves in two different formats: raw flux or corrected flux. The latter has been processed for planet transit search by the Pre-search Data Conditioning (PDC) pipeline which is sometimes known to remove astrophysical features and which does not preserve all stellar variability. Hence here, and for the study of variable stars in general, we make use only of the raw time series.

As the spacecraft is rotated every quarter orbit, the target falls on different CCDs after each ‘roll’, resulting in differences in average flux due to different sensitivity levels. Additionally, trends might

occur due to image motion on the CCD or sensitivity changes. The scaling and detrending which has to be performed before starting the analysis is a delicate task especially for targets like RR Lyrae stars which have high amplitudes, long periods and changes in the amplitudes [see Celik et al. (2012) for a detailed discussion]. Here, we removed linear trends which were determined from a running average separately for every quarter, and scaled every quarter to the same mean brightness. The continuity of the upper and lower envelope of the light curve was a good indicator of correct scaling. Note that due to the gap during Q5, the continuity could not be checked there. For this reason, the scaling of the data obtained after the gap might not exactly be consistent with the scaling applied before Q5.

The scaled and detrended data that were used in this analysis are available as online material in the format displayed in Table 1 (see Supporting Information).

Fig. 1(a) shows the complete combined data set of V445 Lyr. A total of 5.5 and 3.5 Blazhko cycles were observed before and after the large gap, respectively, and 900 pulsation cycles were observed. From panel (a) it is obvious that the Blazhko effect shows strong and fast changes, with almost all observed cycles having a different appearance. Panel (b) compares in a phase diagram directly a light curve from a Blazhko maximum with one obtained during the subsequent Blazhko minimum, illustrating the extremely low pulsation amplitude that occurs during some, but not all, modulation minima. Note that due to the very small amplitude and the distorted light curve showing a double maximum (see also Fig. 1d) it would not be possible to recognize the RR Lyrae nature of this star when

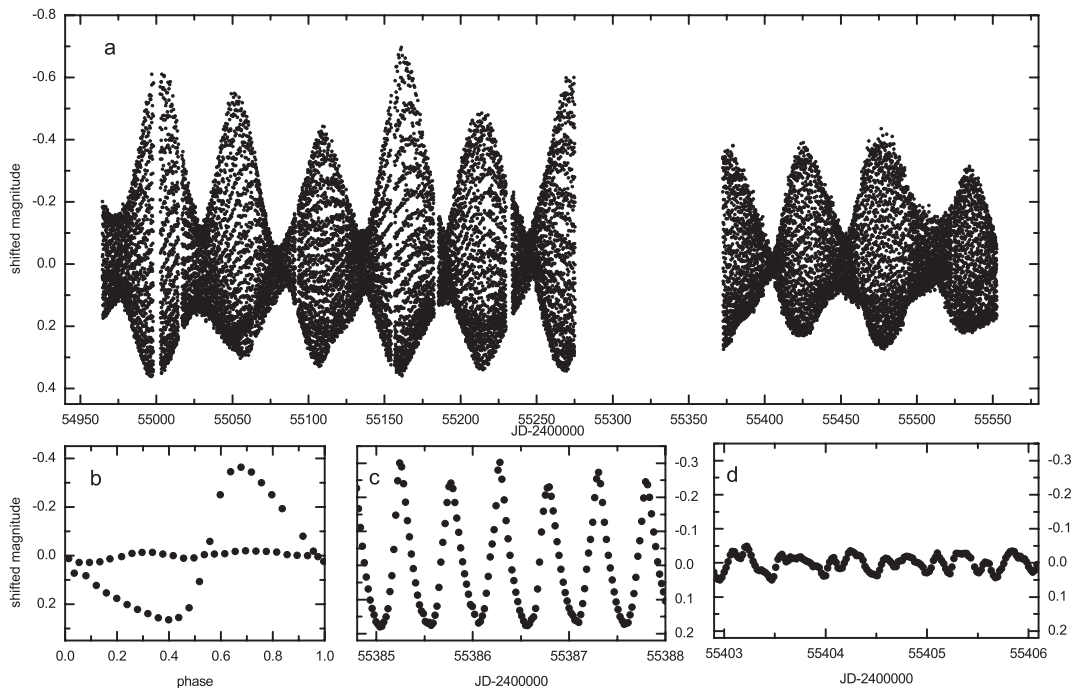


Figure 1. Panel (a) shows the complete light curve of V445 Lyr presented in this paper, including quarters Q1–Q7. Due to failure of a module, there are no data from Q5, resulting in the gap from MJD 55273 to 55372. Panel (b) illustrates the extreme Blazhko modulation by comparing a pulsation cycle at Blazhko maximum to one at Blazhko minimum. The light variation has an extremely low amplitude during this Blazhko minimum and shows a double maximum. In panel (c), a zoom into a region with period doubling is shown as an example and panel (d) emphasizes the distorted light-curve shape that occurs during some Blazhko minima.

652 *E. Guggenberger et al.*

Table 1. The scaled and detrended data set of V445 Lyr that was used for the analysis in this paper. Column 1 gives the truncated Barycentric Julian Date, column 2 gives the magnitude with the average shifted to zero and column 3 gives the quarter in which data were obtained. The full table is available as Supporting Information with the online version of the paper.

HJD – 240 0000	Magnitude	Quarter
54964.512 11	0.044 188 798	Q1
54964.532 54	0.038 912 686	Q1
54964.552 98	0.017 979 982	Q1
54964.573 41	–0.023 960 246	Q1
54964.593 85	–0.099 222 117	Q1
...	...	...

observing it only during Blazhko minimum where the peak-to-peak amplitude can be as low as 70 mmag. Extremely low pulsation amplitudes during Blazhko minima were recently also reported by Sódor et al. (2012) for two of the RRab type stars, and the occurrence of a strong bump during Blazhko minimum was noted in RZ Lyr (Jurcsik et al. 2012). In Fig. 1(c), a small part of the light curve around JD 245 5386 is shown, illustrating the phenomenon of period doubling (alternating higher and lower light maxima) which was recently discovered in *Kepler* Blazhko stars (Szabó et al. 2010) and which is also present in V445 Lyr.

4 ANALYSIS AND RESULTS

Due to the quasi-continuous coverage and the high photometric precision, the conditions for a Fourier analysis are more than favourable. The spectral window function (see Fig. 2) is almost perfect, without any alias peaks visible at first glance. Because of the Earth-trailing orbit, no orbital frequencies like the ones that cause trouble in the data from many other space missions are present here.

A well-known feature in the *Kepler* data is the momentum desaturation of the reaction wheel, which happens every 2.98 d. During

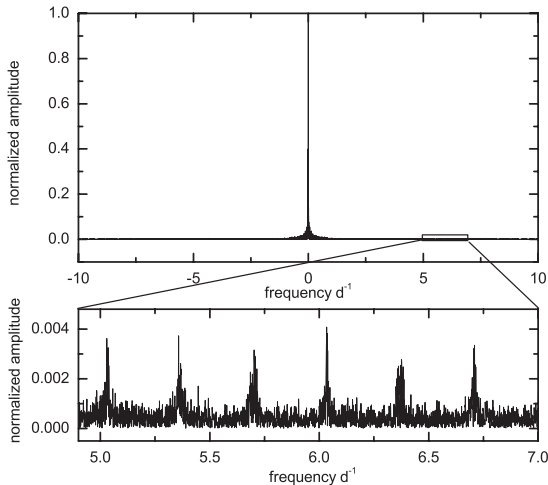


Figure 2. Spectral window function of the complete V445 Lyr data set. Lower panel: magnification of the region between 5 and 7 d^{−1}, showing some examples of the low-amplitude features caused by the reaction wheel.

the thruster firings which are necessary to release the angular momentum that has built up in the reaction wheels, the spacecraft momentarily loses the fine point control (Van Cleve & Caldwell 2009). This results in a missing data point during every desaturation in the otherwise regularly spaced data, leading to a comb-like structure in the Fourier transform with a spacing of 0.335 d^{−1}. In the spectral window, those peaks have a very low normalized amplitude of only 0.004 mag. A zoom into the spectral window (see lower panel of Fig. 2) reveals this comb of tiny peaks. When carefully removing all high-amplitude peaks from the Fourier spectrum before turning to interpreting features with amplitudes which are orders of magnitude smaller as discussed in Section 4.1.5, those alias peaks are not expected to cause any trouble.

Other features in the spectral window function are two harmonics of the monthly data downlink frequency, at 0.065 and 0.13 d^{−1}, with normalized amplitudes of 0.05 and 0.03 mag, respectively.

Due to the time base of 588 d, the Rayleigh frequency resolution is 0.0017 d^{−1}.

4.1 Fourier analysis of the full data set

As a first step, a Fourier analysis of the complete data set was performed, keeping in mind that changes in the fundamental period might occur during the time of the observations and that the changes of the Blazhko modulation cause a large number of peaks close to the classical pulsation and modulation components. The Fourier analysis of the full data set, however, is necessary to obtain an overall picture of the pulsation and modulation properties of V445 Lyr to find the mean values of the pulsation and modulation periods and to detect possible long-term periodicities which can be resolved with a long time base only.

The Fourier analysis of the complete data set was performed with PERIOD04 (Lenz & Breger 2005) and then checked with SIGSPEC (Reegen 2007). The results agreed within the errors. The Fourier analysis revealed a mean pulsation period of 0.513 075 ± 0.000 005 d and a mean Blazhko period of 53.1 ± 1 d with the ephemeris

$$\text{HJD}(T_{\text{max,pulsation}}) = 245\,5550.514 + 0.513\,075 E_{\text{pulsation}},$$

$$\text{HJD}(T_{\text{max,Blazhko}}) = 245\,5534.2 + 53.1 E_{\text{Blazhko}}.$$

Note that the presence of close peaks has a great influence on the fitting and frequency optimization procedure, and the errors are therefore larger than would normally be expected for a Fourier fit to data of the given quality.

4.1.1 Multiplet components

The Blazhko multiplets (i.e. the pattern of peaks which is typical for Blazhko stars with peaks at the positions $kf_0 \pm nf_B$, with k and n being integers denoting the harmonic order and the multiplet order, respectively, and with f_0 and f_B denoting the fundamental and the Blazhko frequency) were found to be very asymmetric in amplitude. Much higher amplitudes appeared on the right-hand (higher frequency) side than on the left. This is the more common case, which is observed in three-fourths of all Blazhko RRab stars (Alcock et al. 2003). Components were detected up to quintuplet order on the right-hand side, while on the left-hand side of the main pulsation component only one side peak (i.e. a triplet component, $n = 1$) could be found. In some orders, peaks were found near the positions that would be expected for septuplets, but the deviations

from the exact frequency values were considered too big to identify the peaks safely as septuplet components.

In addition to the classical Blazhko multiplets around the fundamental mode and its harmonics, a secondary modulation component, f_s , could also be identified. It manifests itself as a series of additional peaks next to the classical modulation side peaks of the Fourier spectrum, appearing in every order with a spacing of $0.00698 \pm 0.00027 \text{ d}^{-1}$, indicating a secondary modulation period of $143.3 \pm 5.8 \text{ d}$. The secondary peaks appearing on the right-hand side of the classical peaks show surprisingly high amplitudes, while the secondary peaks to the left of the classical multiplet have small amplitudes and could only be detected after pre-whitening a large number of higher amplitude peaks. Interestingly, the peaks belonging to this additional series could also be detected at higher multiplet orders ($n = 3$) than the classical multiplet, making it difficult to explain the peaks as combination frequencies. Their amplitudes seem to decrease less quickly with increasing harmonic order k (see also Section 4.1.3), making them easier to spot at high orders.

Fig. 3 shows the Fourier transform of the data, providing also zooms into the regions around the third, fourth and fifth harmonic order where both the classical multiplet and the additional components can be seen. The highest peaks among the multiplet components, which can be seen even before pre-whitening the original data, are marked with arrows.

Fig. 4 illustrates the pattern of detected frequencies in the vicinity of the fundamental pulsation and its harmonics in the style of an ‘echelle’ diagram. In this diagram, which is similar to the diagrams used to unveil equally spaced peaks in helioseismology, the frequency of each peak is plotted against $(f \bmod f_0)$, i.e. $f/f_0 - \text{INT}(f/f_0)$ or $f/f_0 - \text{INT}(f/f_0) - 1$ for peaks to the left of the harmonic, therefore clearly revealing patterns which repeat in every harmonic order. Peaks belonging to the same group of combinations align in vertical ridges. We stress that unlike in the helioseismic application, where the ridges denote different radial orders of same degree, in this case the echelle diagram only serves the purpose of displaying in a very practical and easy way the repeating patterns in different harmonic orders of non-sinusoidal fundamental radial pulsation.

4.1.2 Deviation of the harmonics

Due to the non-sinusoidal light-curve shape typical for RR Lyrae stars, harmonics of the fundamental mode are expected to appear at frequencies kf_0 , where k is an integer denoting the harmonic order. The classical Blazhko multiplets in the modulated stars are spaced equidistantly, implying frequency values of $kf_0 \pm nf_B$ with n denoting the multiplet order. Long-term period changes and close peaks caused by irregular phenomena, however, can distort this frequency pattern. When analysing time series of Blazhko RR Lyrae stars, there are two options for fitting the data: one is to fix the frequencies of the harmonics and Blazhko multiplets to their expected values of $kf_0 \pm nf_B$, thereby reducing the number of free parameters in the fit. The other option is to let all parameters, including the frequency values, free. When the latter option was applied to this data set, the harmonics were observed to deviate systematically and significantly from their expected values, which can also be noticed as a slight rightwards tilt of the ridges in the echelle diagrams (Fig. 4). Normally, one would expect that this is simply caused by a wrong value of f_0 , but in this case, no value of f_0 could be found which could solve the issue, i.e. every detected harmonic, when divided by its order, required a different f_0 . We therefore decided in favour of

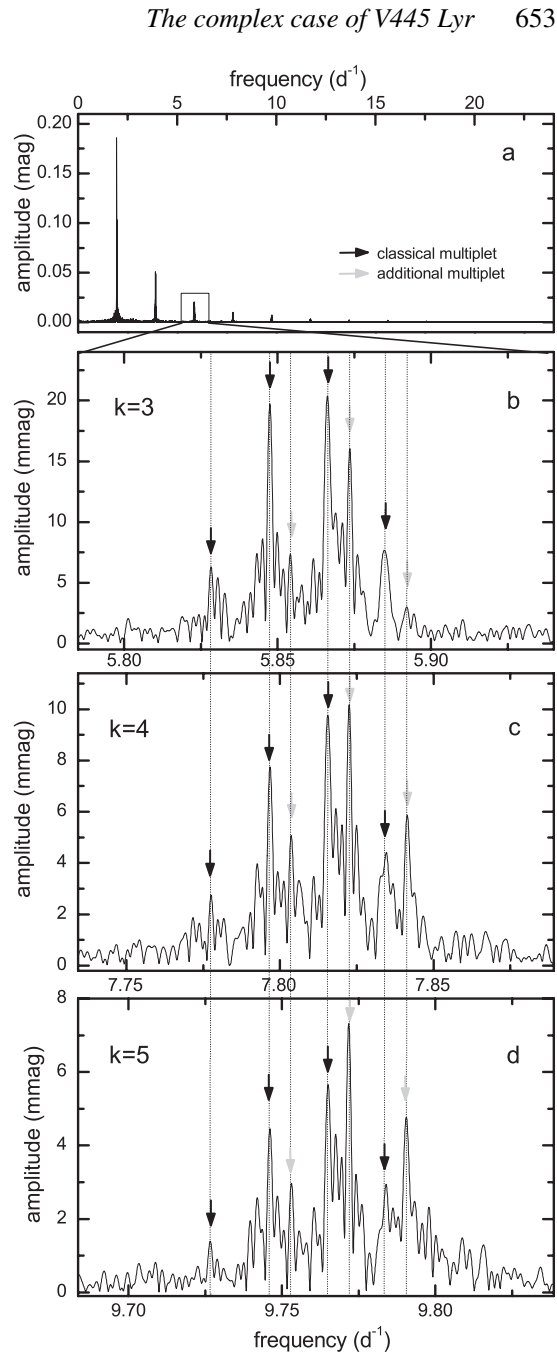


Figure 3. Fourier transform of the complete V445 Lyr data set (upper panel). In the lower panels (b, c and d), the regions around the harmonics kf_0 with $k = 3, 4$ and 5 are shown in detail. Black arrows indicate the peaks belonging to the classical Blazhko multiplet with $kf_0 - f_B$, kf_0 , $kf_0 + f_B$ and $kf_0 + 2f_B$, while grey arrows indicate some of the peaks belonging to the secondary multiplet which within itself has a spacing equal to the Blazhko frequency, but is shifted with respect to the classical multiplet by 0.00698 d^{-1} . Note that from order $k = 4$ onwards, the highest amplitude peak in this order is a peak belonging to the secondary multiplet.

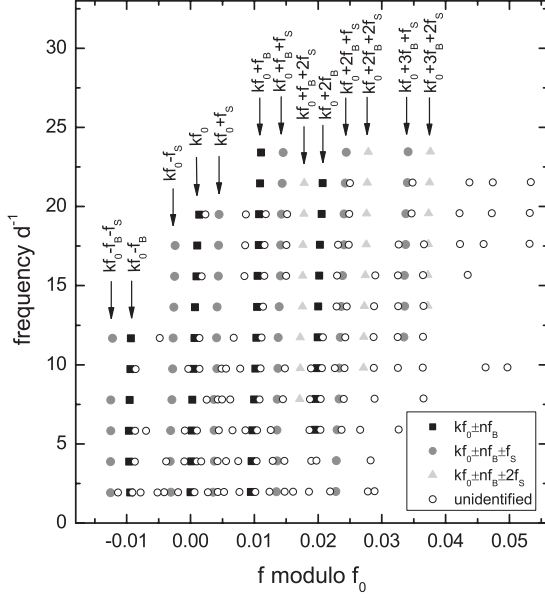


Figure 4. ‘Echelle’ diagram of the peaks detected in the vicinity of the fundamental pulsation mode and its harmonics. Frequency is plotted versus f modulo f_0 , so that regularly spaced peaks which appear in every order align in vertical patterns, making it easy to identify combinations with f_0 . Peaks belonging to the category $k f_0 \pm n f_B$ are shown as black squares, peaks of the group $k f_0 \pm n f_B + f_S$ are shown as grey circles and components of $k f_0 \pm n f_B + 2 f_S$ are plotted with light-grey triangles. Open circles denote unidentified and/or unresolved peaks, some of which originate from the non-repetitive nature of the modulation and long-period changes.

the more pure approach and did not fix the frequency values to the expected positions, but left all parameters free in the fit of the complete data set. The problem disappeared, however, when analysing different subsets of data separately (see Section 4.2), and we therefore suspect it to be either the result of period changes which take place during certain seasons (see also Section 4.3) and/or close unresolved peaks which are known to strongly influence the results of both the Fourier analysis and the multisine fitting procedure.

4.1.3 Amplitudes versus harmonic order

It is a well-known fact that in Blazhko RRab stars the amplitudes of the multiplet side peaks decrease less rapidly with harmonic order than that of the main component. This was first described by Jurcsik et al. (2005), and then confirmed for other well-studied stars such as SS For (Kolenberg et al. 2009), RR Lyr (Kolenberg et al. 2011) and CoRoT 105288363 (Guggenberger et al. 2011). As expected, the result is the same for V445 Lyr (see Fig. 5), but in an extreme way with the amplitude of the right-hand side peak exceeding that of the main component as early as in the third order. Additionally, the amplitudes of the secondary modulation multiplet, i.e. combinations with the secondary modulation f_S , could be studied in this case. It turned out that the amplitudes of the secondary multiplet components decrease even less steeply, therefore dominating the Fourier spectrum from the fourth order onwards. The strongest signal then comes from the combination $f_0 + f_B + f_S$, i.e. the peak on the right-hand side of the right triplet component. Also, combina-

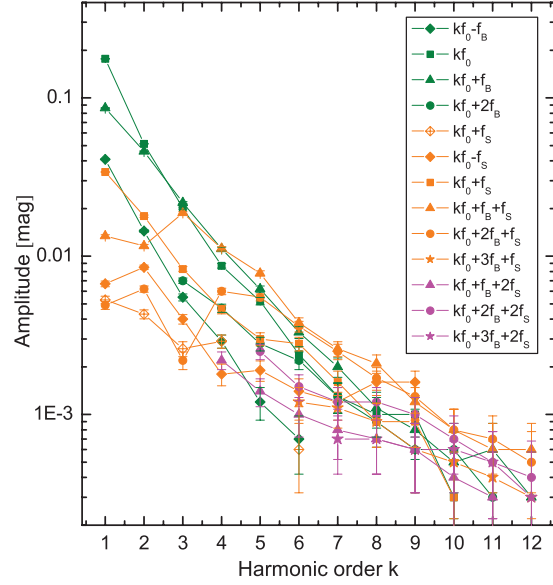


Figure 5. Amplitudes of all components versus harmonic order. Components belonging to the classical Blazhko multiplet are shown with green symbols, peaks which are combinations with f_S are shown in orange, and components with a $2 f_S$ term are shown in magenta. It can be seen that the amplitude of the f_S multiplets decrease less steeply than those of the classical Blazhko multiplet, reaching the same amplitude in the fourth order and dominating the frequency spectrum for higher orders.

tions with the term $2 f_S$ could be detected, and their amplitudes are plotted in Fig. 5. They also show a very slow amplitude decrease.

4.1.4 Number of relevant frequencies

Due to the dense spectrum of peaks which is caused by the cycle-to-cycle changes of the Blazhko effect, an analysis in the classical sense, i.e. taking into account all frequencies down to a certain signal-to-noise ratio level or a certain significance criterion, might not be optimal in a case like V445 Lyr, as it does not yield meaningful results. A large number of the detected peaks is likely to be the result of ‘stellar noise’ caused by irregular and/or long-periodic phenomena, and many of them are not resolved with the available time span. Tests revealed that as many as 771 frequencies can be found when performing an analysis until the generally adopted criteria of significance are reached. Many of them were not resolved, and many could not be attributed to any combination of other modes, and did not show repeating patterns in the echelle diagrams. Therefore, instead of choosing the classical approach, the analysis was stopped after a certain number of the highest peaks in every harmonic order were found and pre-whitened, usually around 20 peaks per order. It turned out that after subtracting approximately 20 peaks in a given harmonic order, no meaningful combinations could be identified among the following peaks, and many unresolved peaks appeared. In Fig. 4 only the highest peaks of every order are shown, already including some unresolved peaks which could not be avoided due to their high amplitudes. As the Nyquist frequency of LC data is 24.4 d^{-1} , 12 harmonic orders could be observed, and 239 frequencies were subtracted around the main pulsation components until the attention was turned towards the additional peaks which are

present in the region between the harmonics of the fundamental mode (see the next section).

Altogether, 239 frequencies were included, of which one is the fundamental mode, nine are harmonics of the fundamental mode, 104 are combinations of f_0 or its harmonics with the Blazhko frequency f_B and/or the secondary modulation f_S and 125 are unidentified.

4.1.5 Additional frequencies: radial overtone and non-radial pulsation

It was already noted by Benkő et al. (2010) that V445 Lyr shows a rich spectrum of frequencies in the region between the harmonics of the fundamental mode. Those frequencies are not at all typical for ab-type RR Lyrae stars and have never been detected in such a large number in an RR Lyrae star. Some peaks were suspected to be radial overtones by Benkő et al. (2010), and also frequencies which are half-integer multiples of the fundamental mode are expected to appear in this region as a consequence of the period-doubling phenomenon as described by Szabó et al. (2010). However, there is more than this in the case of V445 Lyr.

Fig. 6 shows the frequency spectrum after subtraction of the relevant peaks around the multiples of the fundamental pulsation as discussed in the previous section (their former positions are marked with arrows). The additional frequencies can clearly be seen to be the dominant signal with an amplitude of 3.7 mmag for the highest peak. The region between the fundamental mode and its first harmonic is indicated with a grey box and enlarged in the insert (panel b). Four frequency regions with enhanced signal can be noted in the enlargement: around 2.65, 2.8, 2.9 and 3.33 d^{-1} . This pattern repeats in every harmonic order, indicating combinations of the frequencies with the fundamental mode and its surrounding peaks. The presence of combinations is a strong evidence that the additional signal is not introduced by a possible background star.

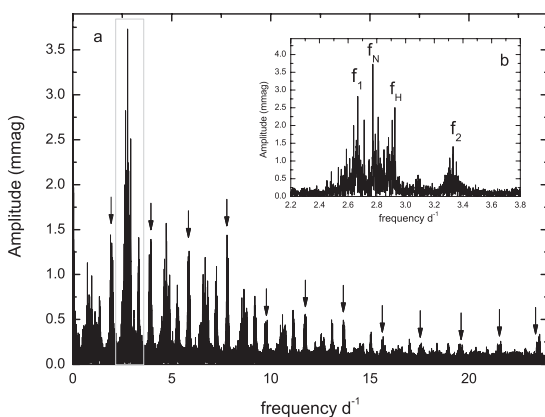


Figure 6. Fourier spectrum after pre-whitening 239 frequencies in the vicinity of the fundamental mode and its harmonics. Very clearly, additional frequencies can be seen between the harmonic orders and their combinations with f_0 which are present up to high harmonic orders. Arrows mark the places where the harmonics and the Blazhko as well as the secondary multiplets were located before pre-whitening. Some signal remains around their positions, as discussed in Section 4.1.4. The insert (panel b) shows a zoom into the region between the fundamental mode and the first harmonic (2–4 d^{-1}), indicated as a grey square.

The complex case of V445 Lyr 655

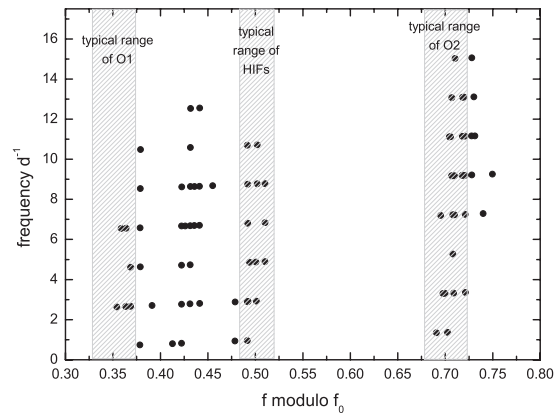


Figure 7. Echelle diagram of the additional frequencies, showing how the patterns repeat in every harmonic order. Shaded boxes indicate the ranges which would be typical for the first and second overtones (O1 and O2, respectively), as well as for the HIFs.

In a Fourier analysis of the relevant frequency regions, 80 peaks (including combinations) were considered significant and were subtracted. A closer inspection of the result revealed that the dominant peaks formed combinations not only with the fundamental mode but also with the Blazhko multiplet peaks (including quintuplets!) and in some cases also with the peaks belonging to the secondary multiplet. Negative combinations such as $f_N - f_0 - f_B$ also occur. Significant combination peaks can be traced up to the fifth harmonic order, but an excess in signal is visible in the Fourier spectrum even at much higher orders (see Fig. 6). In Fig. 7, an echelle diagram is plotted for the additional peaks, clearly showing the combinations with the fundamental mode aligned in vertical patterns. Shaded boxes indicate the typical regions in which overtone modes and half-integer combination frequencies would be expected to be situated. Please note that it was shown by Szabó et al. (2010) that due to the onset and offset of the period-doubling phenomenon, the half-integer frequency (HIF) peaks are not necessarily located at the exact positions of the half-integer multiples, but might deviate by several per cent. Therefore, the shaded box at $(f \bmod f_0) = 0.5$ in Fig. 7 has a distinct width.

In V445 Lyr, the frequency at 2.9256 d^{-1} deviates by only 0.0021 d^{-1} (i.e. 0.07 per cent) from the exact value of $3f_0/2$. Given the fact that clear signs of period doubling are indeed visible in the light curve (see Fig. 1c), and considering the above-mentioned findings of Szabó et al. (2010), it is quite safe to interpret this frequency as an HIF caused by period doubling. We hereafter refer to it as f_H . Four significant HIFs (which can also be interpreted as combinations of f_H with f_0) were found in the Fourier spectrum: $3f_0/2$, $5f_0/2$, $9f_0/2$ and $11f_0/2$. Combinations with the Blazhko frequency, both positive and negative, could also be identified (see Table 2 for a complete list).

Another interesting feature is the peak at 3.3307 d^{-1} which shows a frequency ratio of $f_0/f_2 = 0.585$ with the fundamental mode, and which we hereafter refer to as f_2 . Its period ratio is typical for the second overtone. Peaks with similar period ratios have already been reported for several RR Lyrae stars. Poretti et al. (2010) were the first to find them in the star CoRoT 101128793. The frequency ratio in their study was 0.584 with the fundamental mode at $f_0 = 2.11895 \text{ d}^{-1}$. They interpreted the peak as the second radial overtone. The same authors also re-analysed the data of V1127

Table 2. List of the highest peaks in every one of the four regions of excess signal, and their combinations.

	Frequency (d ⁻¹)	Amplitude (mmag)
f_N	2.7719	3.67
$f_N + f_0$	4.7211	1.58
$f_N + 2f_0$	6.6778	0.74
$f_N + 3f_0$	8.6196	0.51
$f_N - f_0$	0.8228	0.75
$f_N + f_B$	2.7895	1.64
$f_N + f_0 + f_B$	4.7389	1.43
$f_N + 2f_0 + f_B$	6.6880	1.22
$f_N + 3f_0 + f_B$	8.6372	0.83
$f_N + 4f_0 + f_B$	10.5864	0.54
$f_N + 5f_0 + f_B$	12.5359	0.33
$f_N - f_0 - f_B$	0.8044	0.69
$f_N + 2f_B$	2.8091	2.24
$f_N + 2f_0 + 2f_B$	6.7067	0.87
$f_N + 3f_0 + 2f_B$	8.6559	0.57
$f_N + 5f_0 + f_2f_B$	12.5543	0.34
$f_N + 2f_0 + f_S$	6.6778	0.74
$f_N + 2f_0 + f_B + f_S$	6.6964	0.76
$f_N + 3f_0 + f_B + f_S$	8.6456	0.81
$f_N + 3f_0 + 3f_B + f_S$	8.6828	0.53
f_1	2.6676	2.80
$f_1 + f_0$	4.6166	1.08
$f_1 + f_0 + f_B$	4.6362	1.16
$f_1 + 2f_0 + f_B$	6.5851	1.02
$f_1 + 3f_0 + f_B$	8.5343	0.77
$f_1 + 4f_0 + f_B$	10.4838	0.45
$f_1 - f_0 + f_B$	0.7374	1.16
f_H	2.9256	2.55
$f_H + f_0$	4.8736	0.87
$f_H + 3f_0$	8.7743	0.60
$f_H + 4f_0$	10.7234	0.43
$f_H - f_B$	2.9070	2.29
$f_H + f_0 - f_B$	4.8607	0.89
$f_H + 2f_0 - f_B$	6.8060	0.95
$f_H + 3f_0 - f_B$	8.7549	0.57
$f_H + 4f_0 - f_B$	10.7029	0.40
$f_H - f_0 - f_B$	0.9579	1.01
$f_H + f_0 + f_B$	4.8924	1.00
$f_H + 2f_0 + f_B$	6.8413	0.71
$f_H + 3f_0 + f_B$	8.7905	0.58
f_2	3.3307	1.43
$f_2 + f_0$	5.2781	0.85
$f_2 + 2f_0$	7.2268	0.79
$f_2 + 3f_0$	9.1760	1.04

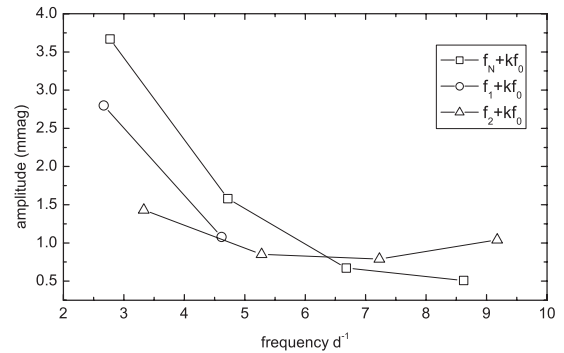
Aql (Chadid et al. 2010) and MW Lyr (Jurcsik et al. 2008) and found frequency ratios of 0.582 ($f_0 = 2.8090\text{d}^{-1}$) and 0.588 ($f_0 = 2.5146\text{d}^{-1}$), respectively. In the sample of *Kepler* RRab stars, Benkő et al. (2010) reported the presence of the second overtone in four different stars: V354 Lyr (a Blazhko star with $f_0 = 1.78037\text{d}^{-1}$), V2178 Cyg (a Blazhko star with $f_0 = 2.05423$), V445 Lyr (the subject of this paper) and the non-modulated RRab star V350 Lyr ($f_0 = 1.68282$) which was the first example of a non-Blazhko double-mode RR Lyrae star with the fundamental (F) and the second over-

tone (O2) excited. Guggenberger et al. (2011) found evidence for the second overtone in CoRoT 105288363, a Blazhko star with rapid changes in the Blazhko effect, and Nemec et al. (2011) found the second overtone in KIC 7021124, therefore providing another example of a non-modulated RRab star pulsating in both F and O2 ($f_0 = 1.606445\text{d}^{-1}$, $f_0/f_2 = 0.593$).

It is interesting to note how different the stars are for which the second overtone has been documented so far: their fundamental frequencies range from about 1.6 to 2.8d^{-1} , covering almost the full bandwidth of RRab pulsation, and with respect to stability they range from non-modulated stars with almost perfectly regular RRab pulsation (V350 Lyr, KIC 7021124) to Blazhko stars with a rather regular Blazhko effect (CoRoT 101128793 and V1127 Aql) and finally to modulated stars that show dramatic changes of their Blazhko modulation (CoRoT 105288363 and V445 Lyr). Moreover, they cover a significant range of Blazhko periods, from 16.6 d to more than 200 d, as estimated for V2178 Cyg.

The combinations of f_2 in V445 Lyr deserve some special attention. While as many as 32 peaks are detected near the positions of $f_2 + kf_0$, and clearly an excess of signal is visible in every harmonic order (see Figs 6 and 7), it was not possible to identify most of the detected peaks as exact combinations with the known frequencies. For f_H (which was discussed in the previous paragraph), 12 out of 16 peaks could be attributed to combinations while for f_2 , only three combinations with f_0 were found at their exact positions. All the other peaks in the vicinity of the combinations deviated too much from the calculated values to be safely matched with the combinations. This is especially remarkable as the amplitudes of those peaks are surprisingly large in higher harmonic orders compared to the combinations of the other additional frequencies. From Fig. 6 it is obvious that in the first harmonic order, f_2 has a small amplitude compared to the other additional frequencies, while at the orders 4–5 they become equal, and at higher orders, the peaks in the area around $f_2 + kf_0$ are the dominant features. This is also illustrated in Fig. 8, where the amplitudes of the safely identified peaks versus frequency are shown. The large number of unidentified peaks around f_2 might indicate that the amplitude of f_2 is variable, either irregularly or on a time-scale other than the Blazhko frequency. This will be discussed in more detail in Section 4.2.1.

The highest amplitude peak among the additional frequencies (3.7 mmag) is the one at 2.7719d^{-1} . This peak was interpreted as the first overtone by Benkő et al. (2010), but its ratio with the

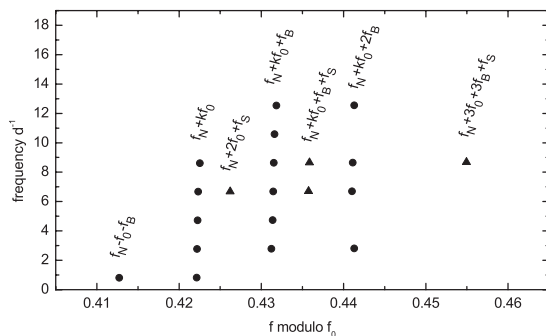
**Figure 8.** Amplitudes of the additional frequencies and their combinations with f_0 versus frequency. While the amplitudes of f_N and f_1 decrease exponentially with harmonic order, the amplitude of f_2 remains almost stable. Amplitude errors are smaller than the symbols.

fundamental ($f_0/f_N = 0.703$) is very low compared to the canonical value of 0.74–0.75. Note that the OGLE III RR Lyrae stars in the Galactic bulge have f_0/f_1 values going down to about 0.726 only (see Soszynski et al. 2011). Extremely high metallicity values would be necessary according to models (Popielski, Dziembowski & Cassisi 2000; Szabó, Kolláth & Buchler 2004; Smolec & Moskalik 2008) to fit this frequency ratio with the first overtone. New spectroscopic results revealed, however, that the metallicity of V445 Lyr is $[\text{Fe}/\text{H}] = -2.0 \pm 0.3$ (see Section 5), rendering it impossible to explain this frequency with a radial overtone mode. f_N is therefore most likely to be a non-radial mode. We note that Van Hoolst, Dziembowski & Kawaler (1998) found in their non-adiabatic and non-radial calculations the excitation of non-radial modes in the vicinity of the radial mode in RR Lyrae stars to be very likely, and Dziembowski & Cassisi (1999) noted in their model survey the presence of strongly trapped non-radial modes with very high growth rates near the first overtone.

Among the additional modes in V445 Lyr, f_N is the one that shows the clearest pattern of combination frequencies: of 20 peaks which were found significant in relation to f_N , all 20 could be unambiguously identified as exact combinations with f_0 , the Blazhko frequency and the secondary modulation frequency (see also Table 2 and Fig. 9, which illustrate the regular pattern of combination peaks). We note that the possible non-radial mode, which was found by Chadid et al. (2010) in V1127 Aql, has a very similar frequency ratio (0.696), may be hinting at a possible systematic preference in non-radial mode excitation in RR Lyrae stars.

There remains, however, the fourth region of increased signal with a main peak at 2.6676 d^{-1} , which, with a frequency ratio of $f_0/f_1 = 0.731$ is in principle in the possible range of the first overtone pulsation. One has to note that double-mode RR Lyrae stars usually follow a well-defined empirical sequence in the Petersen diagram; in other words, there is a relation between f_0 and f_0/f_1 (see Popielski et al. 2000; Soszynski et al. 2009). If the peak at 2.6676 d^{-1} is indeed the first overtone, V445 Lyr would be an exception to this relation, which is very unlikely. On the other hand, outliers from the sequence similar to V445 Lyr have recently been reported by Soszynski et al. (2011) in the OGLE III survey of the Galactic bulge.

The metallicity needed to reproduce a frequency ratio of $f_0/f_1 = 0.730$ with models ($Z = 0.004$, see Fig. 10) is much larger than the



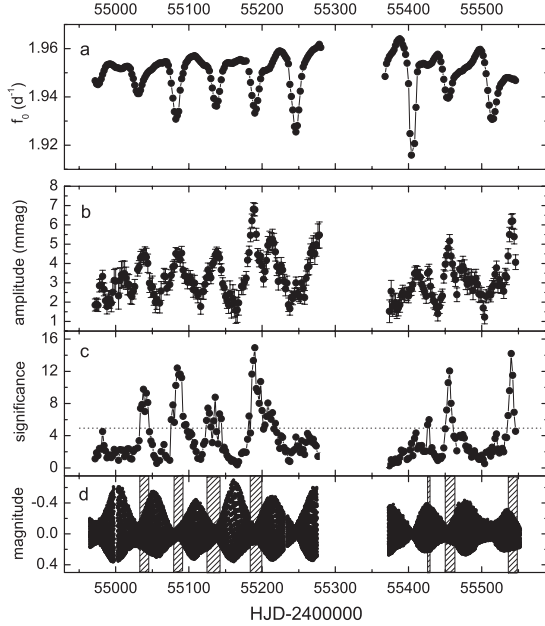
658 *E. Guggenberger et al.*

Figure 11. Variation of f_0 over the complete data set (panel a). Middle panels show the variation of the amplitude (panel b) and the significance (panel c) of the second overtone f_2 , calculated for bins of 15 d duration with a step width of 2 d. The bottom panel (d) shows the light curve for orientation. The times of significant f_2 amplitude are marked with shaded boxes.

deviation of the harmonics as described in Section 4.1.2 is observed. This phenomenon seems to occur only in quarters Q6 and Q7 where the Blazhko periods found in separate analyses of the quarters were 79.8 and 80.4 d, respectively.

4.2.1 Stability of the additional frequencies

The results discussed in Section 4.1.5 hint towards a variability of the amplitude of f_2 , and we therefore studied the temporal evolution of this peak in detail. Using the time-resolved mode of SIGSPEC, we performed a Fourier analysis of overlapping bins with a duration of 15 d in steps of 2 d, limiting the frequency range to the region around f_2 . The resulting amplitudes are plotted in Fig. 11(b). While there is a clear variation of the amplitude ranging from 2 to ~ 7 mmag, no clear periodicity is discernible. We also performed a Fourier analysis on the resulting amplitude curve and found no significant frequency of variability. We note that in Fig. 11, all values of $A(f_2)$ were included, regardless of the significance of the frequency. Only bins with an insufficient number of data points and/or bad frequency resolution were discarded. Therefore we provide as a supporting plot the time-dependent significance of the peaks in panel (c), where the most commonly used significance criterion of $\text{sig} \geq 5$ is indicated with a dashed line.

For better orientation, the bottom panel shows the full data set (light curve) of V445 Lyr, and shaded boxes indicate the regions of enhanced f_2 amplitude. There seems to be a preference for phases close to Blazhko minima, which are also the phases where the minima of the fundamental frequency f_0 occur, but there is no strict

rule that can predict a high f_2 amplitude. This irregular amplitude variability can explain the numerous peaks around f_2 and its combinations which can be seen in the echelle diagram (Fig. 7) and which are discussed in Section 4.1.5.

We also check the temporal variations of the frequency values of all the additional frequencies and find, in addition to the variation of f_0 which is plotted in Fig. 11(a), slight irregular variations of f_1 and f_2 , which lead to an exact parametric resonance during some time intervals in the observed data. This might result in the momentary and transient excitation of f_2 which is seen in Fig. 11. We note that from the theoretical point of view, a resonance is necessary to excite the second overtone in this parameter range, because otherwise this overtone would not become unstable.

4.2.2 Variation of the Blazhko modulation parameters

The modulation parameters are normally used to describe the properties of the Blazhko modulation of a given star. The traditional parameters are $R_k = A_+/A_-$ where A_+ and A_- are the amplitudes of the peak on the higher frequency and the lower frequency sides of the triplet, respectively, and the phase difference $\Delta\varphi_k = \varphi_+ - \varphi_-$. The parameter k denotes the harmonic order. Moreover, the asymmetry parameter $Q = (A_+ - A_-)/(A_+ + A_-)$, which was introduced by Alcock et al. (2003), is widely used, as is the power difference $\Delta A^2 = A_+^2 - A_-^2$. This parameter was recently shown by Szeidl & Jurcsik (2009) to be the physically most meaningful one, as it is directly correlated to the phase difference between the amplitude and the phase modulation components in their model of modulated oscillation.

As the main aspect of V445 Lyr is the variability of the Blazhko cycles, we show here not only the average Fourier parameters for every order (which are listed in Table 3) but also their time-dependent behaviour in Fig. 12. To calculate the modulation parameters for every cycle, the data set was divided into bins, starting and ending around Blazhko minimum. The length of the bins was about 60 d, with the exception of the last bin which was only 50 d. Some overlap was used to guarantee frequency resolution of the Blazhko multiplet.

It was an important result for the star CoRoT 105288363 that the phasing between the two types of modulation was found to change (see section 5.3 of Guggenberger et al. 2011). Such a phase change is also indicated by the variation of ΔA^2 of V445 Lyr (bottom panel of Fig. 12).

4.2.3 Fourier parameters

As the so-called Fourier parameters R_{k1} (amplitude ratio) and φ_{k1} (epoch-independent phase difference) are considered useful tools to

Table 3. Overall modulation parameters of V445 Lyr found from the fit to the complete data set for the first six harmonic orders.

k	R_k	$\Delta\varphi_k$	Q_k	A_k^2
1	2.112	-0.87	0.357	0.005779
2	3.179	0.27	0.521	0.001900
3	3.991	-0.24	0.599	0.000445
4	3.806	-0.08	0.584	0.000114
5	5.382	-0.30	0.687	0.000037
6	4.715	-0.39	0.650	0.000011

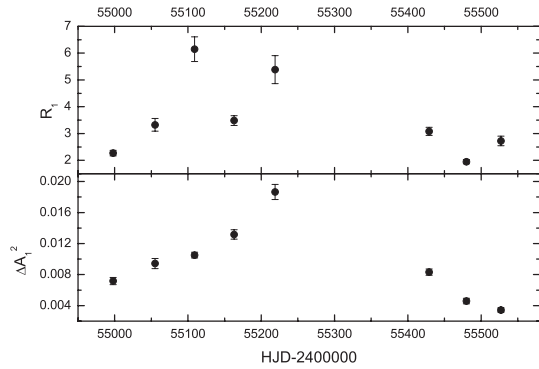


Figure 12. Modulation parameters of V445 Lyr versus time. The top panel shows the variation of R_1 , which is defined as the amplitude ratio between the right and the left modulation side peak, and the bottom panel displays the variation of the power difference ΔA_1^2 . The variation of ΔA_1^2 points towards a shift in the phasing between the two types of modulation.

study and compare the properties of RR Lyrae stars, we calculated their time variability for V445 Lyr. In contrast to the modulation parameters discussed in the previous section, they describe the pulsation rather than the modulation properties. The Fourier parameters

The complex case of V445 Lyr 659

are defined as $R_{k1} = A_k/A_1$ and $\varphi_{k1} = \varphi_k - k\varphi_1$. The data were subdivided into 239 bins of 2 d duration, therefore containing about four pulsation periods. On such short time-scales, the Blazhko effect is expected to play only a minor role. The effect of period doubling, however, causes a large error in some bins which are more affected by this effect than others. A fit including the fundamental pulsation and 10 harmonics is calculated for each bin, and the results are displayed in Fig. 13 (amplitude ratios are shown in the left-hand panels and phase differences in the right-hand panels). The average values of the parameters (derived from the complete data set) are given in Table 4.

Some interesting details are immediately obvious: while the amplitude A_1 of 0.18 mag is quite small compared to other RR Lyrae stars, but still in the normal range, the amplitude ratios R_{k1} are significantly smaller than those of the non-modulated stars (for comparison, see fig. 6 in Nemec et al. 2011). The sharp upward spikes are an intriguing feature in the R_{21} variation, which occur only during some of the observed Blazhko minima. When looking at the phases one notes that, while φ_1 has a smooth periodic variation, the phases φ_2 , φ_3 and φ_4 show a more or less continuous progression (with exceptions in some cycles), leading to apparent phase jumps in the φ_{k1} parameters.

The stability of the results was tested by also using other binnings, and the size of the bins was found to play only a minor role.

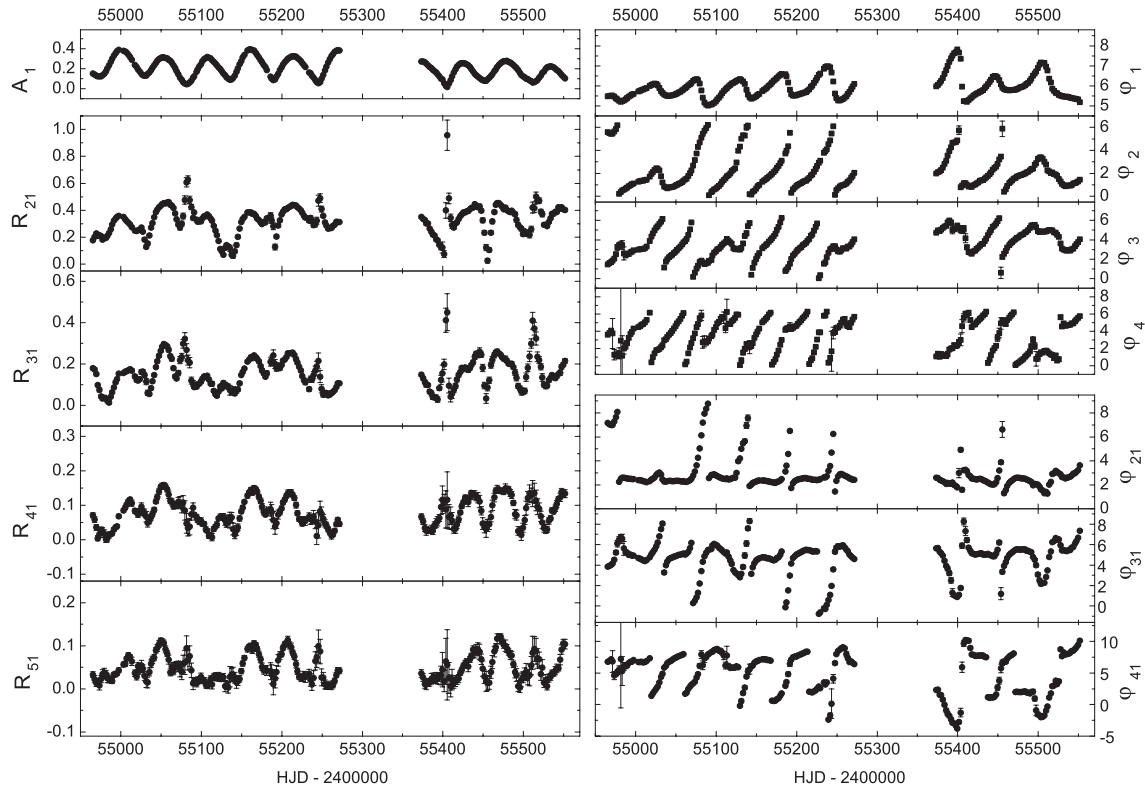
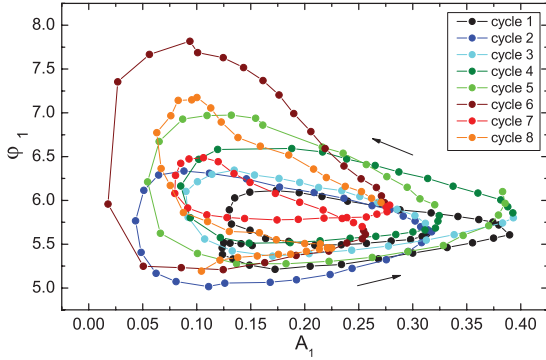


Figure 13. Variation of the Fourier parameters during the observed time span, calculated for subsets of 2 d duration each. Left-hand panels: at the top, the amplitude A_1 is displayed to indicate where Blazhko maxima and minima are located, while lower panels show the amplitude ratios R_{21} , R_{31} , R_{41} and R_{51} . Right-hand panels: at the top, the phases φ_1 , φ_2 , φ_3 and φ_4 are plotted, while the lower panels show the phase differences φ_{21} , φ_{31} and φ_{41} in the sine frame. Where error bars are not visible, they are smaller than the symbols.

660 *E. Guggenberger et al.***Table 4.** Average Fourier parameters of V445 Lyr.

Parameter	Value	Parameter	Value
A_1	0.184	ϕ_1	5.84
R_{21}	0.268	ϕ_{21}	2.34
R_{31}	0.096	ϕ_{31}	4.95
R_{41}	0.033	ϕ_{41}	1.08
R_{51}	0.013	ϕ_{51}	3.69

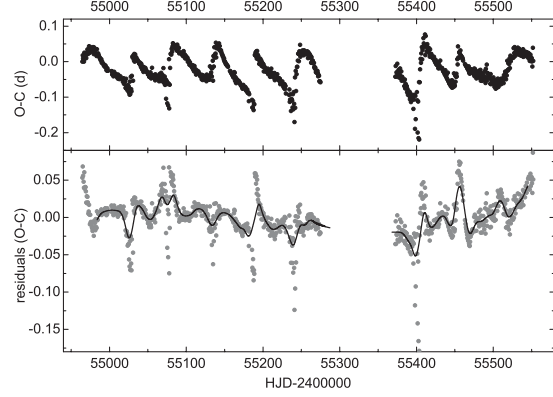
**Figure 14.** ϕ_1 versus A_1 diagram of V445 Lyr. In this plot it can be seen how various observed cycles differ from each other. Both the phase modulation component and the amplitude modulation component change over the observed time span. Moreover, their relative phasing changes from cycle to cycle.

4.2.4 Loop diagrams

A good indicator for the relative contributions of phase modulation and amplitude modulation, and for the phasing between those two types of modulation, is the A_1 versus ϕ_1 diagram. The resulting loops for V445 Lyr are plotted in Fig. 14. The direction of motion is indicated with arrows. Cycles are defined for this purpose as from one maximum of A_1 to the next, except for the beginning and the end of the data set where additional points are added to the adjacent cycles. Cycles 1 to 5 correspond to data obtained before the gap in the observations, and cycles 6 to 8 correspond to data after the gap. Even though the contents of Fig. 14 are partly redundant with the upper panels of Fig. 13, the representation as a loop diagram allows us to better compare the observed Blazhko cycles. All observed Blazhko cycles have a different appearance in this diagram, and the contributions of amplitude and phase modulation change without notable correlation between each other.

4.3 O – C diagrams and long-term period change

In addition to the Fourier analysis which reveals the average Blazhko period, and the time-dependent analysis which shows the fundamental mode as a function of time, we also constructed an O – C diagram, as it can reveal additional details, especially when it comes to long-term period changes. The O – C diagram obtained from all maxima in the *Kepler* V445 Lyr light curve is shown in the top panel of Fig. 15. An intriguing feature is the non-sinusoidal variation of the O – C values with a few points at very low O – C values in some of the cycles. A closer inspection of the phase diagrams at the affected times reveals that these drops in O – C are happening at the epochs with the very unusual distorted light-curve shape show-

**Figure 15.** O – C diagram of the complete data set of V445 Lyr (top panel), and residuals after subtracting a fit with the Blazhko frequency, its harmonics and the secondary modulation frequency (bottom panel). To guide the eye, a line through the means of the residuals in bins of 10 maxima has been plotted.

ing double maxima (the double maxima are illustrated in Figs 1b and d). The determination of the time of the light maximum becomes ambiguous here, depending on the maximum that is chosen. The original maximum seems to move ‘to the left’ (causing negative O – C values) while a bump on the descending branch gets stronger and takes the role of the maximum for the next Blazhko cycle. This also explains the rather abrupt transition from very low to high O – C values.

We also performed a Fourier analysis on the O – C data to check whether the secondary modulation is also present in the phase variation. We clearly found the Blazhko frequency f_B , in this case 0.0184 d^{-1} , as well as the harmonics $2f_B$ and $3f_B$ in the O – C curve, which are introduced by the non-sinusoidal variation of the O – C values. The secondary modulation, with a value of $f_S = 0.0064 \text{ d}^{-1}$, as well as the combination peak $f_B + f_S$, was also directly detected in the Fourier spectrum. We note that slight differences in the frequency values obtained from the O – C diagram compared to those obtained from the magnitudes do not come unexpectedly, as the phase and AMs are not strictly correlated.

As the quasi-periodic Blazhko modulation is the dominant signal in the O – C curve, it is necessary to subtract a fit including the above-mentioned frequencies from the O – C curve to be able to identify long-term changes. The residuals of this fit are shown in the bottom panel of Fig. 15 and reveal quite clearly a long-term period change. It remains unclear, however, whether it is a periodic or a continuous linear period change.

4.4 The analytic modulation approach

Due to the limitations of the classical Fourier analysis discussed in Section 4, we applied a new method of analysis to the *Kepler* data of V445 Lyr, which was recently described by Benkő et al. (2011, hereafter B11). In this approach, the amplitude and frequency modulations are treated similarly to the theory of electronic signal transmission, reducing dramatically the necessary number of free parameters. This would be especially useful for stars like V445 Lyr where a classical Fourier analysis yields several hundreds of combination peaks.

As a first step of such an analysis we have to select the fitting formula, using table 1 in B11. The AM with the frequency of f_B is

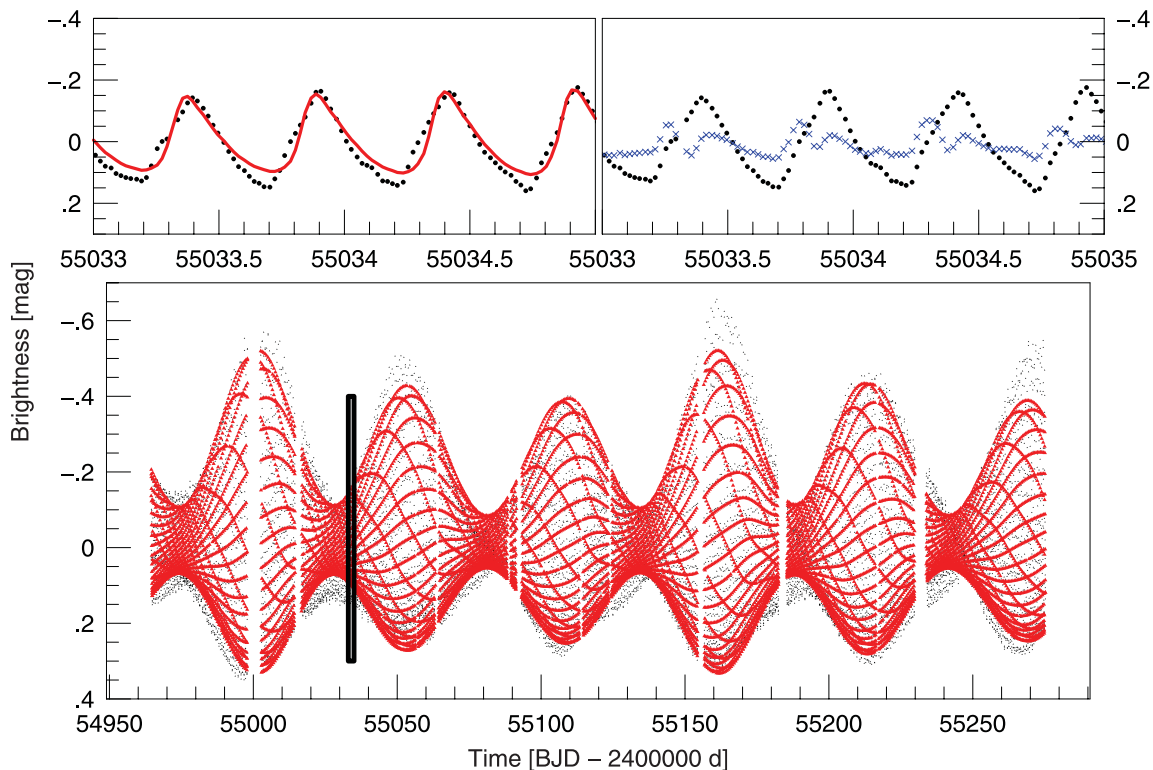


Figure 16. The light-curve fit of V445 Lyr during Q1–Q4 using the modulated signal approach. The bottom panel shows the global 32-parameter fit (red continuous line) with the original data (black dots). The upper panels show a local fit (left) and residual light curves (blue crosses) in the interval indicated by the rectangle in the bottom panel.

evident already from the shape of the light curve in Fig. 1. Since the envelope curve is nearly horizontally symmetric for all Blazhko cycles, the AM of f_B can be approximated by a simple sinusoidal function (see formulae 20 and 21 in B11).

The high asymmetry of the multiplet peaks' amplitudes suggests a frequency modulation (FM) as well. Its non-sinusoidal nature is clear from both the frequency variation function (Fig. 11a) and the O–C diagram (Fig. 15). The combined sinusoidal AM and non-sinusoidal FM modulation of f_B can be described by formula (49) in B11, where $q' = 1$.

As mentioned above V445 Lyr shows a secondary modulation f_S as well, which is included in the form of an AM because of the changing amplitudes of the Blazhko cycles. As a first approximation we also assumed this modulation as sinusoidal. The linear combination of f_B and f_S shows interaction between the two modulations; therefore, we have to apply the formula of modulated modulation (AM cascade – equation 27 in B11).

The situation of the FM in f_S is a bit controversial. The existence of an FM seems to be well established, based upon the detection of f_S in the Fourier analysis of the O – C diagram; however, a combined AM with FM in f_S does not improve the significance of our numerical Levenberg–Marquardt fit. This may be explained on the basis of the long cycle length of this modulation and/or its weak FM.

The used best-fitting model contains a sinusoidal AM and a non-sinusoidal FM represented by a three-term Fourier sum for the

Blazhko modulation and a sinusoidal AM for the second modulation. The two modulations are assumed to be modulating each other. The free parameters are the pulsation frequency f_0 and its harmonics' amplitude and phase up to the ninth order ($A_1, A_2, \dots, A_9, \varphi_1, \varphi_2, \dots, \varphi_9$), the modulation frequency f_B , the amplitudes and phases of its AM (a_{B1}^A, φ_{B1}^A) and FM ($a_{B1}^F, \varphi_{B1}^F, i = 1, 2, 3$), the secondary modulation frequency f_S and its AM modulation parameters (a_{S1}^A, φ_{S1}^A). They represent 32 parameters (with the zero-point a_{00}). The model light curve shows the global properties of the observed one (see Fig. 16); however, the variance of the residual (observed minus fitted) is surprisingly high (0.0025 mag).

There may be various reasons for this large variance. Some of them are method specific, others are object specific. An important limit of the method is (as mentioned by B11) that it does not describe the migration of the humps and bumps caused by the Blazhko effect, a phenomenon which is exceptionally strong in V445 Lyr. The situation is demonstrated well in the upper panels of Fig. 16. The other problem is that our method assumes regular signals. The light curve of V445 Lyr shows, however, irregular behaviour. The loop diagram in Fig. 14 illustrates the cycle-to-cycle variations of the relative strengths of the AM and FM components of the modulation. Any static (regular) models including the Fourier method face similar troubles when using them for such a time-dependent (irregular) phenomenon. Therefore, we conclude that even though applying the method leads to a success in obtaining a reasonable fit with a comparably small number of parameters, it is

nevertheless not optimal for a complicated data set like the one on V445 Lyr.

5 SPECTROSCOPY, COLOUR PHOTOMETRY AND FUNDAMENTAL PARAMETERS

In the framework of ground-based follow-up observations, three spectra were obtained with the HIRES spectrograph at the Keck 10-m telescope in 2011 August (Nemec, Cohen & Sesar, in preparation). Exposure times were 1200 s, and according to the ephemerides given in Section 4.1 the spectra were obtained shortly after maximum light. Due to its faintness ($Kp = 17.4$ mag), V445 Lyr is not an easy target to observe. From a preliminary analysis, heliocentric radial velocities of -392 , -390 and -388 km s $^{-1}$, and a metallicity of $[Fe/H] = -2.0 \pm 0.3$ dex on the Carretta et al. (2009) scale, corresponding to $Z = 0.0003$, were obtained.

Based on the metallicity value derived from spectroscopy and with the frequency value of the second overtone mode, we were able to constrain the mass and luminosity of V445 Lyr with the help of a theoretical Petersen diagram which is shown in Fig. 17. Linear pulsation models (Smolec & Moskalik 2008) were calculated for a set of masses (0.55, 0.65 and 0.75 $M_{\odot}$, which are plotted as solid, dashed and dotted lines, respectively) and different luminosities (40, 50, 60 and 70 $L_{\odot}$, plotted as circles, pluses, squares and triangles, respectively). The metallicity values necessary to theoretically fit the observed frequencies agree very well with the measured metallicity, and the luminosity and mass of V445 Lyr found from Fig. 17 are 40–50 $L_{\odot}$ and 0.55–0.65 $M_{\odot}$, respectively.

As the model period ratios depend on the opacity tables and the abundance mixture used in the computations, we tested the stability of our results. The effects of different opacities and mixtures (Grevesse & Noels 1993; Asplund et al. 2009), however, were checked and found to play only a minor role. In Fig. 17, the models based on OPAL opacities and the mixture of Asplund et al. (2004) are shown. V445 Lyr is plotted as a black square in the diagram, while the other RRab stars for which the presence of the second overtone has been reported are shown as open squares. From the wide spread which the stars show in Fig. 17 it is obvious that very different parameters are needed to model different stars that show the second overtone. Larger masses are necessary to fit the period

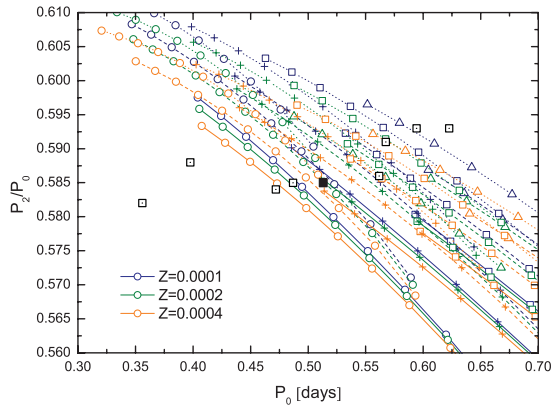


Figure 17. Petersen diagram for V445 Lyr (shown as black square) for the second overtone, based on models computed with the Warsaw code (Smolec & Moskalik 2008). Other RRab Lyr stars with possible second overtones (as discussed in Section 4.1.5) are plotted as open squares.

ratios of the stars with longer periods, while higher metallicities are needed to obtain a model for the shorter periods. Models for V350 Lyr and V354 Lyr have already been shown by Benkő et al. (2010) in their fig. 6 and by Nemec et al. (2011) in their fig. A2. It is already noted in Section 4.1.5 that the stars in which the second overtone is excited form a very diverse sample, therefore it is not surprising that they also cover a wide range in mass and metallicity.

5.1 Ground-based colour photometry

To complement the *Kepler* data with colour information on our target, V445 Lyr was observed from the ground in *BVRI* (of which the *RI* bands are in Cousins system) using telescopes at the Lulin Observatory, including the Lulin One-metre Telescope (LOT), Lulin 0.4 m SLT and the Tenagra II Observatory (TNG, with a 0.8-m telescope). The imaging data were reduced with IRAF in a standard manner, including bias and dark subtraction, and flat-fielding. Photometry was obtained from the images using SEXTRACTOR (Bertin & Arnouts 1996), and calibrated to the standard magnitudes using standard star observation from Landolt (2009). Further details about the telescopes, the CCDs and the reduction of the imaging data can be found in Szabó et al. (2011) and Ngeow (2012), who used the same instrumentation for monitoring the Cepheid V1154 Cyg located within the *Kepler* field of view (Szabó et al. 2011).

The observations were performed between 2011 March 29 and July 24 (i.e. during the course of two Blazhko cycles) and they comprised about 70 measurements per filter with typical uncertainties of about 0.06 mag. As the data cover the pulsation cycle well, they allow the determination of an average brightness in each colour. The following average magnitudes in the standard system were obtained for V445 Lyr on the basis of the magnitudes of the single measurements: $B = 17.80$ mag, $V = 17.38$ mag, $R = 17.09$ mag and $I = 16.81$ mag.

6 COMPARISON WITH COROT 105288363

With the tools developed for the analysis of V445 Lyr, we revisited CoRoT 105288363 to apply the same techniques in a consistent way. Unlike in previous studies, the frequencies were kept as free parameters during the pre-whitening and fitting procedure, in spite of the increase of computing time. This has the advantage that the Blazhko period can be determined not only from one measured distance between two peaks, but also from a large number of independently detected peaks. The standard deviation of that set of measured values also gives a good error estimate. The Blazhko period found by this method is 34.6 ± 1.1 d and our solution agrees within the error of the previous published value of 35.6 d (Guggenberger et al. 2011).

When the echelle diagram diagnostic was applied to CoRoT 105288363, some previously undiscovered features could be unveiled. The first and most important finding is a well-resolved secondary modulation which is very similar to the one in V445 Lyr, in the sense that it has a ratio of $f_B/f_S = 2.5 \pm 0.27$ with the primary modulation, which is close to the value of $f_B/f_S = 2.7 \pm 0.12$ in V445 Lyr. Moreover, its combination peaks appear in similar positions: they are clearly found in the higher frequency side of the harmonics, and also preferentially on the higher frequency side of the classical Blazhko multiplets. The echelle diagram for CoRoT 105288363 is shown in Fig. 18. One has to note that, unlike in V445 Lyr, no systematic deviation of the harmonics from their expected positions (see Section 4.1.2) is found in CoRoT 105288363. Therefore, no tilt of the orders in the echelle diagram can be seen.

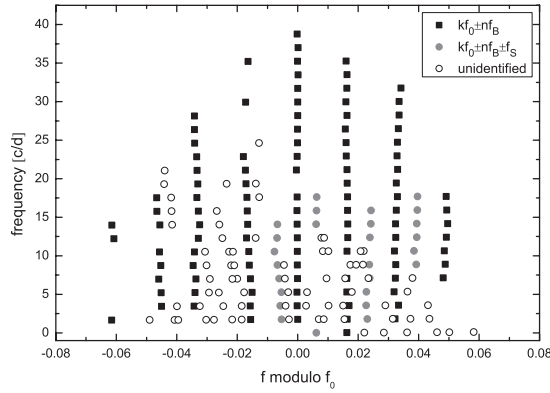


Figure 18. Same as Fig. 4 but for CoRoT 105288363. Note that the multiplet structure is more symmetrical than in V445 Lyr, in the sense that approximately the same number of multiplet components appear on both sides of the fundamental mode. The peaks belonging to the secondary modulation are in similar positions as in V445 Lyr. Again, several additional peaks occur which cannot be identified as combination peaks of either one of the modulations. This is most likely due to either the irregular or the yet unresolved changes of the Blazhko effect. Unlike in V445 Lyr, no combinations including a $2f_S$ term could be found.

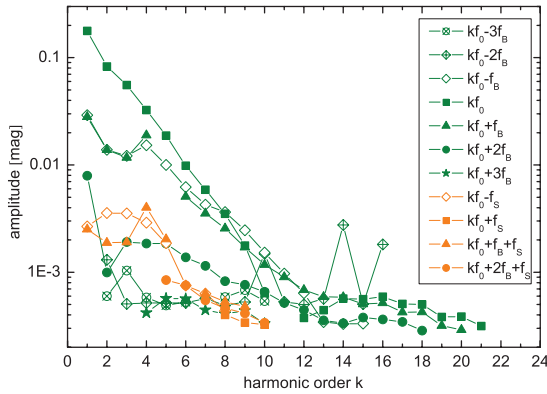


Figure 19. Same as Fig. 5 but for CoRoT 105288363. Here, in contrast to V445 Lyr, the components belonging to the secondary modulation never reach amplitudes higher than that of the classical multiplet, which might be connected to the fact that the changes in the Blazhko effect of CoRoT 10528836 are not so dramatic as they are in V445 Lyr. Their amplitude decrease is almost as rapid as for the classical components.

There are, however, some irregularities in the pattern with some peaks showing deviations from the exact position, though not in a systematic manner. The decrease of amplitudes of the secondary modulation components with increasing harmonic order is shown in Fig. 19. These figures should be compared to the corresponding ones for V445 Lyr (Figs 4 and 5, respectively).

The data of CoRoT 105288363 were then inspected carefully for signal outside the vicinity of the Blazhko multiplets to find evidence for overtones and other possible additional modes. The pre-whitening of not only the classical Blazhko multiplet but also the secondary modulation and the additional peaks (which also leads to the disappearance of all aliases) significantly reduced the noise level of the residuals in the frequency region of interest. The

The complex case of V445 Lyr 663

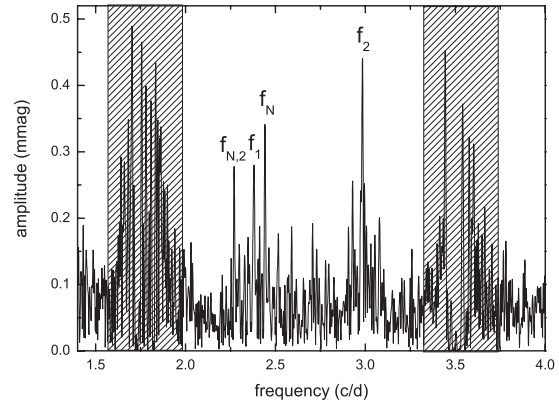


Figure 20. Fourier spectrum of CoRoT 105288363 after subtraction of 135 frequencies around the fundamental mode and its harmonics. A zoom into the region between f_0 and $2f_0$ is shown, clearly revealing the four additional peaks discussed in the text. The former positions of the multiplets around f_0 and $2f_0$ are marked with shaded boxes.

second overtone that was reported by Guggenberger et al. (2011) was also found in the new analysis (see Fig. 20, where it is labelled f_2). Due to the reduced noise, combinations of f_2 with kf_0 up to $k = 5$ could also be detected, clearly indicating that the frequency is not due to noise and is not caused by a background star. Moreover, three additional frequencies could be found (see also Fig. 20). A peak at 2.3793 d^{-1} with an amplitude of 0.3 mmag is found to be most likely the first overtone due to its ratio of $f_0/f_1 = 0.741$ with the fundamental mode. Moreover, a resonance with f_0 and f_2 is possible in this case, because $2f_1 - f_2 - f_0$ is only 0.01 . Another peak appears at $f_N = 2.4422 \text{ d}^{-1}$ with an amplitude of 0.35 mmag . It cannot be attributed to any overtone. This and the fact that it appears between the positions of the first and the second overtones makes it quite similar to the observations in V445 Lyr (see Section 4.1.5). Furthermore, its amplitude is slightly higher than that of the suspected first overtone, as is the case for V445 Lyr. The third frequency found in this range is at $f_{N,2} = 2.2699 \text{ d}^{-1}$ and has an amplitude of 0.3 mmag . It cannot be identified as a radial overtone, and it has no counterpart in V445 Lyr.

Table 5 compares the main characteristics of the two stars, including the ratios of the Blazhko modulation, while Table 6 compares the additional (overtone) modes.

Table 5. Comparison of the main characteristics of the two stars. The fundamental mode frequencies, the Blazhko periods and the periods of the secondary modulation are very different. Interestingly, however, the ratios between the primary and the secondary modulations are very similar.

	CoRoT 105288363	V445 Lyr
$f_0 \text{ (d}^{-1}\text{)}$	1.762 31	1.949 03
$P_0 \text{ (d)}$	0.5674	0.5131
$P_B \text{ (d)}$	34.6	53.1
$f_B \text{ (d}^{-1}\text{)}$	0.0289	0.0188
$f_S \text{ (d}^{-1}\text{)}$	0.0115	0.0069
$P_S \text{ (d)}$	86.5 ± 9	143.3 ± 5.8
P_B/P_S	2.5 ± 0.27	2.7 ± 0.12
P_B/P_0	60.9	103.5

664 *E. Guggenberger et al.***Table 6.** Comparison of the overtone modes and the additional frequency of the two stars.

	CoRoT 105288363	V445 Lyr
f_2 (d^{-1})	2.9856	3.3307
$A(f_2)$ (mmag)	0.5	1.4
f_0/f_2	0.590	0.585
f_1 (d^{-1})	2.3793	2.6676
$A(f_1)$ (mmag)	0.3	2.7
f_0/f_1	0.741	0.731
f_N (d^{-1})	2.442	2.7719
$A(f_N)$ (mmag)	0.4	3.6
f_0/f_N	0.722	0.703

In CoRoT 105288363, there is no sign of period doubling, and no frequencies could be detected at or near the positions of the characteristic HIFs ($3f_0/2$, $5f_0/2$, etc.).

7 SUMMARY AND CONCLUSIONS

7.1 An unusual star with unusual phenomena

V445 Lyr is an RRab star with such a strong Blazhko modulation that at Blazhko minimum the peak-to-peak amplitude decreases down to 0.07 mag compared to approximately 1 mag during Blazhko maximum (a difference by a factor of 14), leading to the rather low overall amplitude A_1 of 0.18 mag.

The light curve around Blazhko minimum shows a strong distortion with a secondary maximum, making it impossible to even identify V445 Lyr as an RRab pulsator when observed only during Blazhko minimum.

In V445 Lyr the full variety of all the recently discovered new features in RR Lyrae stars – period doubling, strong irregular changes in the Blazhko effect, a secondary modulation, radial overtone pulsation and a non-radial mode – are combined in one single star. Therefore, it serves as an example of how ultraprecise and uninterrupted space photometry can change our view on seemingly well-known types of stars. The Fourier phases show an unusual behaviour which has not been detected before in an RR Lyrae star. Moreover, the distinct spikes in the temporal variation of the Fourier amplitude ratios are a previously unknown feature which is most likely caused by the pronounced double maximum at those phases.

7.2 Secondary modulation, irregular behaviour and long-term period change

In V445 Lyr, we find the most extreme variations of the Blazhko modulation known so far. This is partly, but not fully, explained by the secondary modulation of 143 d which we find in the *Kepler* data. Irregular/chaotic changes of the Blazhko modulation and/or even longer modulation periods also seem to be present, leading to a dense spectrum of peaks around the harmonics of the fundamental mode, in which with classical methods up to 771 frequencies would be found.

The amplitudes of the peaks connected to the secondary modulation were found to decrease less steeply with harmonic order than the components of the classical Blazhko multiplets. This interesting feature still awaits a physical explanation.

A long-term period change is also present, but it could not yet unambiguously be determined whether it is a periodic or a linear

change (or neither). Future *Kepler* observations in the upcoming quarters will certainly reveal more about this long-term change.

7.3 Additional frequencies

We find at least four additional frequencies not connected to the fundamental mode, its harmonics and the Blazhko peaks. One of these peaks was interpreted as the second radial overtone, the second one could possibly be the first radial overtone, the third one was found to be due to period doubling and the fourth one was attributed to a non-radial frequency.

The second overtone is not always present during the observations. A strict dependence of the f_2 amplitude on the Blazhko phase could not be found. Instead, it seems to vary rather irregularly.

Amplitudes and frequencies of all additional peaks change notably during the time span of the data. It is possible that fluctuations in the frequency values of f_1 lead to transient resonances which temporarily excite the second overtone.

The additional peaks form numerous combinations with f_0 and the Blazhko multiplets (including quintuplet peaks) and also with the peaks belonging to the secondary modulation, indicating that they are all intrinsic to the target. Altogether, 80 peaks were found above the significance level at or near the combinations of those four frequencies with the other intrinsic frequencies of the target.

7.4 Spectroscopy, Petersen diagrams and an alternative method of light-curve analysis

Spectroscopy with the Keck telescope revealed a metallicity of $[\text{Fe}/\text{H}] = -2.0 \pm 0.3$, and Petersen diagrams based on linear pulsation models point towards a mass of $0.55\text{--}0.65 M_\odot$ and a luminosity of $40\text{--}50 L_\odot$.

We also applied the new analytic modulation technique to the light curve, and found that the best model contains a sinusoidal AM, a non-sinusoidal FM and a sinusoidal AM for the secondary modulation. Due to the migration of a strong bump feature and due to the irregular/stochastic changes, however, the method faces troubles similar to that of Fourier analysis.

7.5 Comparison with another peculiar star

A revisit of the data on CoRoT 105288363 revealed a secondary modulation period with a similar period ratio (2.5) with the primary modulation period as V445 Lyr (2.7).

The new analysis of the CoRoT 105288363 data also points towards the excitation of more additional modes than the previously published second overtone. A non-radial mode as well as the first overtone might also be excited.

V445 Lyr also shows a change in the phasing of the two types of modulation (amplitude and phase modulation), similar to what was observed in CoRoT 105288363.

ACKNOWLEDGMENTS

Funding for this discovery mission is provided by NASA's Science Mission Directorate. EG acknowledges support from the Austrian Science Fund (FWF), project number P19962-N16. KK is presently a Marie Curie Fellow (IOF-255267). The research leading to these results has received funding from the European Commission's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 269194 (IRSES/ASK). RSz and JMB are supported by the Lendület programme of the Hungarian Academy of Sciences

and the Hungarian OTKA grants K83790 and MB08C 81013. RSz was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. C-CN thanks the funding from the National Science Council (of Taiwan) under the contract NSC 98-2112-M-008-013-MY3. We acknowledge the assistance of the queue observers, Chi-Sheng Lin and Hsiang-Yao Hsiao from the Lulin Observatory, and we thank Jhen-kuei Guo and Neelam Panwar for coordinating observations at the Tenagra II Observatory. JGC and BS are grateful to NSF grant AST-0908139 for partial support. Support for MC is provided by the Ministry for the Economy, Development, and Tourism's Programa Inicativa Científica Milenio through grant P07-021-F, awarded to The Milky Way Millennium Nucleus; by Proyecto Basal PFB-06/2007; by FONDAP Centro de Astrofísica 15010003; by Proyecto FONDECYT Regular #1110326; and by Proyecto Anillo ACT-86. The authors gratefully acknowledge the entire *Kepler* team, whose outstanding efforts have made these results possible.

REFERENCES

- Alcock C. et al., 2003, *ApJ*, 598, 597
- Arellano Ferro A., Bramich D. M., Figuera Jaimes R., Giridhar S., Kuppuswamy K., 2012, *MNRAS*, 420, 1333
- Asplund M., Grevesse N., Sauval A. J., Allende Prieto C., Kiselman D., 2004, *A&A*, 417, 751
- Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, *ARA&A*, 47, 481
- Benkő J. M. et al., 2010, *MNRAS*, 409, 1585
- Benkő J. M., Szabó R., Paparó M., 2011, *MNRAS*, 417, 974 (B11)
- Bertin E., Armouts S., 1996, *A&AS*, 117, 393
- Blazhko S. N., 1907, *Astron. Nachr.*, 175, 325
- Buchler R., Kolláth Z., 2011, *ApJ*, 731, 24
- Carretta E., Bragaglia A., Gratton R., D'Orazi V., Lucatello S., 2009, *A&A*, 508, 695
- Catelan M., 2009, *Ap&SS*, 320, 261
- Çelik L. et al., 2012, preprint (arXiv:1202.3607)
- Chadid M. et al., 2010, *A&A*, 510, 39
- Christiansen J. L. et al., 2011, *Kepler Data Characteristics Handbook* (KSCI-19040-002). NASA Ames Research Center, Moffett Field, CA
- Dziembowski W., Cassisi S., 1999, *Acta Astron.*, 49, 371
- Grevesse N., Noels A., 1993, in Prantzos N., Vangioni-Flam E., Casse M., eds, *Origin and Evolution of the Elements*. Cambridge Univ. Press, Cambridge, p. 15
- Guggenberger E., Kolenberg K., Chapellier E., Poretti E., Szabó R., Benkő J. M., Paparó M., 2011, *MNRAS*, 415, 1577
- Haas M. et al., 2010, *ApJ*, 713, L115
- Jenkins J. M. et al., 2010, *ApJ*, 713, L87
- Jurcsik J. et al., 2005, *A&A*, 430, 1049
- Jurcsik J. et al., 2008, *MNRAS*, 391, 164
- Jurcsik J. et al., 2009, *MNRAS*, 400, 1006
- Jurcsik J. et al., 2012, *MNRAS*, 423, 993
- Koch D. G. et al., 2010, *ApJ*, 713, L79
- Kolenberg K. et al., 2009, *MNRAS*, 396, 263
- Kolenberg K. et al., 2010, *ApJ*, 713, 198
- Kolenberg K. et al., 2011, *MNRAS*, 411, 878
- Kolláth Z., Molnár L., Szabó R., 2011, *MNRAS*, 414, 1111
- Kukarkin B. V., Kholopov P. N., Kukarkina N. F., Perova N. B., 1973, *Inf. Bull. Var. Stars*, 834, 1
- Landolt A. U., 2009, *AJ*, 137, 4186
- Lenz P., Breger M., 2005, *Commun. Asteroseismol.*, 146, 53
- Nemec J. M. et al., 2011, *MNRAS*, 417, 1022
- Ngeow C.-C., 2012, in Qian S., Leung K.-C., Zhu L., Kwok S., eds, *ASP Conf. Ser. Vol. 451, The 9th Pacific Rim Conf. on Stellar Astrophysics*, Astron. Soc. Pac., San Francisco, p. 103
- Popielski B. L., Dziembowski W. A., Cassisi S., 2000, *Acta Astron.*, 50, 491
- Poretti E. et al., 2010, *A&A*, 520, A108
- Reegen P., 2007, *A&A*, 467, 1353
- Romano G., 1972, *Inf. Bull. Var. Stars*, 645, 1
- Shapley H., 1916, *ApJ*, 43, 217
- Smolec R., Moskalik P., 2008, *Acta Astron.*, 58, 193
- Smolec R., Moskalik P., Kolenberg K., Bryson S., Cote M. T., Morris R. L., 2011, *MNRAS*, 414, 2950
- Sódor A. et al., 2011, *MNRAS*, 411, 1585
- Sódor A. et al., 2012, preprint (arXiv:1201.5474v1)
- Soszyński I. et al., 2009, *Acta Astron.*, 59, 1
- Soszyński I. et al., 2011, *Acta Astron.*, 61, 1
- Stothers R., 2006, *ApJ*, 652, 643
- Szabó R., Kolláth Z., Buchler J. R., 2004, *A&A*, 425, 627
- Szabó R. et al., 2010, *MNRAS*, 409, 1244
- Szabó R. et al., 2011, *MNRAS*, 413, 2709
- Szeidl B., Jurcsik J., 2009, *Commun. Asteroseismol.*, 160, 17
- Van Cleve J., Caldwell D. A., 2009, *Kepler Instrument Handbook* (KSCI 19033). NASA Ames Research Center, Moffett Field, CA
- Van Hoolst T., Dziembowski W. A., Kawaler S. D., 1998, *MNRAS*, 297, 536

The complex case of V445 Lyr 665

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. The scaled and detrended data set of V445 Lyr that was used for the analysis in this paper.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.

Chapter 4

A bisector analysis of the prototype RR Lyrae (Paper IV)

Part of the work described in this chapter has been published in the article:

- **Guggenberger, E.**; Shulyak, D.; Tsymbal, V.; Kolenberg, K.: *Bisector analysis of RR Lyrae: atmosphere dynamics at different phases*, published in “Precision Asteroseismology”, Proceedings of the International Astronomical Union, IAU Symposium, Volume 301, pp. 261-264 (2014)

The contribution of the author of the thesis to the paper was the following:

- assisted in preparing the spectra for the bisector analysis (i.e., prepared a selection of the spectra)
- selected lines suitable for analysis
- calculated bisectors and radial velocities for the selected lines
- computed synthetic spectra and derived atmospheric bisectors
- interpreted the results with respect to models
- wrote the paper

It was explained in Section 1.2 that RR Lyrae stars pulsate radially, either in the fundamental mode (RRab stars) or in the first overtone (RRc stars). But if one imagines a star that pulsates in the radial fundamental mode, one might have a simplified picture in mind in which – for the fundamental mode – all layers of the star expand or contract simultaneously, depending on the phase of the pulsation (this would represent a standing wave). But the reality is more complex, as running waves move through the star, and different layers have different velocities. One consequence of this fact is that RR Lyrae stars show a strong Van Hoof effect, i.e., a systematic difference between the velocity curves of different lines (see also Section 4.6). Also, strong shock waves are known to propagate through the stellar atmosphere (Fokin 1992; Fokin & Gillet 1997), leading to phenomena such as line doubling or line broadening in the spectra of RR Lyrae stars. These shock waves can also be observed photometrically, as they cause short-lived luminosity increases that are visible in the light curves (the so-called *bump* and *hump*), as well as UV excesses due to the high temperatures provoked by the shock.

The study of stellar spectral lines enables us to obtain a three-dimensional picture of the dynamic interior of the stellar atmosphere, as spectral lines are formed in different regions facing different environments. Tracing the asymmetry of one or more spectral lines through the pulsation cycle can provide us with a map of the motion of atmospheric layers. Also, as different parts of single lines are formed at different layers in the star, line asymmetries are a powerful tool to study stellar atmospheres. The line bisectors (see below for a definition) have become the standard tool to quantify and study line asymmetries.

In this chapter of the thesis this method will for the first time be applied to an RR Lyrae star, and the pulsational velocity fields within the atmosphere will be studied. First, however, the spectra used for the analysis need to be described.

4.1 Work preceding the bisector study

This section introduces the set of spectra and the studies that have been performed with it before the bisector analysis could be started. It briefly summarizes the work that was published by Kolenberg et al. (2010), as some of their results will be used as a basis for the study described later in this chapter. Additionally, the work that will be published by Fossati et al. (2014, in prep.) will be mentioned as the author of this thesis contributed to this analysis, and also because the results are an essential ingredient in the subsequent bisector study.

The spectra used for this bisector study were described in detail by Kolenberg et al. (2010). The original full data set consisted of 64 spectra that were obtained with the Robert G. Tull Coudé Spectrograph at the 2.7 m telescope at McDonald observatory and was provided by them for this bisector study. The resolution is $R=60000$, and the exposure time was always below a maximum of 960 s in order not to let the strong pulsation velocity changes smear out the lines. The data were taken between June 26 and August 27 in 2004. For calibration, Th-Ar

spectra were taken several time each night. The observed wavelengths range from 3633 to 10849 Å, but some parts in the longer wavelength range, however, were strongly influenced by telluric features and instrumental gaps. For further technical details, especially concerning the normalization which is important for temperature determination, we refer to Kolenberg et al. (2010). Of those 64 spectra, 7 spectra turned out not to be useful because of a wrong setting of the blaze angle during observations. 45 of the remaining spectra were taken at a Blazhko phase of around 0.3, and 12 were taken near a Blazhko phase of around 0.8.

A first inspection of the spectra already reveals many characteristics of the star, as can be seen in Figure 4.1 where spectra in wavelength scale are plotted in the order of increasing pulsation phase: The high amplitude of the radial velocity variation (several tens of km/s are typical for RR Lyrae stars) causes a displacement of the lines. At the same time, strong changes in temperature and pressure influences the depths of the lines. Some neutral lines (like the FeI line in Figure 4.1) even disappear during some phases, at least at the given S/N of typically between 100 and 300. A distortion of the lines is also present and is going to be measured quantitatively with the bisector method. Only the spectra near Blazhko phase of 0.3 are plotted here.

4.1.1 The “quiet” phase

The problem in the study of pulsation stars is that for the computation of synthetic spectra, only static model atmospheres are available, while the star itself is not static at all. In the first paper in their series Kolenberg et al. (2010) therefore selected among their data the spectrum taken during the most quiescent pulsation phase, as this is the one that is as close as possible to a static atmosphere. The phase around maximum radius turned out be the most unperturbed, according to their nonlinear stellar pulsation models and according to the variation of full width at half maximum (FWHM) with phase. The corresponding spectrum which was taken at a pulsation phase of 0.278 (and is referred to as spectrum number 260) was used to determine the chemical composition of RR Lyrae. This result in turn can serve as a basis for the analysis of the remaining data, as the abundances are not expected to change during the pulsation. The abundances of 45 elements were determined by Kolenberg et al. (2010). They determined a $(\log g)$ of 2.4 ± 0.2 , a temperature of $T_{\text{eff}} = 6125 \pm 50$ K, and a metallicity of $\text{Fe}/\text{H} = -1.30 \pm 0.1$ dex. During their analysis it became clear that it was necessary to use a depth-dependent microturbulent velocity, which they quantified.

In what follows we refer to the phase in which the spectrum shows the least distortion due to pulsation as the quiet phase. We are aware of the relativity of this expression, as an RR Lyrae atmosphere is never really “quiet”.

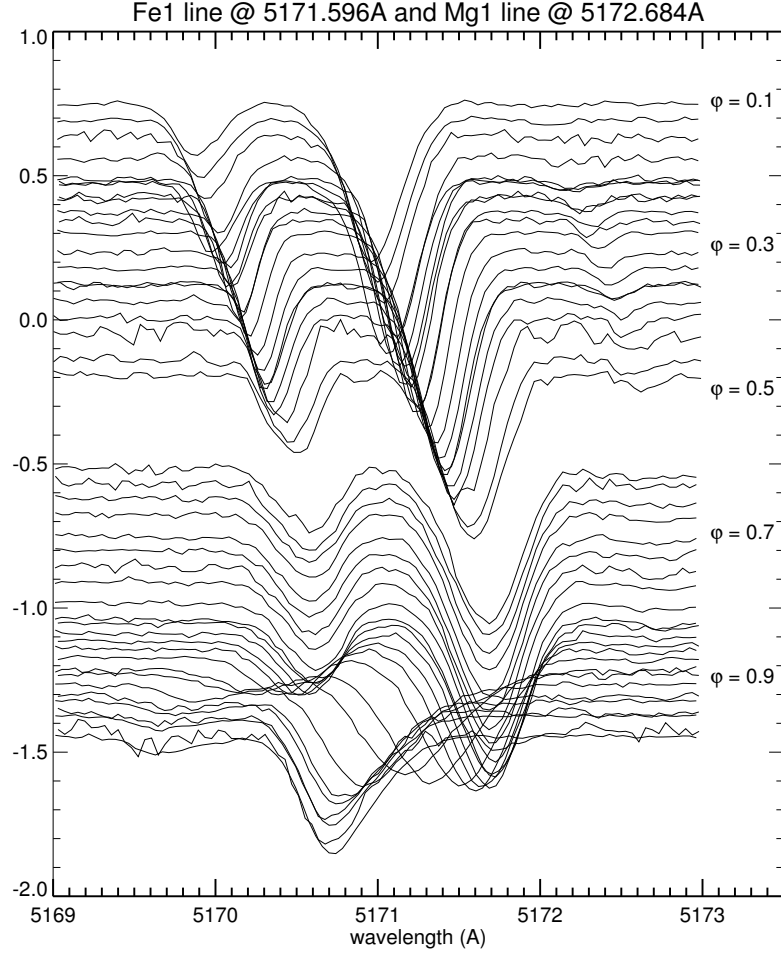


Figure 4.1: The set of spectra available for analysis shown. Spectra are sorted by phase from top to bottom and are plotted with an arbitrary shift in the y-scale. The motion of one iron and one magnesium line during the pulsation cycle can be seen.

4.1.2 Consistent analysis: parameters of all phases

As the bisector points of the observed spectra needed to be brought into context with the corresponding atmospheric depths, it was necessary to have synthetic spectra available for all phases which contain information on the optical depth of formation of the wavelength points. This, in turn, required an accurate value of the temperature for each phase, as well as an atmosphere model and knowledge of the microturbulence velocity profile. Therefore, a consistent analysis of all spectra was a basic requirement. This analysis of the whole set of the spectra was an iterative process. The detailed results of this analysis will be published by Fossati et al. (2014, in preparation) which is the second paper in the series on this data set of RR Lyrae. The author of this thesis contributed by processing in the described way

a subset of the spectra which were specifically important for the bisector study. To obtain line parameters, the VALD database (Kupka et al. 1999, 2000; Ryabchikova et al. 1997; Piskunov et al. 1995) was used. The gravity ($\log g$) was fixed to 2.4 (the value that had been found for the quiescent phase) for all spectra, as the expected changes are smaller than the uncertainty in the value. As the goal was a consistent study of different pulsation phases, it was important that all spectra were treated in exactly the same way. The process described below was therefore applied to all spectra.

1. The starting point was an indicative value of T_{eff} . This value was found based on the v_{mic} depth profile of the quiet phase and is therefore only preliminary but accurate enough to be a starting value. As the v_{mic} profile influences the resulting model atmosphere, and as v_{mic} is expected to change with pulsation, new models are needed for each spectrum.
2. Using the initial temperature and the v_{mic} profile of the quiet phase, an abundance analysis was performed. The WIDTHV code was used for this purpose. A list of 237 suitable lines had been selected for this step. They are all unblended lines, and their equivalent widths have been measured during the preparation of the analysis. Abundances were determined using only lines with small equivalent widths, as they are mostly independent of v_{mic} .
3. In the next step, we determined a new v_{mic} profile. This was done by eliminating the dependence of abundance and equivalent width. For this step, only ions that have several observed lines (4 lines minimum) and that have a wide range in equivalent width were used.
4. On the basis of the new v_{mic} profile, new atmosphere models were calculated for a range of different temperatures using the LLMODELS code (Shulyak et al. 2004). Usually a sequence of 5-9 models in temperature steps of 25K were calculated.
5. New synthetic spectra were calculated based on those models using the SYNTH3 code by Kochukhov (2007, 2012). The spectra were created only for the region around the $H\gamma$ line, as this was the one used to find the temperature.
6. A refined T_{eff} was measured by comparing the $H\gamma$ line with these new synthetic spectra. This was done with the help of the BINMAG software which allows easy viewing of observed and synthetic spectra. The temperature which reproduces the wings of the $H\gamma$ line best was selected.
7. Again, the WIDTHV code was used to determine new abundance values. As in the previous iteration only ions that fulfill the requirements (i.e., that have enough lines and with a wide spread in equivalent width) were chosen, and

abundances were determined using only the weak lines which are independent of v_{mic} .

8. A new v_{mic} profile was computed as in step 3.
9. This refined v_{mic} profile was used to perform a last abundance analysis (using the updated temperature). This time, however, in contrast to the previous abundance measurements, all lines (also strong lines with a large equivalent width) were taken into account. Due to the use of the now correctly determined v_{mic} profile the dependence on equivalent width had disappeared, and the abundances were all in good agreement.

In this way, final abundances were obtained for each spectrum (i.e., each observed pulsation phase). These, of course, only serve as error indicators, as the actual stellar abundances do not change during the pulsation.

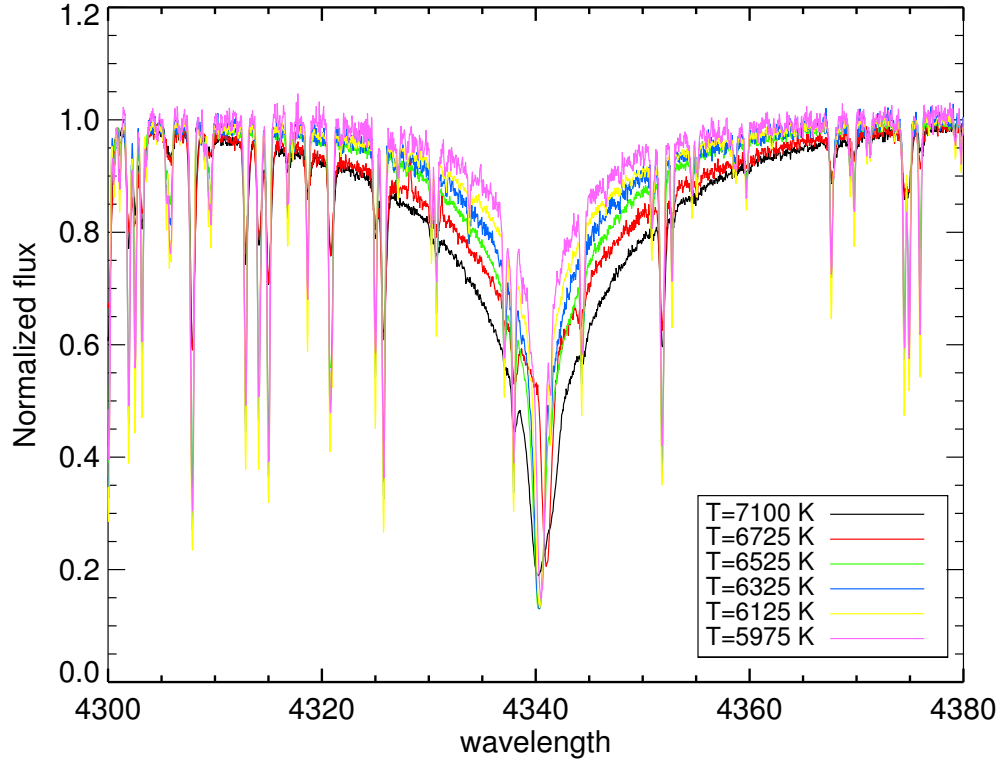


Figure 4.2: The effective temperature of RR Lyrae can vary by more than 1000 K (i.e., by about one sixth of the stars temperature) during the pulsation. This figure illustrates how much the $H\gamma$ line changes due to the differing temperatures during the pulsation.

This procedure was followed for all the spectra. Finally, besides the abundances, consistently determined temperatures and v_{mic} profiles were available for all of

them, and the derived abundances were in good agreement, as expected. Those final models were used as a basis for the synthetic spectra computed for the bisector analysis.

Temperature variations during the pulsation cycle in RR Lyrae stars can be large. In our spectra, temperatures between 5950 and 7125 K were observed. Figure 4.2 illustrates how strongly the effective temperature alters the $H\gamma$ line which was used as an indicator for T_{eff} .

The derived v_{mic} profiles for the various phases agree quite well in the relevant region where the line formation mainly takes place, and deviate only in the outer regions.

Now, after all relevant stellar parameters have been determined for all phases, and the best stellar model for each spectrum has been found, the actual bisector analysis can be started.

4.2 The Basics of Bisector analysis

The bisector of a spectral line is obtained by connecting the midpoints of horizontal lines running from one side of the line profile to the other side. Therefore, the ordinate is usually the intensity normalized to the continuum, and the abscissa in the wavelength or – more frequently – the velocity value of the bisector point. A schematic illustration of this concept is given in Figure 4.3. Bisectors are a powerful and quantitative tool to study line asymmetries. A perfectly symmetric line, of course, has a vertical straight bisector, while a distorted line shows a curved and/or tilted bisector. The span of the bisector, i.e., the difference between the highest and lowest measured velocity is usually termed the bisector *amplitude*. Bisector analyses are best analyzed in high-resolution spectra with $R \geq 60000$, as one needs as many observed points in a line as possible. The higher the resolution (and the S/N), the finer the details and the smaller the velocity fields that can be studied.

4.2.1 Methods of constructing the bisectors

Interpolation is always needed when constructing a bisector, because even with very high spectral resolution there will not always be observed spectral points available at exactly the same intensity on both sides of the line profile. Different strategies can be applied to find the bisector. One is the method used for example by Gray (1992) who uses interpolation only on the right side of the profile, while on the left (lower wavelength) side the observed points are used. This method might lead to a varying number of available bisector points depending on the width and depth of the line, missing data, etc. Another approach is to request bisector points at fixed fractions of the intensity (for example at 0.1, 0.2,... times the central line intensity). This approach requires interpolation on both profile wings, but leads to a fixed number of available bisector points. For this thesis, as we want to

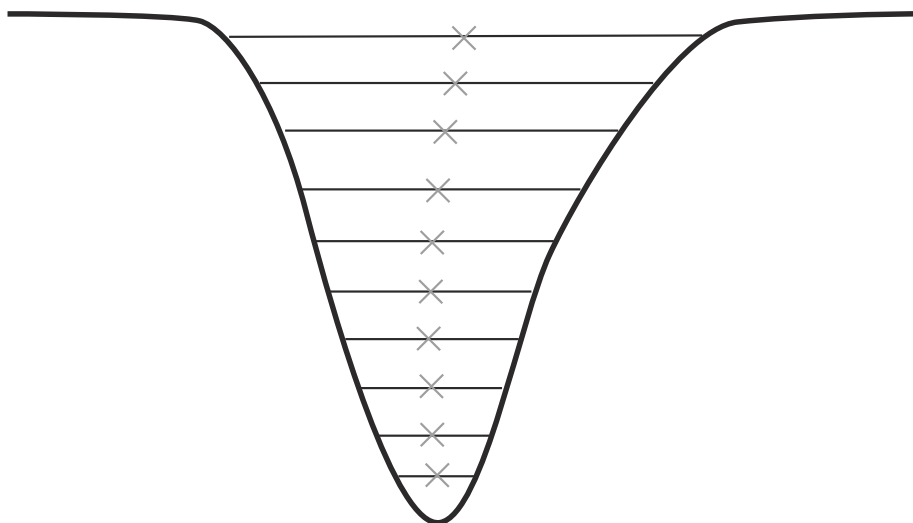


Figure 4.3: Schematic illustration of a spectral line bisector. It is constructed by finding the midpoints of the horizontal lines connecting the line wings.

compare bisectors obtained in different spectra and of different lines, it was more convenient to use the second method, in order to have a fixed number of points at fixed positions in the intensity for all spectra and all lines.

4.2.2 Applications of line bisectors

Bisectors are indicators of all kinds of atmospheric velocity fields and are used with various goals in mind:

Bisectors as indicators of granulation and convection: One possible cause for a line asymmetry is when velocity differences are associated with a brightness gradient. This happens when solar and stellar granulation and convection are present. The study of these phenomena is probably the most famous application of line bisectors. In the case of granulation the asymmetry of spectral lines arises because the rising and falling material contribute different amounts of the light. At the same time, they are shifted to different wavelengths: The hot rising granules move towards the observer and hence produce a blue-shifted component, which is strong due to the brightness of the granules. The intergranular lanes, on the other hand, are fainter and contribute a red-shifted, weaker component as they move away from the observer (see Figure 18.12 of Gray 1992). This leads to most frequent shape of a bisector: the classical “C”-shape that is seen in almost all

cool stars where convection plays a role. A comprehensive review on this topic is provided by Gray (1992).

Hot stars, however, usually show a reversed “C” shape and are separated from the cool stars by the so-called *granulation boundary* (see Figure 4.4). The cause of the reversed “C”-shaped bisectors has been a long-standing puzzle. A possible explanation is the one provided by Gray (2010) who proposed that a steep decline of the velocities with height in the star’s atmosphere together with a flux deficit in a part of the red wing might be responsible for the shape. The shape of bisectors therefore are a useful tool to check whether granulation is present in a star or not.

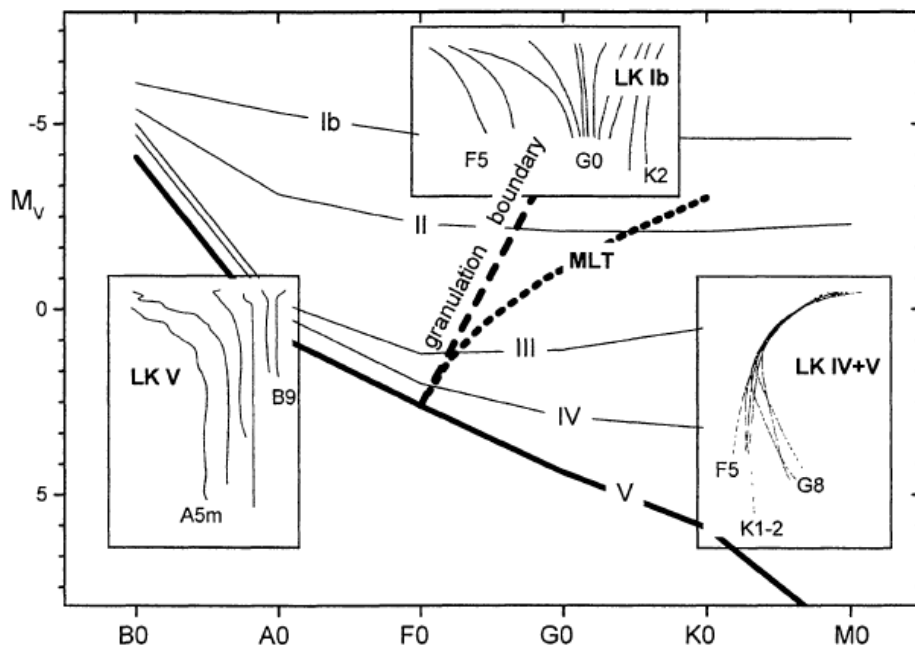


Figure 4.4: Illustration of different bisector shapes across the HRD from Weiss & Kupka (1999).

Bisectors as discriminants of Luminosity and Gravity: Not only is the overall shape of the bisector (“C” versus “reversed-C”) an indicator of temperature and hence the presence of convection, but also the fine details of its shape give information about the parameters of the star. This has been discovered by Gray (2005) who analyzed 54 cool stars and found the height of the bluest point of the line bisector depends on the luminosity class and gravity. This point, when used as an empirical luminosity indicator, can give a finer luminosity resolution than the common statement of a luminosity class.

Bisectors in planet hunting: Interestingly, bisector analyses is not only used for the study of stellar astrophysics. Also planet hunters, when trying to rule out

false positive detections, make use of bisectors. The underlying principle is that, when an orbiting planet causes a change in the radial velocity of the star, it should not alter the line profile (unless there is a transit), leaving the line bisector constant. If on the other hand the bisector changes together with the changing radial velocity, then the variation is most likely caused by phenomena in the stellar atmosphere such as pulsation rather than by a planet. An example for a study using this method can be found in Martínez Fiorenzano et al. (2005).

Bisectors to study the solar cycle: In the sun the metallic lines that are formed near the photosphere have the typical “C”-shape as it is expected for a cool star that is governed by convection. Some chromospheric lines, however, show a reversed “C”-shape which is still not fully explained. Already in the 1980s it was noted that the bisector amplitudes of certain photospheric lines change on timescales of years (Livingston 1984) which was attributed to the influence of the magnetic activity on the convection and hence to the solar cycle. Pietarila & Livingston (2011) on the other hand used a chromospheric (reversed C-shape) line of Ca II and found that the solar cycle affects only the part of the line that is formed in deeper layers, while the line core is not correlated with activity.

Bisectors to study pulsation: In some studies bisectors have been used to study the pulsation of stars, as it is also the goal of this study. For example, Wallerstein et al. (1992) applied the method to the H α line of Cepheids. He used the resulting bisector as a tool to determine whether line asymmetry is present, how strong it is, and when during the pulsation it occurs. The asymmetry of the lines in certain phases was attributed to a wave propagating through the line forming region. However, only a very small number of bisector points (two) were used by Wallerstein et al, with one point near the core of the line, and one point at half of the line depth. In this thesis a larger number of points will be used and hence more layers in the star will be studied.

A very detailed study of high-resolution ($R \simeq 100000$) spectra was performed by Elkin et al. (2008) who used line bisectors of different ions in the roAp star 10 Aql to investigate the atmospheric motions. From their spectra obtained at the VLT they could derive velocity amplitudes for different bisector points, demonstrating an increase of pulsation amplitude with atmospheric height, which is consistent with a wave running outward to layers with lower densities. Differing amplitudes of lines of different ions allowed them to map the velocity fields of the atmosphere. In roAp stars, the presence of pulsation nodes within the line forming region can even lead to phase jumps in the bisectors (Elkin et al. 2008) and to very different radial velocity amplitudes depending on the ion causing the line, and therefore depending on depth in the atmosphere.

In spite of their usefulness, bisector analyses, however, have not been applied to RR Lyrae stars before. In those large-amplitude stars it can be expected that

pulsation is by far the strongest signal influencing the line shape and therefore the bisector. Also, as we perform a relative analysis by comparing different phases of the same star with each other, factors that influence all spectra equally will in most cases be irrelevant.

4.3 Line selection for the bisector analysis

To study bisectors it is of great importance to select lines which are not blended with others, as this would introduce a spurious line distortion that is unrelated to pulsation. When following a bisector of a given line through the pulsation, it is also good to select lines that do not fully disappear in the more violent phases of the star. To select useful lines, both the observed and the synthetic spectra were inspected, as the latter are important to identify weak blends that would not be obvious in the observations. Also, metallic lines that lie within the extended wings of hydrogen lines were excluded. For those lines, which at their wings never reach continuum level, it is impossible to get bisector points at high intensity values that are comparable with those of other lines.

The final sample of lines used is listed in Table 4.1 and consists of strong as well as weak lines mainly of iron and titanium, but also some lines of other elements were included. Both neutral and ionized lines are used, which in the following are designated with the numbers 1 for neutral lines, and 2 for singly-ionized lines, according to the usual convention. In the wavelength region beyond 6500 Å, instrumental effects as well as telluric lines play such a big role that the lines that were selected for the bisector analysis can only be found between 4000 and 6500 Å. Another reason is that lines in RR Lyrae stars are quite sparse at longer wavelengths.

Table 4.1: List of selected lines.

Table 4.1					
$\lambda(\text{\AA})$	ion	$\lambda(\text{\AA})$	ion	$\lambda(\text{\AA})$	ion
Fe 1 lines					
4062.4409	Fe1	4494.5630	Fe1	5324.1790	Fe1
4067.9777	Fe1	4602.9410	Fe1	5339.9290	Fe1
4132.8990	Fe1	4607.6460	Fe1	5369.9610	Fe1
4147.6690	Fe1	4890.7540	Fe1	5383.3690	Fe1
4184.8910	Fe1	4891.4920	Fe1	5397.1270	Fe1
4187.0380	Fe1	4903.3080	Fe1	5405.7750	Fe1
4199.0950	Fe1	4920.5020	Fe1	5415.1990	Fe1
4202.0280	Fe1	5014.9420	Fe1	5434.5230	Fe1
4217.5456	Fe1	5049.8198	Fe1	5569.6180	Fe1
4238.8090	Fe1	5133.6880	Fe1	5572.8420	Fe1

4250.1190	Fe1	5192.3440	Fe1	5586.7559	Fe1
4250.7869	Fe1	5194.9410	Fe1	5615.6439	Fe1
4271.7600	Fe1	5232.9390	Fe1	6136.6150	Fe1
4325.7619	Fe1	5269.5370	Fe1		
Fe 2 lines					
4178.8620	Fe 2	4491.4050	Fe 2	4576.3400	Fe 2
4303.1760	Fe 2	4508.2880	Fe 2	4582.8350	Fe 2
4385.3870	Fe 2	4515.3390	Fe 2	4620.5210	Fe 2
4416.8300	Fe 2	4520.2240	Fe 2	5197.5770	Fe 2
4489.1830	Fe 2	4541.5240	Fe 2	5534.8470	Fe 2
Ti 2 lines					
4053.8209	Ti2	4443.7940	Ti2	4529.4740	Ti2
4312.8599	Ti2	4444.5545	Ti2	4563.7574	Ti2
4394.0510	Ti2	4450.4820	Ti2	4571.9680	Ti2
4395.0311	Ti2	4470.8532	Ti2	4708.6621	Ti2
4395.8389	Ti2	4501.2698	Ti2	4805.0850	Ti2
4399.7651	Ti2				
other lines					
4034.4830	Mn1	4425.4370	Ca1	5857.4510	Ca1
4121.3110	Co1	4554.0290	Ba2	5895.9240	Na1
4167.2710	Mg1	4588.1990	Cr2	6122.2170	Ca1
4208.9770	Zr2	5172.6840	Mg1	6141.7130	Ba2
4215.5190	Sr2	5528.4050	Mg1	6162.1730	Ca1
4246.8220	Sc2	5588.7490	Ca1	6347.1090	Si2
4254.3360	Cr1				

As a first step, the asymmetry. i.e., the bisector, of given single lines was traced through the pulsation cycle. As a starting point, a rough estimate of the radial velocity of each phase was necessary. This value was determined in advance. Based on this initial velocity, the line was found automatically in the spectrum, and the wavelength and intensity of twenty bisector points were determined. The result for a few selected lines can be seen in Figure 4.5 (for an Fe 1 and an Fe 2 line) and Figure 4.6 (a Mg 1 line and a Ti 2 line). At this stage, the wavelength was not yet transformed to velocity, to illustrate the line motion during pulsation as it appears in the observed spectrum. Bisector points above 0.95 in intensity should not be considered reliable, because noise in the data as well as slight blends start to play a significant role in this region.

The overall behavior is the same for all lines or elements, respectively: The motion of the lines in these plots is counterclockwise, with the long, almost vertical bisector near the middle of the plot belonging to the quiescent phase of maximum radius. Then, the star contracts and causes the lines to appear redshifted in the right part of the diagram. Around minimum radius lines become shallow due to

the prevailing temperature and pressure, and tilted due to velocity gradients in the stellar atmosphere. During expansion lines are in the left part of the diagram, i.e., blue-shifted from the viewpoint of an observer. Some important pulsation phases are labeled in the upper panel of Figure 4.5.

Similar to the findings of Elkin et al. (2008) we also observe that the tips of the bisectors (that represent the part of the line which has formed higher up in the atmosphere) have a larger range in wavelength and hence velocity, indicating already that velocity amplitudes are higher in the outer part of the star.

To compare the bisector shapes more directly, the wavelength values were then converted to velocities, and the bisectors from different spectra were plotted on top of each other by removing the velocity that was determined for the line in each spectrum. An example for this is given in Figure 4.7. The velocity of the center of gravity of the line was used in the case shown in Figure 4.7, resulting in an overlap of the middle part of the lines. Different velocity determination methods (for example, fitting the tip of the line) lead to a different stacking of the lines. The shape of the bisectors can more easily be compared in this plot.

4.3.1 Shifts between different ions

When the lines of different ions have different velocities, then consequently also the bisectors appear systematically shifted. In Figure 4.8, all bisectors of all used ions are shown for the quiet pulsation phase. Different colors indicate the elements: black is neutral Fe, red is Ti 2, green is Fe 2 and blue are the remaining lines of several other elements listed in Table 4.1. An approximate gamma velocity of RR Lyrae of 80 km/s was subtracted from all lines for this plot.

It is obvious that there is a clear shift between the bisectors of different lines. This figure is reminiscent of the graphs shown by Gray (2009) in connection with the so-called “third signature of convection”. In this nomenclature, the macroturbulence, which describes large-scale velocity fields, is the first signature of granulation. The shape of the bisectors is the second signature, and the differential shifts between bisectors of different lines is the third signature. In the Sun, as well as in other stars, weaker lines have been found to be more blueshifted than the stronger lines, because weak lines are usually formed in deeper layers of the atmosphere than the cores of stronger lines and therefore are affected by other convective velocities. Scaling factors can be found to transform the solar pattern to other stars with different temperatures (Gray 2009). Interestingly, Gray (2009) also found the same pattern for a hot star on the blue side of the granulation boundary.

However, in a pulsating star with such a high amplitude, one can expect that granulation, even if it were there, would most likely be hidden beneath the strong signal of the pulsation motions. In this sense, the only chance to check for granulation in an RR Lyrae star would be during the most quiescent phase.

Another difference between Figure 4.8 and the study of Gray (2009) is that they used only lines of Fe 1, while in our diagram, different elements and ions can

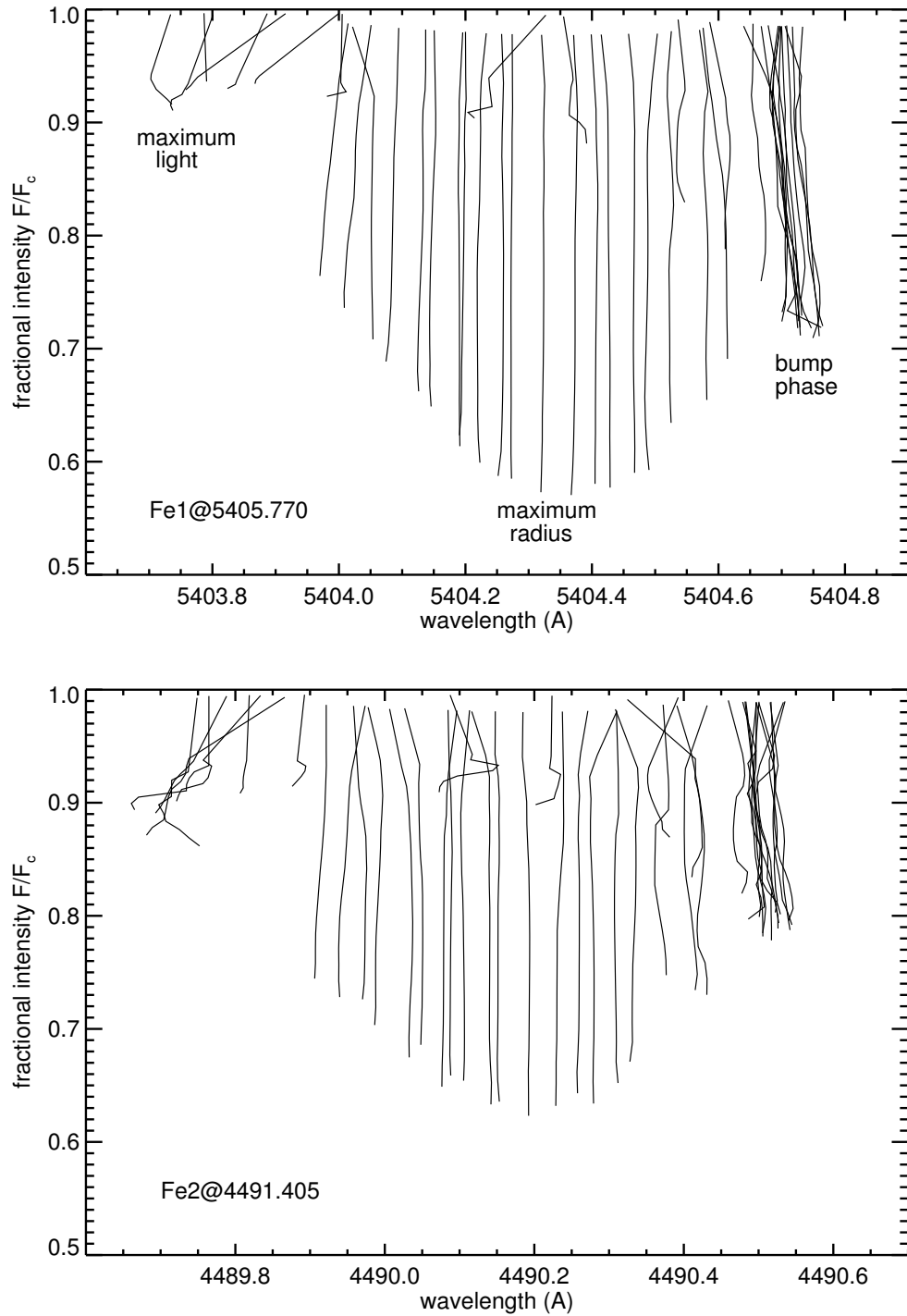


Figure 4.5: Tracing the Fe 1 line at 5407.770 $\text{\AA}$ and the Fe 2 line at 4491.405 $\text{\AA}$ through the pulsation cycle. Note how lines gets deeper and shallower due to the drastic change in temperature and pressure.

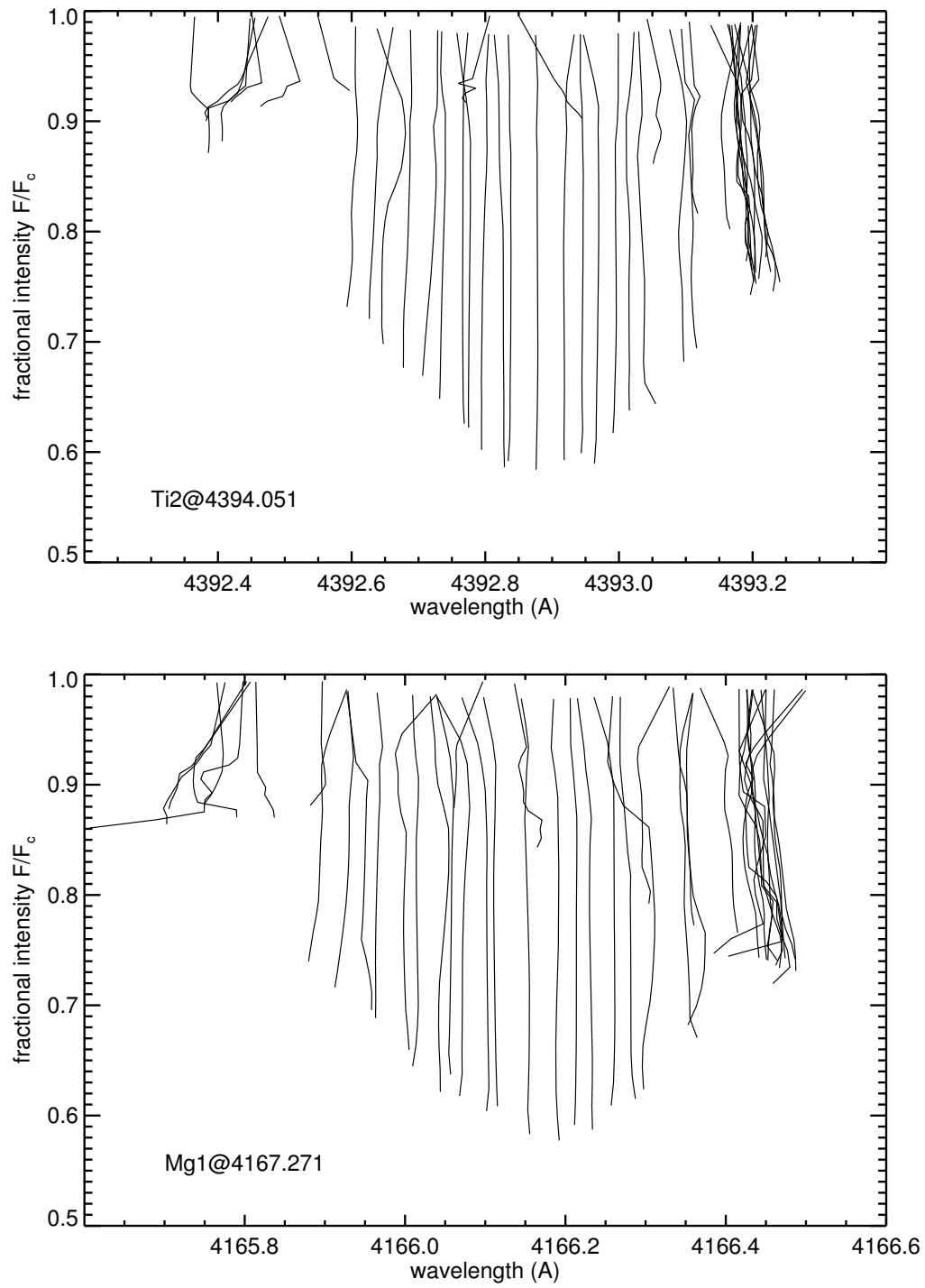


Figure 4.6: Same as Figure 4.5 but for the Ti 2 line at 4394.051 and the Mg 1 line at 4167.271 $\text{\AA}$

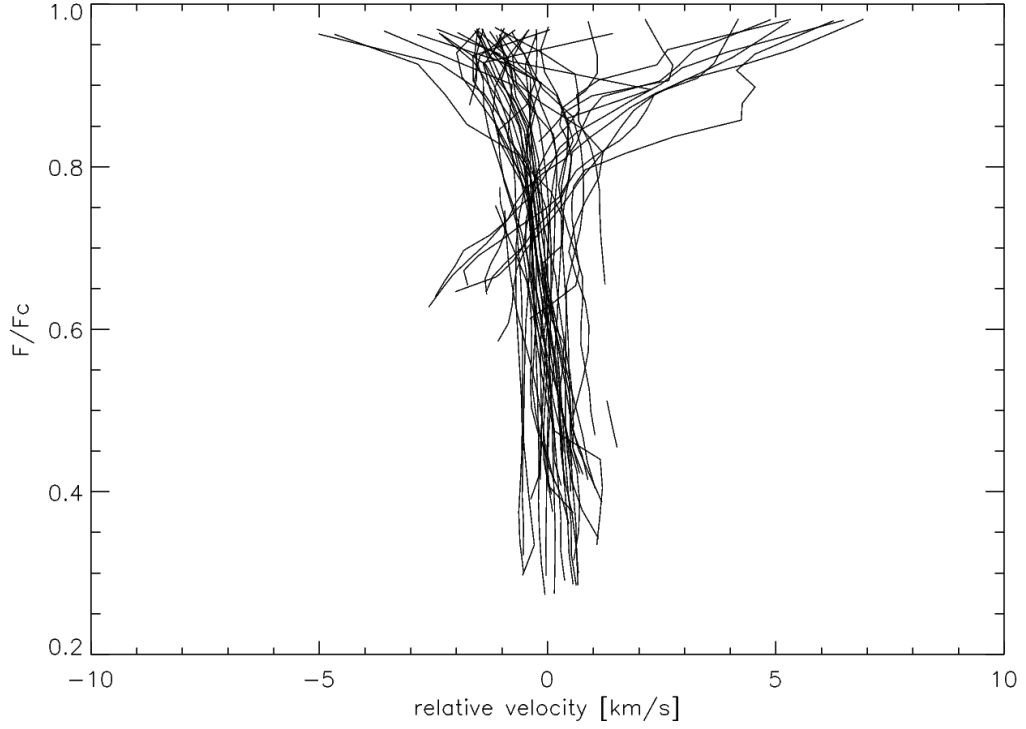


Figure 4.7: Motion of the 4383.545 Å line during the pulsation cycle, corrected for the radial velocity of each spectrum so that lines are plotted on top of each other.

be found, and a strong shift occurs between the lines of Fe1 and Fe 2. Even though Fe 2 lines are typically more shallow, the observed shift is not purely caused by line depth, as it can be seen, for example, from the shallow Ti 2 lines which are shifted in the opposite direction as the shallow Fe 2 lines.

The possibility that the effect is caused by an instrumental drift which influences the wavelength calibration can be excluded because the lines of all ions were not selected from different regions but are spread over the same wavelength range and therefore should be affected in the same way if an error in the wavelength calibration were present.

4.4 The bisector in atmospheric depth

So far, the bisectors had only been calculated in the classical sense, i.e., as observed intensity versus wavelength (or velocity). This had not been done for an RR Lyrae star before. In this section, however, we go even a step further and connect the points on the line wings to an actual position in the star by using the optical depths which are found in the synthetic spectra, as well as the column mass, $\int \rho dx$, that can be extracted in a subsequent step from the atmosphere models. In this way we construct a *atmospheric bisectors*, i.e., Rosseland $\log(\tau)$ versus velocity or column

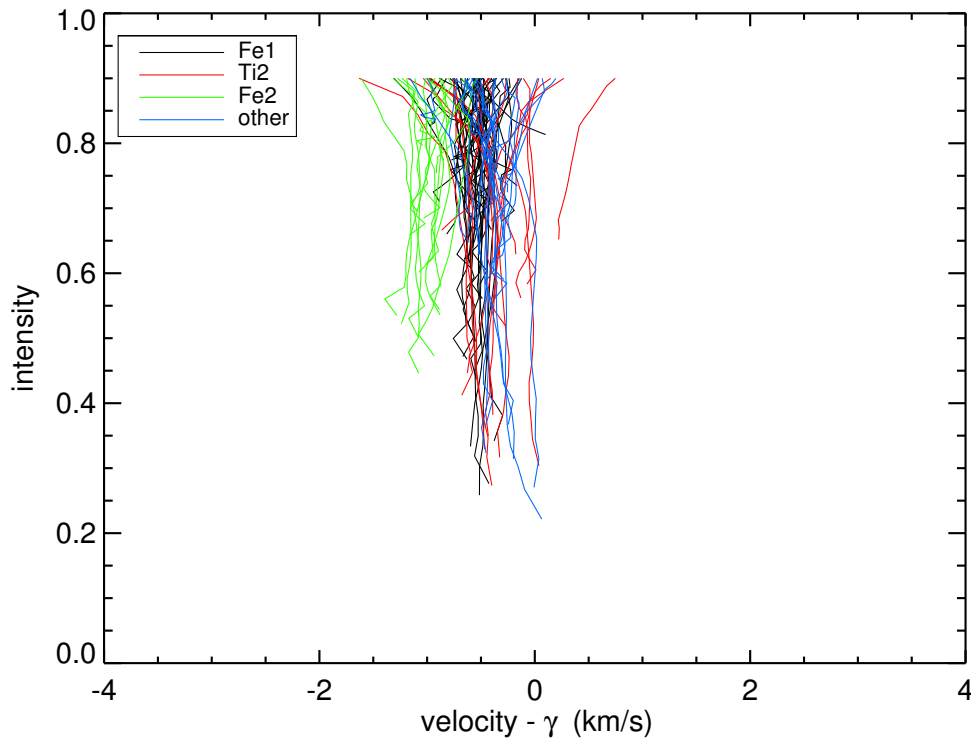


Figure 4.8: Classical bisectors for all selected lines in the quiet phase. The different ions show different velocities.

mass versus velocity, which indicate the velocity in difference depths in the stellar atmosphere.

For this purpose, synthetic spectra over the complete wavelength range were computed using the SYNTHV code (Tsymbal 1996). This spectrum synthesis code produces spectra from a given atmosphere model and a line list, for example as the ones extracted from VALD. In contrast to other synthesis codes, it can handle depth-dependent microturbulent velocities which can be provided in an optional additional input file, and it was modified to provide the optical depth in the output together with the regular synthetic spectrum.

Concerning the rotation and macroturbulence velocities v_{ini} and v_{macro} , respectively, several combinations were tested. In contrast to the bluer horizontal branch stars, RR Lyrae stars are generally slow rotators with narrow lines and usually only upper limits for their rotation can be given (see for example Peterson et al. 1996). For the same reason, Kolenberg et al. (2010) could not determine definite values for the velocities but were able to give ranges for them: v_{ini} is between 0 and 9 kms^{-1} , and v_{macro} is between 6 and 11 kms^{-1} . The values are not independent of each other as both contribute to line broadening. Therefore, using the minimum value of v_{macro} requires using the maximum of v_{ini} and vice versa.

After testing several combinations, the values that were finally used to convolve our synthetic spectra were $v_{\text{ini}} = 9$ km/s and $v_{\text{macro}} = 6$ km/s, as this turned out to fit the observed spectra best.

To be able to compare the synthetic spectra to the observations, they were convolved to have the correct instrumental resolution so that they match the observed spectra. One has to note that due to the finite resolution, the narrow core of the line (which is formed in the highest layers) is not fully resolved, decreasing our ability to study these parts of the atmosphere. The convolution leads to a mixture of different τ values, which especially results in a decrease in the maximum atmospheric height that can be observed. We therefore cannot probe the highest line forming regions. This means that, even though lines are normally formed in a region between $0.5 \geq \log(\tau) \geq -3$, after convolution we can almost exclusively investigate values in the range $0.5 \geq \log(\tau) \geq -2$.

Figure 4.9 shows all selected lines together with their classical bisectors (middle panels) and their bisectors in atmospheric depth (right panels). Only results for the “quiet” phase is shown here as an example as the full set of lines for all spectra would require too much space.

The procedure to arrive at an atmospheric bisector then was the following: For each line the code reads in the spectrum as well as a previously estimated velocity of the photosphere at the phase in question. This value was found by analyzing the LSD profile of the spectrum. Based on this velocity, each desired line can be correctly located in the observations. After that, the synthetic spectrum is read by the code, and the selected line is cut from it. Using the known laboratory wavelength, both lines (the observed as well as the synthetic one) are transformed to velocity space. The data are then interpolated to the desired bisector points at the given fractions of total line depth (see Section 4.2.1), and the horizontal middle points between the interpolated line points (the bisector points) are calculated.

In the next step, the code estimates the corresponding formation depth τ , as well as the interpolated layer number for each point in the line profile using information provided by the spectrum synthesis. With the help of the layer number, the column mass $\int \rho dx$ as well as the Rosseland optical depth $\log(\tau_{\text{Ross}})$ can be extracted from the model atmosphere. The result is a file that contains the bisector information on all selected lines in the input list for a given spectrum.

The projection of the line profile points to the $\log(\tau_{\text{Ross}})$ function and to the column mass, respectively, was not an easy step, as several aspects needed to be considered. One is that the lines in the synthesis are always symmetric, as the synthesis is based on a static model atmosphere. In reality, the lines are not symmetric, because we are dealing with a fast pulsating star. The line distortions that are present in the observations are therefore not represented in the synthesis, and it would make a difference whether the blue or the red wing of the observed line is mapped to the function of $\log(\tau_{\text{Ross}})$. Also, it is necessary to consider the wavelength shift caused by the overall radial velocity of the star to connect the observed wavelength to the correct part of the line in the synthetic spectrum. Not

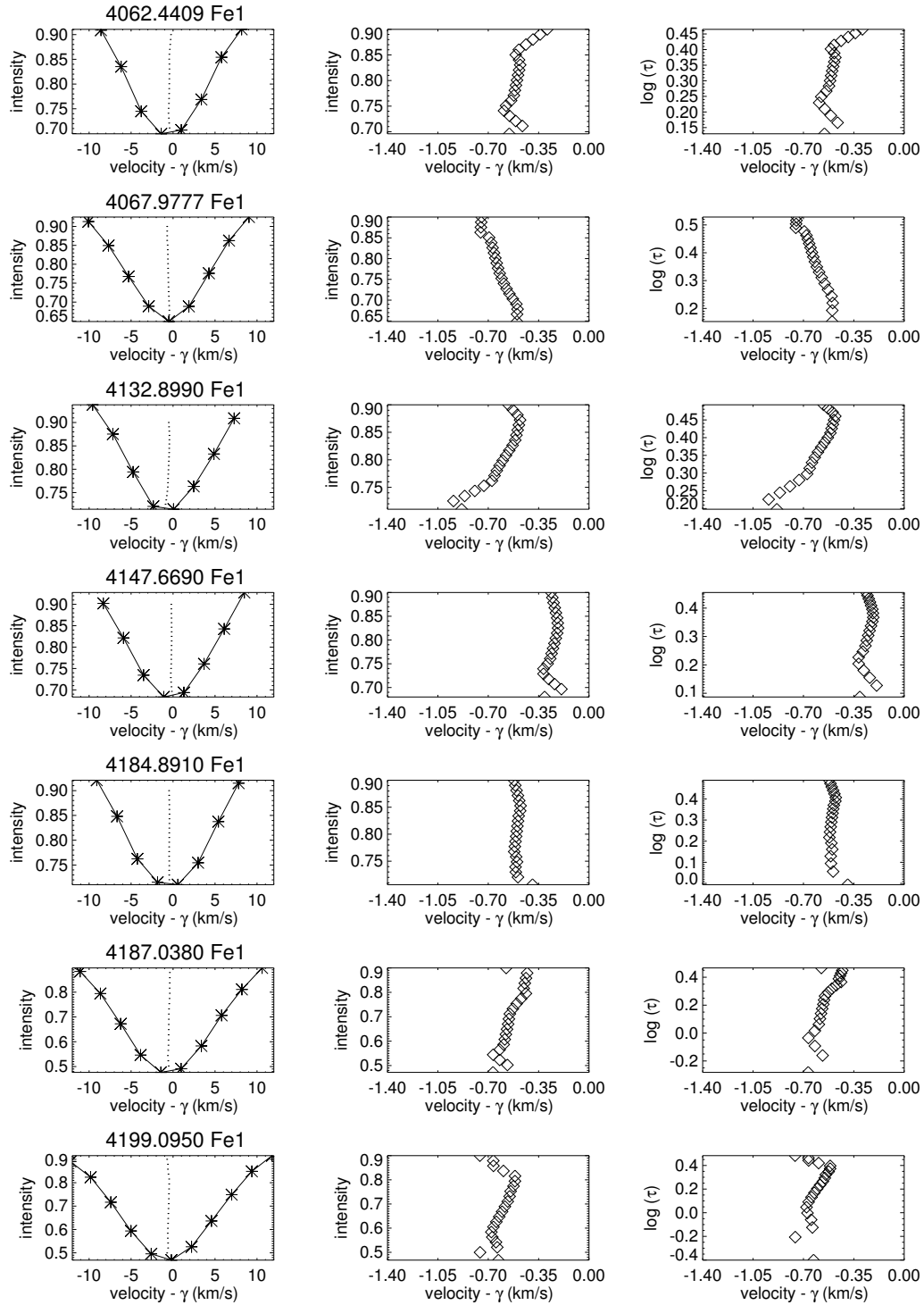


Figure 4.9: Observed data in velocity space (left panel), classical bisectors (middle panel), and atmospheric bisectors (right panel). Asterisks represent observed spectral points, dots and diamonds are the calculated bisector points.

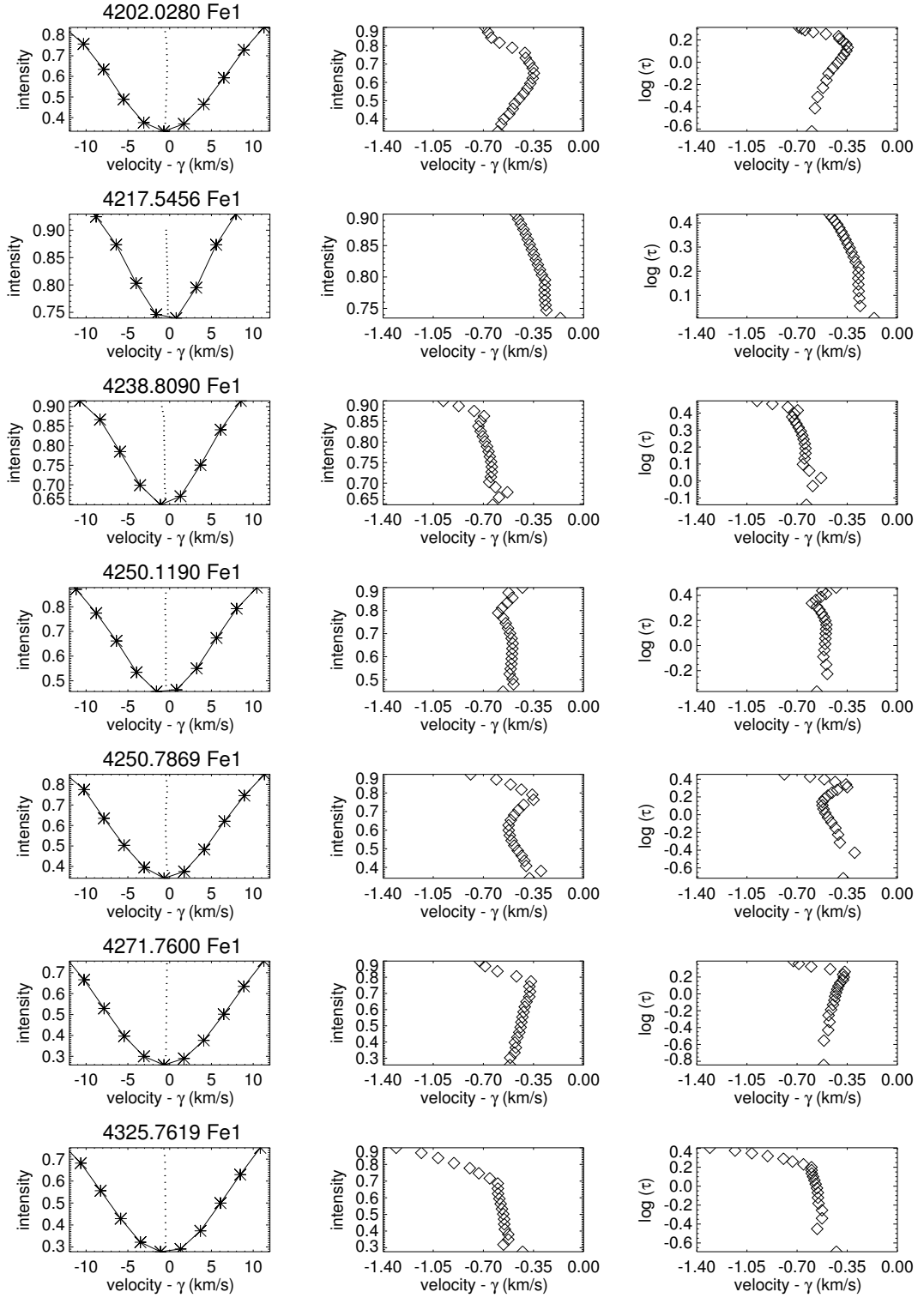


Figure 4.9: continued

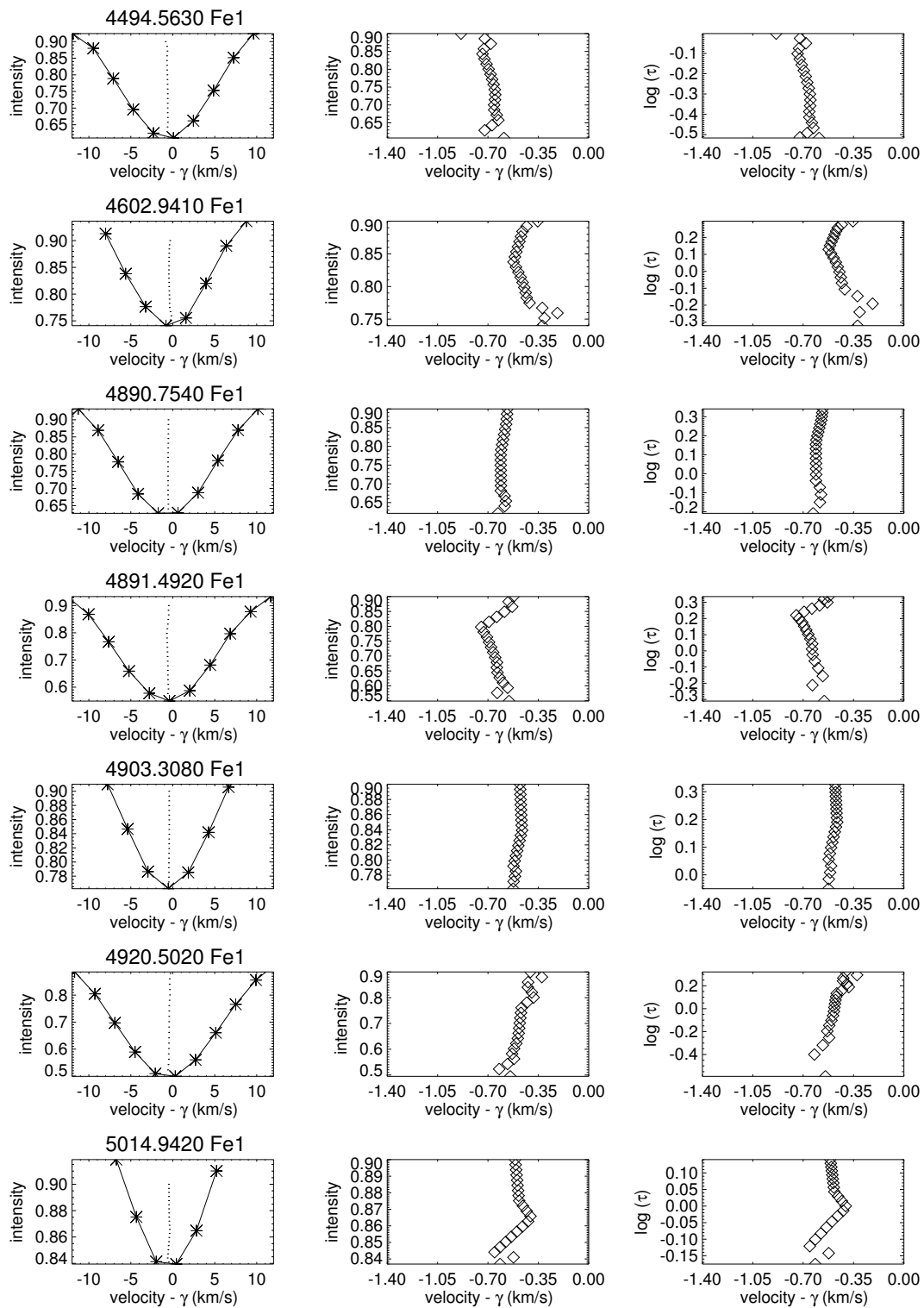


Figure 4.9: continued

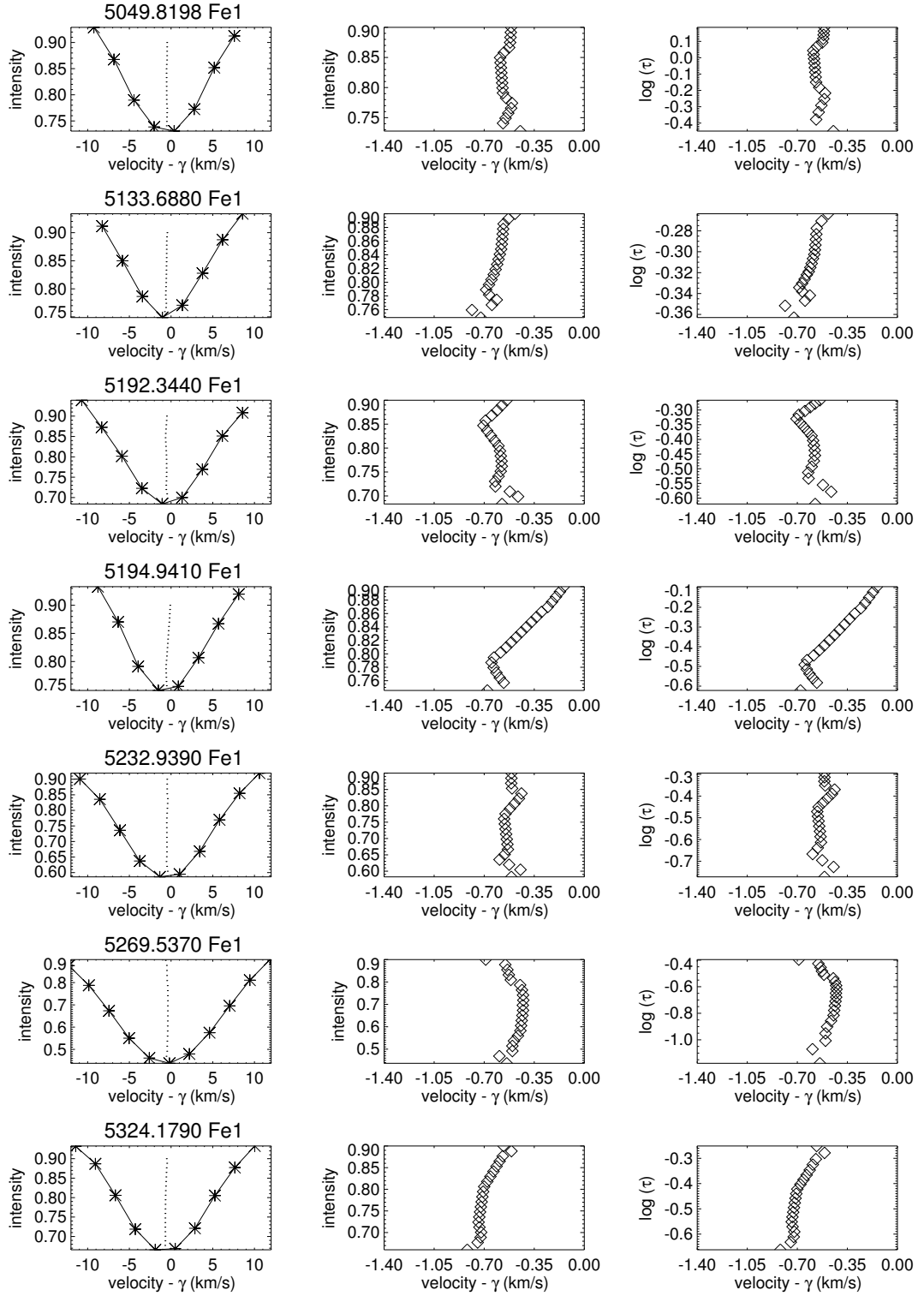


Figure 4.9: continued

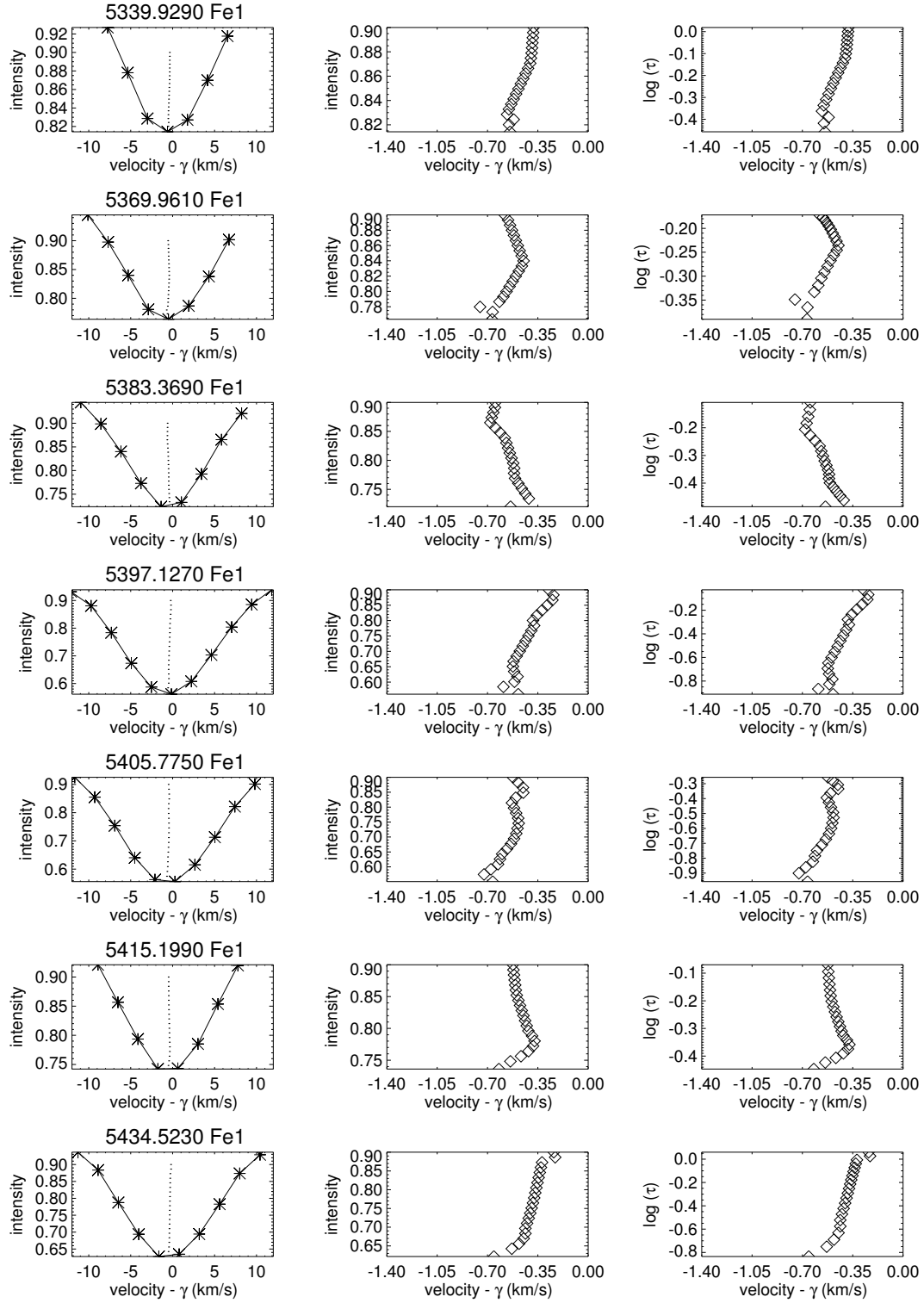


Figure 4.9: continued

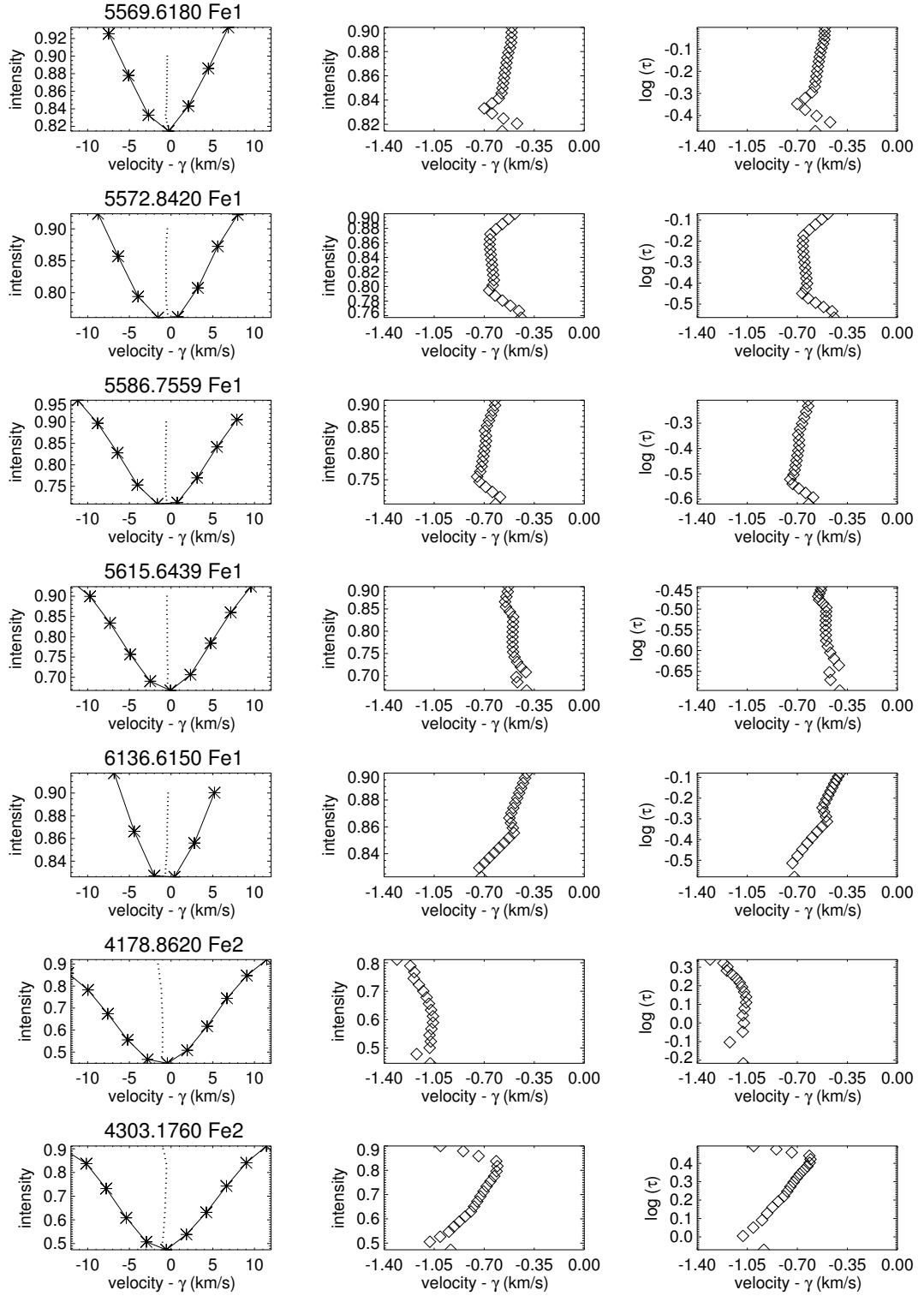


Figure 4.9: continued

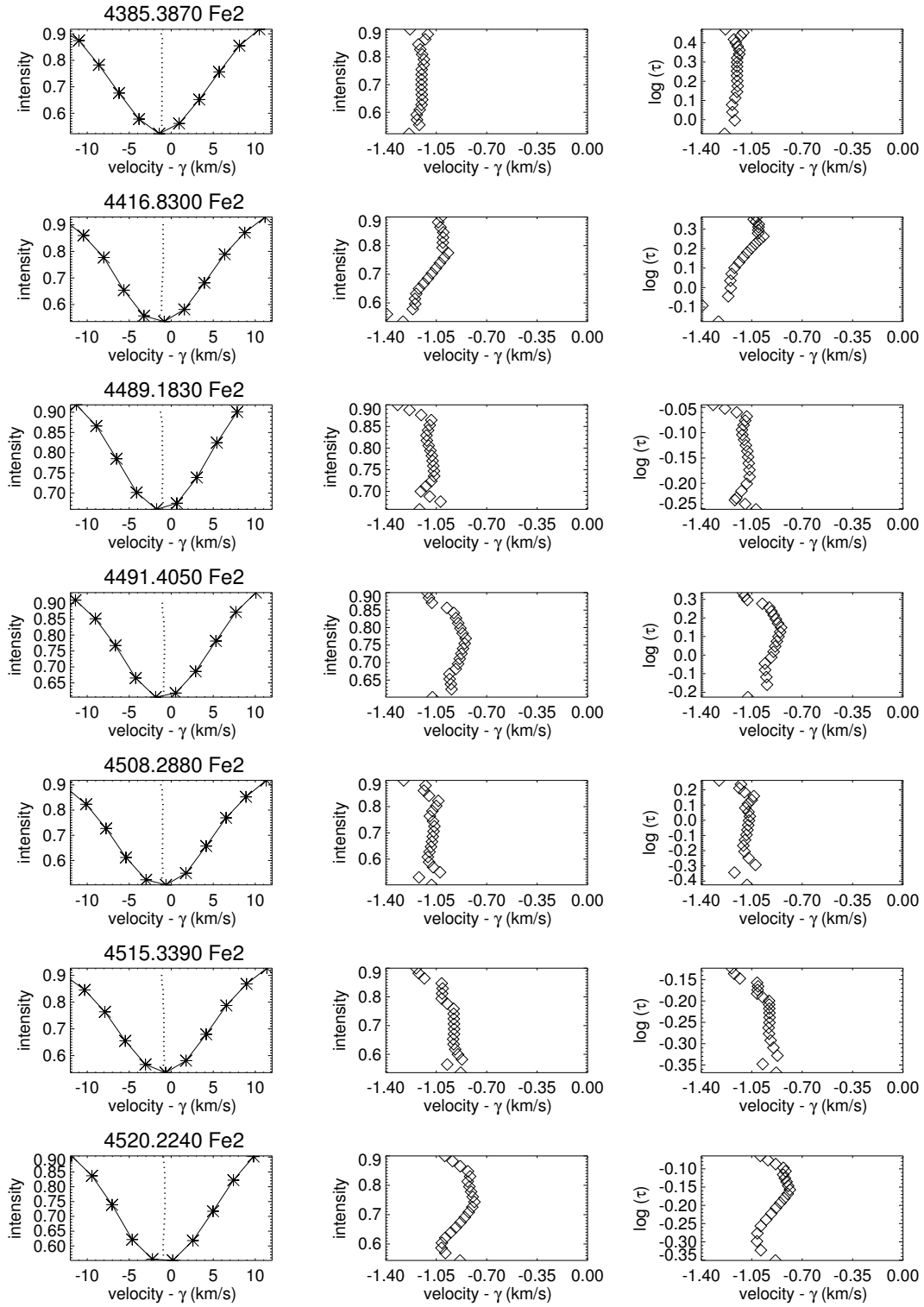


Figure 4.9: continued

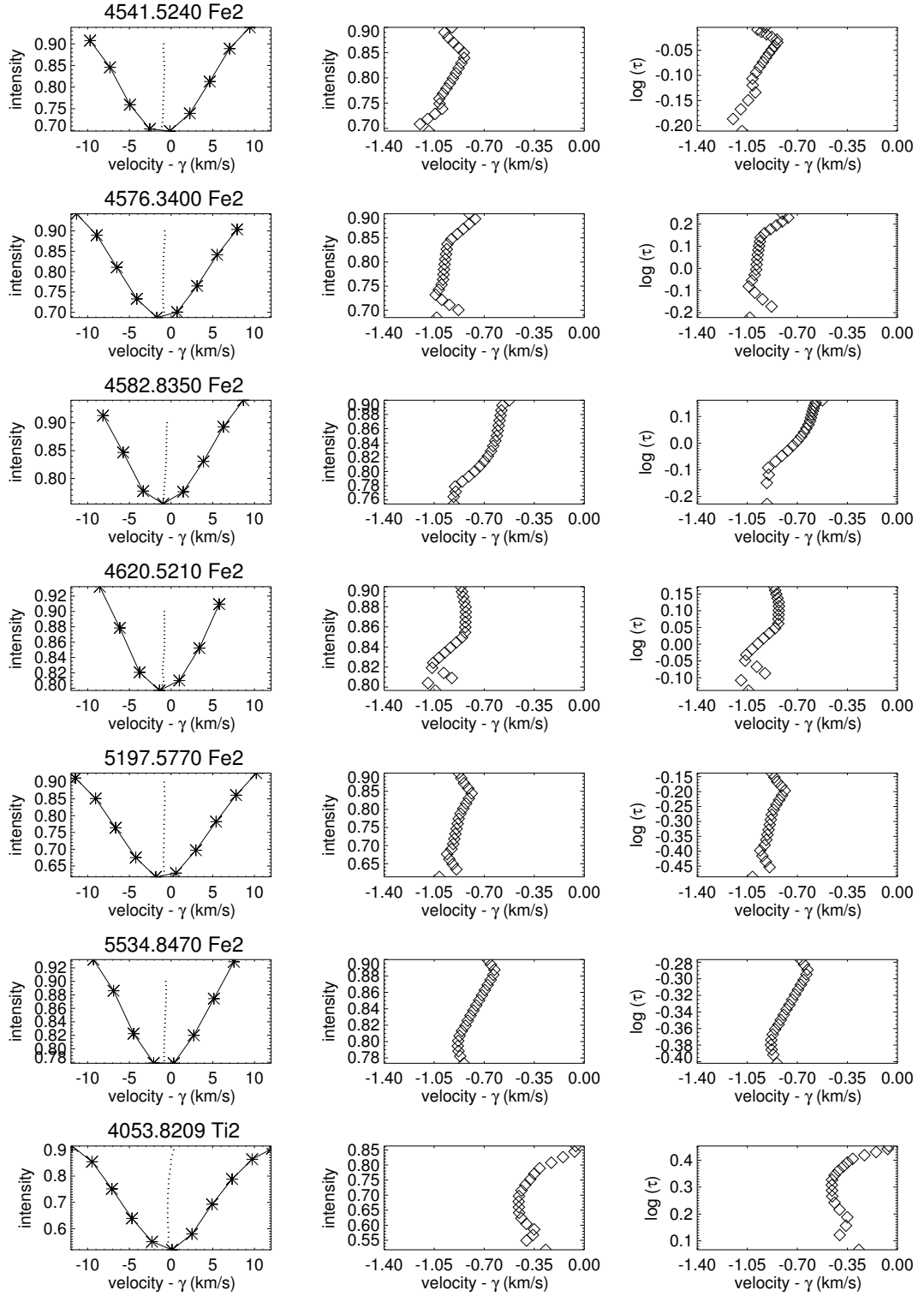


Figure 4.9: continued

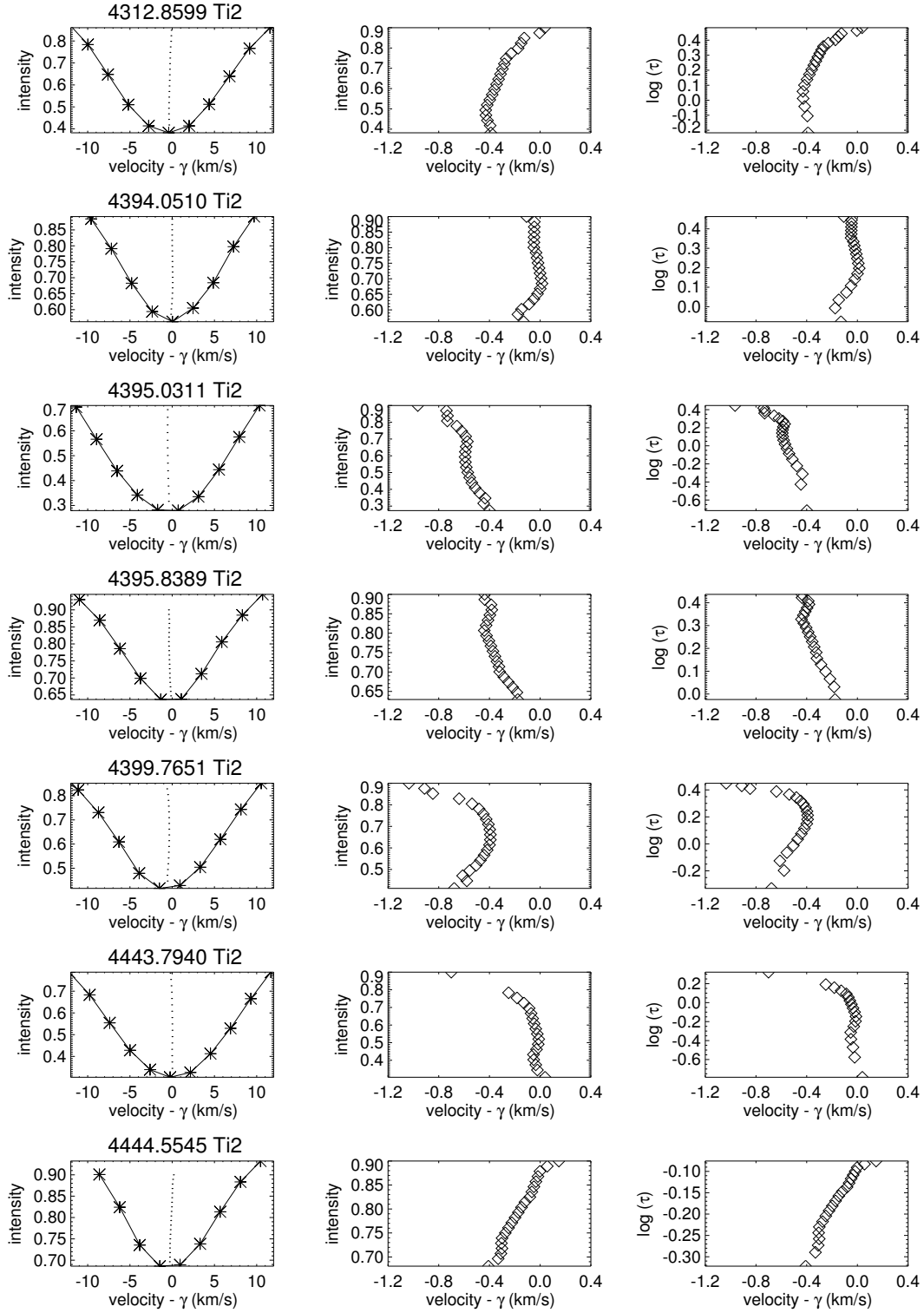


Figure 4.9: continued

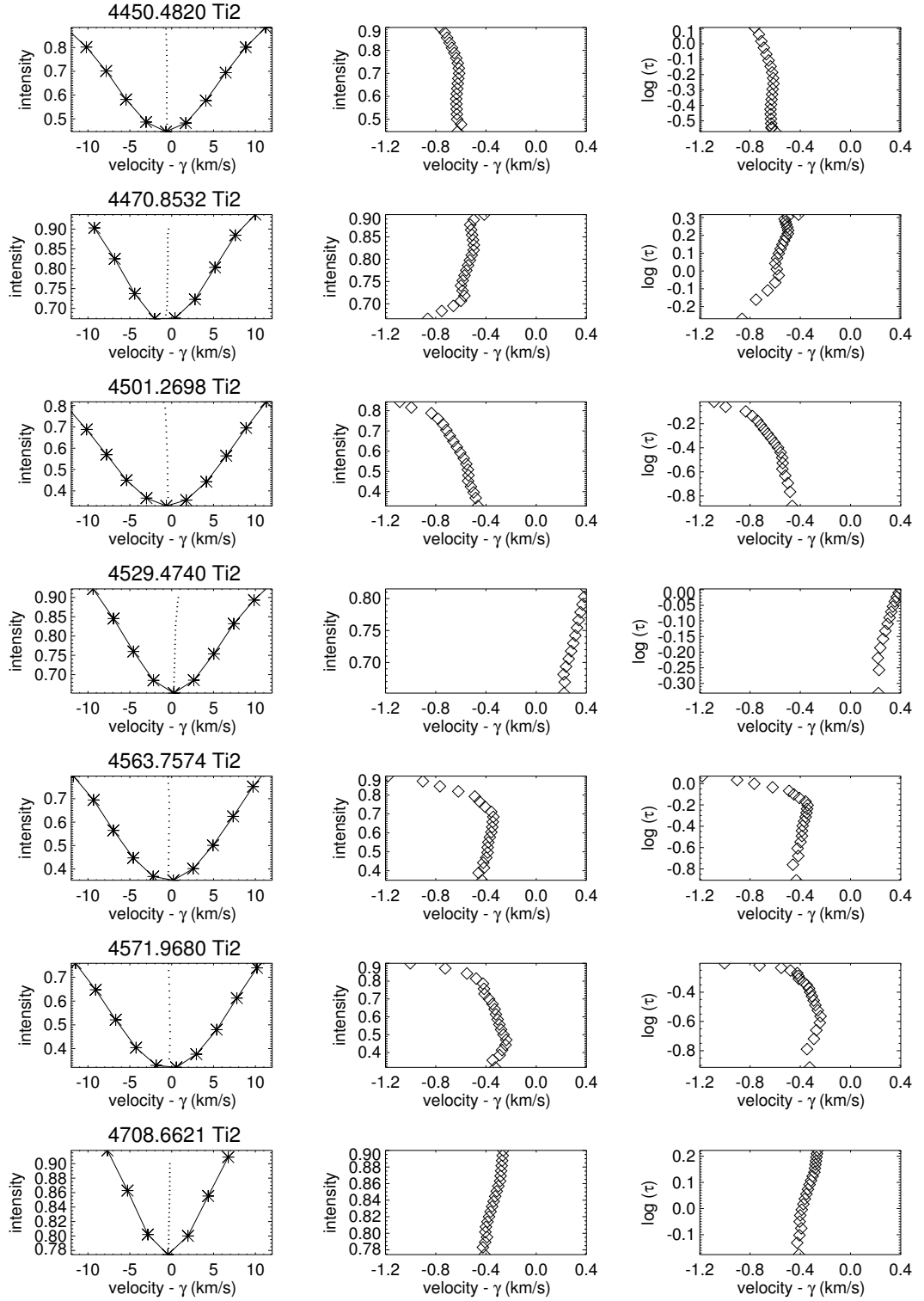


Figure 4.9: continued

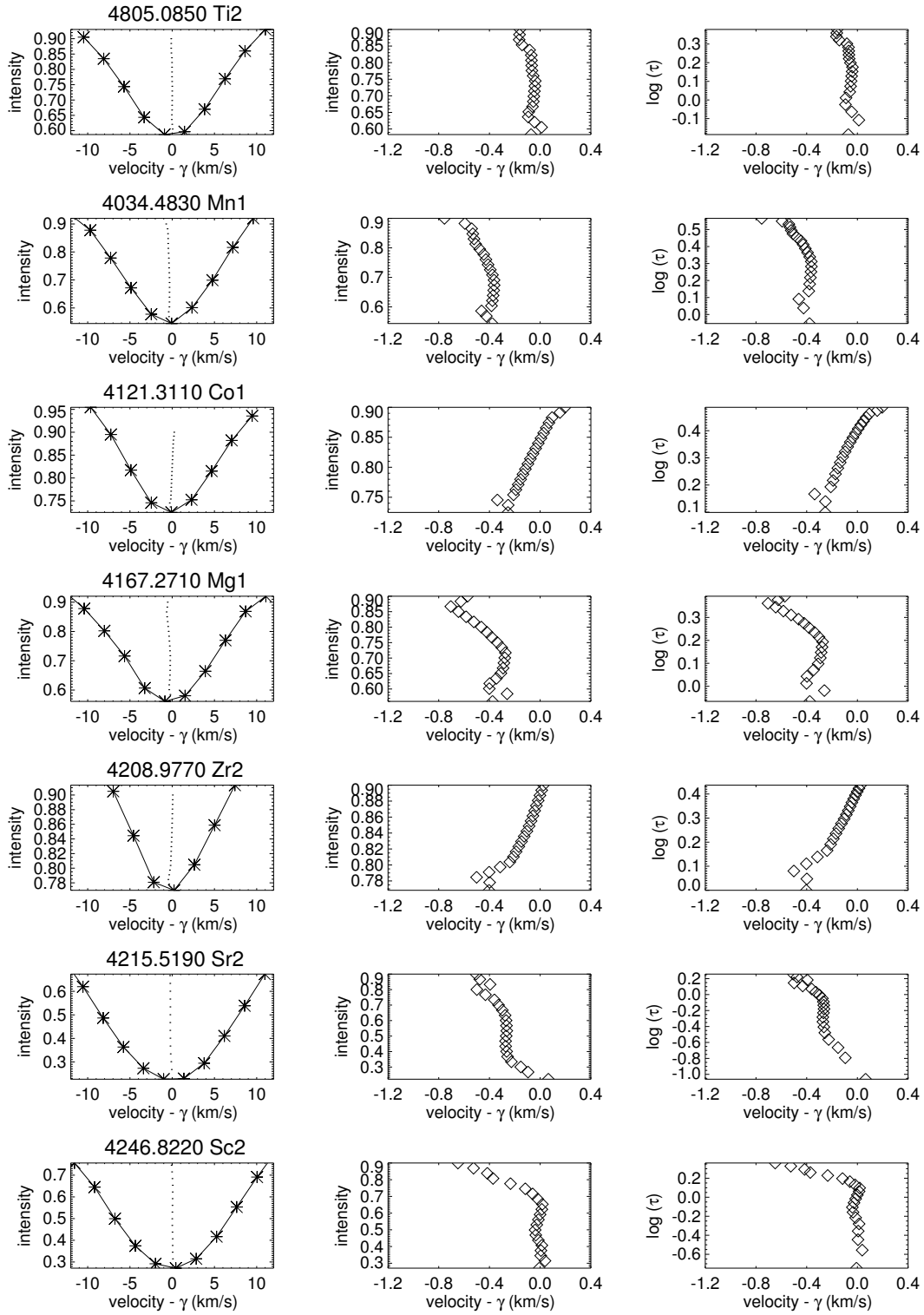


Figure 4.9: continued

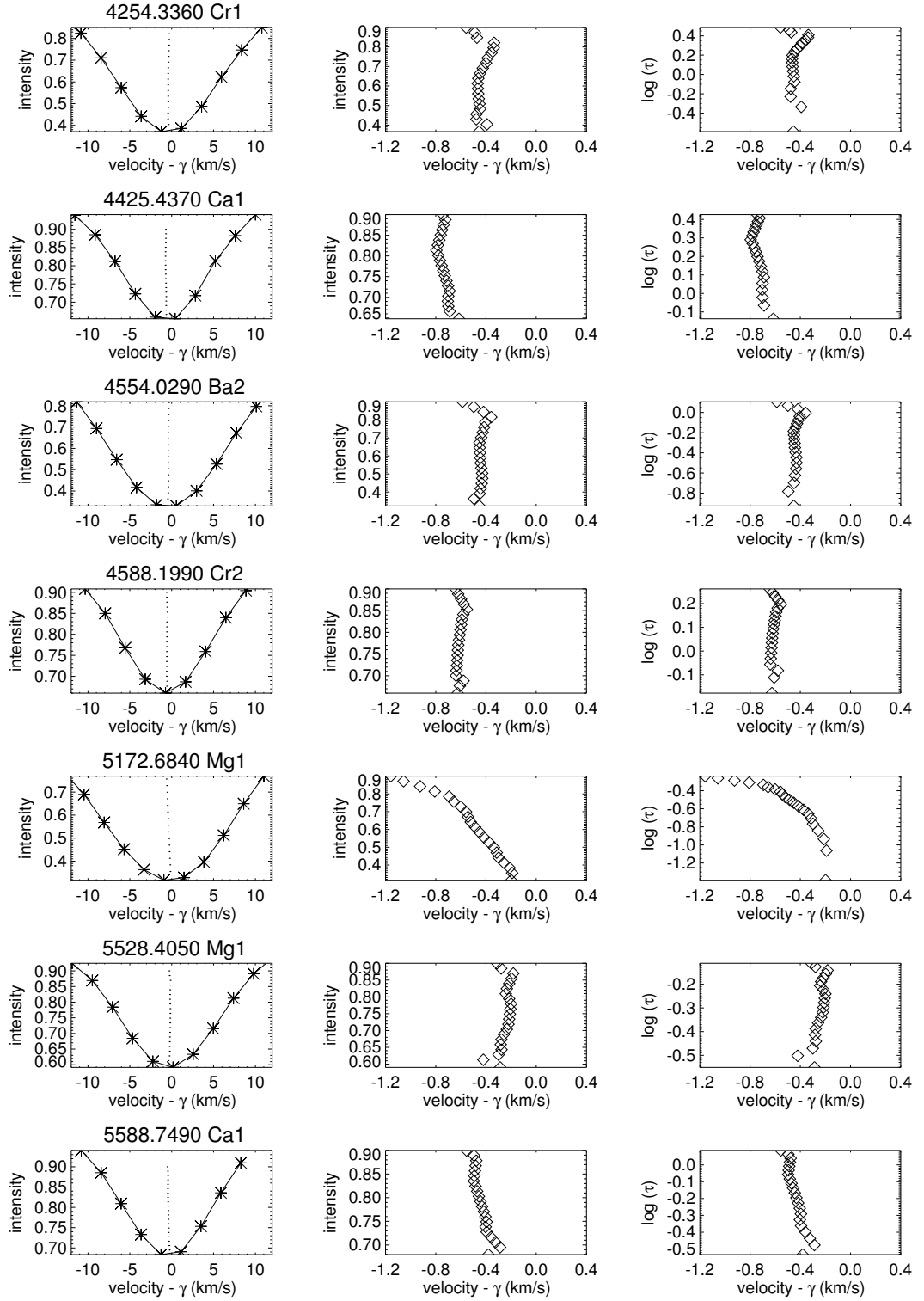


Figure 4.9: continued

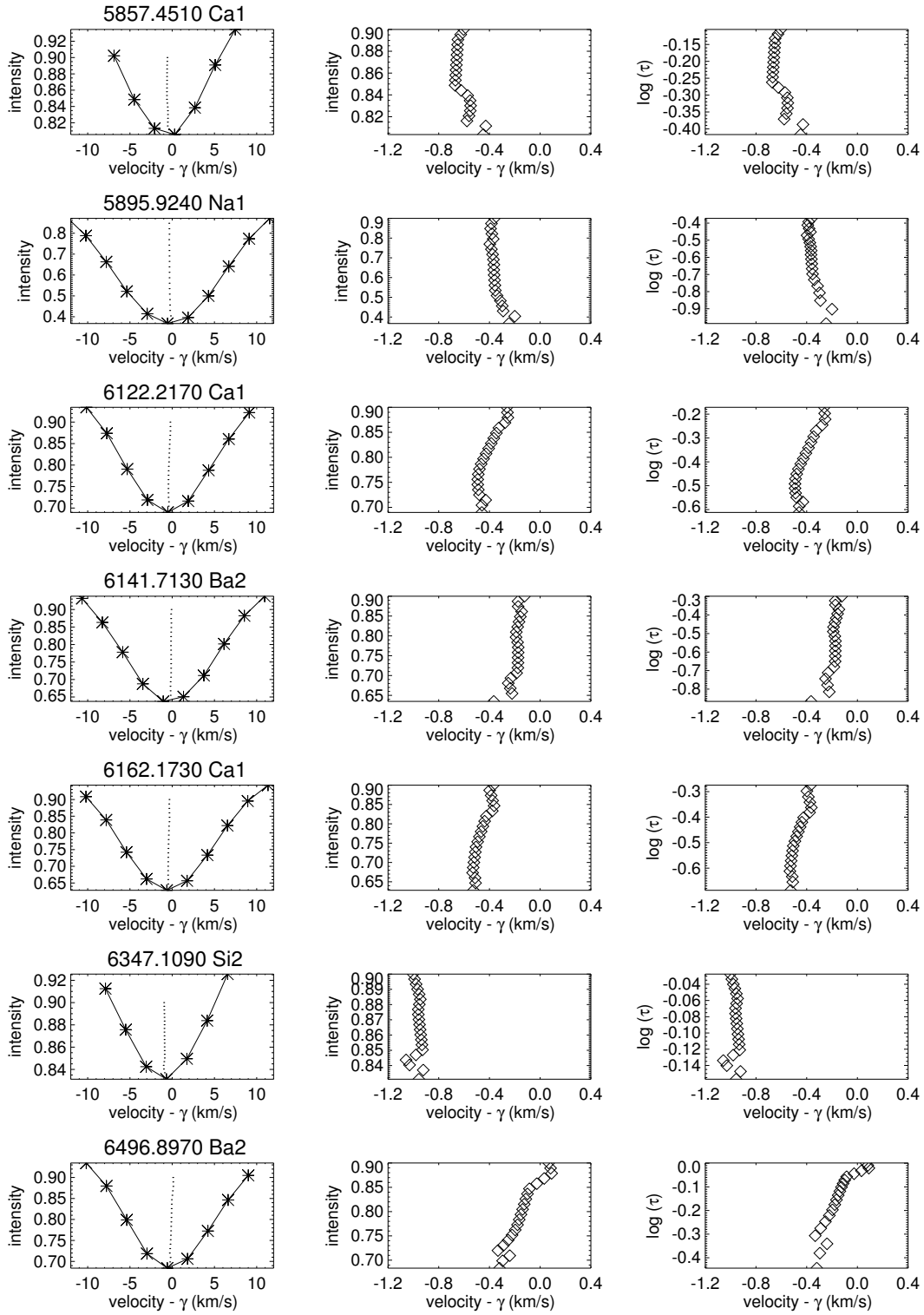


Figure 4.9: continued

every line has the same velocity. Shifting the points of a certain line by the overall velocity of the star might result in not accurately matching the line center with that of the synthetic line, again introducing an error.

In order to avoid these problems, the synthetic line (intensity versus wavelength) served as an intermediate step between the observed line and the τ and column mass profiles. This means that the intensity values of the observed spectrum were first projected to the synthetic spectrum which in turn provided the velocity values that could subsequently be connected correctly to the corresponding optical depth and layer information.

Even though, in principle, lines that correspond to the same optical depth τ must be formed at similar atmospheric depths because their opacity coefficients are equal, there are more factors that play a role. A difference in excitation potential, for example, also causes the lines to form at different physical heights where the temperatures are different, even though their optical depths are equal. Therefore it was necessary to connect the line profile points to the column mass, which is a more physical variable to describe the height in the atmosphere. This value was extracted from the atmosphere model that had served as the basis for the spectrum synthesis.

In Figure 4.10, the resulting atmospheric bisectors of all selected lines are shown in the same plot for comparison. Even though in principle the formation depth is taken into account during the spectral synthesis, a difference in velocity like discussed in the previous section is still present for different ions.

The mean bisector: Bisectors of different lines, especially when transformed to optical depth or column mass in the atmosphere, should have similar shapes. Therefore, it is possible, in order to decrease the scatter in the data, to calculate a mean bisector using a large set of lines rather than only one single line. Before averaging, however, all lines were inspected carefully, and those which showed anomalies for example due to blends which had been undetected before or due to strong observational errors, were removed. Because of the velocity shifts between different elements that was discussed in the previous section, only lines of the same element were averaged.

Figure 4.11 shows the average Fe I bisector (red asterisks) for spectrum 260 (the quiet phase) and the subsequent spectrum number 261 which was taken about 20 minutes later, plotted together with the individual bisectors of all used Fe I lines (in black).

It is this mean bisector that will be used in the next step to calculate a pulsation acceleration that can be compared to hydrodynamical models.

4.5 Comparison to pulsation models

Hydrodynamical pulsation models have been very successful in reproducing the observed light curves and radial velocity curves of RRab as well as RRc stars. One

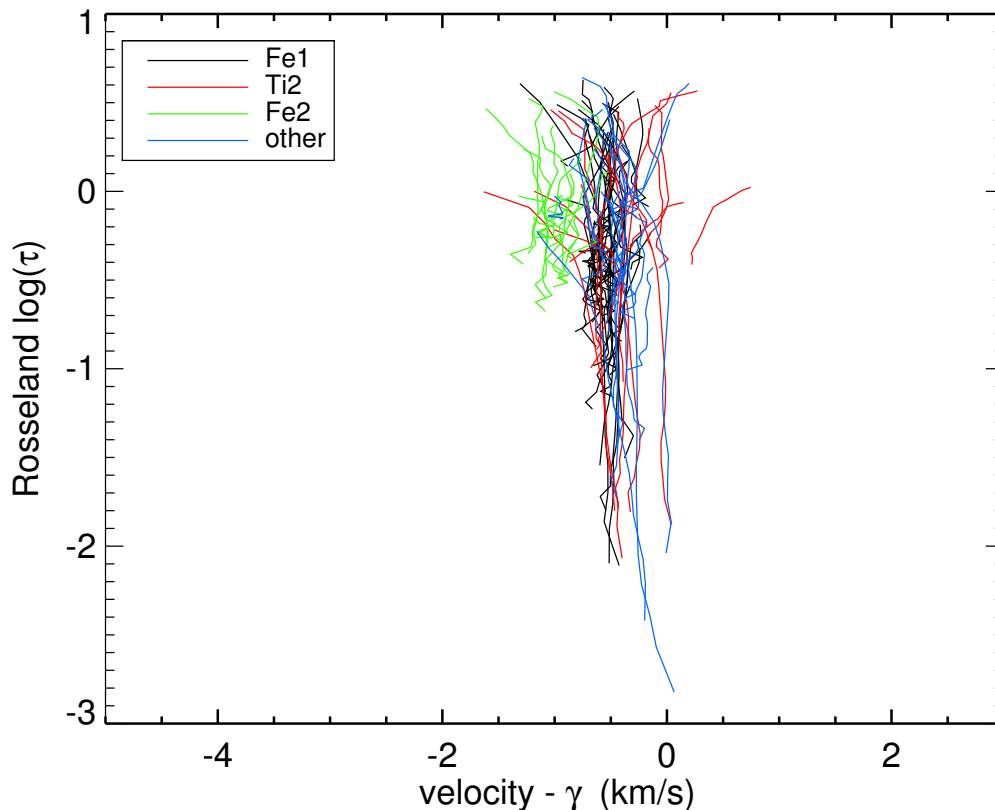


Figure 4.10: Atmospheric bisectors for all selected lines in the quiet phase. The different ions still have different velocities.

example for a detailed hydrodynamical nonlinear model for RR Lyrae stars is that of Fokin (1993) which have kindly been provided for comparison with the data.

Using our bisector results, we were now able to check whether also the predicted pulsational velocity fields agree with the observations, at least in the part of the line forming region which we could investigate with our spectra. For this purpose, first the theoretical accelerations were calculated from the radius change provided in the model output for the phase near maximum radius (which corresponds to the “quiet” phase). Then we calculated the observed acceleration from the velocity difference of the bisectors of the quiet phase (spectrum number 260) and the surrounding spectra that were taken in intervals of about 20 minutes.

The resulting acceleration turned out to be of the same order of magnitude over a large range of column mass, but the curve showed a different shape in the deepest layers. In this region the pulsation accelerations that occur in the model show a steep rise and are too large. The accelerations for other nearby pairs of spectra were also calculated to check whether the difference could be due to an offset in phase, meaning that the midpoint between the times when spectrum 260 and 261 were

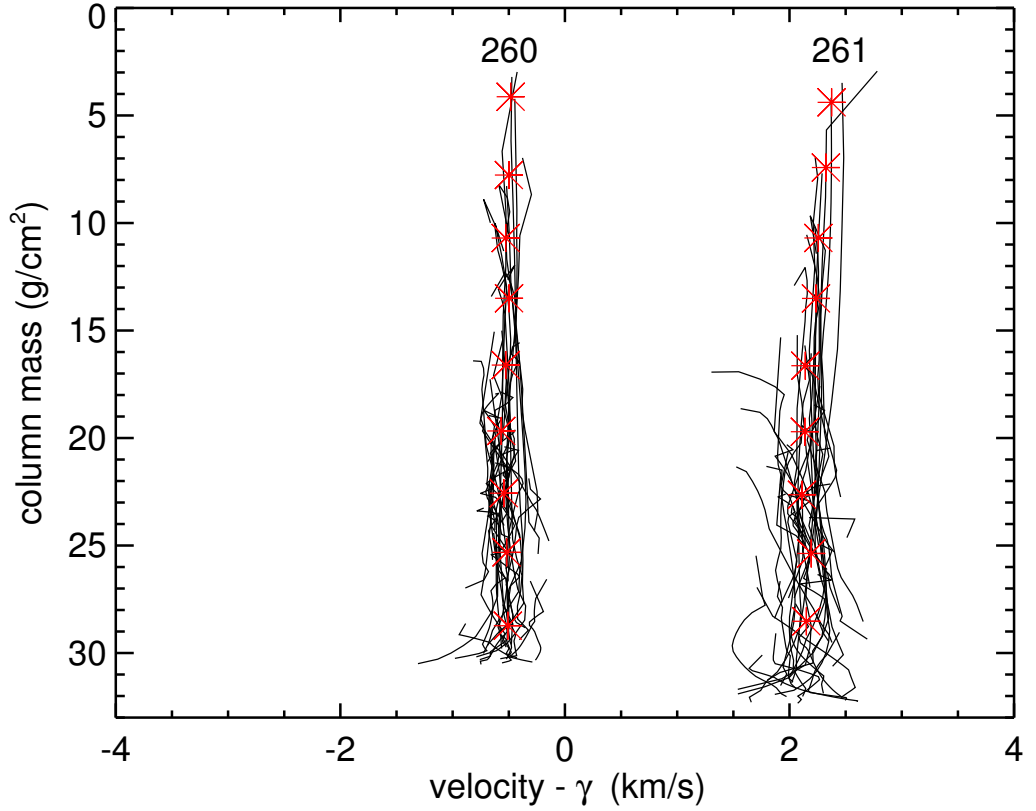


Figure 4.11: All FeI bisectors for spectrum number 260 (the quiet phase, see Kolenberg et al., 2010) and the subsequent spectrum 261. Overplotted in red are the corresponding mean bisectors.

recorded does not exactly correspond to the time of maximum radius. However, the resulting values for the other spectrum pairs turned out to be comparable. The accelerations calculated from four pairs of spectra around the quiet phase, as well as that of the model are shown in Figure 4.12. The mean bisector of Fe 1 is shown in black, Fe 2 is shown in red, and the other elements are plotted in green. It can be seen that the accelerations observed in different elements are comparable, and that the predicted rise in acceleration near the photosphere of the model is not present in the data.

In any case, the observed acceleration seems to be in good agreement in the upper parts of the atmosphere (i.e., at lower column mass). The slope of the acceleration is small, indicating that the quiet phase can indeed be considered rather “quiet”.

It is definitely worth to try this kind of analysis with RR Lyrae spectra of a higher resolution, thereby increasing the range of optical depth that can be investigated, as with a higher spectral resolution the signal will not be smeared

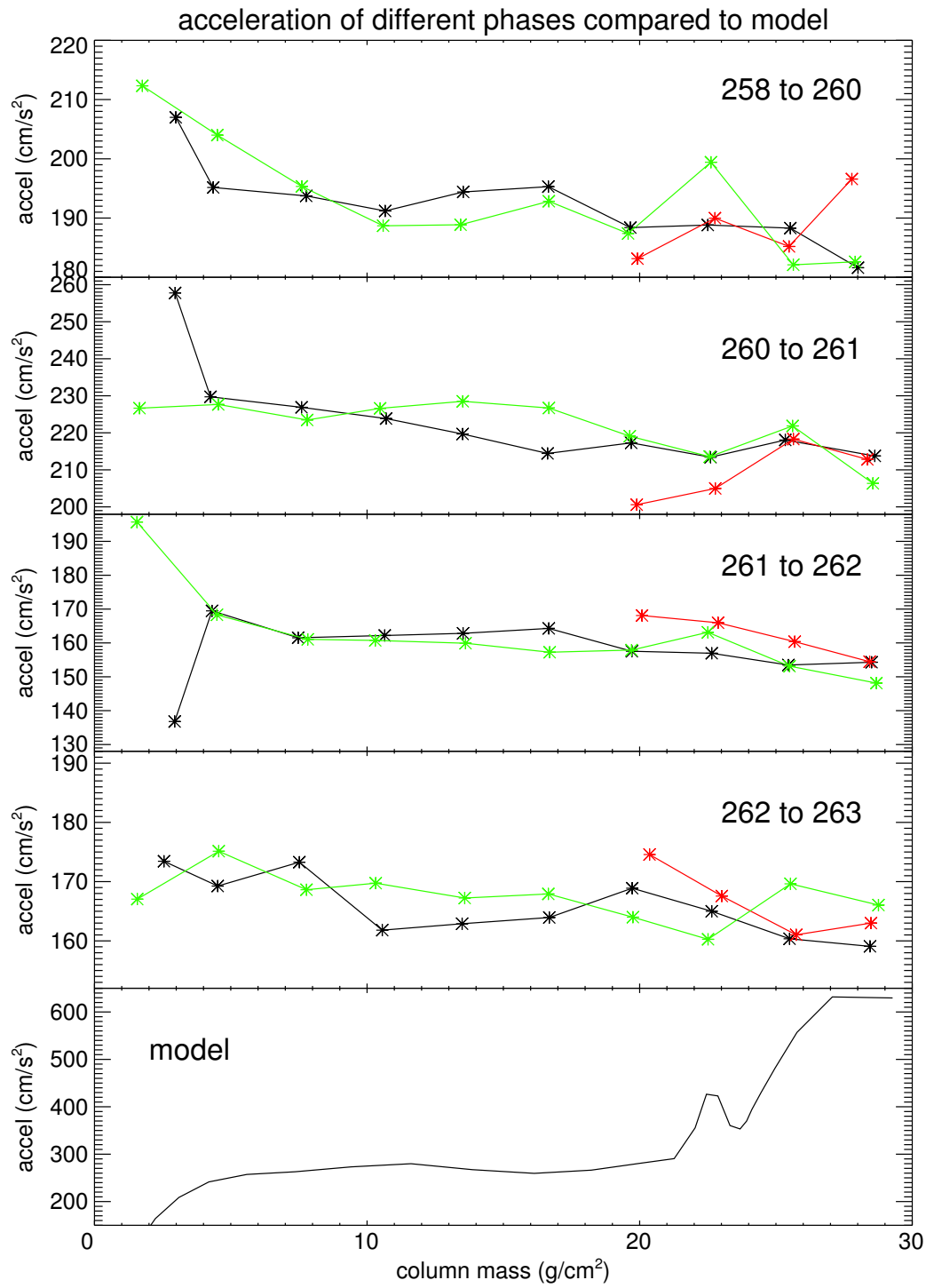


Figure 4.12: Accelerations calculated from the mean observed line bisectors (top four panels) and model accelerations (bottom panel). Fe 1 is shown in black, Fe 2 in red, and other elements in green.

out to this extent. For example, increasing the resolution to a feasible value of $R=100.000$ would make $\log(\tau)$ values in the range between -1.5 to -2 accessible. Also a higher S/N would increase the ability to study bisector points closer to continuum than a fractional intensity of $F/F_c=0.9$ which in our data are already highly influenced by random noise.

4.6 The Van Hoof effect

Even when not looking into as much detail as in a full bisector study, it can in principle be observed that the different layers of a pulsating star have different velocities. Just by deriving the overall velocities of different lines and comparing the results, differences can emerge. Especially phase lags between velocity curves can rather easily be found when plotting the velocity curves of lines against each other, instead of plotting the velocity against time or phase. As radial velocity curves of all our selected lines necessarily emerge as a byproduct of our bisector analysis, we present them here in a separate section in this classical way. The main purpose is to compare the results to previous studies that were performed at different Blazhko phases.

The phenomenon of phase lags that occur between the velocity curves derived from different elements or lines is called the *Van Hoof effect*, because it was first described by van Hoof & Struve (1953). They reported that in their spectra of β Canis Majoris (a β Cephei star) the radial velocity curve of the $H\gamma$ line lagged behind that of the oxygen II lines at 4345 and 4349 Å by 17 minutes, which is a logical consequence of a running wave propagating through the atmosphere. A similar behavior was already at that time expected to appear in Cepheids and RR Lyrae stars.

Phase lags and velocity differences can, of course, even cause different signs in the velocities of different layers (with respect to the stellar center), as some layers might be still contracting while others have already reached their turning point and start expanding.

Mathias & Gillet (1993) were the ones to propose the Van Hoof effect as a tool to study wave propagation through the atmosphere. They proposed a method of detection using velocity curves of different elements plotted directly against each other. This method is robust against error sources which could cause differences in velocity curves without the presence of a Van Hoof effect, like different velocity amplitudes of the elements. The method is also mostly independent of parameters like the projection (limb darkening correction) factor. Their method of detection and plotting is the one that will be used in this section.

Mathias & Gillet (1993) were also the first ones to unambiguously find a Van Hoof effect between metallic lines. Both β Cephei stars studied by them showed this effect. Previously, the Van Hoof effect was only found between Balmer lines on the one side, and metallic lines on the other side. The fact that hydrogen lines are formed much higher in the atmosphere than metallic lines causes large velocity

differences which are easier to detect, while metallic lines are all formed at similar depths with only small velocity differences, which makes the detection of the Van Hoof effect much more challenging. The previous results of van Hoof & Struve (1953) on this topic had been inconclusive due to large error bars.

For Cepheids, velocity differences and phase shifts between $H\alpha$ lines and metallic line have been documented in detail for several stars by Wallerstein et al. (1992), who also used bisectors of $H\alpha$ to quantify the line asymmetries that were present during certain pulsation phases.

In RR Lyrae, the Van Hoof effect had been proven to exist by Mathias et al. (1995). In their data set of four nights of spectra centered around the $H\beta$ and $H\gamma$ lines, respectively, they clearly found a strong phase difference when comparing the hydrogen lines to nearby metallic lines. Their results were consistent with the concept of a running wave propagating from the deeper atmosphere where the metallic lines are formed to the upper layers where the hydrogen line cores are formed. Due to low spectral resolution, however, they could not detect a Van Hoof effect between different metallic lines. This phenomenon was later claimed to be detected by Chadid & Gillet (1998).

During the bisector analysis for this thesis, we automatically obtained accurate radial velocities for a large number of lines. In principle, the velocity derived for a specific line corresponds to the bisector points in the line core. This allows a comparison with previous works on RR Lyrae based on different data that were taken in different cycles of this drastically changing star. By applying the method proposed by Mathias & Gillet (1993) we were able to study the Van Hoof effect in our extensive data set that also has a much higher resolution than the one used for the previous studies. Keeping in mind that the pulsation behavior of RR Lyrae stars changes dramatically with the Blazhko effect and also on longer time scales, having studies of the atmospheric dynamics based on data sets obtained in different years is extremely valuable. A comparison can allow to see the differences that the Blazhko effect causes in the motion of the line forming layers.

4.6.1 The Van Hoof effect in our spectra

In principle, radial velocity curves are available for all 91 unblended lines that were used for calculating line bisectors, but for reasons of space, we show and discuss only a few of them. For comparison purposes, preferably lines that have been used in previous studies are shown.

The Fe 2 line near 4924 Å that was used by Mathias et al. (1995) was not in our bisector sample because of a slight blend with an Fe 1 line, but we calculated its velocities specifically for this section. The other lines shown by Mathias et al. (1995), Ti 2 near 4563 Å and Fe 1 near 4920 Å, were part of the bisector sample.

As the preferred method to find line velocities we chose the center of gravity of the lower half of the line, as this is a very robust method also for distorted lines where Gaussian fitting might not be adequate. Heliocentric corrections for

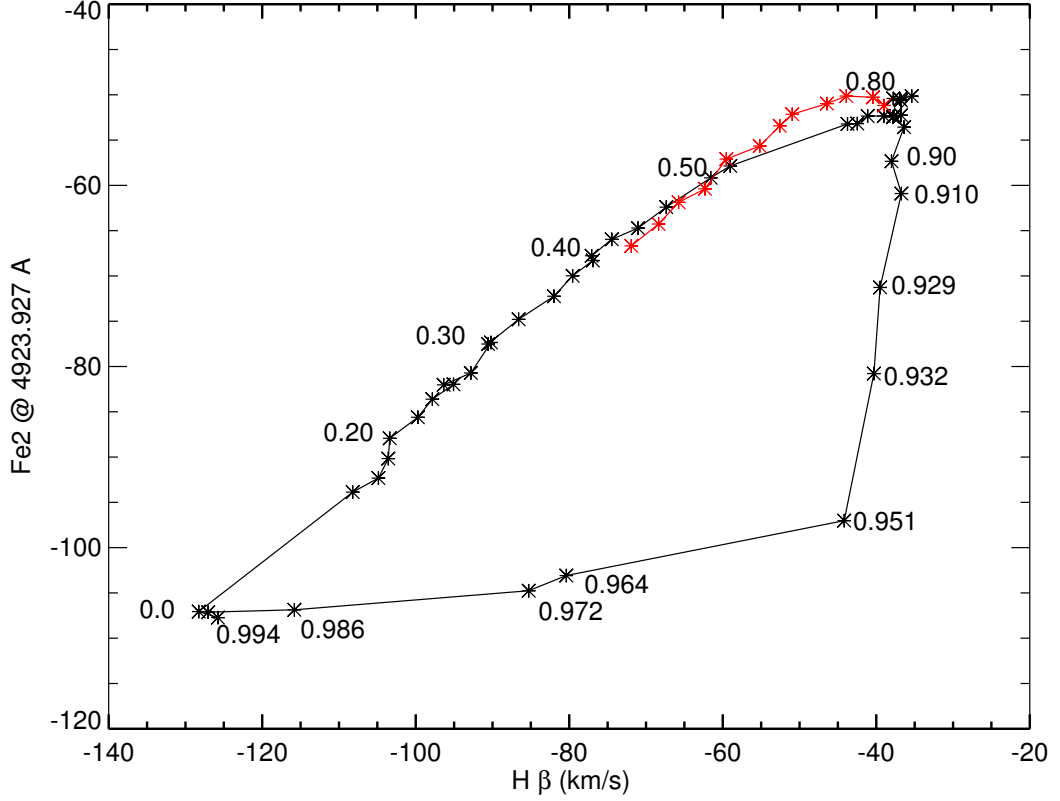


Figure 4.13: The phase lag between the $H\beta$ line and the Fe 2 line becomes obvious in the velocity-velocity diagram. This Figure can be compared to Figure 1 in Mathias et al. (1995). The same two lines are shown. Red symbols indicate a different Blazhko phase.

the measured velocities were determined for each spectrum using the *iraf* task *rvcorrect*.

Figure 4.13 shows a velocity-velocity diagram of a hydrogen line (in this case $H\beta$) and can be compared directly to Fig. 1 of Mathias et al. (1995). The spectra that were taken around a Blazhko phase of about 0.3 are shown in black, while the small range for which spectra at a different Blazhko phase (around 0.8) are available is shown in red. A sharper edge in the curve near 0.8 is obvious for the Blazhko phase 0.3 while the red curve is smoother and resembles more the results of Mathias et al. (1995).

The comparison with the previous study also reveals a steeper slope between phases 0.9 and 0.95 which might also be attributed to the different Blazhko phase at which the sets of spectra were taken. The steep slope is a sign that during this phase, the region where the Fe 2 line is formed experiences a strong acceleration while the layer where the core of $H\beta$ has its origin is almost at a constant velocity. Afterwards, from phases 0.95 to 0.0, the opposite is the case. The velocity ranges

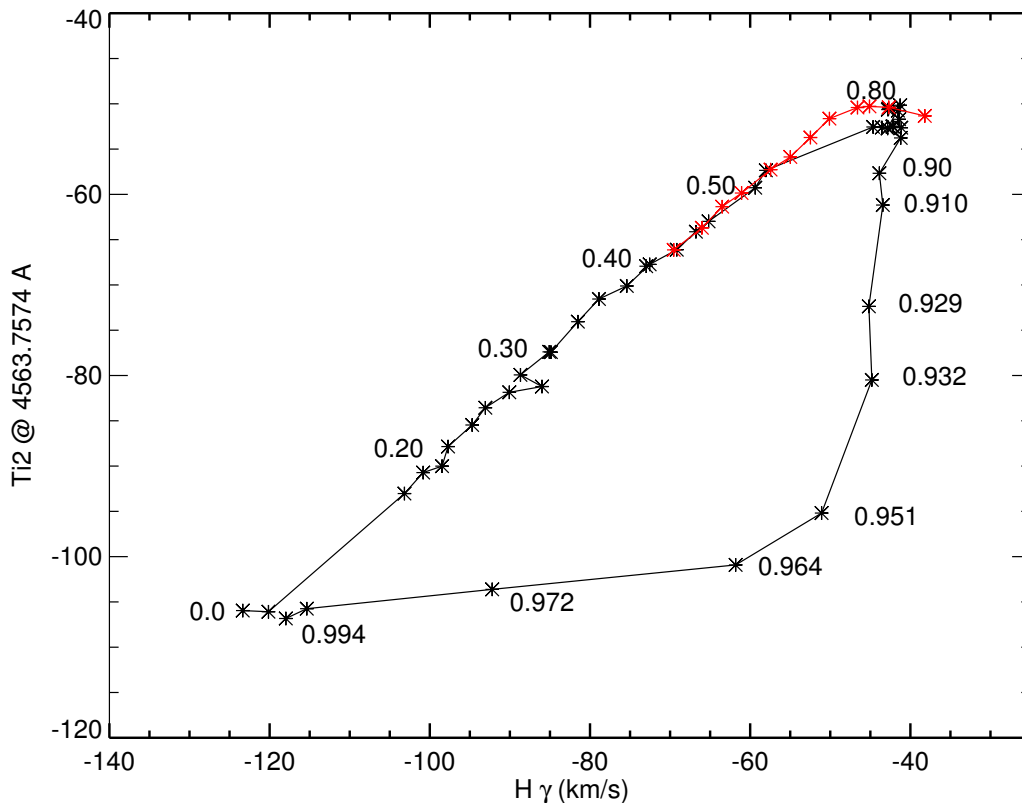


Figure 4.14: Velocity-velocity diagram for $H \gamma$ and the Ti 2 line at 4563.757 Å. This Figure can be directly compared to Figure 2 in Mathias et al. (1995). The same two lines are shown. Red symbols indicate a different Blazhko phase.

in this work are comparable to those of Mathias et al. (1995) with the velocity of $H\beta$ ranging from about -130 km/s to about -35 km/s. For the Fe 2 line, velocities seem to reach slightly higher values (-45 km/s) in the data of Mathias et al. (1995) while in our data, no velocities above -50 km/s occur. Again, this might be a result of a difference in the Blazhko cycle.

Figure 4.14, which allows a direct comparison with Figure 2 of Mathias et al. (1995) is an entirely different case. While the shape of the curve is similar to our Figure 4.13, it differs a lot from previous results on the same line. We see again a distinct time interval where the metallic line experiences strong acceleration, followed by a phase of acceleration of the hydrogen line. Mathias et al. (1995) measured a different behaviour. This might indicate that the Blazhko phase makes a larger difference in the pulsation of the layer where $H\gamma$ is formed than at the region of $H\beta$. The red curve which was obtained from a Blazhko phase around 0.8 this time does not resemble the previous results on these lines either.

The metallic lines were found to show a very similar behaviour to the one documented by Mathias et al. (1995) and Chadid & Gillet (1998). An example,

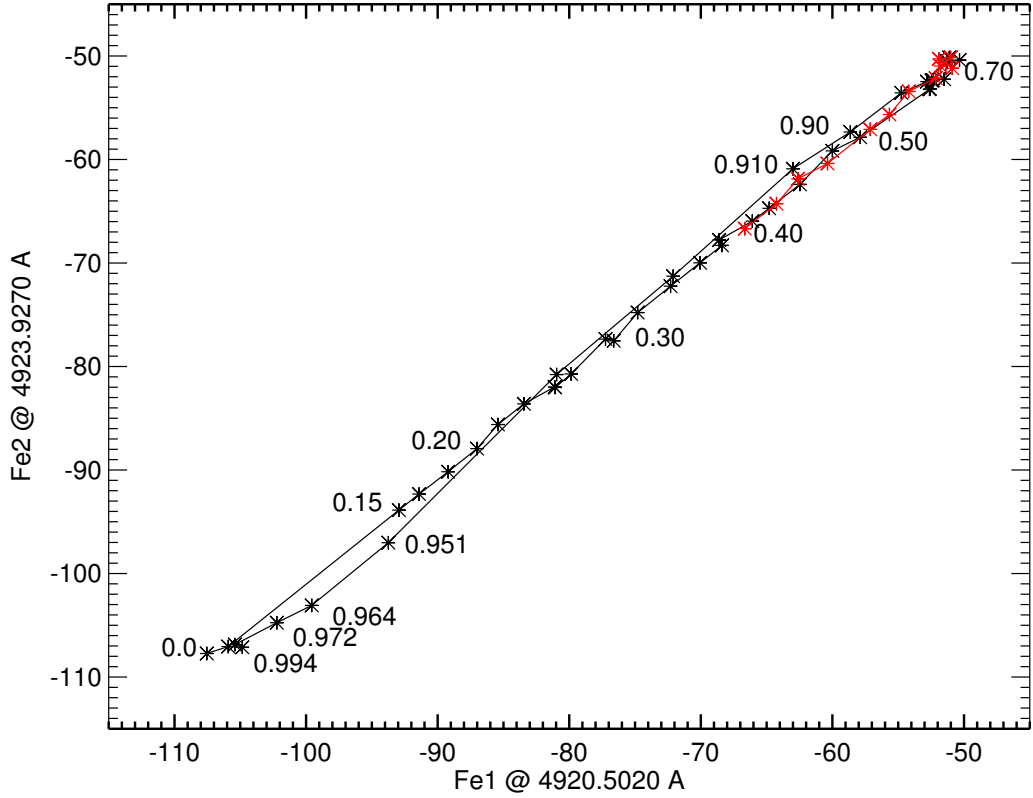


Figure 4.15: Velocity-velocity diagram for the Fe 1 line at 4920.502 Å and the Fe 2 line at 4923.927 Å. This Figure can be directly compared to Figure 3 in Mathias et al. (1995) and Figure 2 of Chadid & Gillet (1998). The same two lines are shown. Errors amount to about 0.5 km/s

using the same lines that had been used in previous studies, is shown in Figure 4.15 which can be compared to Figure 3 of Mathias et al. (1995) and Figure 2 of Chadid & Gillet (1998). The “8”-shaped double loop that had been present in previous works is also present in this study. The Blazhko phase in this case does not cause a noticeable change in the curve.

Chapter 5

Discussion and Outlook

Several models have been proposed in the past as possible explanations for the Blazhko effect that manifests itself as a modulation of the amplitude and/or phase of the light curve of about 50% of all RRab Lyrae stars. One of the most promising models was the oblique rotator-pulsator model which involves a strong dipole magnetic field. The presence of such a field is a prediction that can be tested with measurements, which was one of the goals of this thesis.

By the means of spectropolarimetry, in this thesis five RR Lyrae stars have been searched for the presence of a strong magnetic field. All measurements resulted in null detections, which is consistent with the findings of Kolenberg & Bagnulo (2009). The use of high-resolution spectroscopy instead of the low-resolution spectroscopy and the revisit of some previously observed targets ensured that the non-detections in the past were not a consequence of limited resolution. High resolution spectropolarimetry had before only been performed for a single star: the prototype and brightest member of the class of RR Lyrae stars: RR Lyr itself. For other stars, only low-resolution measurements had been available.

This study increased the number of RR Lyrae stars for which spectropolarimetric observations have been performed to twenty-one. With the reported null-detections for all of them, even with high-resolution data, the magnetic oblique pulsator-rotator model that had been one of the most plausible explanations for the mystery of the Blazhko effect can be considered ruled out.

Another aspect that discriminates different types of models is the regularity of the predicted effect. For a long time, the Blazhko effect was considered a strictly periodic phenomenon, and in the literature usually only one Blazhko period was given for each star. Consequently some proposed models linked the modulation directly or indirectly to rotation, making it difficult to explain irregularities, should they be present. Before the space age, however, the regularity of the Blazhko effect and the presence of irregularities was very difficult to test. For this goal, very long time series are needed. As the typical duration of a Blazhko cycle is several months,

and several cycles need to be observed to check the effect's regularity, an enormous amount of data spread over a long period of time is required. Not only would the required effort be huge to obtain such a data set from the ground, the data would unfortunately also suffer from daytime/weather gaps and long interruptions during seasons in which the target is not observable.

As a consequence, the clues on possible changes in the Blazhko modulation were sparse. There were reports on discrepancies in the measured modulation amplitudes or modulation periods for some stars, but due to large gaps between the observations it remained a mystery whether those differences were caused by superimposed secondary modulations, long term continuous (evolutionary) changes, sudden period jumps or chaotic irregularity. On top of this, most checks of the long-term stability made it necessary to combine data obtained by different authors with different instruments and filters, possibly introducing errors.

Only with the availability of satellites providing uninterrupted homogeneous data sets with a time base of months and even years for RR Lyrae stars it became possible to study the stability of the Blazhko effect. **By using data provided by the CoRoT and *Kepler* space missions, the irregular nature of the Blazhko effect was demonstrated in this thesis and its changes were documented in detail for two stars.**

The thorough analysis of the ultra high-precision light curves **also revealed many previously unknown features in the Fourier spectra of these stars, like the presence of possible non-radial modes and the excitation of radial overtone modes.** Before that, non-radial pulsation modes had only been unambiguously detected in an RRd star, also using satellite data (Gruberbauer et al. 2007). **With the analyses that form part of this thesis it became clear that RR Lyrae stars and also the Blazhko effect effect are more complex than previously thought and that new models are required to explain the full variety of observed features. In particular, it turned out that new models that can reproduce irregular or even chaotic modulations are needed, while the models that require exact clock-work like repetition of the Blazhko effect consequently face severe problems.** The discoveries in the satellite data of which some are part of this thesis have triggered new modeling efforts.

During the time the last part of this thesis was written, promising new models and ideas have been developed. They do not require strong magnetic fields and can reproduce irregularities in the modulation. One of them is the scenario described by Gillet (2013), who makes use of the observations that Blazhko stars seem to occur only in the region of the instability strip where both the first overtone and the fundamental mode are excited. He suggests a shock wave termed the “overtone shock” causes a slowdown of the atmosphere layers during the stellar contraction, leading to a change in compression which influences the κ mechanism. This shock wave is one out of five shocks that occur during a pulsation cycle according to the models of Fokin & Gillet (1997). The interaction of the main

shock with the overtone shock finally causes the Blazhko effect. Gillet explicitly predicts an irregular Blazhko effect. Also, some other observational aspects are in good agreement with the predictions of this scenario. For example, the observed decrease in average effective temperature during the Blazhko maximum that was observed by Jurcsik et al. (2009) can be connected to a dissipation of energy that is expected to occur when the main shock reaches its highest amplitude. Also, for example, the observed movement of the bump in the light curve during the Blazhko effect cycle is consistent with the predictions. One has to note, however, that this model is still in a purely descriptive state and that the hydrodynamical computations did not yet produce modulated light curves.

Another very promising approach was presented by Buchler & Kolláth (2011) who could demonstrate with the help of amplitude equations that a 9:2 resonance between the fundamental mode and the 9th overtone can lead to a modulation of the amplitudes. The same resonance had before been shown by Szabó et al. (2010) to be the reason for the phenomenon of period doubling in the light curves of three RR Lyrae stars observed with *Kepler*. Also, it had been found by Kolláth et al. (2011) to be the explanation for the alternating cycles that occurred in their hydrodynamical models of RR Lyrae stars. This 9th overtone appears as a surface mode, also called “strange mode”. The resulting Blazhko periods are in the same range as the observed ones, and the phenomenon is found in a wide range of parameters of their amplitude equations (Buchler & Kolláth 2011). But even though the amplitude equations deliver such a clear picture of modulated amplitudes, both of regular and irregular type, the hydrodynamical models are not yet able to produce a Blazhko modulation. Buchler & Kolláth (2011) mention that this might be due to the numerous difficulties that a surface mode such as the 9th overtone poses.

Modeling the non-linear pulsation of RR Lyrae stars in detail is not an easy task. After facing difficulties in the beginning, however, hydrodynamic models have in the last decades become very good at reproducing observed light and radial velocity curves. Those models also predict, among other parameters, radius changes and gas velocities for many different layers in the star, which need to be compared to observational data. In most cases, however, the observer can only study the photosphere of the star. But by studying spectral lines it is possible to gather some information about various depths in the star, as different parts of the line are formed in different regions. The best way to study atmospheric velocity fields are spectral line bisectors which for this reason have been used by some authors on pulsation stars. Such an analysis had, however, never before been performed for an RR Lyrae star. **To apply this method for the first time to an RR Lyrae star was also part of this thesis**, and the brightest known member, RR Lyrae itself has been chosen as a target, especially since it is also a Blazhko star.

Line asymmetries were quantified through the pulsation cycle for several selected lines, and are now available for comparison to other RR Lyrae

stars and to spectra of the same star taken at a different time. Additionally, **the different parts of the line profile were brought into context with their depth of formation using thoroughly determined stellar parameters and atmosphere models. As expected from pulsation theory, the velocity amplitude was found to be larger for the outer layers of the star. A comparison of the observed pulsation acceleration around the phase of maximum radius with the hydrodynamic models of Fokin (1993) revealed similarities with only a slight offset.** A comparison with new models, as well as similar studies for other RR Lyrae stars and especially the use of higher spectral resolution data would be an interesting goal for the future.

Unfortunately, during the work of this thesis, both satellites which delivered extremely precise uninterrupted time series of RR Lyrae stars, have ended their primary mission: CoRoT has been terminated due to a computer failure, and *Kepler*, after two reaction wheels failed, cannot observe its original field of view any more. It will, however, continue to obtain high-quality data for stars, among which are also several RR Lyrae stars, near the ecliptic in its second part of the mission, K2.

Nevertheless, new discoveries might still be made with the data of the *Kepler* primary mission. Even though the working group for RR Lyrae stars has been very active and has analyzed several stars as well as many aspects of the data, there are still *Kepler* light curves which have not been analyzed in detail. Only a few *Kepler* stars have enjoyed such a detailed analysis as it was presented in this thesis for V445 Lyr. The remaining light curves might still lead to unexpected discoveries, and should be analyzed in the future.

These upcoming analyses of *Kepler* data might, now that it is known that RR Lyrae stars can have additional radial overtone modes as well as non-radial modes, answer the next logical question about the statistics: which percentage of stars do show an irregular Blazhko effect, and how many show a regular Blazhko effect? In which of them are the overtones and additional frequencies present, and which stellar parameters do discriminate those groups of stars? Is there a relation between the newly discovered features and the position within the instability strip or the evolutionary status of the stars?

Another puzzling aspect of RR Lyrae stars is their apparent lack in binary systems. Even though normally around 50% of all stars found in binary or multiple systems, and many RR Lyrae stars can be considered well-studied, only very few of them are known members of a binary system. And this does not seem to be caused by their low metal content. Interestingly, according to Machida (2008) the fraction of binaries in low-metallicity environments should even be higher than in solar-metallicity environments, so given the low metal content of RR Lyrae stars, an even higher number of binaries would be expected. Of course, during their evolution, RR Lyrae stars might have interacted with their companion, if there was one, so the very close systems might have been destroyed. Nevertheless, systems in wider orbits should exist, and it is surprising that only so few of them

have been observed. **It is already planned by the author to tackle this question as a next step in RR Lyrae research.**

Additionally, the few known RR Lyrae binaries deserve to be studied in detail, which is another project by the author that has already started. Besides the unusual object OGLE-BLG-RRLYR-02792 which was found by Pietrzyński et al. (2012) to have a mass of only $0.26 M_{\odot}$ - too small to ignite helium and therefore not an RR Lyrae star in the classical sense, there is only one other confirmed star: TU UMa, which is considered the only known classical RR Lyrae binary. The binary nature of this star needs confirmation with recent data, as the last orbit calculations are meanwhile 15 years old. **New data of TU UMa, both photometric and spectroscopic, have already been obtained by the author and will, together with other published O-C values, lead to a refined and updated orbit solution of this unique object.**

Summing up, RR Lyrae stars definitely remain objects worth studying, and a lot of work still remains to be done before they are fully understood.

Abstract

This thesis is dedicated to the study of Blazhko stars, i.e., RR Lyrae stars whose light curves are modulated by a still unexplained mechanism. Photometric data provided by two space missions have been analyzed. But as photometry alone cannot answer all the questions, also spectroscopic studies were performed.

Several models have been proposed to explain the Blazhko effect that modulates the light curves of about half of all R Rab Lyrae stars. Resonances with non-radial or radial modes were among the possible explanations, as well as a cyclic quenching of the pulsation due to changes in the convection. One of the most promising models, however, was the one that required a strong magnetic dipole field which alters the observed pulsation through rotation, similar to the scenario that is widely accepted in the case of roAp stars. Magnetic field measurements of RR Lyrae stars had been contradictory, and were – except for one study – mostly focused on a single star: the prototype RR Lyrae itself. In this thesis, spectropolarimetric measurements were presented for a sample of RR Lyrae stars.

This study increased the number of RR Lyrae stars with available spectropolarimetric measurements to 21, finding no magnetic field in any of the observed objects. Also, some of the stars previously only observed with low-resolution spectroscopy were observed with higher resolution, confirming the non-detection of a strong dipole field, and therefore ruling out the magnetic oblique rotator-pulsator model for the Blazhko effect.

Even though its origin still is a mystery, the Blazhko effect was usually considered a simple phenomenon which modified the pulsation in a strictly periodical way. Uninterrupted high-precision time series provided by the satellite missions CoRoT and *Kepler* allowed for the first time to investigate the long-term regularity of the Blazhko effect. In this thesis, the detailed analyses of two satellite data sets are presented, and the irregular nature of the effect is demonstrated and documented. Non-radial modes have been found in the Fourier spectra of the studied stars, as well as the presence of higher overtone pulsations, which in some cases can be transient. Peterson diagrams were used to diagnose the identity of the modes.

Additionally, in this thesis, for the first time, a bisector analysis was performed for an RR Lyrae star. This analysis was performed on the best-studied Blazhko star: RR Lyrae itself. Velocity profiles of observed spectral lines were not only studied with respect to the observed intensity, but were also connected to the profile of formation depth via synthetic spectra. This allowed to observe the velocity fields

within the stellar atmosphere and to compare the motions to those predicted by pulsation models. Also, the Van Hoof effect in RR Lyrae was studied on the basis of our spectra, and the results were compared to previous studies.

Zusammenfassung

Diese Arbeit widmet sich der Analyse von Blazhko-Sternen, also solchen RR Lyrae Sternen, deren Lichtkurven durch einen unbekannten Mechanismus moduliert werden. Dafür wurden Daten zweier verschiedener Satellitenmissionen ausgewertet. Da aber photometrische Daten alleine nicht für die Beantwortung aller Fragestellungen geeignet sind, wurden auch Sternspektren analysiert.

Für den Blazhko Effekt, der die Lichtkurven etwa der Hälfte aller RR Lyrae Sterne moduliert, wurden schon viele mögliche Erklärungen vorgeschlagen. Darunter waren unter anderem Resonanzen zwischen radialen und nichtradialen sowie zwischen mehreren radialen Schwingungsmoden, oder auch eine zyklisch wiederkehrende Störung der Pulsation durch Veränderungen der Konvektion. Eines der vielversprechendsten Modelle war aber jenes, dem zufolge ein starkes Dipol-Magnetfeld, das zur Rotationsachse geneigt ist, die Pulsation beeinflusst.

Die verfügbaren Magnetfeldmessungen von RR Lyrae Sternen waren allerdings widersprüchlich. Außerdem bezogen sie sich – bis auf eine Studie – alle auf nur einen einzigen Stern: RR Lyrae selbst, den Prototypen dieser Klasse von Sternen. In der vorliegenden Arbeit wurden Messungen für fünf RR Lyrae Sterne durchgeführt, und damit die Anzahl der RR Lyrae Sterne für die Magnetfeldmessungen verfügbar sind, deutlich vergrößert. Ausserdem wurde, im Gegensatz zu früheren Studien, dabei eine hohe spektrale Auflösung verwendet. Einige der bereits zuvor mit niedrigerer Auflösung beobachteten Sterne wurden neu gemessen, wobei sich die Nichtdetektionen jeweils bestätigten. Damit kann das Modell des geneigten Rotator-Pulsator endgültig als ausgeschlossen angenommen werden.

Obwohl der Blazhko Effekt ein ungelöstes Rätsel darstellt, wurde er doch meist für ein zumindest relativ einfach zu beschreibendes Phänomen gehalten, das zu einer exakt periodischen Modulation führt. Die extrem langen und lückenlosen Datensätze, die von den Satelliten *CoRoT* und *Kepler* aufgenommen wurden, erlaubten nun aber erstmals eine Überprüfung dieser angenommenen Regelmäßigkeit.

In dieser Arbeit werden die detaillierten Analysen zweier solcher Datensätze vorgestellt, und die irreguläre Natur des Blazhko Effektes wird aufgezeigt und dokumentiert. Zudem wurden nicht-radiale Schwingungsmoden sowie Obertöne der Grundschiwingung nachgewiesen, die teilweise nur vorübergehend auftreten. Petersen-Diagramme wurden dabei zur Diagnose verwendet.

Weiters wird in dieser Arbeit erstmals eine sogenannte Bisektoren-Analyse für einen RR Lyrae Stern präsentiert. Diese wurde an RR Lyrae selbst, dem

bisher am besten dokumentierten Blazhko-Stern, durchgeführt. Dabei wurden die Geschwindigkeitsprofile der beobachteten Linien nicht nur im klassischen Sinn, also in Bezug auf die beobachtete Intensität berechnet, sondern mit Hilfe von synthetischen Sternspektren auch in Bezug auf die tatsächliche Tiefe in der Sternatmosphäre. Das ermöglichte eine Betrachtung der Geschwindigkeitsfelder in der Atmosphäre und dadurch einen Vergleich mit hydrodynamischen Pulsationsmodellen. Dabei konnte auch der sogenannte Van Hoof Effekt untersucht und mit früheren Studien verglichen werden.

Bibliography

- Aerts C., Christensen-Dalsgaard J., Kurtz D. W., 2010, *Asteroseismology*
- Alcock C., Allsman R., Alves D. R., Axelrod T., Becker A., Bennett D., Clement C., Cook K. H., Drake A., Freeman K., Geha M., Griest K., Kovács G., Kurtz D. W., Lehner M., Marshall S., 2000, *ApJ*, 542, 257
- Alcock C., Allsman R. A., Alves D. R., Axelrod T. S., Becker A. C., Basu A., Baskett L., Bennett D. P., Cook K. H., Freeman K. C., Griest K., Guern J. A., 1998, *ApJ*, 492, 190
- Alcock C., Allsman R. A., Axelrod T. S., Bennett D. P., Cook K. H., Freeman K. C., Griest K., Marshall S. L., Peterson B. A., Pratt M. R., Quinn P. J., Rodgers A. W., Stubbs C. W., Sutherland S., Welch D. L., 1996, *AJ*, 111, 1146
- Alcock C., Alves D. R., Becker A., Bennett D., Cook K. H., Drake A., Freeman K., Geha M., Griest K., Kovács G., Lehner M., Marshall S., Minniti D., Nelson C., Peterson B., Popowski P., 2003, *ApJ*, 598, 597
- Baade W., Swope H. H., 1961, *AJ*, 66, 300
- Babcock H. W., 1956, *PASP*, 68, 70
- Babcock H. W., 1958, *ApJS*, 3, 141
- Bailey S. I., 1902, *Annals of Harvard College Observatory*, 38, 1
- Balázs J., 1959, *Kleine Veroeffentlichungen der Remeis-Sternwarte zu Bamberg*, 27, 26
- Balázs-Detre J., Detre L., 1962, *Veroeffentlichungen der Remeis-Sternwarte zu Bamberg*, 34, 90
- Bedding T. R., Mosser B., Huber D., Montalbán J., Beck P., Christensen-Dalsgaard J., Elsworth Y. P., García R. A., Miglio A., Stello D. e. a., 2011, *Nature*, 471, 608
- Benkő J. M., Kolenberg K., Szabó R., Kurtz D. W., Bryson S., Bregman J., Still M., Smolec R. e. a., 2010, *MNRAS*, 409, 1585

- Berdnikov L. N., Vozyakova O. V., Kniazev A. Y., Kravtsov V. V., Dambis A. K., Zhuiko S. V., 2012, *Astronomy Reports*, 56, 290
- Blažko S., 1907, *Astronomische Nachrichten*, 175, 325
- Buchler J. R., Kolláth Z., 2011, *ApJ*, 731, 24
- Butler D., Manduca A., Bell R. A., Deming D., 1982, *AJ*, 87, 640
- Cacciari C., Clementini G., Prevot L., Buser R., 1989, *A&A*, 209, 141
- Chadid M., Gillet D., 1998, *A&A*, 335, 255
- Chadid M., Wade G. A., Shorlin S. L. S., Landstreet J. D., 2004, *A&A*, 413, 1087
- Christy R. F., 1966, *ApJ*, 144, 108
- Clement C. M., Goranskij V. P., 1999, *ApJ*, 513, 767
- Clementini G., Corwin T. M., Carney B. W., Sumerel A. N., 2004, *AJ*, 127, 938
- Cousens A., 1983, *MNRAS*, 203, 1171
- Cox A. N., 1993, in Nemec J. M., Matthews J. M., eds, *IAU Colloq. 139: New Perspectives on Stellar Pulsation and Pulsating Variable Stars The Periods of RR Lyrae*. p. 409
- Deutsch A. J., 1956, *PASP*, 68, 92
- Donati J.-F., Semel M., Carter B. D., Rees D. E., Collier Cameron A., 1997, *MNRAS*, 291, 658
- Dziembowski W. A., Cassisi S., 1999, *Acta Astron.*, 49, 371
- Elkin V. G., Kurtz D. W., Mathys G., 2008, *MNRAS*, 386, 481
- Feast M. W., Laney C. D., Kinman T. D., van Leeuwen F., Whitelock P. A., 2008, *MNRAS*, 386, 2115
- Feuchtinger M. U., 1998, *A&A*, 337, L29
- Feuchtinger M. U., 1999, *A&A*, 351, 103
- Fokin A., 1993, in Nemec J. M., Matthews J. M., eds, *IAU Colloq. 139: New Perspectives on Stellar Pulsation and Pulsating Variable Stars A Full-Amplitude Nonlinear Model for RR Lyrae: Pulsations, Shock Waves and H alpha Peculiarities*. p. 265
- Fokin A. B., 1992, *MNRAS*, 256, 26

- Fokin A. B., Gillet D., 1997, *A&A*, 325, 1013
- For B.-Q., Sneden C., Preston G. W., 2011, *ApJS*, 197, 29
- Gillet D., 2013, *A&A*, 554, A46
- Gray D. F., 1992, *The observation and analysis of stellar photospheres*.
- Gray D. F., 2005, *PASP*, 117, 711
- Gray D. F., 2009, *ApJ*, 697, 1032
- Gray D. F., 2010, *ApJ*, 721, 670
- Gruberbauer M., Kolenberg K., Rowe J. F., Huber D., Matthews J. M., Reegen P., Kuschnig R., Cameron C., Kallinger T., Weiss W. W., Guenther D. B., Moffat A. F. J., Rucinski S., Sasselov D., Walker G. A. H., 2007, *MNRAS*, 379, 1498
- Guggenberger E., Kolenberg K., 2006, *Communications in Asteroseismology*, 148, 21
- Guggenberger E., Kolenberg K., Chapellier E., Poretti E., Szabó R., Benkő J. M., Paparó M., 2011, *MNRAS*, 415, 1577
- Hekker S., 2013, *Advances in Space Research*, 52, 1581
- Hill S. J., 1972, *ApJ*, 178, 793
- Huber D., Chaplin W. J., Christensen-Dalsgaard J., Gilliland R. L., Kjeldsen H., Buchhave L. A., Fischer D. A., Lissauer J. J., Rowe J. F., Sanchis-Ojeda R. e. a., 2013, *ApJ*, 767, 127
- Hurta Z., Jurcsik J., Szeidl B., Sódor Á., 2008, *AJ*, 135, 957
- Iben I., 2012, *Stellar Evolution Physics*
- Iben Jr. I., 1971, *PASP*, 83, 697
- Jerzykiewicz M., Wenzel W., 1977, *Acta Astron.*, 27, 35
- Jurcsik J., Kovacs G., 1996, *A&A*, 312, 111
- Jurcsik J., Sódor Á., Szeidl B., Hurta Z., Váradi M., Posztobányi K., Vida K., Hajdu G., Kővári Z., Nagy I., Molnár L., Belucz B., 2009, *MNRAS*, 400, 1006
- Jurcsik J., Sódor Á., Szeidl B., Kolláth Z., Smith H. A., Hurta Z., Váradi M., Henden A., Dékány I., Nagy I., Posztobányi K., Szing A., Vida K., Vityi N., 2009, *MNRAS*, 393, 1553
- Jurcsik J., Szeidl B., Nagy A., Sodor A., 2005, *Acta Astron.*, 55, 303

- Jurcsik J., Szeidl B., Sódor Á., Dékány I., Hurta Z., Posztobányi K., Vida K., Váradi M., Szing A., 2006, *AJ*, 132, 61
- Kinman T., Castelli F., Cacciari C., Bragaglia A., Harmer D., Valdes F., 2000, *A&A*, 364, 102
- Kinman T. D., Cacciari C., Bragaglia A., Smart R., Spagna A., 2012, *MNRAS*, 422, 2116
- Kippenhahn R., Weigert A., 1994, *Stellar Structure and Evolution*
- Kochukhov O., , 2012, *Synth3: Non-magnetic spectrum synthesis code*
- Kochukhov O. P., 2007, in Romanyuk I. I., Kudryavtsev D. O., Neizvestnaya O. M., Shapoval V. M., eds, *Physics of Magnetic Stars Spectrum synthesis for magnetic, chemically stratified stellar atmospheres*. pp 109–118
- Kolenberg K., 2002, PhD thesis, Institute of Astronomy, K.U. Leuven, Belgium
- Kolenberg K., Bagnulo S., 2009, *A&A*, 498, 543
- Kolenberg K., Fossati L., Shulyak D., Pikall H., Barnes T. G., Kochukhov O., Tsybmal V., 2010, *A&A*, 519, A64
- Kolenberg K., Guggenberger E., Medupe T., Lenz P., Schmitzberger L., Shobbrook R. R., Beck P., Ngwato B., Lub J., 2009, *MNRAS*, 396, 263
- Kolenberg K., Smith H. A., Gazeas K. D., Elmasli A., Breger M., Guggenberger E., van Cauteren P., Lampens P., Reegen P., Niarchos P. G., Albayrak B., Selam S. O., Özavcı I., Aksu O., 2006, *A&A*, 459, 577
- Kolláth Z., Molnár L., Szabó R., 2011, *MNRAS*, 414, 1111
- Kovács G., 2009, in Guzik J. A., Bradley P. A., eds, *American Institute of Physics Conference Series Vol. 1170 of American Institute of Physics Conference Series, The Blazhko Effect*. pp 261–272
- Kupka F., Piskunov N., Ryabchikova T. A., Stempels H. C., Weiss W. W., 1999, *A&AS*, 138, 119
- Kupka F. G., Ryabchikova T. A., Piskunov N. E., Stempels H. C., Weiss W. W., 2000, *Baltic Astronomy*, 9, 590
- Landi Degl’Innocenti E., Landolfi M., eds, 2004, *Polarization in Spectral Lines Vol. 307 of Astrophysics and Space Science Library*
- Le Borgne J. F., Klotz A., Boer M., 2009, *Information Bulletin on Variable Stars*, 5877, 1

- Le Borgne J. F., Paschke A., Vandenbroere J., Poretti E., Klotz A., Boër M., Damerdjy Y., Martignoni M., Acerbi F., 2007, *A&A*, 476, 307
- Livingston W., 1984, in Keil S. L., ed., *Small-Scale Dynamical Processes in Quiet Stellar Atmospheres Secular Change of Full Disk Line Asymmetry*. p. 330
- Machida M. N., 2008, *ApJ*, 682, L1
- Martínez Fiorenzano A. F., Gratton R. G., Desidera S., Cosentino R., Endl M., 2005, *A&A*, 442, 775
- Martinez-Gonzalez M. J., Semel M., 2008, Some notes about SemPol
- Mathias P., Gillet D., 1993, *A&A*, 278, 511
- Mathias P., Gillet D., Fokin A. B., Chadid M., 1995, *A&A*, 298, 843
- Mizerski T., 2003, *Acta Astron.*, 53, 307
- Moskalik P., 1986, *Acta Astron.*, 36, 333
- Moskalik P., Poretti E., 2003, *A&A*, 398, 213
- Mosser B., Goupil M. J., Belkacem K., Marques J. P., Beck P. G., Bloemen S., De Ridder J., Barban C., Deheuvels S., Elsworth Y., Hekker S., Kallinger T. e. a., 2012, *A&A*, 548, A10
- Nagy A., Kovács G., 2006, *A&A*, 454, 257
- Nowakowski R. M., Dziembowski W. A., 2001, *Acta Astron.*, 51, 5
- Olech A., Kaluzny J., Thompson I. B., Pych W., Krzeminski W., Schwarzenberg-Czerny A., 1999, *AJ*, 118, 442
- Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2011, *ApJS*, 192, 3
- Peterson R. C., Carney B. W., Latham D. W., 1996, *ApJ*, 465, L47
- Pickering E. C., Bailey S. I., 1895, *ApJ*, 2, 321
- Pickering E. C., Colson H. R., Fleming W. P., Wells L. D., 1901, *ApJ*, 13, 226
- Pietarila A., Livingston W., 2011, *ApJ*, 736, 114
- Pietrzyński G., Thompson I. B., Gieren W., Graczyk D., Stępień K., Bono G., Moroni P. G. P., Pilecki B., Udalski A., Soszyński I., Preston G. W., Nardetto N., McWilliam A., 2012, *Nature*, 484, 75

- Piskunov N. E., Kupka F., Ryabchikova T. A., Weiss W. W., Jeffery C. S., 1995, *A&AS*, 112, 525
- Preston G. W., 1959, *ApJ*, 130, 507
- Preston G. W., 1964, *ARA&A*, 2, 23
- Preston G. W., 1967, in Cameron R. C., ed., *Magnetic and Related Stars Studies of Stellar Magnetism-Past, Present, and Future*. p. 3
- Preston G. W., Smak J., Paczynski B., 1965, *ApJS*, 12, 99
- Prialnik D., 2000, *An Introduction to the Theory of Stellar Structure and Evolution*
- Romanov Y. S., Udovichenko S. N., Frolov M. S., 1987, *Soviet Astronomy Letters*, 13, 29
- Ryabchikova T. A., Piskunov N. E., Kupka F., Weiss W. W., 1997, *Baltic Astronomy*, 6, 244
- Sanford R. F., 1949, *ApJ*, 109, 208
- Schnerr R. S., Henrichs H. F., Neiner C., Verdugo E., de Jong J., Geers V. C., Wiersema K., van Dalen B., Tijani A., Plaggenborg B., Rygl K. L. J., 2008, *A&A*, 483, 857
- Schwarzschild M., 1946, in *Publications of the American Astronomical Society Vol. 10 of Publications of the American Astronomical Society, Symposium: Intrinsic Stellar Variation. Recent studies of the pulsation theory*. p. 117
- Semel M., Donati J.-F., Rees D. E., 1993, *A&A*, 278, 231
- Sesar B., 2010, PhD thesis, University of Washington
- Shapley H., 1916, *ApJ*, 43, 217
- Shibahashi H., 2000, in Szabados L., Kurtz D., eds, *IAU Colloq. 176: The Impact of Large-Scale Surveys on Pulsating Star Research Vol. 203 of Astronomical Society of the Pacific Conference Series, The Oblique Pulsator Model for the Blazhko Effect in RR Lyrae Stars. Theory of Amplitude Modulation I.* pp 299–306
- Shibahashi H., Takata M., 1995, in Stobie R. S., Whitelock P. A., eds, *IAU Colloq. 155: Astrophysical Applications of Stellar Pulsation Vol. 83 of Astronomical Society of the Pacific Conference Series, Oblique Pulsator Model for the Blazhko Effect of RR Lyrae Stars*. p. 42
- Shulyak D., Tsymbal V., Ryabchikova T., Stütz C., Weiss W. W., 2004, *A&A*, 428, 993

- Silva Aguirre V., Catelan M., Weiss A., Valcarce A. A. R., 2010, *Ap&SS*, 328, 123
- Smolec R., 2005, *Acta Astron.*, 55, 59
- Soszyński I., Udalski A., Szymański M. K., Kubiak J., Pietrzyński G., Wyrzykowski Ł., Ulaczyk K., Poleski R., 2010, *Acta Astron.*, 60, 165
- Soszyński I., Dziembowski W. A., Udalski A., Poleski R., Szymański M. K., Kubiak M., Pietrzyński G., Wyrzykowski Ł., Ulaczyk K., Kozłowski S., Pietrukowicz P., 2011, *Acta Astron.*, 61, 1
- Soszyński I., Udalski A., Szymański M. K., Kubiak M., Pietrzyński G., Wyrzykowski Ł., Szewczyk O., Ulaczyk K., Poleski R., 2009, *Acta Astron.*, 59, 1
- Stothers R., 1980, *PASP*, 92, 475
- Stothers R. B., 2006, *ApJ*, 652, 643
- Struve O., 1947, *PASP*, 59, 192
- Szabó R., Kolláth Z., Molnár L., Kolenberg K., Kurtz D. W., Bryson S. T., Benkő J. M., Christensen-Dalsgaard J., Kjeldsen H., Borucki W. J., Koch D., Twicken J. D., Chadid M., di Criscienzo M., 2010, *MNRAS*, 409, 1244
- Szeidl B., 1976, in Fitch W. S., ed., *IAU Colloq. 29: Multiple Periodic Variable Stars Vol. 60 of Astrophysics and Space Science Library, Multiple Periodic RR Lyrae Stars: Observational Review.* p. 133
- Szeidl B., 1988, in Kovacs G., Szabados L., Szeidl B., eds, *Multimode Stellar Pulsations Multimode stellar pulsations*
- Szeidl B., Jurcsik J., 2009, *Communications in Asteroseismology*, 160, 17
- Trujillo-Bueno J., Moreno-Insertis F., Sánchez F., eds, 2002, *Astrophysical spectropolarimetry*
- Tsymbal V., 1996, in Adelman S. J., Kupka F., Weiss W. W., eds, *M.A.S.S., Model Atmospheres and Spectrum Synthesis Vol. 108 of Astronomical Society of the Pacific Conference Series, STARSP: A Software System For the Analysis of the Spectra of Normal Stars.* p. 198
- van Hoof A., Struve O., 1953, *PASP*, 65, 158
- Van Hoolst T., Dziembowski W. A., Kawaler S. D., 1998, *MNRAS*, 297, 536
- Wallerstein G., Jacobsen T. S., Cottrell P. L., Clark M., Albrow M., 1992, *MNRAS*, 259, 474

Wallerstein G., Kovtyukh V. V., Andrievsky S. M., 2009, ApJ, 692, L127

Weiss W. W., Kupka F., 1999, in Gimenez A., Guinan E. F., Montesinos B., eds, Stellar Structure: Theory and Test of Connective Energy Transport Vol. 173 of Astronomical Society of the Pacific Conference Series, Observational Evidence for Convection in Main Sequence Star Atmospheres. p. 21

List of Publications

Elisabeth Guggenberger

List of Publications

First-author refereed publications

- 1 **2014, IAUS 301, 261: Bisector analysis of RR Lyrae: atmosphere dynamics at different phases.**
Guggenberger E., Shulyak D., Tsymbal V., Kolenberg K.
- 2 **2012, MNRAS 424, 649: The complex case of V445 Lyr observed with Kepler: two Blazhko modulations, a non-radial mode, possible triple mode RR Lyrae pulsation, and more.**
Guggenberger E., Kolenberg K., Nemec J. M., Smolec, R., Benkő J. M., Ngeow C.-C., Cohen J. G., Sesar B., Szabó R., Catelan M., Moskalik P., Kinemuchi K., Seader S. E., Smith J. C., Tenenbaum P., Kjeldsen H.
- 3 **2012, AN 333, 1044: RR Lyrae stars seen from space.**
Guggenberger E.
- 4 **2011, MNRAS 415, 1577: The CoRoT star 105288363: strong cycle-to-cycle changes of the Blazhko modulation.**
Guggenberger E., Kolenberg K., Chapellier E., Poretti E., Szabó R., Benkő J. M., Paparó M.

Co-authored refereed publications

- 1 **2012, MNRAS, 424, 2380: A multisite photometric study of two unusual β Cep stars: the magnetic V2052 Oph and the massive rapid rotator V986 Oph.**
Handler G., Shobbrook R. R., Uytterhoeven K., Briquet M., Neiner C., Tshenye T., Ngwato B., van Winckel H., Guggenberger E., Raskin G., Rodríguez E., Mazumdar A., Barban C., Lorenz D., Vandenbussche B., Sahin T., Medupe R., Aerts C.
- 2 **2011, MNRAS, 417, 1022: Fourier analysis of non-Blazhko ab-type RR Lyrae stars observed with the Kepler space telescope.**
Nemec, J. M.; Smolec, R.; Benkő, J. M.; Moskalik, P.; Kolenberg, K.; Szabó, R.; Kurtz, D. W.; Bryson, S.; Guggenberger, E.; and 16 coauthors
- 3 **2011, A&A, 531, 135: Periodicity search as a tool for disentangling the contaminated colour light curve of CoRoT 102781750.**
Paparó, M.; Chadid, M.; Chapellier, E.; Benkő, J. M.; Szabó, R.; Kolenberg, K.; Guggenberger, E.; Regály, Zs.; Auvergne, M.; Baglin, A.; Weiss, W. W.
- 4 **2011, MNRAS, 411, 878: Kepler photometry of the prototypical Blazhko star RR Lyr: an old friend seen in a new light.**
Kolenberg, K.; Bryson, S.; Szabó, R.; Kurtz, D. W.; Smolec, R.; Nemec, J. M.; Guggenberger, E.; Moskalik, P.; Benkő, J. M.; and 12 coauthors

- 5 **2010, MNRAS, 409, 1585: Flavours of variability: 29 RR Lyrae stars observed with Kepler.**
Benkő, J. M.; Kolenberg, K.; Szabó, R.; Kurtz, D. W.; Bryson, S.; Bregman, J.; Still, M.; Smolec, R.; Nuspl, J.; Nemec, J. M.; and 11 coauthors
- 6 **2010, A&A, 520, 108: CoRoT light curves of RR Lyrae stars. CoRoT 101128793: long-term changes in the Blazhko effect and excitation of additional modes.**
Poretti, E.; Paparó, M.; Deleuil, M.; Chadid, M.; Kolenberg, K.; Szabó, R.; Benkő, J. M.; Chapellier, E.; Guggenberger, E.; Le Borgne, J. F.; and 6 coauthors
- 7 **2010, ApJ, 713, 198: First Kepler Results on RR Lyrae Stars.**
Kolenberg, K.; Szabó, R.; Kurtz, D. W.; Gilliland, R. L.; Christensen-Dalsgaard, J.; Kjeldsen, H.; Brown, T. M.; Benkő, J. M.; and 16 coauthors
- 8 **2010, A&A, 510, 39: First CoRoT light curves of RR Lyrae stars. Complex multiplet structure and non-radial pulsation detections in V1127 Aquilae.**
Chadid, M.; Benkő, J. M.; Szabó, R.; Paparó, M.; Chapellier, E.; Kolenberg, K.; Poretti, E.; Bono, G.; Le Borgne, J.-F.; Tringuet, H.; and 7 coauthors
- 9 **2009, MNRAS, 396, 263: A photometric study of the southern Blazhko star SS For: unambiguous detection of quintuplet components.**
Kolenberg, K.; Guggenberger, E.; Medupe, T.; Lenz, P.; Schmitzberger, L.; Shobbrook, R. R.; Beck, P.; Ngwato, B.; Lub, J.
- 10 **2006, A&A, 459, 577: The Blazhko effect of RR Lyrae in 2003-2004.**
Kolenberg, K.; Smith, H. A.; Gazeas, K. D.; Elmasli, A.; Breger, M.; Guggenberger, E.; van Cauteren, P.; Lampens, P.; Reegen, P.; Niarchos, P. G.; and 4 coauthors
- 11 **2006, A&A, 455, 673: Pulsation of the Lambda Bootis star HD 210111.**
Breger, M.; Beck, P.; Lenz, P.; Schmitzberger, L.; Guggenberger, E.; Shobbrook, R. R.
- 12 **2005, A&A, 435, 955: Detection of 75+ pulsation frequencies in the ? Scuti star FG Virginis.**
Breger, M.; Lenz, P.; Antoci, V.; Guggenberger, E.; Shobbrook, R. R.; Handler, G.; Ngwato, B.; Rodler, F.; Rodriguez, E.; López de Coca, P.; and 2 coauthors

Non-refereed first-author publications

- 1 **2009, AIPC, 1170, 278: High-Resolution Magnetic Field Measurements of RR Lyrae Stars with SemPol.**
Guggenberger E., Kolenberg K., Marsden S. C., Waite I. A., Henrichs H. F., Lüftinger T.
- 2 **2008, CoAst, 157, 313: Photometric observations of southern Blazhko Stars.**
Guggenberger E., Kolenberg K., Medupe T.
- 3 **2008, JPhCS, 118, 2056: Analysing periodic amplitude changes in RR Lyrae and other types of variable stars .**
Guggenberger E., Kolenberg, K. Breger M.
- 4 **2007, CoAst, 150, 379: RR Lyrae stars: The changing light curve shape during the Blazhko cycle.**
Guggenberger E., Kolenberg K.

- 5 **2006, CoAst, 148, 21: The moving bump in the light curves of SS For and RR Lyr.**
Guggenberger E., Kolenberg K.

Non-refereed co-author publications

- 1 **2009, AIPC, 1170, 240: Shock wave and pulsation connection in a mono periodic CoRoT RR Lyrae star.**
Paparó, M.; Szabó, R.; Benkő, J. M.; Chadid, M.; Poretti, E.; Kolenberg, K.; Guggenberger, E.; Chapellier, E.
- 2 **2009, AIPC, 1170, 235: First RR Lyrae light curves from CoRoT: Big challenge and constraint to the theoretical models.**
Chadid, M.; Baglin, A.; Benkő, J.; Bono, G.; Chapellier, E.; Guggenberger, E.; Kolenberg, K.; Paparó, M.; Poretti, E.; Szabó, R.; and 2 coauthors
- 3 **2008, CoAst, 153, 67: Johnson photometry of southern Blazhko targets.**
Kolenberg, K.; Guggenberger, E.; Medupe, T.
- 4 **2007, CoAst, 150, 381: Photometric campaigns for the Blazhko Project.**
Kolenberg, K.; Guggenberger, E.; Blazhko Collaboration
- 5 **2006, MmSAI, 77, 498: How to make progress in the understanding of the Blazhko effect.**
Kolenberg, K.; Guggenberger, E.; Breger, M.; Smith, H.; Barnes, T.
- 6 **2005, ASPC, 335, 115: Spurious Period Shifts and Changes among Variable Stars.**
Rodler, F.; Guggenberger, E.
- 7 **2005, CoAst, 146, 11: OV And, a new field RRab Blazhko star?.**
Kolenberg, K.; Guggenberger, E.; Lenz, P.; van Cauteren, P.; Lampens, P.; Wils, P.

Popular Science (in German language)

- 2007, S&W, 46, 7: Das 100-jährige Rätsel der RR Lyrae Sterne.**
Guggenberger, E & Kolenberg, K
- 2007, S&W, 46, 2: Rußende Sterne als Sprösslinge Weißer Zerge.**
Guggenberger, E
- 2007, S&W, 46, 7: CoRoT: Erfolgreichen Debut.**
Guggenberger, E
- 2006, S&W, 45, 21: Schwarze Löcher in Staubkokons.**
Guggenberger, E
- 2006, S&W, 45, 6: Die Rote Kante der Vegetation.**
Guggenberger, E
- 2005, S&W, 44, 12: Molekülbildung auf rauem Staub.**
Guggenberger, E
- 2005, S&W, 44, 9: Am Anfang war die ideale Flüssigkeit.**
Guggenberger, E

Curriculum Vitae

Elisabeth Guggenberger

Curriculum Vitae

Education

- 2008–present **PhD student**, *University of Vienna*.
Topic of research: RR Lyrae stars in the space age
- 2008 **Diploma in Astronomy**, *University of Vienna*.
exam passed with distinction
- 1999 **High school diploma**.
passed with distinction
- 1993–1999 **neusprachliches Gymnasium**, *Mater Salvatoris, Kenyongasse 4-12, 1070 Wien*.
- 1992–1993 **German European School Singapore**, *72, Bukit Tinggi Road, Singapore 289760 (Bukit Timah)*.
- 1987–1992 **Volksschule und Gymnasium**, *Mater Salvatoris, Kenyongasse 4-12, 1070 Wien*.

PhD Thesis

- Title *RR Lyrae stars in the space age: new insights from high-precision photometry and high-resolution spectroscopy*
- Supervisors Michel Breger & Katrien Kolenberg
- Status to be finished this year

Masters Thesis

- Title *Stellar Cycles: Photometric observations of the Blazko effect in RR Lyrae stars*
- Supervisor Michel Breger
- Download homepage.univie.ac.at/elisabeth.guggenberger/Thesis.pdf

Work Experience in Astronomy

- 2008–2013 **Employment in FWF-project "Modulated RR Lyrae stars"**, *PhD student*, Project lead by Katrien Kolenberg & Theresa Lüftinger, Institut für Astrophysik, Universität Wien.
Magnetic field measurements (spectropolarimetry) of RR Lyrae stars, detailed analysis of CoRoT and Kepler data, analysis of high-resolution spectra of RR Lyrae.
- 2004–2007 **Employment in FWF-project "Stellar Cycles"**, *Undergraduate student*, Project lead by Michel Breger, Institut für Astrophysik, Universität Wien.
Analysis and acquisition of ground-based high-precision photometry. Observing trips to South Africa

- 2003–2004 **Employment in FWF-project "Seismology of the Stars in the Instability Strip"**, *Undergraduate Student*, Project lead by Michel Breger, Institut für Astrophysik, Universität Wien.
Data reduction of photometry obtained by a robotic telescope

Observing experience and research visits

- 2013 **Harvard-Smithsonian Center for Astrophysics, USA**, *2 weeks, research visit*.
Worked on the spectra of RR Lyrae with focus on the analysis of line bisectors with Katrien Kolenberg. Learned about synthetic spectra calculations in collaboration with Robert Kurucz
- 2013 **Leuven, Belgium**, *4 days, research visit*.
Worked on the paper on the analysis of the spectra of RR Lyrae with Katrien Kolenberg, Luca Fossati and Denis Shulyak
- 2009 **Saas Fee Advanced Course on Magnetic Fields**, *1 week, winter school*.
- 2008 **AAT+SemPol, Australia**, *2 weeks, observing run*.
Magnetic field measurements of a selected sample of RR Lyrae stars using the SemPol polarimeter at the Anglo Australian Telescope in collaboration with Stephen Marsden
- 2008 **Paris Observatory, France**, *1 week, research visit*.
Learned how to use, assemble and calibrate the SemPol polarimeter in the working group of Meir Semel
- 2005 **SAAO, South Africa**, *5 weeks, observing run*.
Photometry of a sample of RR Lyrae stars with the 20" and 30" telescope
- October 2004 **SAAO, South Africa**, *3 weeks, observing run*.
Photometry of a sample of RR Lyrae stars with the 20" and 30" telescopes
- April 2004 **SAAO, South Africa**, *3 weeks, observing run*.
Photometry of a sample of Delta Scuti and β Cephei stars with the 20" telescope

Teaching

- 2013 **Talk in a lecture course on variable stars**.
Contributed the part on RR Lyrae stars to the latest lecture course on variable stars held at the University of Vienna
- 2008 **Tutor**, *Lecture on astronomical instrumentation*.
- 2006–2008 **Tutor**, *Introductory course in astronomy*.
- 2004–2005 **Tutor**, *Practical observing training with the vienna little telescope*.

Conference Presentations and Talks

- 2013 **IAU Symposium 301**, *Wrocław, Poland*, Oral presentation.
A bisector analysis of RR Lyrae
- 2013 **Talk at Harvard-Smithsonian CfA**, *Cambridge, USA*, Talk.
Simple or complex? Some observational news on RR Lyrae stars
- 2012 **KASC5 meeting**, *Balatonalmádi, Hungary*, Oral presentation.
From simple to complex: an extreme RR Lyrae star seen with Kepler
- 2012 **ESF Conference**, *Obergurgl, Austria*, Oral presentation.
RR Lyrae stars seen from space

- 2011 **Stellar Pulsation Conference Series**, *Granada, Spain*, Poster presentation.
Changing Blazhko modulations: KIC 6186029 in comparison with other cases of non-repetitive Blazhko cycles
- 2009 **Stellar Pulsation Conference Series**, *Santa Fe, USA*, Poster presentation.
High-Resolution magnetic field measurements of RR Lyrae stars with SemPol
- 2008 **Wroclaw HELAS workshop**, *Wroclaw, Poland*, Poster presentation.
Photometric observations of southern Blazhko stars
- 2007 **HELAS meeting**, *Göttingen, Germany*, Poster presentation.
Beating or not? Periodic amplitude changes in RR Lyrae and other types of variable stars
- 2006 **The future of Asteroseismology meeting**, *Vienna, Austria*, Poster presentation.
RR Lyrae stars: The changing light curve shape during the Blazhko cycle

Languages

German **Mother tongue**
 English **fluent**
 Spanish **basic**
 French **basic**