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Introduction

Amplitude and also phase variability in pulsating stars has been known for more than a century. The first to report it was Sergei Nikolaevich Blazhko (1907) on the star RW Dra. He classified the star -which was at this time called Var. 87.1906 Draconis- to be of the type 'Antalgol' which is the historical designation for stars with RR Lyrae-like light curves. Blazhko stated that a periodic change of period was necessary to describe the star's light curve. Nowadays, "Antalgols" are referred to as RR Lyrae stars, and the phenomenon of amplitude and phase variation is named after its discoverer: it is called the **Blazhko effect**.

Since then, the Blazhko effect has been found in many stars of RR Lyrae type, for a long time the most often cited incidence rate was 20-30 % for RRab stars and about 5% for RRc, recent estimates even give values around 50% and higher. But the phenomenon seems to reach even farther: from long term photometric studies with high precision it has become clear that also other types of variable stars show periodic amplitude and phase changes: Delta Scutis, white dwarfs and Cepheids are also affected. But the physics of these stars are very different, and the question arises whether the observed variability of the amplitudes is indeed the same effect in all of these classes of pulsators or whether is has entirely different reasons in each of them and the effects just happen to look very much alike.

It is the aim of this thesis to summarize the current standard of knowledge from the observational side and to present new photometric results which were obtained in the framework of the "Blazhko Project".

Chapter 1

RR Lyrae stars

1.1 Stellar parameters

RR Lyrae stars are population II stars which means they are old and contain only very little heavy elements. They usually have a mass of about 0.5-0.8 solar masses, radii of about 4-6 $R_\odot$ and pulsation periods of about 0.2-1 days. As they can often be found in globular clusters and were discovered in the globular cluster ω Cen, they were formerly called "cluster variables". Now they are named after the prototype, the brightest star among them which was discovered by Mrs. Williamina Fleming (1899): RR Lyrae. They usually have luminosities of $L \approx 45 - 50 L_\odot$ and pulsation amplitudes of 0.3-2 mag. Their temperatures range from 6000K to 7200K, with fundamental mode pulsators found at lower and overtone pulsators at the higher side of the temperature range, respectively. As in Cepheids, there is a relation between their period and their luminosity and their temperature, and RR Lyraes are therefore important standard candles for distance determination within our galaxy.

1.2 Bailey types

According to their light curve shape RR Lyrae stars are divided into different types, the so called **Bailey types**. Bailey type **RRab** refers to stars with a very nonsinusoidal light variation and high amplitudes of about 1-2 mag. Also, Bailey RRab stars are known to pulsate in the radial fundamental mode. Their skewness factor ε, which is definded as

$$\varepsilon = \frac{T_{Max} - T_{Min}}{P}$$

usually ranges from 0.1 to 0.3. T_{Max} and T_{Min} are the times of maximum and minimum light respectively and P denotes the pulsation period. Pulsation periods of RRab stars are typically longer than 0.45 days. For the typical light curve shape of an RRab star see figure 1.1.

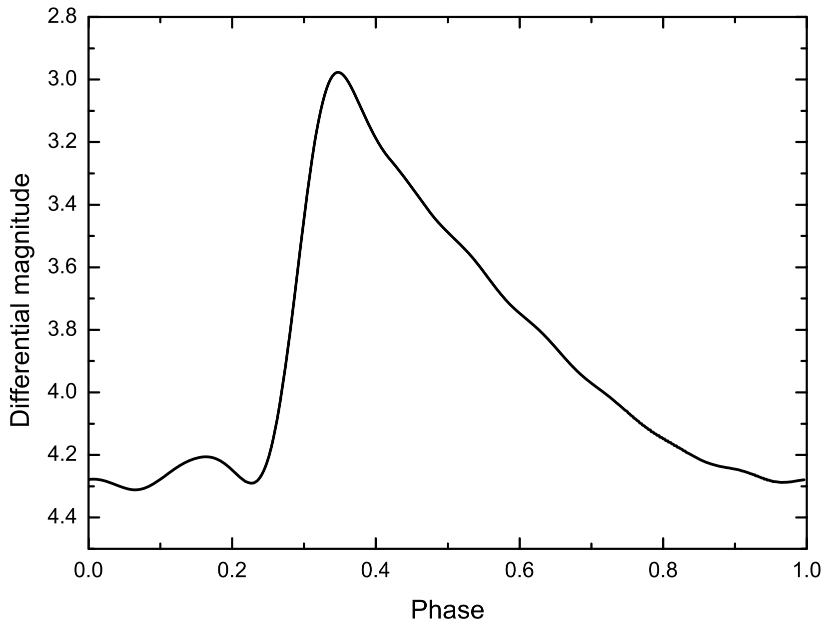

Figure 1.1: Schematic light curve of an RRab star. Note the very non-sinusoidal shape: a steep rising branch and a slow decrease of brightness after the maximum are characteristic for RRab stars. The conspicuous bump right before the beginning of the rising branch is also a very common and interesting feature and will be treated in section 4.6.

Although RRab stars might only oscillate in one mode of pulsation, for a mathematical description more than one sine frequency is necessary to describe the asymmetric light curve. Those additional frequencies needed to reproduce the light curve are referred to as *harmonics*. They are integer multiples of the fundamental mode and inevitably appear in every Fourier analysis of RRab stars due to the asymmetry of the light curve.

Originally, RRa and RRb existed as separate types, but were later merged to "ab" because the gradual transition between them made them almost undistinguishable. Bailey (1902) himself stated that the subclass b "is similar to a, of which it may be regarded as a modification". Besides that, later on it was found that, in contrast to the RRc stars, they pulsate in the same mode, namely the radial fundamental.

RRc stars pulsate in their first radial overtone. Stars of type RRc show more sinusoidal light curves and smaller amplitudes of less than 0.5 mag.

Their skewness ε is about 0.4-0.5 and their periods range from 0.2 to 0.4 days.

RRd stars pulsate both in the radial fundamental and in the first overtone. They were discovered much later than their monoperiodic counterparts: It was in 1977 that Jerzykiewicz & Wenzel (1977) announced the discovery of two pulsation modes in AQ Leo, a field star. Some years later the first detection of an RRd star in a globular cluster (V68 in M3) was published by Goranskij (1981).

The number of known RRd stars increased dramatically with the large microlensing surveys that produced as a byproduct an enormous amount of photometric data of variable stars. With 73 new discoveries Alcock et al (1997) doubled the number of known RRd stars, and some years later, Alcock et al (2000) increased the number of RRd stars in the Large Magellanic Cloud to 181. Nowadays, several hundred RRd pulsators are known.

Usually, the first overtone which occurs in a rather small period range of $0.33d < P_1 < 0.41d$ has a higher amplitude than the fundamental mode and is therefore the dominant mode. In a Bailey diagram (see section 1.4), RRd stars occupy the region between the RRab and the RRc pulsators. The range in period of the fundamental mode is $0.46d < P_0 < 0.55d$, and the period ratio P_1/P_0 is typically around 0.745. RRd stars play a very important role in determining stellar parameters and testing pulsation and evolution models as it is possible to estimate their mass from the observed periods.

In the HR diagram, RRd stars are thought to be found in the transition zone between the fundamental blue edge and the first overtone red edge of the instability strip.

For a long time, RRd stars had been a challenge to theorists, until in 1998, Feuchtinger & Dorfi managed to obtain a stable solution with their model by including time-dependent turbulent convection. According to their model, there is a narrow temperature range where double-mode pulsation is possible. Also, they can reproduce the property of RRd stars, that the first overtone amplitude is higher than that of the fundamental frequency.

Still under discussion is the existence of **RRe** stars which are said to pulsate in the second overtone. This class of overtone pulsators was predicted by Stellingwerf (1987) who calculated model light curves for RRc stars and tried those models also on the second overtone. The resulting light curves had a sharper peak at maximum than the RRc stars. He expected the second overtone RR Lyraes to have the shortest periods and hottest effective temperatures. Finally, he proposed the designation 'RRe' for the second overtone RR Lyraes.

In observational data, the RRe pulsators manifest themselves in an additional peak in the period distribution of RR Lyrae stars. Such a peak at periods slightly shorter than those of RRc stars has been observed by many authors in their period histograms of various star systems. Van Albada & Baker (1973) noticed it in their data of galactic globular clusters, Alcock et al. (1996) found it in their database of RR Lyrae stars in the Large Magellanic Cloud, and it has also been observed in the Sculptor dwarf galaxy as well as in the Small Magellanic Cloud. A typical value for the period of those stars would be 0.281d.

Kovacs (1998) on the other hand, calculated linear non-adiabatic models for some suspected RRe pulsators and showed that second overtone pulsation can only occur at periods significantly shorter than the ones observed (around 0.22d rather than 0.28d). He proposes that the alleged RRe stars might be ordinary RRc stars at the short-period end of the instability strip.

For the explained categories of RR Lyrae stars, there exists another rather new nomenclature using numbers instead of letters. his nomenclature is, among others, used by Alcock et al (2000). Correlating designations are listed in table 1.1.

old	new	pulsation mode
RRab	RR0	fundamental
RRc	RR1	first overtone
RRd	RR01	fundamental + first overtone
RRe	RR2	seond overtone

Table 1.1: The two nomenclatures for the different types of RR Lyrae stars

Other categories of yet unconfirmed RR Lyrae pulsators are those stars which are thought to pulsate in the first and second overtone simultaneously (RR12) and those stars that might pulsate in the third overtone (RR3). For both categories only a few candidates have been found so far and their mode of pulsation has not been confirmed yet.

1.3 The Petersen Diagram

When two modes of radial pulsation are excited, as it is the case in RRd Lyrae stars, it is possible to estimate their mass and other basic parameters like absolute magnitude and metallicity. This is done with the help of the so called Petersen diagram, which is in principle a period ratio versus fundamental period (P_1/P_0 vs. P_0) diagram. It was first used by Petersen (1973) to estimate the masses of double mode Cepheids.

As periods can be observed with very high accuracy, the position of a certain RRd star in the Petersen diagram can be determined precisely and rather easily. Model calculations show that the position of a star in the Petersen diagram is a function of mass and metallicity. This makes it a powerful tool for analysis. If one plots a large number of stars of a certain system in the Petersen diagram, the data points align on a characteristic curve. The shape of this band can give crucial information about parameters of the star system and can be used for testing evolution models. An example is shown in Figure 1.2 for stars in the Small and Large Magellanic clouds observed by the OGLE project.

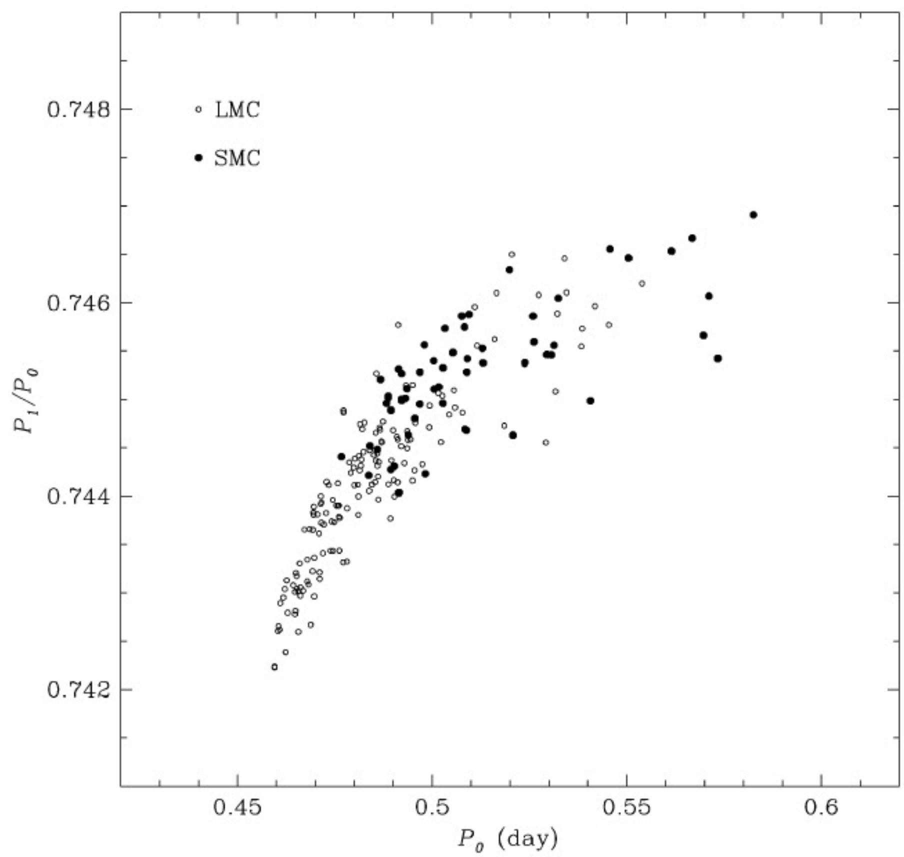

Figure 1.2: Petersen diagram of the RRd stars in the SMC and LMC taken from Soszynski et al. (2002)

1.4 The Bailey Diagram

The so called Bailey diagram is a powerful tool for analysing features of RR Lyrae stars. It is in principle a period-amplitude diagram, that clearly shows the differences between the Bailey types. At the shorter periods and lower amplitudes the RRc stars form a very distinct group with almost no dependence of the amplitude on the period. The RRab pulsators on the other hand show a clear correlation between amplitude and period (see figure 1.3. With a large amount of high quality data it also becomes obvious that the function A(P) is nonlinear for the RRab stars. This nonlinearity has also been predicted by theoretical models. Besides it is believed that the metal content influences the position of a star in the Bailey diagram, moving it further to the left, i.e. to shorter periods with increasing metallicity. It is this diagram that Szeidl (1988) uses to suggest that the Blazhko effect might be a supressing phenomenon (see section 2).

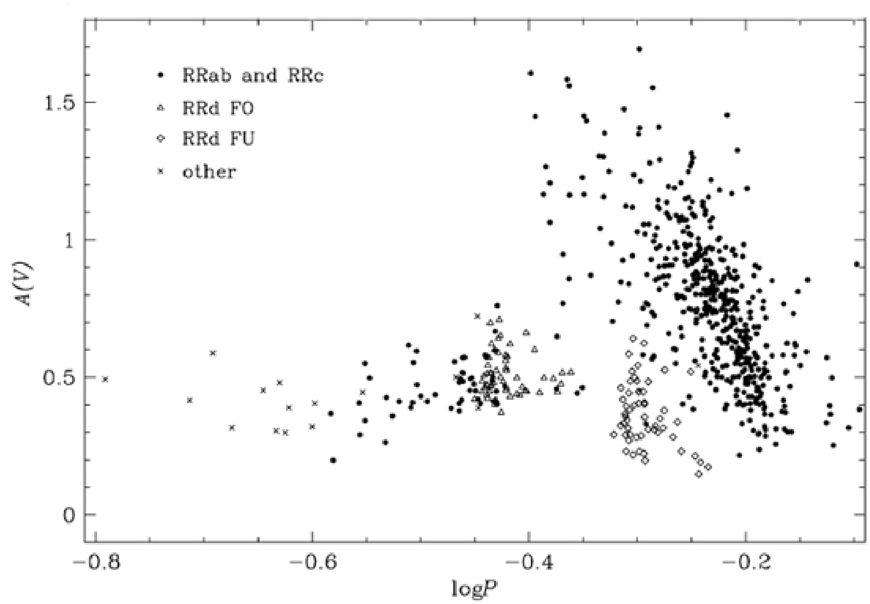

Figure 1.3: Bailey diagram of the RR Lyrae stars in the Small Magellanic Cloud taken from Sozsynski et al. (2002). RRab and RRc stars are depicted with dots and form two well-seperated groups. RRd stars are represented by open triangles and open diamonds for their first overtone and fundamental period, respectively.

To the left of the RRc stars sometimes another group of stars appears in the Bailey diagram. These stars are the potential second overtone pulsators, but as mentioned before, they might also be extreme RRc variables.

The RRd stars in the Bailey diagram occupy the gap between the fundamental and overtone pulsators, what has been expected from theoretical considerations.

1.5 The Oosterhoff dichotomy

When looking at the distribution of periods of RRab Lyraes in different globular clusters, one is bound to notice that two groups of clusters seem to exist. The typical periods of RRab stars are 0.65 and 0.55 days for the two groups, respectively. The first to make this observation was Oosterhoff (1939). He stated that the five globular clusters he observed fall in two distinct groups, according to the mean periods of the RR Lyrae variables they contain. These groups are therefore now called the two *Oosterhoff groups*, or Oo type I and Oo type II.

	OoI	OoII
$< P_{ab} >$	0.55 d	0.65 d
$< P_c >$	0.38 d	0.32 d
$N_{overtone}/N_{fundamental}$	0.18	0.44
$[Fe/H]$	-1.5	-2.0
P_1/P_0 (RRd)	0.744	0.746
P_0 (RRd)	0.48 d	0.55 d

Table 1.2: The differences between the two Oosterhoff groups

Oosterhoff also saw that the typical periods of RRc stars differ from one group to the other. They are 0.38 and 0.32 days, respectively. Another difference between the Oosterhoff groups lies in the incidence rate of RRc variables compared to RRab stars. The ratio of the number of RRc varables (N_{RRc}) to that of the RRab Variables (N_{RRab}) is between 0.43 and 0.5 for OoII while it is much lower (around 0.18) for OoI clusters. Nowadays, for calculating this ratio one often uses the total number of overtone pulsators ($N_{RRc} + N_{RRd} + N_{RRe}$) rather than ($N_{RRc}$) but, of course, RRd and RRe stars were not known at the time when the Oosterhoff dichotomy was discovered. Later it was observed that the metallicities of the two Oosterhoff groups are different. Typical values would be [Fe/H]= -0.15 and -0.20 for OoI and OoII, respectively. Oosterhoff groups can also be differentiated by the period ratios and fundamental mode periods of RRd stars. The ratio of overtone period to fundamental period for RRd stars is usually around 0.745,

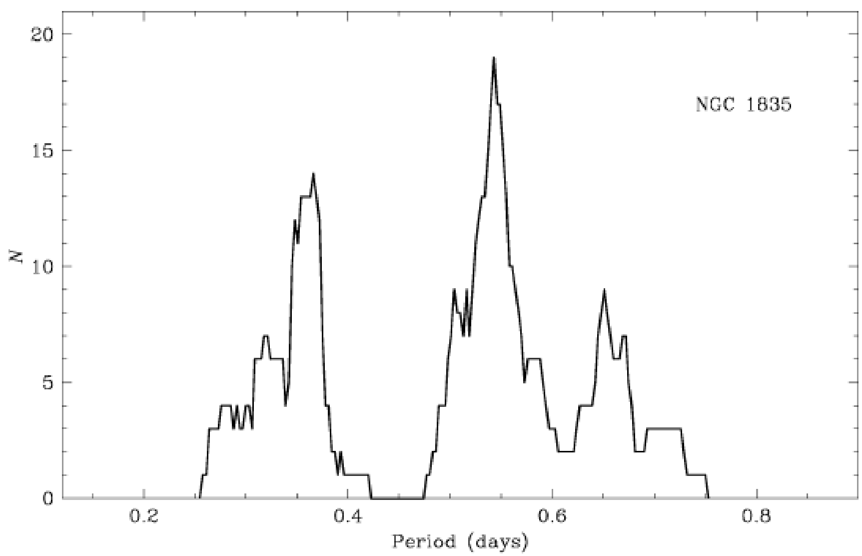

Figure 1.4: Period histogram of the LMC globular cluster NGC 1835 taken from Soszynski et al. (2003).

but it tends to be smaller (0.744) in OoI clusters and larger (0.746) in OoII clusters. The fundamental mode periods of RRd stars are $P_0 = 0.48 \pm 0.005d$ and $P_0 = 0.55 \pm 0.02d$ for OoI and OoII, respectively. The observed differences between the two Oosterhoff groups are summarized in table 1.2

Normally, globular clusters can be unambiguously attributed to one of the two groups, but recently clusters in the Large Magellanic Cloud were found which seem to show features of both Oosterhoff groups, i.e. two peaks in the period distribution and a value for (N_{RRc}/N_{RRab}) of 0.34 which is between the typical values for the Oosteroff groups. A period histogram of such an 'Oosterhoff-intermediate' cluster is shown in Figure 1.4. Note the obvious two peaks in the distribution of the RRab periods: one at 0.55d and one at 0.65d.

The question why there exist two groups as distinct as the Oosterhoff groups when one would suspect that physical parameters are distributed continuously, is still under discussion. There are several models trying to explain the observed characteristics. The most recent and widespread one links the existence of the two groups to evolution. According to this scenario, OoI clusters are zero-age horizontal branch objects, while OoII clusters have evolved farther.

Chapter 2

Phenomenology of the Blazhko effect

Until a few years ago no extensive statistic could be made about the Blazhko effect. Only the large surveys which were carried out in the recent past made it possible to give general information about the effect and its overall characteristics like incident rate and strength. Before that, the knowledge about the general properties of Blazhko stars was comparatively low, as every star seemed to behave differently. Statistics on the Blazhko effect were based on results on individual stars observed by various authors. Their different goals and observational techniques made data on Blazhko stars a very inhomogeneous sample.

To get information about the modulation behaviour of a star means one has to cover not only the pulsation period but also the much larger modulation period with observations, a task that requires a lot of telescope time. This section summarizes the facts that are currently known about the general properties of the Blazhko effect. Most of the information comes from recent large surveys like the MAssive Compact Halo Object (MACHO) project and the Optical Gravitational Lensing Experiment (OGLE), but also high-precision campaigns on single objects or analyses of small samples of stars make an important contribution.

This thesis deals only with the aspects derived from photometry.

2.1 The Length of the Cycle

Usually the Blazhko effect is vaguely defined as a secondary periodicity of "tens to hundreds of days", "ten to hundred times the pulsation period" or as "a modulation on a timescale of months". The most famous example -

the star RR Lyrae itself - shows a modulation period of about 40 days, and this indeed seems to be a very common value among fundamental mode RR Lyrae stars. Large surveys made it possible to investigate the distribution of Blazhko frequencies. Alcock et al (2003) find for the Large Magellanic Cloud (LMC) that modulation periods larger than 40 days are very common, while there is a sharp decrease towards shorter periods, though there exist some extreme cases with periods down to about 8 days. Soszynski et al. (2003) confirm this result with their OGLE data of the LMC. The period distributions for the LMC obtained from those two surveys can be seen in Fig. 2.1. Their similarity is obvious. The most common modulation periods are between 30 and 70 days with a slow decrease to longer and a sharp decrease towards shorter periods.

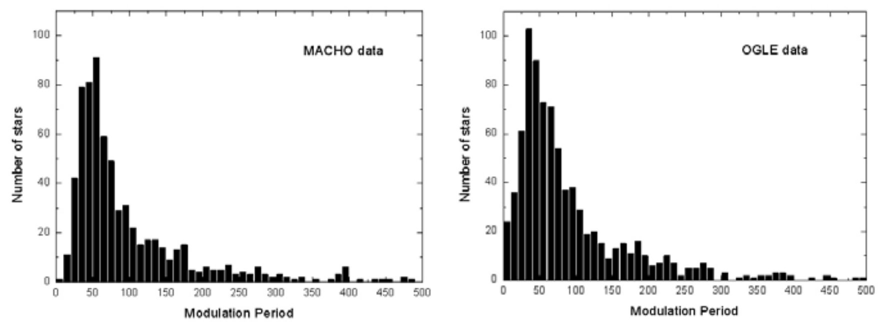

Figure 2.1: Distribution of the modulation periods of fundamental mode RR Lyrae stars in the Large Magellanic Cloud using data of the MACHO and OGLE survey, respectively.

The shortest known modulation period occurs in SS Cnc. As recently discovered by Jurcsik et al. (2006) it shows a modulation with a period of only 5.31 days. Other examples for very short Blazhko periods are RR Gem with $P_{mod} = 7.23d$ and AH Cam ($P_{mod} = 10.9d$). The longest detectable periods depend strongly on the time base of the available data. There seems to be a smooth transition between Blazhko stars and those stars classified as RR Lyraes with long term period changes. These stars also show frequencies close to the fundamental mode, but these peaks cannot be resolved properly. Usually, RS Boo with $P_{mod} = 533d$ is given as the star with the longest known Blazhko period, but there are many possible candidates for extremely long Blazhko periods. Alcock et al (2000) report that 10% of their RRc stars in the LMC show period changes which are to fast to be of evolutionary nature. In 141 cases they found a peak so close to the main frequency that it could not be resolved with the available time span of 6.5

years. They classify those stars RR1-PC for 'period change'. This could indeed be a continuous period change, but the peak could also be caused by a Blazhko effect on a very long time scale. Also in the Galactic Bulge there are similar cases: In addition to their Blazhko stars, Moskalik & Poretti (2003) found 10 stars with unresolved frequencies next to the main component. Again, this leads to suspected Blazhko periods of many years.

RRc stars seem to have much shorter Blazhko periods than the fundamental mode stars, with periods shorter than 10 days being very common. Olech et al (1999b) found some Blazhko RRc stars in the globular cluster M55 with close frequencies corresponding to modulation periods of 11.7, 78.3 and 3.6 days for V9, V10 and V12, respectively and one star in M5 with $P_{mod} = 4.88d$. Most of these values are much smaller than the ones known for RRab stars. The same result is obtained by Moskalik & Poretti (2003) for stars in the Galactic Bulge. They find the frequency separation Δf to be larger for RRc stars, which leads to shorter Blazhko periods in those stars.

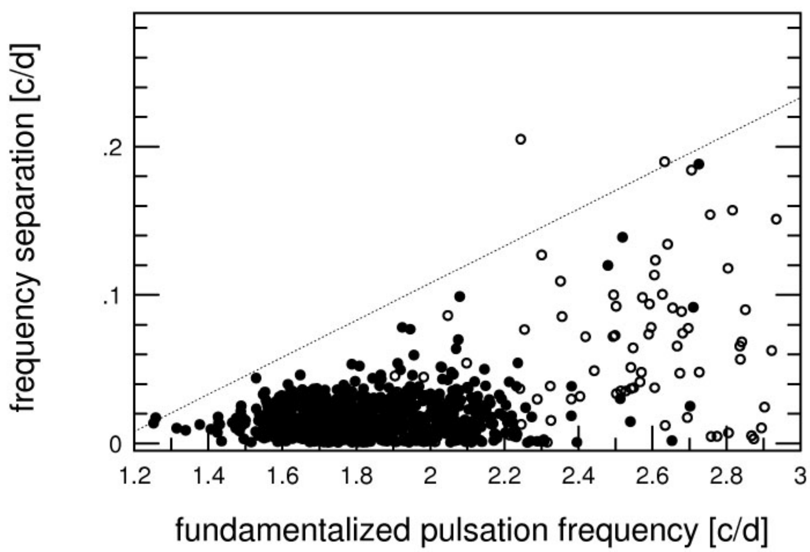

Figure 2.2: Frequency separation versus pulsation period for 894 stars, taken from Jurcsik et al (2005). Filled dots and open circles represent RRab and RRc stars, respectively. The line shows the limiting modulation frequency obtained from the given formula. The only outliner in this figure has already been re-classified twice and its frequency solution is still unreliable.

For a long time no correlation between the Blazhko period P_{mod} and the pulsation period P_0 could be found. Recently, Jurcsik et al (2005b) discovered a relation between P_0 and the possible range of the modulation period. For their research they used data available from surveys of 894 stars in different star systems (LMC, Galctic Bulge and the Sagittarius dwarf galaxy).

According to them the largest possible frequency spacing (i.e. the shortest possible modulation period) is a function of P_0 with the shortest P_{mod} occuring only in short period stars and stars pulsating with long periods ($P_0 > 0.6d$) being restricted to modulation periods longer than 20d. The field stars which hold the record for the shortest Blazhko periods also fit into this results: SS Cnc, RR Gem and AH Cam all have very short pulsation periods of less than 0.4 days. In other words: the larger f_{puls}, the larger can Δf be. They express the limiting modulation frequency in the following formula:

$$\mathrm{Max(f_{mod}) = 0.125f_0 - 0.142}$$

with f_{mod} and f_0 designating the modulation period and the fundamental period, respectively.

Their diagram with the limiting frequency obtained with the above formula is shown in Figure 2.2.

The Blazhko period does not always remain constant. In some stars changes in the period of their modulation are observed, and the Blazhko effect is therefore not considered to be a strictly repetitive phenomenon. The most famous example is the star RR Lyrae: its Blazhko period was long believed to be 40.8 days but new observations in the framework of the Blazhko Project (Kolenberg et al. 2006) yield a modulation period of 38.8 days. Also the star RW Dra seems to exhibit changes in his modulation period as can be seen in the O-C diagram in Fig. 2.3.

In short, the known facts about the length of the Blazhko cycle can be summarized as follows:

- The most common periods range from 30 to 70 days, but extreme cases between 5 and about 500 days also exist.
- RRc stars have shorter modulation periods than fundamental mode pulsators.
- There is a relation between the main pulsation period and the range of possible values of the modulation period.
- The length of the Blazhko cycle is not necessarily constant .

2.2 Regularity and Multiple Modulation Periods

That the Blazhko period is not always constant has already been discussed. But only few field stars have enough observations to allow a detailed analysis of their Blazhko properties. Even fewer stars have been monitored long

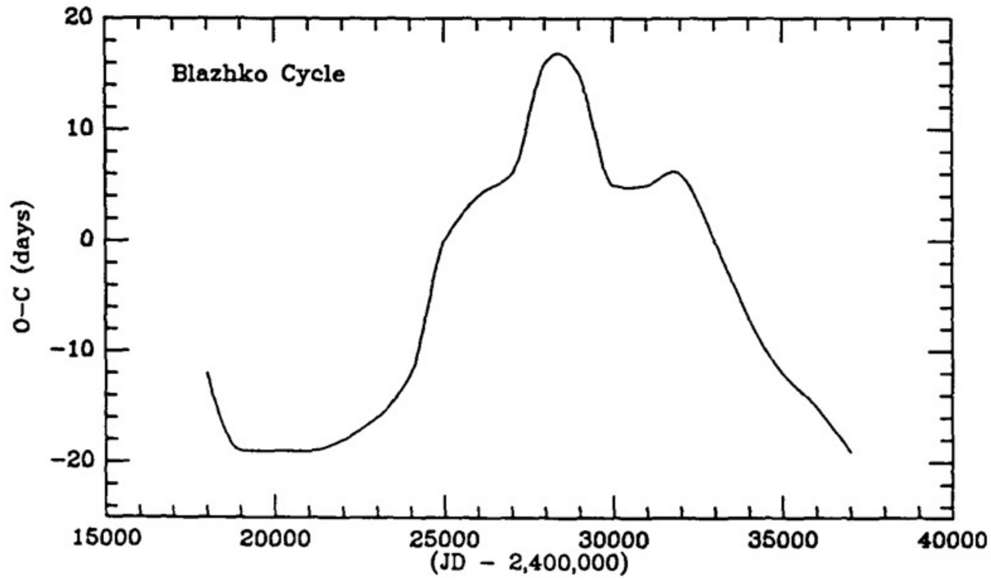

Figure 2.3: O-C diagram for the Blazhko period of RW Dra, taken from Smith (1995).

enough to find changes in their modulation periods P_{BL}. XZ Dra is one of those stars. There are 70 years of data available, and a clear variation of P_{BL} on a timescale of 7200 d is visible. Jurcsik et al (2002) analysed this star in detail and found a linear relation of P_{BL} and P_0 which exhibit parallel changes. Similar relations have also been found for other stars, but the order of magnitude as well as the sign of the relation seem to be different from star to star. Table 2.1 lists the relations. Also for RR Lyr and AR Her it was reported that P_{BL} and P_0 seem to show changes with opposite sign, but no mathematical relation was given.

Star	$\frac{dP_{BL}}{dP_0}[d/d]$	reference
XZ Dra	$+7.7 \pm 1.1 * 10^4$	Jurcsik, Benko, Szeidl (2002)
XZ Cyg	$-8 \pm 1 * 10^3$	LaCluyze et al (2004)
RV UMa	$-1 * 10^6$	Hurta et al. (2008)
RW Dra	$-7 * 10^3$	Tsesevich (1969)
RR Gem	$+1.6 \pm 0.8 * 10^3$	Sodor, Szeidl, Jurcsik (2007)

Table 2.1: Relation of changes in the Blazhko and fundamental periods of field stars.

One has to note, however, that the periods are not always strictly cor-

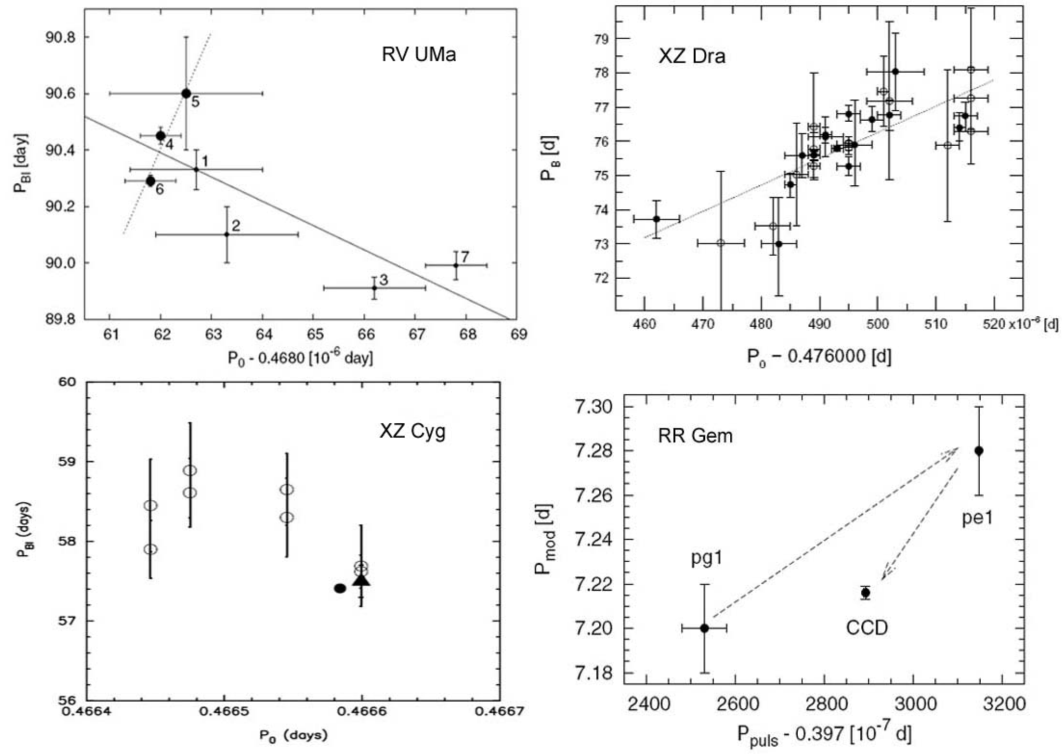

Figure 2.4: Modulation period versus pulsation period for four stars showing changes in the length of their Blazhko cycles.

related, and that the given relations sometimes rely on only few observed epochs. In RV UMa, for example, the anticorrelation is broken by a period in which P_{BL} and P_0 show parallel changes and for example in RR Gem, the relation is based on only three points in the P_{BL} versus P_0 diagram. Figure 2.4 is a collection of the available P_{BL} versus P_0 diagrams for the discussed stars.

Smith et al. (1975) pointed out that an opposite behavior of P_{Bl} and P_0 would be exactely what one would expect on the basis of the beating hypothesis. If the Blazhko period is the result of beating between the fundamental period P_0 with a close frequency P_1, the following relation holds:

$$\frac{1}{P_1} - \frac{1}{P_0} = \frac{1}{P_{BL}}$$

If one assumes that P_1 remains constant while P_0 changes it is possible to calculate the new P_{Bl} after the change:

$$\Delta\frac{1}{P_0} + \Delta\frac{1}{P_{BL}} = 0$$

The observed parallel changes in some stars, of course, make the situation more difficult, and the above relation holds only for the assumption that P_1 remains constant.

Besides the discussed variations in modulation period, also the strength of the modulation can be variable on long timescales. For serveral RR Lyrae stars secondary modulation periods are known. In the most well-known example, RR Lyrae itself, it is a cycle of about 4 years that modulates the Blazhko cycle. It was reported that the modulation was barely noticeable in 1963, 1967, 1971 and 1975. These dates obviously correspond to the minima of the secondary cycle. During these minima, a phase shift of $\pm\frac{\pi}{2}$ in the phase of the Blazhko cycle usually occured.

Also for RR Gem there are reports that the modulation had disappeared in 1940, but it was observed again by Jurcsik et al. (2005c) with a modulation amplitude of $\Delta M_{max} < 0.1$mag. In SW And the Blazhko effect also seems to have changed on a long time scale: it was more pronounced in 1956 and now it is hardly noticeable. Also the stars SU and SW Dra were reported to show amplitude modulation in the past (Sperra 1910), but later observations could not find any indications for a Blazhko effect. Such reports about changing Blazhko cycles may point towards secondary modulation periods, but a very long time base would be necessary to resolve them. On the other hand, as was pointed out by Szeidl (1976) the observed starting and ceasing of the Blazhko effect in some stars raises the question whether the modulation might happen more than just once in the lifetime of an RR Lyrae star of whether maybe all RR Lyrae stars become Blazhko pulsators at least once.

Another intriguing phenomenon is the occurrence of clearly asymmetrically spaced triplets in the Fourier spectrum and stars showing multiple additional frequencies. In the analysis of the MACHO data performed by Alcock et al (2000, 2003), several cases of these two classes appeared. Sodor et al. (2007) performed a systematic study on bright field RR Lyrae stars using high precision photometry and also report multiperiodic stars. As many as three out of the 12 stars included in their study show multiperiodic behavior.

The clearest cases are UZ UMa and CZ Lac. In CZ Lac the two modulation periods have similar amplitudes and are closely spaced. This leads to a beat effect in the envelope of the light curve and resembles the 4-year cycle of RR Lyrae. Mizerski (2003) also finds a lot of stars (86 RRab and 41 RRc pulsators) that show multiperiodic behavior with either more than 2 additional frequencies or strongly non-equidistant triplets. He suggests to call them RR-BL3, because they have some features in common with the other two classes of Blazhko stars (doublet and triplet stars, or RR-BL1 and RR-BL2).

Other RR Lyrae stars for which multiple additional periods were reported are for example RS Boo, RW Cnc, XZ Cyg, AR Her, Y LMi. But theses third periods were sometimes not confirmed by subsequent studies and might just be an attempt to describe irregularities in the light curves.

2.3 Classification and Nomenclature

The Blazhko effect was, at the beginning of its history, defined as a variation in the times of maximum light and later also as a periodic change in the height of the maxima. Now, with Fourier analysis being the prime means of investigation, the appearance of additional peaks close to the dominant pulsation component became the main indicator of the presence of the Blazhko effect. These secondary peaks are often regarded as nonradial modes of pulsation present in the star.

Though, when for the first time frequencies were found close to the radial mode, this was at first not associated with the Blazhko effect. For example, after analysing the Fourier features of globular cluster stars, Olech et al (1999b) stated that for the first time he had found nonradial modes in RRc stars. But the Blazhko effect in RRc stars had been known before, with Szeidl (1976) listing TV Boo, BV Aqr, RU Psc as RRc stars with known Blazhko periods. Moskalik (2000) also distinguished strictly between the Blazhko effect and nonradial modes. They first excluded obvious Blazhko stars from their sample and then searched for additional frequencies in the remaining stars. They found 14 stars with close frequencies and therefore stated that they had found nonradial modes for the first time also in RRab stars. Some years later, Moskalik & Poretti (2003) already treated close frequencies and the Blazhko effect as the same phenomenon: according to them the beating of the nonradial modes with the primary pulsation leads to the long term phase and amplitude modulation known as the Blazhko effect.

Not all modulated stars show the same pattern in their Fourier spectra. In many cases, a triplet structure with one peak at each side of the fundamental mode is visible, but others show only two close components (a doublet). For quite a long time, there was a disagreement whether both of these two phenomena deserved the name Blazhko effect, and the fact that different authors used different nomenclatures and definitions made the literature a very confusing read. One has to take the different definitions into account when comparing the incidence rates of the Blazhko effect given by different authors.

One of the most common classifications to establish clarity is the one introduced by Alcock et al. (2000), in which he adds "$\nu 1$" and "BL" to their Bailey classification for stars showing a doublet feature and triplet, respectively. Later, after some authors had stated that doublet and triplet features probably had the same origin, they used RR0-BL1 and RR0-BL2 instead. Their original classification for fundamental mode RR Lyrae stars is given in table 2.2.

designation 1	designation 2	observed features
$RR0-\nu 1$	$-BL1$	two closely spaced frequencies (doublet)
$RR0-BL$	$-BL2$	three close components (triplet)
$RR0-\nu 2$	$-BL3$	a triplet, but asymmetrically spaced
$RR0-PC$	$-PC$	stars showing a long-term period change
$RR0-\nu M$	$-BL3$	multifrequency close components

Table 2.2: Classification schemes according to their frequency spectra for fundamental mode (RR0) stars.

Other terms for the class $RR0-\nu M$ are for example $RR0-MC$ which is used by Nagy & Kovacs (2006) and stands for "multiple close" frequencies, as well as $RR0-BL3$, a designation introduced by Mizerski (2003) who argue that the multiple frequency RR Lyrae stars have common features with Blazhko stars and therefore might be treated as a subclass of those.

In any case, nowadays both doublet and triplet stars are considered Blazhko stars, because it is not clear whether the transition between them in abrupt or smooth (Kovacs 2002). Jurcsik et al. (2006) argued that the amplitudes of the triplet features are usually asymmetric and the weaker component might therefore be hidden in the noise. Therefore the division in the two subclasses "$\nu 1$" and "BL" might just be an artefact of noise and data sampling. Cases of stars which were classified differently depending on the data subsets used for analysis supported their assumption. Though it cannot be excluded yet that different physical phenomena cause the two classes of frequency patterns, there are many indications that they are caused by a common effect. Jurcsik et al. (2005b) call the doublet stars a "special border-line case of these showing the equidistant triplet". Dziembowski & Mizerski (2004) even go farther with the definition of the term Blazhko effect in RR Lyrae stars: "The term Blazhko stars is now used to denote all objects whose oscillation spectra exhibit peaks with frequency spacing much closer than the spacing between consecutive radial modes."

2.4 Features in the Fourier Spectra

The Blazhko effect manifests itself in various forms in the Fourier spectra of the stars. As mentioned before, both triplets (i.e. additional frequencies on both sides of the main component) and doublets (only one additional peak next to the main component) may occur, and the theory in some cases also predicts quintuplets. But even among the stars showing the same feature, there are usually large differences. The additional peak might appear on the left side or on the right side of the radial component, triplets might be symmetric in amplitude or strongly asymmetric, and even the frequency spacing might be non-equidistant.

With their large sample of RR Lyrae stars in the Large Magellanic Cloud, the MACHO project made the first extensive statistics about the side peak amplitudes possible. Alcock et al (2003) The found the right side peak (i.e., the one on the higher frequency side) to have the larger amplitude in 74% of the cases. As a test, they also treated doublets and triplets separately and obtained similar results: in 79% of the doublets, the sidepeak appears on the higher frequency side, and in 68% of the triplets, the right side peak is the higher one. Altogether, this results in the often cited probability od 3/4 that the higher peak appears on the right side of the main component.

They introduced a parameter Q to describe the asymmetry:

$$Q = \frac{(A_+ - A_-)}{(A_+ + A_-)}$$

A_+ and A_- designate the amplitude of the sidepeak at the higher (right) and at the lower frequency (left) side of the radial component, respectively. This parameter would be equal to zero if the amplitudes were exactly equal, and it is positive when the higher peak is on the right side. For most of their stars, Q is between 0.1 and 0.6.

In the Galactic Bulge, the situation is similar. Moskalik & Poretti (2003) analysed a sample of 150 RRab stars of the Galctic Bulge of which 34 were modulated, and obtained a value of 80% of all cases in which the right side peak is the higher one. Instead of using Q as an discriminant, they calculated the frequency difference $\delta f = f_1 - f_0$ and plotted it against the radial pulsation period. f_1 and f_0 are the frequency values of the side peak and the main frequency, respectively. A positive value of δf therefore denotes a sidepeak at the right side. Their results can be seen in Figure 2.5. Note that most of the stars show positive values of δf, and the negative values seem to occur only in a very narrow range of pulsation period: $0.49 < P < 0.53$.

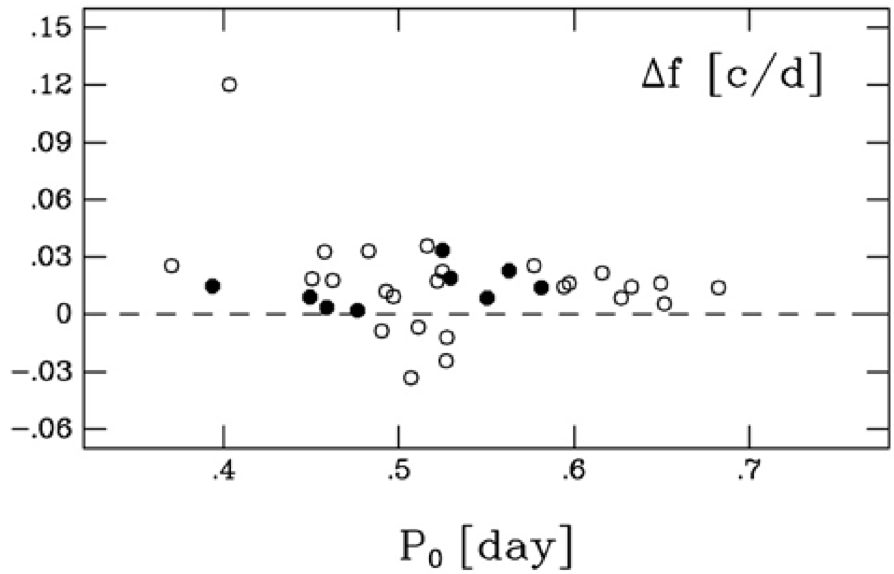

Figure 2.5: Frequency difference versus pulsation period for Blazhko RR Lyrae stars in the Galcactic Bulge, adapted from Moskalik & Poretti (2003). Filled circles: BL2 (triplet) stars, open circles: BL1 (doublet) stars.

Also in the most famous Blazhko star, RR Lyrae itself, the right side peaks $kf_0 + f_m$ are high, while the left components $kf_0 - f_m$ are only marginal. k denotes the harmonic order, f_0 and f_m are the radial fundamental frequency and the modulation frequency.

A very detailed analysis of the amplitudes of the sidepeaks was performed by Jurcsik et al (2005c). They obtained high precision photometric data of RR Gem, an RRab star with a very short modulation period of only 7.23 days. The amplitudes of the side peaks were shown to decrease linearly from one harmonic order to the next, while the amplitudes of the harmonics decrease exponentially (see Figure 2.6). The amplitudes of the sidepeaks and the harmonics were also investigated by Smith et al. (1999) in the star AR Her. There, the modulation components sometimes even towered above the pulsation components for harmonic orders larger than 4, but the amplitudes differed for the two data sets obtained in different years. Also, the method of prewhitening, i.e., whether the frequencies were fixed or let free during the analysis played a role.

The asymmetry parameter Q of RR Gem equals -0.035, indicating that the triplet is almost symmetric, with the left side peak being slightly higher. They also tested the stability of this result using different subsets of their

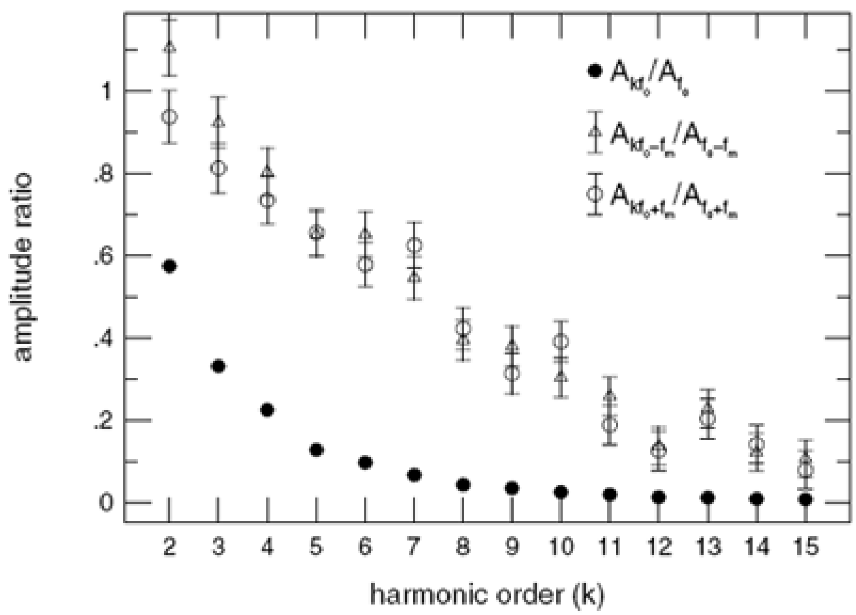

Figure 2.6: Decrease of amplitude from one harmonic order to the next for RR Gem, adapted from Jurcsik et al (2005c). Filled circles: main pulsation components, open triangles: left sidepeaks, open circles: right sidepeaks.

data. The symmetry of the amplitudes turned out to be strongly dependent on data sampling. One therefore has to be very careful when interpreting the side peak amplitudes and their asymmetry, especially when only incomplete light curves are available. The above mentioned different results in the study of the star AR Her is another good example for this effect. In well observed stars like RR Lyrae, however, independent analyses yield the same result, so there is probably also real information in the asymmetry of the triplets. Besides this, statistics based on large numbers of stars are probably not influenced too much by this effect.

For RRc stars the picture seems to be completely different: Alcock et al (2000) found the sidepeak on the left side of the main frequency in 63% of the cases. There is even one extreme case in which the highest frequency of the triplet is not the radial component but the left sidepeak. Almost all triplets were strongly asymmetric in amplitde.

The Blazhko RRc stars discovered by Olech et al (1999a) in globular clusters fit into that scheme: two of them have their side peak on the left and one of them on the right side of the main frequency.

Besides the discussed asymmetry in amplitude there sometimes seems to be an asymmetry in frequency with the side peaks not spaced exactly equidistantly. Alcock et al (2003) also investigated this phenomenon with the MACHO data. They defined the asymmetry of the frequencies as

$$\delta f = (f_+ + f_- - 2f_0)$$

with f_+ and f_- standing for the frequency values of the right and left sidepeak, respectively. f_0 is the frequency of the radial pulsation. Altough they found almost all deviations to be smaller than 0.0002 cycles per day, this value is significant. It cannot be fully explained by frequency shifts introduced by noise.

On the other hand, Alcock et al (2000) performed a similar test for their data of RRc stars in the LMC and found the deviations not to be significant. In this case the values of δf were likely to be introduced by observational noise. The same holds for the data set of the Galctic Bulge used by Moskalik & Poretti (2003). They found the deviations to be smaller than 0.00005 c/d which is not significant for their data set. Also in RR Lyr itself, the frequency spacing is equidistant for all the relevant harmonics.

Some of the theoretical models for RR Lyrae stars predict a triplet structure in the Fourier diagram, others predict a quintuplet. Therefore, it is important to know whether the observed features are indeed triplets or whether they are quintuplets with their outermost peaks hidden in the noise. For a long time, no quintuplets were observed altough researchers were specifically looking for them. Alcock et al (2003), for example, gave an upper limit of 0.004 for possible quintuplet features, if they exist at all, because they could not find any in their data. Also, Moskalik & Poretti (2003) report a negative result for their search for quintuplets. Not even in RR Lyrae, in spite of the huge amount of data available for this star and the high quality of some data sets a quintuplet structure could be observed, at least not above the level of significancy. It was only recently that Hurta (2007) reported the first detection of a quintuplet structure in an RR Lyrae star. For their analysis they used data with a time span of more than 17 years of RV UMa, an RRab star with a very strong amplitude modulation. Afer substracting the equidistant triplet, peaks at $kf_0 - 2f_m$ could be detected with a signal-to-noise of 6.2, 5.5 and 4.6, respectively. Because their positions were very close to the expected quintuplet positions and the peaks were present in both filters and both subsamples of the data, the authors concluded that they must be real. RV UMa is so far the only RR Lyrae star with an observed quintuplet structure in the Fourier spectrum.

The observational facts about the Fourier features can be summarized as follows:

- RRab Blazhko stars have the higher side peak on the right side of the main pulsation component in 3/4 of the cases.
- For increasing harmonic orders the amplitudes of the sidepeaks decrease more linearly, while the amplitudes of the radial component decrease exponentially.
- The observed amplitudes are strongly dependent on data sampling and the method of prewhitening.
- RRc stars more often have the higher side peak on the left side of the main component.
- In some cases, the peaks in the triplets deviate slightly from exact equidistancy.
- So far, only for one star a quintuplet structure has been found in the Fourier spectrum.

2.5 Differences from monoperiodic stars

The most obvious differences between Blazhko stars and monoperiodic RR Lyrae stars are the appearance of additional peaks in the Fourier spectra and, of course, a change in amplitude and/or phase of the pulsation. But besides this, it is important to know whether Blazhko stars are different from the typical non-modulated stars with respect to their basic physical parameters like average brightness, fundamental period etc. This might give a clue about the origin of the modulation.

Szeidl (1988) plotted a Bailey (= period vs. amplitude) diagram (see Section 1.4) for a sample of RR Lyrae stars containing both Blazhko and non-Blazhko stars. His graph is shown in Figure 2.8. Two stars observed during the Blazhko project are added: SS For and UV Oct. While ordinary RR Lyraes are represented by a single dot in the diagram, modulated stars contribute two dots: one for minimum and one for maximum amplitude during the Blazhko cycle. It is obvious that modulated stars best fit into he trend of "normal" stars when they reach their highest amplitude of pulsation. This indicates that the Blazhko effect may be a suppressing phenomenon. Szeidl (1988) drew a diagram like this both for field RR Lyrae stars and for stars in the globular cluster M3. The result is the same in both cases.

Alcock et al. (2003) tested whether modulated stars can be distinguished from ordinary RR Lyrae stars with the help of their average brightness. The calculated the average Johnson V magnitude for their large sample of stars

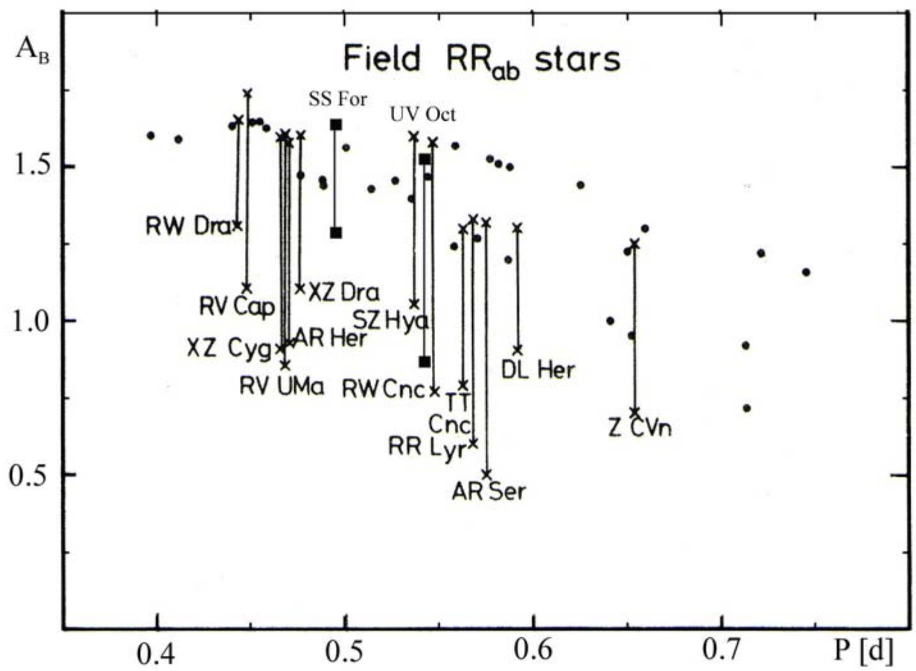

Figure 2.7: Period-amplitude diagram of Blazhko and non-Blazhko stars after Szeidl (1988). SS For and UV Oct, two stars observed for this thesis are included (filled rectangles). Note that they show the same behavior as the stars investigated by Szeidl.

and plotted it against the period. The result was that both groups of stars cover the same range of parameters. Blazhko stars therefore cannot be said to have a tendency to be brighter or fainter than monoperiodic RR Lyrae stars.

On the other hand, the total amplitudes of the modulated stars turned out to be smaller than those of the non-modulated stars. This agrees well with the before described findings of Szeidl (1988). In their analysis, Alcock et al. (2003) calculated the Fourier parameters for all available stars and found out that, with increasing order, the Fourier amplitudes of Blazhko stars become lower than those of their monoperiodic counterparts. This implies not only a lower overall amplitude but also a smaller skewness for Blazhko stars, because the amplitudes of the harmonics give the asymmetry of the light curve. For the Fourier phases the result was similar, but the effect much weaker.

Theoretical models also predict a reduced amplitude for Blazhko stars. Dziembowski & Mizerski (2004) propose a scenario where energy transfer occurs from radial to nonradial modes. The amplitude of Blazhko stars therefore has to be smaller because energy is used to "feed" the nonradial modes. Their model therefore predicts a lower amplitde for Blazhko stars.

In spite of the theoretical predictions and the good agreement of the observational results of different authors, the effect of weakened amplitudes is not undisputed. Moskalik & Poretti (2003) find the peak-to-peak amplitudes of their Blazhko stars in good agreement with those of monoperiodic stars in their data of the Galactic Bulge. They conclude that "the presence of secondary frequencies neither depends on nor affects the amplitude of the primary (radial) pulsation".

According to them, the presence of close frequencies does not depend on the period of pulsation either. The phenomenon occurs at all pulsational periods with approximately the same probability. Therefore, Blazhko stars cannot be distinguished from monoperiodic stars by means of their fundamental period. This is in good agreement with the results of Mizerski (2003) who shows that the period distribution of his sample of RRab Blazhko stars in the galactic center is the same as for monoperiodic RR Lyrae stars.

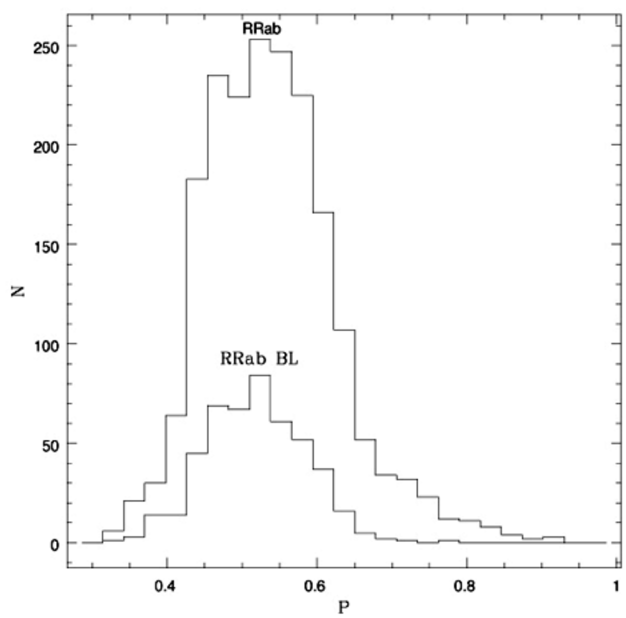

Figure 2.8: Period distribution of Mizerski et al. (2003) for all Blazhko and non-Blazhko RRab stars in his data of the Galactic Bulge

Another interseting finding is that the incidene of the Blazhko effect seems to depend on the metallicity. This is not only suggested by a comparison of the incidence rates in different star systems like the Galactic Bulge and the LMC, but it is also visible in the Fourier phases of the stars. Moskalik & Poretti (2003) plotted the Fourier phases ϕ_{31} and ϕ_{41} versus the fundamental period. In this diagram the singly periodic stars form three tails with the highest tail corresponding to the highest and the lowest tail to the lowest metallicity. The modulated stars seem to prefer the highest tail, indicating that their $[Fe/H]$ must be *high*. The total average metallicity of a sample of Blazhko stars is therefore expected to be higher than that of the monoperiodic stars in the same star system.

A different approach with the exact opposite result was used by Szeidl (1976): He divided a sample of RRab Lyrae stars into three subclasses according to metallicity and determined the incidence of the Blazhko effect for each of the subsamples. The result was intriguing: In the sample with ΔS between 0 and 2 the incidence was 10%, but it was 20 % for stars with ΔS between 3 and 5, and even 30 % for the stars with ΔS between 6 and 10. He therefore concluded that the incidence of the Blazhko effect was a function of metallicity with modulated stars generally showing *lower* metallicities.

A recent study of Smolec (2005) showed that the different metallicities in the Galactic Bulge and the LMC cannot explain the different incidence rates of the Blazhko effect. For their analysis they used data gathered by the OGLE survey and calculated the metallicities using the Fourier parameters of the light curves. This method, developed by Kovacs & Zsoldos (1995) and described in more detail in chapter 4.7.1, originally uses Johnson V-band light curves. Therefore, Smolec (2005) calibrated the formula to the Cousins I-band in which the OGLE data were observed. After applying the formula to both Blazhko and non-Blazhko stars it became obvious that the different incidence rates of Blazhko stars cannot be attributed to the metallicity difference in the systems. Both in the LMC and the Galactic Bulge the metallicities of Blazhko (RR-BL) and non-Blazhko stars (RR-S) lie close to each other. Table 2.3 summarizes their results. Columns 2 and 3 are the average metallicities of all singly periodic and Blazhko variables, respectively.

The comparison between Blazhko and non-Blazhko stars can therefore be summarized as follows:

- The average brightness of Blazhko and non-Blazhko stars is the same.
- The average amplitude is lower for Blazhko stars than for non-Blazhko stars.

	RR-S	RR-BL
$[Fe/H]$ Galactic Bulge	-1.04 ± 0.03	-1.01 ± 0.05
$[Fe/H]$ LMC	-1.218 ± 0.004	-1.28 ± 0.01

Table 2.3: Photometric metallicities calculated by Smolec (2005). Note that the values for singly periodic and Blazhko stars lie close to each other.

- Blazhko stars have more symmetric average light curves (smaller skewness) than non-Blazhko stars.
- Blazhko stars show the same period distribution as non-Blazhko stars.
- The question whether Blazhko stars tend to have higher or lower metallicity than ordinary RR Lyrae stars is still highly controversial.

2.6 The incidence rate of the Blazhko effect

In spite of the large amount of available data from different surveys, it is still impossible to make a reliable comparison of the incidence rates of the Blazhko effect in different stellar systems. The data are inhomogeneous because the various surveys used different filters, obtained a different data sampling, photometric precision and time base, and used different methods of data analysis. On top of this, different definitions of what a Blazhko star is and what not complicate the situation. Nevertheless, the most important surveys, their results and the most often cited values for the percentage of affected RR Lyrae stars are summarized in this paragraph. In any case, the general trend seems to be a continuous increase of the estimated number of affected stars: Improved methods of data analysis increase the number of known modulated stars in the LMC, and high-precision surveys of field stars reveal very small modulation amplitudes that suggest that lower-precision surveys might have missed many Blazhko stars.

One of the first estimates for the number of modulated RRab stars came from Szeidl (1976) who gave 15-20 % as a value for field stars. This number was based on a homogeneous sample of 90 stars of which 15 were found to be modulated. Later, Szeidl (1988) gave the most often cited value of 20-30 % as a more recent value for field RRab stars. The question whether RRc stars also can show a Blazhko effect was still under discussion at this time, though there were 3 stars which were considered candidates for modulated RRc stars.

For the Large Magellanic Cloud (LMC), two large surveys are available. In the MACHO data, Alcock et al. (2003) found 731 out of 3158 RRab to have additional frequencies next to the main component. This yields an incidence rate of $11.9 \pm 0.4\%$. Here, both frequency doublets and triplets are counted as Blazhko variables. For RRc stars, Alcock et al. (2000) found a rate of 3.9 % with 24 RRc stars showing a doublet and 28 stars showing a triplet in the frequency spectrum. A total data set consisted of 1350 RRc stars. From the other campaign, OGLE, Soszynski et al (2003) found a percentage of 15% of the RRab and 6% of the RRc in the LMC to have peaks next to the radial pulsation components. Nagy & Kovacs (2006) reanalysed the MACHO data of overtone pulsators and raised the incidence rate of modulated RRc stars to 7.5% by using an improved method of analysis.

About Blazhko pulsators in the SMC not much is known, altough it was included into the OGLE survey. Soszynski et al. (2002) only mention "dozens" of stars showing close frequencies and give rates of 10% both for RRab and for RRc stars, unfortunately without giving any details.

Of the Galactic Bulge, data of the OGLE survey are available. Moskalik & Poretti (2003) performed a detailed analysis and a systematic search for multiperiodic pulsators on the OGLE-1 data. Based on 150 RRab and 65 RRc stars, they found 23.4% of the RRab stars and 4.6% of the RRc stars to show the Blazhko effect. They raised the question whether the difference to the LMC might be caused by the different metallicities of the systems, but this was later refuted by Smolec (2005). The Galactic Bulge was also observed by the OGLE-2 project. In this data set which contains 1942 RRab and 771 RRc stars and was analysed by Mizerski (2003), 19.8% of the RRab stars and 6.7% of the RRc stars have a Blazhko effect. This holds for the definition of triplet and doublet stars being Blazhko pulsators. If one includes also the stars with more frequencies than those (named BL3 by the authors) and stars with rather uncertain classification, one obtaines 25.0% and 12.3%, respectively. An overview of the incidence rates of modulated RRab and RRc stars both in the LMC and the Galactic Bulge is given in table 2.4. Note that in both systems, Blazhko RRab stars are much more frequent than Blazhko RRc stars.

In the study of field stars performed by Sodor (2007), 6 out of 12 RRab stars turned out to be modulated. Some of them show very small modulation amplitudes and therefore their Blazhko nature would have been missed by surveys with lower precision. Neither MACHO nor OGLE, ASAS or NSVS could have detected such a modulation. The sample of 12 stars may be very small, but nevertheless the occurrence of low amplitude modulation leads to the suspicion that the Blazhko effect might be much more wide-spread than suggested by the discussed surveys. The previously given numbers might therefore be considered a lower limit of the incidence rate of modulation.

type	system	total	rate[%]	survey	reference
RRab	LMC	6158	11.9	MACHO	Alcock et al. (2003)
RRab	Galaxy	150	22.7	OGLE-1	Moskalik &Poretti (2003)
RRab	Galaxy	1942	19.9	OGLE-2	Mizerski (2003)
RRc	LMC	1117	3.9	MACHO	Alcock et al. (2000)
RRc	LMC	1332	7.5	MACHO	Nagy & Kovacs (2006)
RRc	Galaxy	64	4.7	OGLE-1	Moskalik &Poretti (2003)
RRc	Galaxy	771	6.7	OGLE-2	Mizerski (2003)

Table 2.4: Results of the most detailed surveys of the LMC and the Galaxy. For calculating the percentage of Blazhko stars given in column 4 only stars with doublet or triplet features in the frequency spectra were taken into account.

The fact that the Blazhko effect might be temporary in nature and/or might not always be detectable due to cyclic variations in its strength also indicates that the incidence rate is much higher than suggested by observations. One has to take into account that the Blazhko effect is only detected when it has a certain minimum amplitude, a limit defined by the quality of the data. Stars with a generally low modulation amplitude as well as those which are in a temporary phase of weak modulation would be missed by the surveys. Some authors therefore even consider the possibility that the Blazhko effect might be a general intrinsic property of RR Lyrae stars.

2.7 Modulation amplitude

For a long time, no connection between the strength of the modulation and the properties of the pulsation was known. Jurcsik et al. (2005a) tried to find such a relation. As a measure of the modulaion amplitude they proposed to use the sum of the amplitudes of the first four modulation components. These are the two side peaks next to the fundamental period and the two side peaks next to the first harmonic $2f_0$. This definition was chosen because the amplitudes of the first four components were known for a large number of stars observed in the MACHO project. This made a statistical analysis on the basis of a homogeneous data set possible. However, it is difficult to find a good measure for the strength of the modulation, because not only the amplitude of the pulsation, but also the phase (or period) might be modulated.

From their analysis they find that the possible largest value of the modulation increases with the pulsation frequency. That means that stars with a high pulsation frequency, and therefore a short period, can have larger modulation amplitudes than the low frequency pulsators. In numbers that means that RR Lyrae stars with a period of 0.67 days have modulation amplitudes which always seem to be smaller than 0.2 mag while pulsators with a period of about 0.45 days can have modulation amplitudes as high as 0.4 mag. The authors warn, however, that this result might be an artefact of the method of calculating the modulation amplitude.

Furthermore, a relation between the modulation in B and in V was given. The modulation amplitudes in B are usually a factor 1.30 bigger than those in V. This was found on the basis of a small sample of well-studied Blazhko stars. The range they found for the ratio $A_{\mathrm{mod}}(\mathrm{B})/\mathrm{A}_{\mathrm{mod}}(\mathrm{V})$ was 1.23-1.39.

2.8 Detectability and properties of f_m

It has been unclear for a long time whether it is possible to find the Blazhko frequency f_m directly in the Fourier spectra. With the increase of the data quality in the past years, there are now several reports that f_m had a measurable amplitde. Kovacs (1995) found f_m with a B amplitude of 0.005 mag in his data set on RV UMa, Nagy (1998) reports an amplitude of 0.011 in the star RS Boo and Alcock et al. (2003) showed that the average brightness of the 731 Blazhko stars observed in the Large Magellanic Cloud varies with an amplitude of about 0.006 mag during the Blazhko cycle. Also in the Fourier spectra of RR Gem (Sodor et al. 2007) and SS Cnc (Jurcsik et al. 2006), f_m was found with amplitudes of 0.006 mag and 0.008 mag in the B filter, respectively

The fact that f_m has similar amplitudes in all of these stars, although the Blazhko effect is very weak in SS Cnc and RR Gem and strong in RV Uma and RS Boo, is intriguing. It indicates that it is a gerneral property of RR Lyrae stars that f_m is in the order of <0.01 mag and that it does not depend on the amplitude of the modulation. In contrast to this, the amplitudes of the observed side peaks next to the radial pulsation component can have a wide variety of values.

Jurcsik et al. (2006) performed a more detailed analysis of the properties of f_m. They used the multicolor photometry obtained for SS Cnc and RR Gem to investigate the behavior of f_m in different filters. For f_m as well as for the main pulsation components kf_0 and the side peaks $kf_0 \pm f_m$ they calculated amplitude ratios (A_{color1}/A_{color2}) and phase differences ($\varphi_{color1} - \varphi_{color2}$). These parameters are expected to be equal for all the frequencies if the physical reason behind them is the same.

The results were surprising: while the main pulsation components and their sidepeaks showed roughly the same behavior in all the three available amplitude ratios, the values obtained for f_m were significantly different. The difference increased towards redder colors. This hints that the physical origin of the Blazhko frequency f_m itself is a different one than that of the main pulsation component. The side peaks resemble the kf_0 components, which is exactly what one would expect if they are the result of an interaction between f_0 and f_m, because they would rather inherit the properties of f_0 with its much larger amplitude than those of f_m.

The Blazhko effect has long been cosidered to be caused by the interaction of f_0 with its side peak, which was considered a close non-radial frequency. But if those new results can be confirmed and are also obtained for other Blazhko stars one has to consider the possibility that the modulation might be caused directly by f_m. In any case, if one tries to explain the modulation as an interaction of f_o and a side peak, it will be difficult to explain the different color behavior of the Blazhko frequency.

Another interesting result of the work of Jurcsik et al (2006) is that in the two analysed stars f_m shows opposite behavior. In both stars, the difference of the amplitude ratios increases towards redder colors, but in SS Cnc the values are much smaller than those of f_0 and $f_0 \pm f_m$ while in RR Gem they are much larger.

The available results about the Blazhko frequency f_m can be summarized as follows:

- There are now several stars for which the Blazhko frequency has been directly detected in the Fourier spectra.
- It seems to be a matter of data precision whether a detection is possible or not.
- f_m always seems to have a low amplitude of less than 0.01 mag, independently of the amplitude of the Blazhko modulation and the side peak amplitude.
- Concerning the amplitude ratios and phase differences in different colors, f_m shows a different behavior than the main pulsation component, its harmonics and the side peaks.
- The interesting color behavior is not the same in the two stars for which an analysis has been made, but they show opposite trends.

Chapter 3

Photometric campaigns in the Blazhko project

Until now, no extended data sets of southern field Blazhko stars were available. Most studies on Blazhko stars were carried out on northern stars, and even here the data did usually not cover both the pulsation and the modulation period. For a long time, measurements were mainly taken around maximum light, which makes it impossible to perform a Fourier analysis on the data and what does not allow to study the light curve shapes and other interesting features. On the southern hemisphere, large studies like the MACHO and OGLE project greatly improved the knowledge about the Blazhko effect, but MACHO was concentrated on the Magellanic clouds, and like in the OGLE project, the data consisted of rather few datapoints spread over a large time span with large gaps between the data. The first extended survey covering the full Blazhko cycle while obtaining complete light curves was done for the northern star RR Gem by Jurcsik et al. (2005c). For southern stars, long-term campaigns like this were still lacking. The photometric campaings on SS For and UV Oct were dedicated to change this situation.

3.1 SS For

In the years 2004 and 2005 a large dataset of photoelectric measurements of the RRab star SS For was collected in the framework of the Blazhko project. The aim of the campaign was to get a precise data set with a good coverage of the pulsation cycle as well as the Blazhko cycle. Observations were made using photomultipliers at 3 different telescopes. The campaign started on October 9 in 2004 at the 0.5m telescope at the SAAO in Sutherland, South Africa and ended on September 19 in 2005 at the 0.6m telescope at the SSO, Australia. At the SAAO, the 0.75m telescope was also used. The two different longitudes of the sites helped to avoid daily aliasing. Observers and

Observer	no. of nights	no. of datapoints	location
Elisabeth Guggenberger	27	887	SAAO
Lukas Schmitzberger	7	101	SSO
Patrick Lenz	8	91	SSO
Thebe Medupe	5	94	SAAO
Bob Shobbrock	1	26	SSO
Paul Beck	2	19	SAAO
	50	1218	

Table 3.1: Observers of the SS For multisite campaign sorted by number of datapoints obtained

numbers of nights are listed in Table 3.1.

A complete list of all nights, hours of observation and numbers of datapoints is given in Table 3.2. Listed are Julian Date, length of the observations in hours and number of datapoints obtained. The observers were EG: Elisabeth Guggenberger, TM: Thebe Medupe, PB: Paul Beck, PL: Patrick Lenz, LS: Lukas Schmitzberger, BS: Bob Shobbrook.

Altogether 201 hours of photometry containing 1218 datapoints in each filter could be gathered in 50 nights. The total time span was 345 days. The time spread of the data can be seen in Figure 3.1. Large parts of the Blazhko cycle were covered.

For maximum precision we used the 3-star technique described by Breger (1993). Comparison stars were HD 13334 ('C1', α = 02h 09m 45.35s, δ = -27° 06' 12.8", eq = 2000) and HD 13181 ('C2', α = 02h 08m 13.23s, δ = -27° 01' 28.5", eq = 2000). The coordinates of SS For itself are α = 02h 07m 51.98s, δ = -26° 51' 57.7", eq = 2000. The stars were observed in the following sequence: C1 - Var - C2 - C1 - ... . Sky measurements were obtained once each cycle, after the measurement of SS For if there was no or only very little moonlight and after each star measurement, i.e. three times per cycle if the moon was bright and/or close.

Data reduction was done using standard procedures: the sky background curve was smoothed and substracted from all star measurements and the extinction coefficents were determined for each night separately using Bouguer plots. For details on extinction correction please see Rodler (2003). Finally, comparison measurements were interpolated to the time of the measurement of SS For, and the values were substracted from the variable's light curve to obtain differential photometry.

SAAO				SSO			
JD	hours	Points	Obs	JD	hours	Points	Obs
2453288	2.73	18	EG	2453569	0.98	6	PL
2453289	7.30	43	EG	2453571	2.36	11	PL
2453290	8.57	62	EG	2453574	2.39	10	PL
2453292	3.54	24	EG	2453576	2.30	11	PL
2453296	6.07	44	EG	2453580	2.61	12	PL
2453300	5.92	21	EG	2453581	2.73	13	PL
2453301	8.29	60	EG	2453582	2.59	14	PL
2453302	3.67	23	EG	2453583	2.66	14	PL
2453303	7.07	44	EG	2453590	2.66	12	LS
2453304	7.59	51	EG	2453591	2.91	12	LS
2453319	4.01	18	TM	2453610	5.76	27	LS
2453320	3.74	17	TM	2453611	4.81	22	LS
2453321	4.55	19	TM	2453612	1.78	9	LS
2453324	3.75	18	TM	2453621	1.81	10	LS
2453325	4.13	22	TM	2453622	1.58	9	LS
2453367	1.69	6	EG	2453633	3.57	26	BS
2453574	4.29	26	EG				
2453575	4.12	23	EG				
2453576	2.82	20	EG				
2453578	0.54	4	EG				
2453579	3.17	21	EG				
2453580	4.86	29	EG				
2453582	4.81	31	EG				
2453584	4.51	26	EG				
2453587	2.11	12	PB				
2453588	1.48	7	PB				
2453592	3.86	26	EG				
2453593	5.18	34	EG				
2453594	5.38	36	EG				
2453596	5.40	36	EG				
2453598	5.66	40	EG				
2453599	5.60	45	EG				
2453601	5.90	48	EG				
2453602	6.00	46	EG				
SAAO	total	2004	2005		total (=2005)		
Time [h]	158.3	82.6	75.7	Time [h]	43.5		
Points	1000	490	510	Points	218		

Table 3.2: Complete list of observations of SS For.

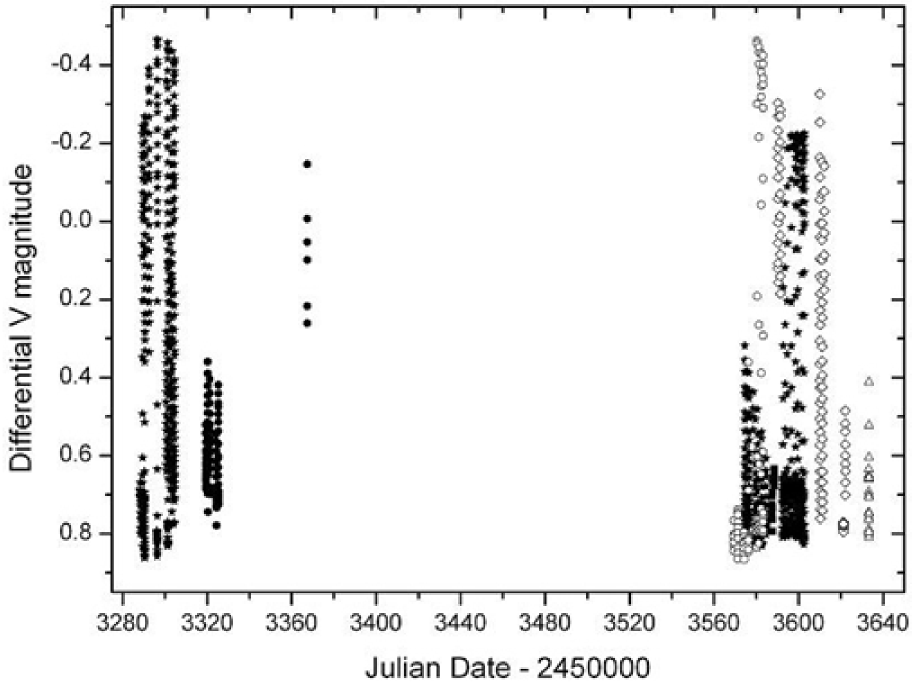

Figure 3.1: Data collected of SS For during the 2004 and 2005 observing seasons. Filled circles: TM, open circles: PL, filled stars: EG, filled squares: PB, open diamonds: LS, open triangles: BS. Filled symbols stand for SAAO observations, empty symbols for SSO.

The typical scatter of the obtained data was a few millimag both in the V and the B filter. Nights with a scatter larger than 10 mmag were rejected.

Figure 3.2 shows the light curves in the B and V filter folded with the main pulsation period. A strong Blazhko variation can be seen at maximum as well as at minimum light. The changes in the height of the maximum are expected for Blazhko stars, but the variations around minimum light are a particularly special feature of SS For. They have already been reported by Lub (1977) and are investigated in more detail in section 4.6. It is also noteworthy, that there is a phase at which the light curve does not change much during the Blazhko cycle. It occurs at $\Psi = 0.3$.

3.2 UV Oct

The southern star UV Oct ($\alpha = 16$h 32m 25.53s, $\delta =$ -83° 54' 10.5", eq=2000) was also observed in the framework of the Blazhko project. With a mean

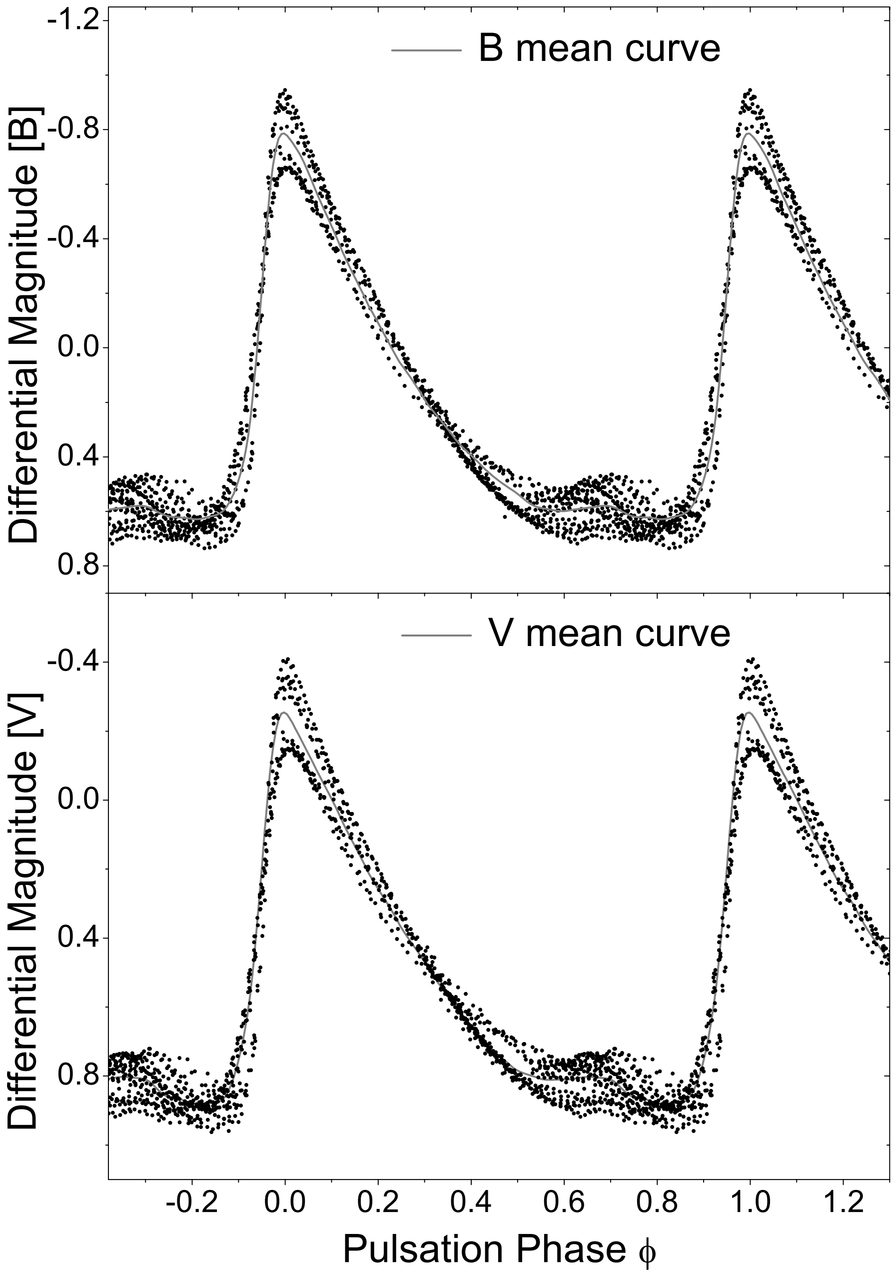

Figure 3.2: Total data collected of SS For. A mean light curve can be seen as a solid line in both curves.

V brightness of 9.46 mag it is one of the brightest Blazhko RR Lyrae stars. As comparison stars we used HD 146164 (α =16h 32m 30.30s, δ = -83° 35' 32.4", eq = 2000), hereafter C1, and CP-83598 (α= 16h 20m 16.31s,

δ = -83° 59' 47.2"), hereafter C2. The observers of the 2005 campaign are listed in Table 3.3. Figure 3.3 illustrates the time spread of the data. The campaign started on April 29, 2005 at the SAAO and ended on September 18, 2005 at the SSO. This yields a total time base of 142.45 days. In Figure 3.3 the change in amplitude due to the Blazhko effect is clearly visible. It can also be seen that the data covers a complete cycle. Altogether, 762 dataponts were collected for each of the two filters Johnson B and V.

Observer	no. of nights	no. of datapoints	location
Elisabeth Guggenberger	18	360	SAAO
Patrick Lenz	7	147	SSO
Thebe Medupe	7	117	SAAO
Lukas Schmitzberger	6	99	SSO
Bob Shobbrock	2	22	SSO
Paul Beck	2	17	SAAO
	42	762	

Table 3.3: Observers of the UV Oct multisite campaign sorted by number of datapoints obtained

The data reduction procedure was the same as for SS For. Again, the three-star-technique was used for the observations, and again, sky measurements were obtained either once or three times per cycle, depending on the sky brightness and the closeness of the moon. As for SS For, the measurements had to be transformed to the Johnson standard system before the data from different observatories could be combined. For the transformation we used our measurements of the comparison stars.

Figure 3.4 displays the data of UV Oct folded with the main pulsation period both in the B filter (top panel) and in the V filter (bottom panel). It can be seen that the Blazhko effect in UV Oct leads to a strong change in amplitude, while the there seems to be only a weak or no change in phase. Also, it is obvious that not only the height of the maximum changes during the cycle, but also the behavior before minimum light is different for the different Blazhko phases. A mean light curve is shown as grey line in both panels. Note that due to gaps in the data and because more data were gathered near the Blazhko maximum, the mean curve seems to be biases towards higher amplitudes.

Another aspect that can be seen in Figure 3.4 is that the pulsation has a larger amplitude in B than in V, which is normal for RR Lyrae stars. The highest peak-to-peak amplitude measured in the B filter is 1.54 mag, while it is only 1.22 mag in the V filter. Note that the magnitude scale used is the

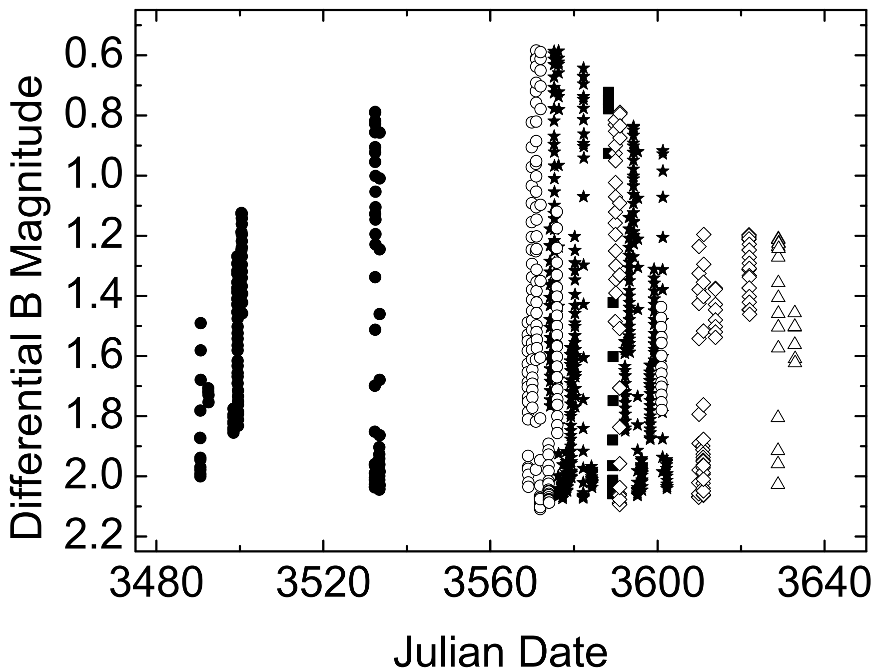

Figure 3.3: Data collected of UV Oct during the 2005 campaign. Filled circles: TM, open circles: PL, filled stars: EG, fille squares: PB, open diamonds: LS, open triangles: BS. Please note that filled symbols stand for SAAO observations, empty symbols for SSO.

same in both panels aso that it is easy to compare the amplitude of pulsation.

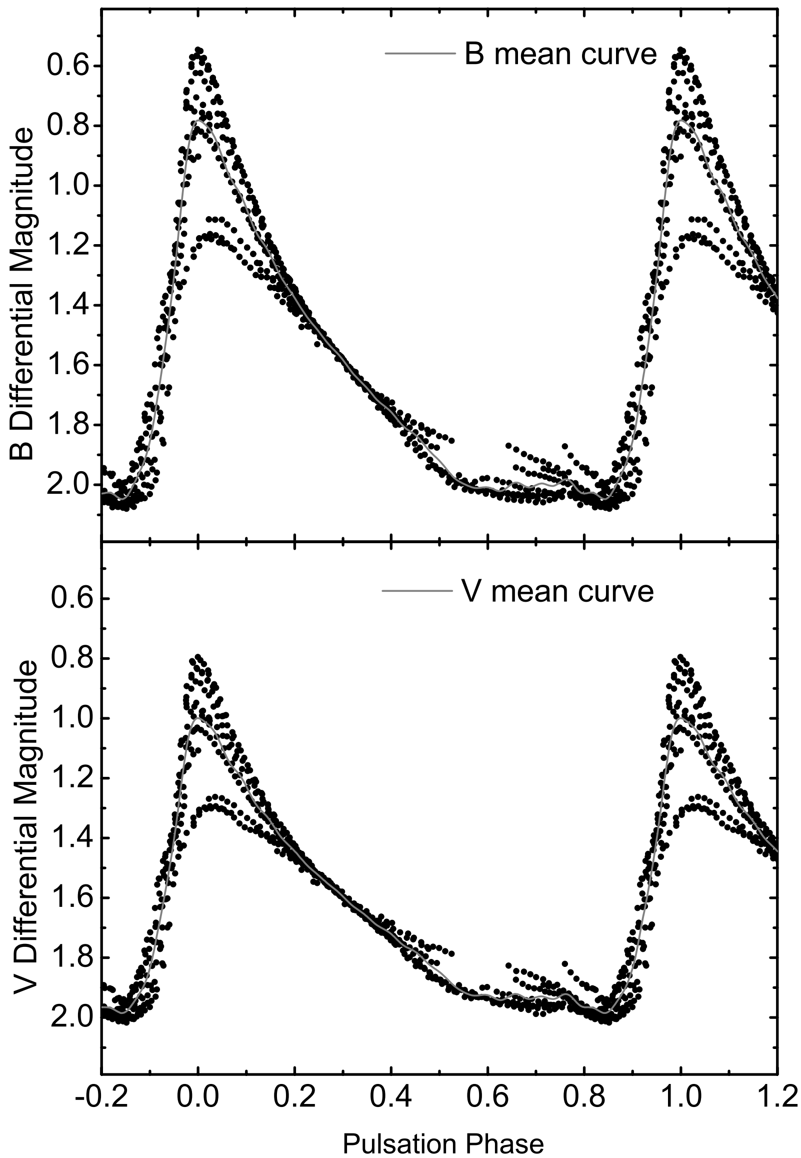

Figure 3.4: Data of UV Oct folded with the main pulsation period. A mean light curve can be seen as a solid line in both curves.

Chapter 4

Analyses

4.1 O-C analysis

O-C analysis was the traditional method for analysing RR Lyrae stars. After its discovery, the Blazhko effect was for a long time only considered a variation in the timings of the maxima. Now, as many other aspects of the Blazhko effect are also known, the O-C analysis is only of marginal importance. It is described here for historic reasons only.

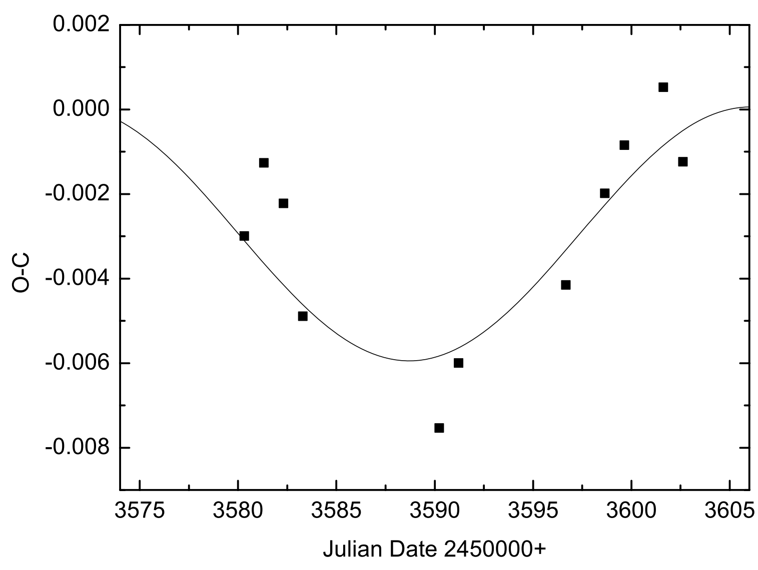

Figure 4.1: O-C diagram of the data of SS For obtained in the summer of 2005. The solid line is a fit with the Blazhko period to show the correlation between the Blazhko cycle and the times of maximum.

When the period of a star is known it is possible to predict the time of the next maxima and to compare this value to observation. This is called an O-C analysis, where O stands for the observed time of the maximum and C for the calculated time of maximum. The results can be plotted against time. Is the period correct, the O-C diagram will show a straight horizontal line. With a wrong constant period, the line will still be straight, but not horizontal. A period that is too high will yield a negative slope while a period that is too short will give a positive slope. Now, if the period is changing like it does during a Blazhko cycle, the O-C curve will be curved and it is possible to find a value for the change of period. For a long time this was the most widespread method to investigate the Blazhko effect. The O-C analysis was mostly applied using observations around maximum light, which was an advantage for observers but unfortunately makes their data unsuitable for Fourier analysis.

4.2 Fourier analysis

Nowadays, the most widespread method to investigate Blazhko variables and stellar pulsation in general is Fourier analysis. The signal can be described as a sum of sinus functions in the following form:

$$m(t) = Z + \Sigma A_i sin(2\pi(\omega_i t + \varphi_i))$$

where Z denotes the zero point and ω_i the frequencies of the fit. A_i are the amplitudes and φ_i the phases of the frequencies involved. For the investigations in this thesis the author used the software package Period04 (Lenz & Breger 2005).

4.2.1 The typical Fourier spectrum of Blazhko stars

In the Fourier spectrum of an RR Lyrae star the most dominant feature usually is the peak of the radial fundamental mode. Also, several harmonics, i.e. integer multiples of the fundamental mode will be visible. They describe the asymmetric shape of the light curve. If a Blazhko effect is present, those features will be accompanied by smaller peaks appearing either on both sides or on one side of the main frequency and its harmonics. The spacing between these so called side peaks and the main frequency is symmetric and identical to the Blazhko frequency. Figure 4.2 gives an example of a typical Blazhko RR Lyrae Fourier spectrum. The radial fundamental frequency and its harmonics are the dominant features in the spectrum. Side peaks with low amplitudes can be seen next to f_1 and some of the harmonics. Around f_1 a triplet structure is formed while harmonics only show doublets. It is suspected that when only a doublet is seen, the third component might be present but hidden in the noise.

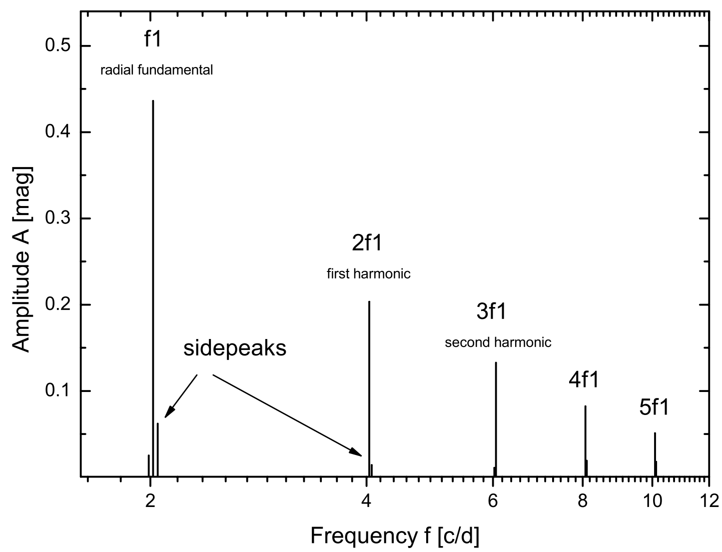

Figure 4.2: Frequency spectrum of a typical Blazhko RR Lyrae star. The y-axis gives the amplitude in magnitudes while the x-axis denotes the frequency in cycles per day on a logarithmic scale for better visibility of the sidepeaks.

4.2.2 The frequency analysis of SS For

The frequency analysis of SS For was carried out using the software package Period04 (Lenz & Breger 2005). The Fourier analysis was first performed on each data subset separately, i.e. with respect to C1 as well as to C2. As there seemed to be no frequencies caused by the comparison stars, we chose HD 13181 (C2) as the preferred comparison star, because its color is more similar to SS For than that of HD 13334, and its coordinates are closer to those of SS For, too.

Before merging the data from the different observing sites, they had to be transformed to the standard color system, because the different instruments cause a slight difference in the effective wavelength. The transformation was done using color equations determined from standard star measurements. Each data set (SAAO, SSO) was analysed separately, and no hints of systematic errors could be found. Combining the different subsets, of course, brought an improvement of the spectral window. The aliasing due to daily gaps was reduced dramatically, and in this way we also obtained a better coverage of the light curves .

To obtain the most reliable frequency values and to improve the frequency resolution, we included the data of the ASAS survey (Pojmansky 2000) into our study. The ASAS data are publicly available and usually have an accuracy of 0.03 mag. For SS For, ASAS data from November 2000 to July 2008 are available. We used 484 data points observed in the time from HJD 2451868.6 to 2454656.9, which yields a time base of 2788 days. ASAS data are only available in the V filter. In order to combine them with our standardized data set, a fit with all detectable frequencies was calculated, and the zero point was then adjusted to the other data set. The frequencies of the combined data set were used as a starting point to optimize the fit for the data gathered at the SAAO and the SSO.

In the analysis the triplet structure, typical for Blazhko RR Lyrae stars, clearly appeared. First, the main pulsation frequency f_0 was found. Then the harmonics emerged. They were fixed to the integer multiples of the fundamental mode. Then, the side peaks were found, yielding a Blazhko period of 34.9 days.

When analysing Blazhko stars, one can choose between two different strategies: one is to leave all the frequencies values free, what leads to a very large number of free parameters. The other strategy is to assume equidistancy. In this case an exactly equidistant triplet structure is imposed on the data. The solution can then be described in the following way:

$$\begin{aligned}
&f(t) = Z + \textstyle\sum_{k=1}^{n}[A_k \sin(2\pi k f_0 t + \phi_k) \\
&+A_{k+} \sin(2\pi(k f_0 + f_B)t + \phi_{k+}) \\
&+A_{k-} \sin(2\pi(k f_0 - f_B)t + \phi_{k-})] \\
&+B_0 \sin(2\pi(f_B t + \phi_B))
\end{aligned}$$

Z is the zero point, n is the number of harmonics included into the fit, A_{k+} and A_{k-} are the amplitudes of the side peaks on the right and the left side, respectively and f_B is the Blazhko frequency.

The Blazhko frequency, f_B, however, is usually not detected, because it has a very low amplitude. The sidepeaks are therefore described as linear combinations of the fundamental pulsation frequency f_0 and its side peak f_N. For f_N, of course, one uses the side peak which has the higher amplitude. In most cases, this is the right side peak (see also section 2.4). And as for most of the Blazhko stars, also for SS For, $f_N = f_0 + f_B$. It is possible to calculate a fit for all the typical frequencies of a Blazhko star with this method, which was first described by Kolenberg (2006).

With our data set we tried both methods, fixed triplets as well as non-fixed values, and the results of the frequencies were the same within the errors. The errors were calculated using Monte Carlo simulations. This analysis was done both for the V and the B filter. Of course, the amplitudes in the B filter are larger, as RR Lyrae stars generally have higher amplitudes in the blue part of the spectrum. The results can be seen in Table 4.1. It lists the frequency values, the amplitudes and the phases in V as well as in B for the fit obtained with the SAAO and SSO data. Values given in italics correspond to frequencies which did not exceed the significance level. Following Breger (1995), a signal to noise ratio of 4 was adopted as significance level for independant frequencies, and a S/N of 3.5 for combination frequencies. Note that when the triplet structures are described as linear combinations of f_0 and f_N, there are only two independant frequencies in the solution:f_0 and f_N.

f [cd^{-1}]		A_V ± 0.003	φ_V $[\frac{\text{rad}}{2\pi}]$	A_B ± 0.003	φ_B $[\frac{\text{rad}}{2\pi}]$
f_0	2.01843	0.424	0.995 ± 0.001	0.550	0.001 ± 0.001
$2f_0$	4.03687	0.200	0.355 ± 0.002	0.248	0.352 ± 0.002
$3f_0$	6.05530	0.129	0.761 ± 0.003	0.159	0.758 ± 0.003
$4f_0$	8.07373	0.080	0.174 ± 0.006	0.097	0.176 ± 0.004
$5f_0$	10.09217	0.052	0.563 ± 0.008	0.063	0.558 ± 0.007
$6f_0$	12.11060	0.039	0.97 ± 0.011	0.047	0.969 ± 0.008
$7f_0$	14.12903	0.027	0.381 ± 0.015	0.034	0.376 ± 0.012
$8f_0$	16.14747	0.019	0.779 ± 0.022	0.024	0.783 ± 0.018
$9f_0$	18.16590	0.013	0.185 ± 0.034	0.015	0.163 ± 0.028
$10f_0$	20.18433	0.011	0.557 ± 0.038	0.013	0.565 ± 0.033
$11f_0$	22.20277	0.008	0.988 ± 0.054	0.009	0.990 ± 0.047
$12f_0$	24.22120	0.006	0.384 ± 0.066	0.007	0.387 ± 0.053
$13f_0$	26.23963	0.005	0.772 ± 0.088	0.005	0.794 ± 0.081
$14f_0$	28.25807	0.003	0.099 ± 0.120	0.004	0.103 ± 0.098
$15f_0$	30.27650	0.003	0.634 ± 0.144	0.003	0.622 ± 0.148
$16f_0$	32.29505	0.002	0.009 ± 0.140	0.002	0.982 ± 0.151
$f_0 + f_B$	2.04705	0.050	0.545 ± 0.007	0.061	0.541 ± 0.006
$f_0 - f_B$	1.98982	0.024	0.399 ± 0.014	0.029	0.403 ± 0.014
$2f_0 + f_B$	4.06548	0.006	0.82 ± 0.06	0.005	*0.874 ± 0.090*
$2f_0 - f_B$	4.00825	0.014	0.642 ± 0.030	0.019	0.621 ± 0.022
$3f_0 + f_B$	6.08392	0.009	0.226 ± 0.038	0.011	*0.215 ± 0.033*
$3f_0 - f_B$	6.02668	0.017	0.036 ± 0.02	0.020	0.043 ± 0.020
$4f_0 + f_B$	8.10235	0.020	0.583 ± 0.018	0.025	0.583 ± 0.016
$4f_0 - f_B$	8.04512	0.012	0.462 ± 0.031	0.015	0.458 ± 0.026
$5f_0 + f_B$	10.12078	0.015	0.05 ± 0.025	0.018	0.039 ± 0.021
$5f_0 - f_B$	10.06355	0.013	0.945 ± 0.026	0.016	0.950 ± 0.024
$6f_0 + f_B$	12.13922	0.011	0.477 ± 0.033	0.013	0.464 ± 0.028
$6f_0 - f_B$	12.08198	0.010	0.345 ± 0.039	0.013	0.339 ± 0.027
$7f_0 + f_B$	14.15765	0.009	0.874 ± 0.042	0.011	0.859 ± 0.038

$7f_0 - f_B$	14.10041	0.008	0.793 ± 0.042	0.011	0.805 ± 0.040
$8f_0 + f_B$	16.17608	0.006	0.247 ± 0.061	0.008	0.256 ± 0.048
$8f_0 - f_B$	16.11884	0.006	0.273 ± 0.060	0.006	0.282 ± 0.070
$9f_0 + f_B$	18.19451	0.005	0.694 ± 0.074	0.005	0.681 ± 0.081
$9f_0 - f_B$	18.13728	0.005	0.644 ± 0.082	0.007	0.654 ± 0.052
$10f_0 + f_B$	20.21295	0.003	0.085 ± 0.118	0.005	0.048 ± 0.073
$10f_0 - f_B$	20.15571	0.004	0.063 ± 0.088	0.005	0.106 ± 0.081
$11f_0 + f_B$	22.23138	0.003	0.426 ± 0.105	0.004	0.452 ± 0.101
$11f_0 - f_B$	22.17415	0.003	0.554 ± 0.116	*0.003*	*0.496 ± 0.140*
$12f_0 + f_B$	24.24981	0.003	0.895 ± 0.124	*0.003*	*0.827 ± 0.141*
$12f_0 - f_B$	24.19258	*0.001*	*0.939 ± 0.330*	*0.003*	*0.008 ± 0.146*
$13f_0 + f_B$	26.26825	0.003	0.299 ± 0.141	0.003	0.319 ± 0.122
$13f_0 - f_B$	26.21101	*0.001*	*0.312 ± 0.366*	*0.002*	*0.279 ± 0.320*
$14f_0 + f_B$	28.28668	*0.002*	*0.763 ± 0.325*	0.001	0.769 ± 0.303
$14f_0 - f_B$	28.22945	0.001	0.728 ± 0.152	0.003	0.718 ± 0.129
$15f_0 + f_B$	30.30511	0.002	0.042 ± 0.156	0.003	0.045 ± 0.128
$15f_0 - f_B$	30.24788	*0.003*	*0.126 ± 0.408*	*0.001*	*0.099 ± 0.276*
f_B	0.02862	0.007	0.907 ± 0.048	0.006	0.887 ± 0.051
Quintuplet components found in the data after substracting the triplet fit:					
$3f_0 + 2f_B$	6.1125	0.008	0.54 ± 0.04	0.014	0.85 ± 0.03
$6f_0 + 2f_B$	12.1678	0.008	0.88 ± 0.04	0.011	0.97 ± 0.04
$5f_0 - 2f_B$	10.0349	0.008	0.26 ± 0.03	0.009	0.33 ± 0.03

Table 4.1: Frequency solution for SS For in B as well as in V.

For calculating the fit to the B data, we used the frequencies found in the V data set as starting point. The resulting amplitudes are larger than in the V filter. The highest peak-to-peak amplitude in our data was 1.65 mag, while in V it was only 1.34 mag. When taking f_0 and 10 harmonics into acount, the amplitudes in B are on average 1.23 times larger.

The ephemerides determined for SS For with the new data collected in the Blazhko project are:

$$T_{Pmax} = 2453296.440 + 0.495433\ E_{puls}$$
$$T_{BLmax} = 2453298.914 + 34.9\ E_{Blazhko}$$

Times are given in Heliocentric Julian Date (HJD). There were several pulsation maxima covered by our data set. The zero point given in the ephemerides is one of them. It is also the highest maximum observed in the campaign. The given time of Blazhko maximum, however, was not directly observed. It is the Blazhko maximum according to the best fit to the data which occured 5 pulation cycles after the highest maximum observed.

When plotting the residuals remaining after substracting the triplet fit (see Figure 4.3), it becomes obvious that the scatter is most prominent at specific phases. Between minimum and maximum light and at the phase where the so-called bump occurs ($\varphi = 0.5 - 0.8$, see also Section 4.6) the scatter is larger than in the other parts of the pulsation cycle. This hints towards additional freqencies that might still be present in the data. Indeed, when searching for periodicities after substracting the triplet fit, peaks at 6.1125 c/d, 12.1678 c/d and 10.0349 c/d emerged. These peaks are located almost exactly at the expected positions of quintuplet components. The separations from the exact quintuplet positions are smaller than the uncertainties of the frequency values. The peaks correspond to the following quintuplet features: $3f_0 + 2f_B$, $6f_0 + 2f_B$ and $5f_0 - f_B$. The same frequencies were found in both filters. It is interesting to note that around f_0 no quintuplet feature was found and that one of the detected peaks corresponds to a peak at the low frequency side of the harmonic.

So far, only in the star RV UMa quintuplet features have been observed (see also section 2.4). SS For is therefore the second star for which the detection of quintuplet components is reported. In Figure 4.3 it can be seen that after substracting the fit which includes the quintuplets, the scatter is much smaller.

4.2.3 The frequency analysis of UV Oct

The Fourier analysis of UV Oct was performed in the same way as for SS For. Again, a large data set collected by the ASAS survey was available online for UV Oct which we used to obtain very precise frequency values. This was possible due to the long time base of the ASAS measurements. The data span from HJD=2451889.9 to HJD=2454726.6 which yields a time base of 2836.7 days or 7.77 years. Only measurements with a low scatter were included into the analysis. The total number of ASAS measurements used in the analysis was 1209. In order to combine the ASAS data with our measurements, a fit was first calculated seperately for both our data and the ASAS data. The offset between the two fits was determined, and the ASAS data were shifted by this constant factor to match our data. Because of the long time span of the ASAS data the frequencies could be determined with high precision. Those frequencies were thereafter used as starting values to optimize the fit to our own measurements.

As before, we checked the comparison stars for variability and then selected the one that shows a color more similar to that of the target for the subsequent analysis. In this case, we selected C1 (HD 146164) also because it is brighter than C2 and therefore shows lower scatter. We also analysed

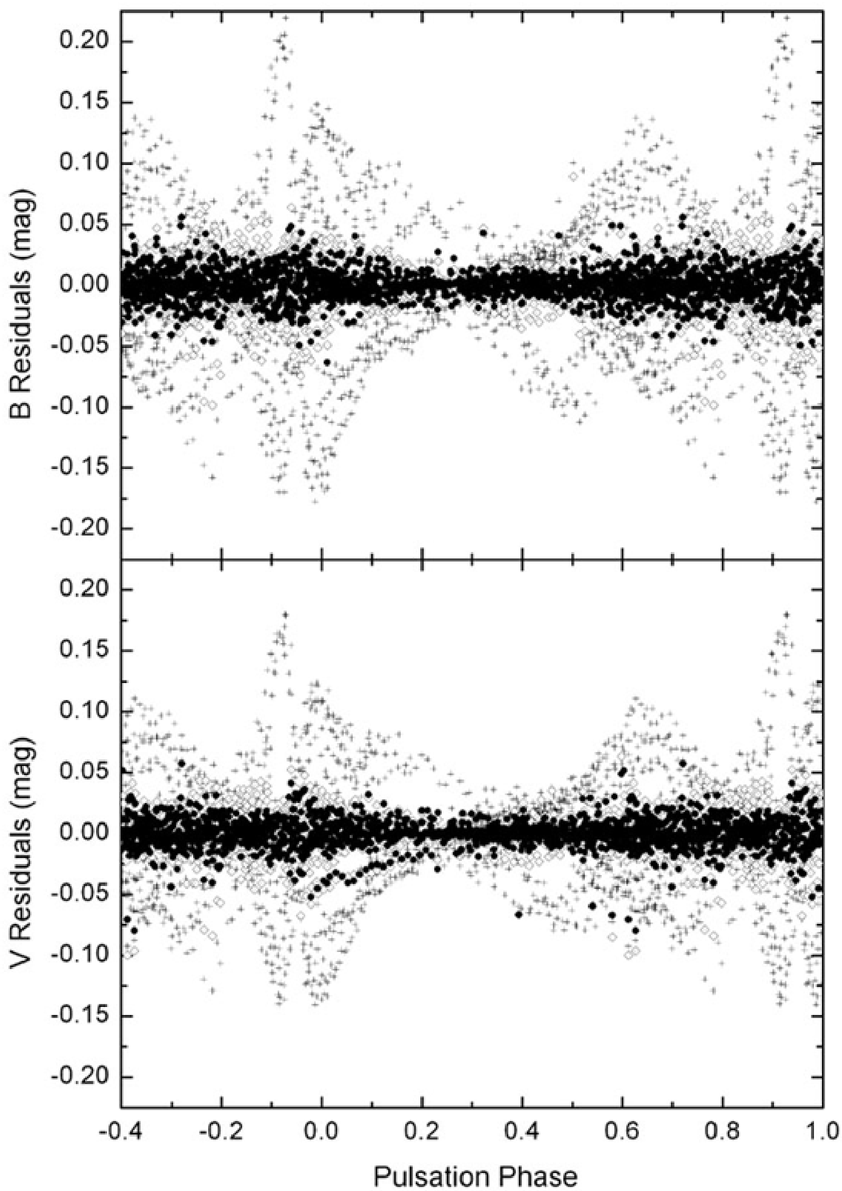

Figure 4.3: Residuals of the SS For data in B (top) and V filter (bottom). Crosses: residuals after substracting the mean light curve, diamonds: residuals after substracting the triplet solution, dots: after substracting the quintuplet solution.

data from different observatories seperately before merging them to exclude the possibility of systematic errors. Then, the frequency analysis was performed for the B and V data of the combined data set. Again, two different methods were applied: first all frequencies were considered independant, and then they were considered linear combinations of f_0 and f_N as described in the previous section. Table 4.2 lists the resulting frequencies, their amplitudes and their phases and errors for the B as well as the V data. Errors were calculated by means of a Monte Carlo simulation using 300 iterations. The results were multiplied by two.

	f [cd^{-1}]	A_V ± 0.003	φ_V [$\frac{\text{rad}}{2\pi}$]	A_B ± 0.003	φ_B [$\frac{\text{rad}}{2\pi}$]
f_0	1.8430531	0.32985	0.23790 ± 0.003	0.42949	0.24648 ± 0.002
$2f_0$	3.6861062	0.15422	0.85918 ± 0.006	0.20736	0.85298 ± 0.005
$3f_0$	5.5291592	0.09836	0.52343 ± 0.010	0.12742	0.52830 ± 0.008
$4f_0$	7.3722123	0.06009	0.16439 ± 0.017	0.07334	0.15659 ± 0.014
5_0	9.2152654	0.04493	0.85553 ± 0.022	0.05847	0.85168 ± 0.017
$6f_0$	11.0583185	0.01651	0.56060 ± 0.060	0.01931	0.55471 ± 0.052
$7f_0$	12.9013716	0.00993	0.05626 ± 0.100	0.01676	0.05436 ± 0.059
$8f_0$	14.7444246	0.00962	0.74139 ± 0.104	0.01194	0.78790 ± 0.083
$9f_0$	16.5874777	0.00455	0.40250 ± 0.219	0.00541	0.33398 ± 0.184
$10f_0$	18.4305308	0.00544	0.04181 ± 0.183	0.00827	0.04193 ± 0.120
$11f_0$	20.2735839	*0.00377*	*0.16986 ± 0.264*	0.00377	0.16986 ± 0.264
$12f_0$	22.1166370	0.00441	0.19018 ± 0.226	0.00462	0.22371 ± 0.216
$13f_0$	23.9596900	0.00354	0.03262 ± 0.282	0.00270	0.99009 ± 0.369
$14f_0$	25.8027431	*0.00101*	*0.51065 ± 0.988*	*0.00183*	*0.59425 ± 0.544*
$15f_0$	27.6457962	0.00249	0.17346 ± 0.400	0.00247	0.21949 ± 0.403
$16f_0$	29.4888493	0.00180	0.89023 ± 0.553	*0.00262*	*0.82593 ± 0.380*
$17f_0$	31.3319024	0.00210	0.45175 ± 0.475	0.00216	0.45552 ± 0.460
$18f_0$	33.1749554	0.00208	0.14173 ± 0.479	0.00218	0.12797 ± 0.457
$19f_0$	35.0180085	*0.00132*	*0.83173 ± 0.307*	0.00215	0.81648 ± 0.204
$f_0 + f_B$	1.8499641	0.05826	0.64429 ± 0.017	0.07704	0.63805 ± 0.013
$f_0 - f_B$	1.8361420	0.04579	0.90594 ± 0.022	0.06207	0.90500 ± 0.016
$2f_0 + f_B$	3.6930172	0.03664	0.27494 ± 0.027	0.04841	0.28716 ± 0.021
$2f_0 - f_B$	3.6791951	0.01371	0.56011 ± 0.073	0.01005	0.57051 ± 0.099
$3f_0 + f_B$	5.5360703	0.03807	0.86540 ± 0.026	0.04735	0.85715 ± 0.021
$3f_0 - f_B$	5.5222482	0.01050	0.06313 ± 0.095	0.01716	0.02795 ± 0.058
$4f_0 + f_B$	7.3791234	0.03553	0.55947 ± 0.028	0.04642	0.56102 ± 0.021
$4f_0 - f_B$	7.3653013	0.01212	0.60564 ± 0.082	0.01469	0.62879 ± 0.068
$5f_0 + f_B$	9.2221764	0.01990	0.26371 ± 0.050	0.02334	0.25652 ± 0.043
$5f_0 - f_B$	9.2083544	0.01603	0.32823 ± 0.062	0.01945	0.31712 ± 0.051
$6f_0 + f_B$	11.0652295	0.01511	0.85336 ± 0.066	0.02246	0.84745 ± 0.044
$6f_0 - f_B$	11.0514074	0.01241	0.06753 ± 0.080	0.01626	0.05607 ± 0.061
$7f_0 + f_B$	12.9082826	0.01460	0.56038 ± 0.068	0.01821	0.58348 ± 0.055
$7f_0 - f_B$	12.8944605	0.00683	0.73047 ± 0.146	0.00828	0.72502 ± 0.120
$8f_0 + f_B$	14.7513357	0.00800	0.24603 ± 0.125	0.00765	0.22402 ± 0.130
$8f_0 - f_B$	14.7375136	0.00631	0.37040 ± 0.158	0.00842	0.35528 ± 0.118
$9f_0 + f_B$	16.5943888	0.00567	0.87373 ± 0.176	0.00845	0.86099 ± 0.118
$9f_0 - f_B$	16.5805667	0.00529	0.04062 ± 0.189	0.00633	0.05351 ± 0.158
$10f_0 + f_B$	18.4374418	0.00455	0.60571 ± 0.219	0.00518	0.61109 ± 0.192
$10f_0 - f_B$	18.4236198	0.00515	0.67767 ± 0.193	0.00513	0.67067 ± 0.194
$11f_0 + f_B$	20.2804949	*0.00137*	*0.09032 ± 0.725*	0.00204	0.04592 ± 0.488
$11f_0 - f_B$	20.2666728	0.00463	0.44852 ± 0.215	0.00601	0.43833 ± 0.166

$12f_0 + f_B$	22.1235480	0.00277	0.78342 ± 0.359	0.00313	0.82703 ± 0.319
$12f_0 - f_B$	22.1097259	*0.00139*	*0.21402 ± 0.717*	0.00205	0.09017 ± 0.486
$13f_0 + f_B$	23.9666011	0.00225	0.76250 ± 0.444	*0.00135*	*0.72297 ± 0.736*
$13f_0 - f_B$	23.9527790	0.00320	0.66095 ± 0.311	0.00285	0.65501 ± 0.350
$14f_0 + f_B$	25.8096542	*0.00092*	*0.84788 ± 1.087*	*0.00192*	*0.05823 ± 0.519*
$14f_0 - f_B$	25.7958321	0.00262	0.40809 ± 0.380	0.00303	0.38791 ± 0.329

Table 4.2: Frequency solution for UV Oct in B as well as in V.

From the frequency analysis of the combined data from the SAAO and the SSO we could determine the following new ephemerides for UV Oct:

$$T_{Pmax} = 2453570.914109 + 0.542578E_{Puls}$$
$$T_{BLmax} = 2453561.690284 + 144.7E_{Blazhko}$$

The Blazhko maximum given in the ephemerides was not directly observed but results from the fit to the data. The highest maximum observed is the one at HJD 2453570.91 which was used as zero point for the pulsation ephemerids. According to the fit the Blazhko maximum must have occurred about nine days earlier.

4.3 The decrease of amplitudes

It was first reportred by Jurcsik (2005c) that with increasing order, the amplitudes of the side peaks decrease less steeply than those of the harmonics (see section 2.4). They suspected that therefore a different explanation for these peaks might be necessary than for the radial mode and its harmonics.

We checked the behavior of the amplitudes also in our data of SS For and found it to be similar: the amplitudes of the harmonics show an exponential decrease, as it was observed for RR Gem by Jurcsik et al. The amplitudes of the sidepeaks decrease less steeply, as it was expected. Their behavior, however, is not exactely linear. There are some irregularities in the lower orders (k=2,3). The results can be seen in Figure 4.4. It shows the relative amplitudes of the harmonics of the radial mode, $A(f_k)/A(f_0)$, and those the left and the right side peaks, $A(f_k + f_B)/A(f_0 + f_B)$ and $A(f_k - f_B)/A(f_0 - f_B)$, respectively.

For UV Oct, the behavior of the amplitudes with increasing harmonic order was also investigated. The results are comparable: again, the radial harmonics show an exponential decrease, while the amplitudes of the side

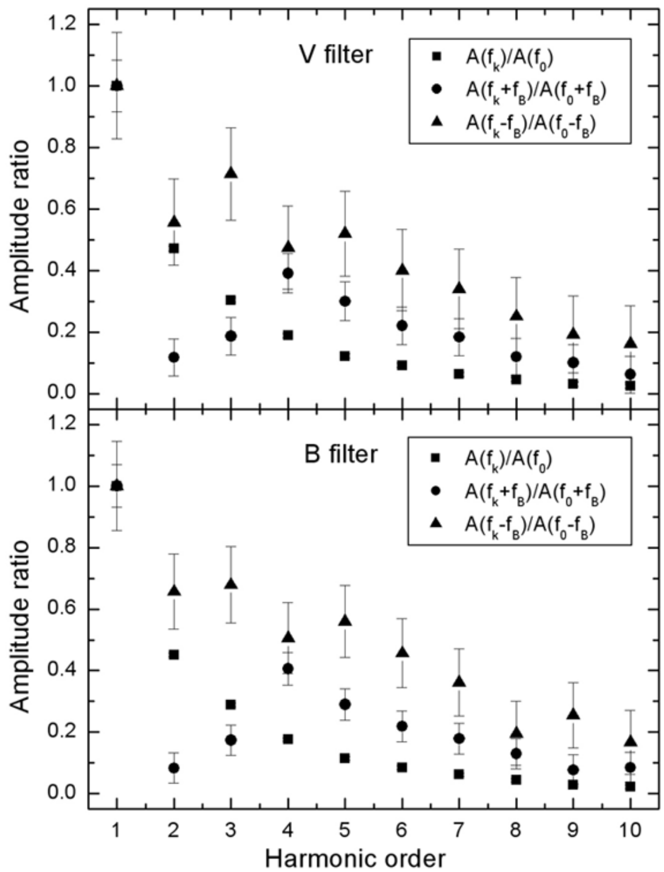

Figure 4.4: SS For: The decrease of the amplitudes with harmonic order for integer multiples and side peaks. Top panel: V filter, bottom panel: B filter

peaks decrease less steeply. Similarly to SS For, the decrease of the side peak amplitudes is not exactly linear, but there are some irregularities, especially at low orders. Figure 4.5 shows the relative amplitudes for each harmonic order in both filters.

4.4 Amplitude ratios, phase differences and asymmetry parameter

The asymmetry parameter Q was already discussed in section 2.4. We calculated Q from our data to investigate the aymmetry of the triplets of SS For and UV Oct for different orders. The results are listed in Table 4.3. For SS For, the asymmetry parameter varies over a wide range from -0.40 to +0.34, indicating that the triplets in the different harmonic orders have a very different appearance. Some are rather symmetric like orders 5 and 6,

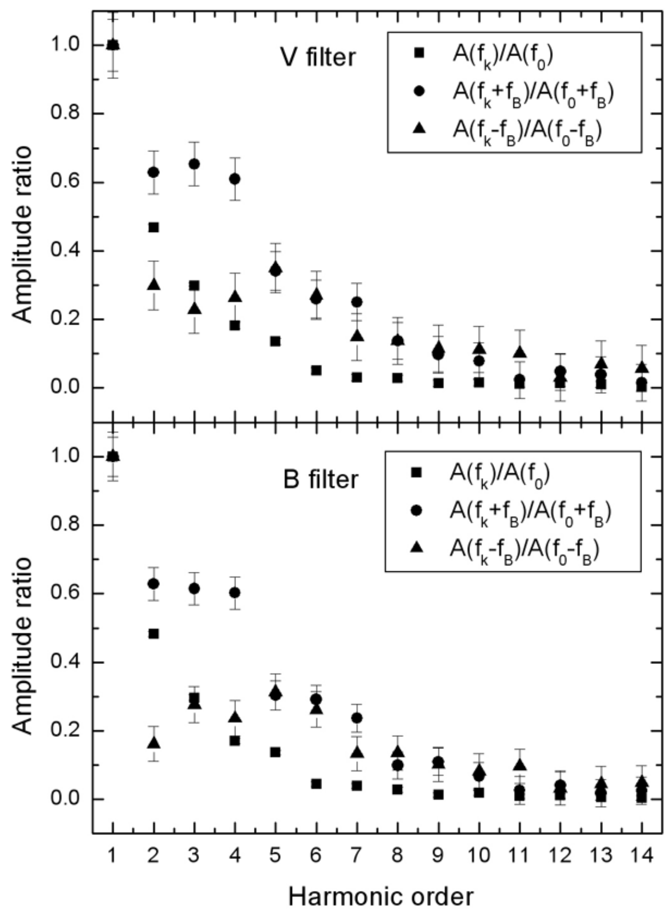

Figure 4.5: UV Oct: The decrease of the amplitudes with harmonic order for integer multiples and side peaks. Top panel: V filter, bottom panel: B filter

others are asymmetric. In the orders 2 and 3 the negative value of Q indicates that the left side peak is higher than the right side peak while in all the other orders, the situation is reversed. The irregular behavior of the orders 2 and 3 has already become obvious when studying the decrease of amplitudes in sucessive orders (section 4.3). In UV Oct, on the other hand, all values of Q are positive, indicating that the right side peak is always higher than the one on the left. Nevertheless, the triplets are still asymmetric, and the values of Q range from 0.10 in order k=6 (indicating only a slight asymmetry) to 0.57 in order k=3 which is a sign for highly asymmetric side peaks. The asymmetry of the observed triplets is still a challenge for the models of the Blazhko effect.

SS For						
Order k	R_k(V)	σR_k(V)	$\Delta\varphi_k$(V)	$\sigma_{\Delta\varphi_k}$(V)	Q (V)	σ_Q(V)
1	2.05	0.28	0.15	0.02	0.34	0.07
2	0.43	0.24	0.18	0.07	-0.40	0.31
3	0.53	0.19	0.19	0.04	-0.30	0.16
4	1.69	0.51	0.12	0.04	0.26	0.11
5	1.18	0.36	0.11	0.04	0.08	0.04
6	1.13	0.46	0.13	0.05	0.06	0.03
Order k	R_k(B)	σR_k(B)	$\Delta\varphi_k$(B)	$\sigma_{\Delta\varphi_k}$(B)	Q (B)	σ_Q(B)
1	2.09	0.24	0.14	0.02	0.35	0.06
2	0.26	0.16	0.25	0.09	-0.58	0.50
3	0.54	0.17	0.17	0.04	-0.30	0.14
4	1.68	0.39	0.12	0.03	0.25	0.08
5	1.08	0.27	0.09	0.03	0.04	0.01
6	1.00	0.32	0.12	0.04	0.00	0.00

UV Oct						
Order k	R_k(V)	σR_k(V)	$\Delta\varphi_k$(V)	$\sigma_{\Delta\varphi_k}$(V)	Q (V)	σ_Q(V)
1	1.27	0.11	-0.26	0.03	0.12	0.01
2	2.67	0.64	-0.29	0.08	0.46	0.16
3	3.63	1.11	0.80	0.10	0.57	0.25
4	2.93	0.79	-0.05	0.09	0.49	0.19
5	1.24	0.31	-0.06	0.08	0.11	0.04
6	1.22	0.39	0.79	0.10	0.10	0.04
Order k	R_k(B)	σR_k(B)	$\Delta\varphi_k$(B)	$\sigma_{\Delta\varphi_k}$(B)	Q (B)	σ_Q(B)
1	1.24	0.08	-0.27	0.02	0.11	0.01
2	4.82	1.52	-0.28	0.10	0.66	0.29
3	2.76	0.53	0.83	0.06	0.47	0.13
4	3.16	0.70	-0.07	0.07	0.52	0.16
5	1.20	0.25	-0.06	0.07	0.09	0.03
6	1.38	0.32	0.79	0.08	0.16	0.05

Table 4.3: Amplitude ratios, phase differences and the asymmetry parameter Q for SS For (top) and UV Oct (bottom) in both filters.

Furthermore, we calculated the amplitude ratios R_k and phase differences $\Delta\varphi_k$ of the first 6 triplets. R_k and Q are partly redund and in the sense that both parameters indicate which of the side peaks is higher and how strong the asymmetry is. Nevertheless, as some people might prefer either the one of the other to compare it to their results, they are given here for completeness. Furthermore, those parameter combinations might provide an important model test, because the current theoretical explanations expect R_k and $\Delta\varphi_k$ to be constant. However, it has to be considered that the amplitudes of the side peaks might strongly depend on the coverage and therefore on the data set used, as was shown by Jurcsik et al (2005c). R_k and $\Delta\varphi_k$ are defined as follows:

$$R_k = A_{kf_0+f_B}/A_{kf_0-f_B}$$
$$\Delta\varphi_k = \varphi_{kf_0+f_B} - \varphi_{kf_0-f_B}$$

The resulting parameters for SS For and their errors are listed in table 4.3 as well. The errors for each parameter were calculated using the laws of error propagation starting from the value of the errors which were determined by means of Monte Carlo simulation for the amplitudes and phases.

Another parameter that was statistically investigated in the framework of the MACHO project is the amplitude of the modulation components relative to the amplitude of f_0: $A_\pm/A_0$. Alcock et al. found the relative amplitudes to be mostly in the range $0.1 < A_\pm/A_0 < 0.3$, with some extreme values as exceptions. In our data of SS For, the values are $A_+/A_0 = 0.118 \pm 0.007$, $A_-/A_0 = 0.057 \pm 0.007$ in V and $A_+/A_0 = 0.111 \pm 0.005$ and $A_-/A_0 = 0.053 \pm 0.005$ in B. For UV Oct we found the values to be $A_+/A_0 = 0.0.177 \pm 0.010$, $A_-/A_0 = 0.139 \pm 0.009$ in V and $A_+/A_0 = 0.179 \pm 0.007$ and $A_-/A_0 = 0.145 \pm 0.007$ in B. SS For therefore shows a rather low relative modulation amplitude compared to the typical values of stars in the MACHO project, while UV Oct lies well with the typical range.

4.5 The modulation in different colors

Not only the pulsation amplitude of an RR Lyrae star is larger in B than in V, but also its modulation amplitude. The question how to define and to determine the amplitude of the modulation was addressed by Jurcsik et al (2005a). They proposed to sum up the amplitudes of the first four modulation components, i.e., the two side peaks next to f_0 and those next to $2f_0$. This was practical and quickly lead to a statistical result, because this quantity is already available for a large number of stars. They state, however, that this method of measuring the modulation amplitude might not be optimal and might introduce a bias into a statistical analysis (see also section 2.7). Of course, the modulation amplitude resulting from this method is smaller than the value obtained when all detectable modulation components are taken into account. For analysing the wavelength dependence of the modulation, they investigated the data of a sample of well-studied field Blazhko stars. They found that the ratio of the modulation amplitude in B to the modulation amplitude in V, A_{mod}(B)/$\mathrm{A}_{\mathrm{mod}}$(V), usually lies in the range 1.23-1.39 with an average of 1.30.

As we detected modulation components in SS For and UV Oct up to a very high order, we did not only calculate the sum of the first four modulation components (order 2), but all sums up to the order 10. But, of course, also the error becomes larger with increasing order. The results are given in Table 4.4. It lists the order up to which the components were taken into acount, the modulation amplitude in B and in V, and the ratio A_{mod}(B)/$\mathrm{A}_{\mathrm{mod}}$(V).

For the modulation amplitude ratio as defined by Jurcsik et al (2005a), i.e., including the first four modulation components, we obtain a value of 1.22 ± 0.10 for SS For. We therefore see that also in SS For the modulation is stronger in B than it is in V. The resulting value is at the lower border of the range of typical values given by Jurcsik et al. It is also worth to note that with increasing order the resulting ratio remains constant. Therefore it does not seem to matter how many modulation components are taken into account when calculating A_{mod}(B)/$\mathrm{A}_{\mathrm{mod}}$(V).

For UV Oct the value of the modulation amplitude as defined by Jurcsik et al (2005b) is 1.28 ± 0.07, indicating that also in this star, the modulation is much stronger in B than it is in V. In contrast to SS For, this lies closer to the average value of 1.30 which was found for other Blazhko stars. Not only the ratio of the modulation amplitudes but also the values of A_{mod}(B) and A_{mod}(V) are higher than the ones determined for SS For. Again, the number of orders taken into account for calculating the ratio does not seem to influence the result much.

4.6 Variations around minimum light

The Blazhko effect is usually defined as a periodic change in amplitude and/or phase, therefore the main attention is directed to the pulsation maximum. In the case of SS For, however, strong variations around minimum light were already noticed and mentioned by Lub (1977). He observed the star in two different nights and noticed a strong deviation around the minimum. After he carefully checked for possible errors he concluded that the observed variations had to be real. We could confirm the existence of these variations and performed a more detailed investigation on them.

SS For			
Order k	A_{mod}(B)	A_{mod} (V)	A_{mod}(B)/$\mathrm{A_{mod}}$(V)
1	0.091 ± 0.004	0.075 ± 0.004	1.21 ± 0.09
2	0.115 ± 0.006	0.094 ± 0.006	1.22 ± 0.10
3	0.146 ± 0.007	0.121 ± 0.007	1.20 ± 0.09
4	0.185 ± 0.008	0.152 ± 0.008	1.21 ± 0.09
5	0.219 ± 0.009	0.180 ± 0.009	1.22 ± 0.08
6	0.246 ± 0.010	0.201 ± 0.010	1.22 ± 0.08
7	0.268 ± 0.011	0.219 ± 0.011	1.22 ± 0.08
8	0.282 ± 0.012	0.231 ± 0.012	1.22 ± 0.08
9	0.294 ± 0.013	0.241 ± 0.013	1.22 ± 0.08
10	0.304 ± 0.013	0.248 ± 0.013	1.23 ± 0.09
UV Oct			
Order k	A_{mod}(B)	A_{mod} (V)	A_{mod}(B)/$\mathrm{A_{mod}}$(V)
1	0.104 ± 0.004	0.139 ± 0.004	1.34 ± 0.07
2	0.154 ± 0.006	0.198 ± 0.006	1.28 ± 0.07
3	0.203 ± 0.008	0.262 ± 0.008	1.29 ± 0.06
4	0.251 ± 0.009	0.323 ± 0.009	1.29 ± 0.06
5	0.287 ± 0.010	0.366 ± 0.010	1.28 ± 0.06
6	0.314 ± 0.011	0.405 ± 0.011	1.29 ± 0.06
7	0.336 ± 0.012	0.431 ± 0.012	1.29 ± 0.06
8	0.350 ± 0.012	0.447 ± 0.012	1.28 ± 0.06
9	0.361 ± 0.013	0.462 ± 0.013	1.28 ± 0.06
10	0.370 ± 0.014	0.472 ± 0.014	1.27 ± 0.06

Table 4.4: Modulation in V and B and ratio for different orders for both stars.

The light curves of RR Lyrae stars sometimes show two characteristic features: the 'bump' and the 'hump'. The feature occuring just before minimum light (at a phase of roughly 0.7) is refered to as the 'bump'. The stillstand in the rising branch at a phase of approximately 0.9, on the other hand, is called the 'hump' and occurs only in some RR Lyrae stars. Bumps are also present in Cepheids, and a connection between the pulsation period and the phase of the bump in Cepheids was found by Ejnar Hertzsprung (1926) and was thereafter called the *Hertzsprung progression*. Hertzsprung investigated 37 stars and described the light curves with a period of less than 6 days as normal without any special features. In the light curves with periods longer than 6 days a bump appears at the end of the descending branch. Note that this is the phase at which we also see a bump in the light curves of RR Lyrae stars. For periods of about 10 to 13 days the bump proceeds to the other side of the maximum and finally leads to a stillstand in the rising branch. In short, with increasing period the bump proceeds to the left, i.e., to earlier phases. Hertzsprung had no physical explanation for the behaviour. Today the most common hypothesis is a resonance between the fundamental mode and the second overtone.

For RR Lyrae stars, the situation is different. In Cepheids the bump can be found at different phases depending on pulsation frequency, but in one specific star the bump always remains at the same position in the phase diagram. Not so for modulated RR Lyrae stars and in particular SS For. Here, the position of the bump in the phase diagram of a specific star changes significantly, and there seems to be no connection between the bump phase and the pulsation period. For the bump in SS For the change in phase is so extreme that it can already be noticed after one day, i.e. two pulsation cycles. Figure 4.6 illustrates the rapid progress of the bump by showing light curves taken in intervals of only five to six days. It can be seen clearly how the bump changes in phase and amplitude.

Other authors such as Gillet & Crowe (1988) already mentioned that the bump phase is variable in Blazhko stars, but no detailed investigation had been performed so far. Here, the first detailed qualitative analysis of the behavior of the bump is presented (see also Guggenberger & Kolenberg 2006).

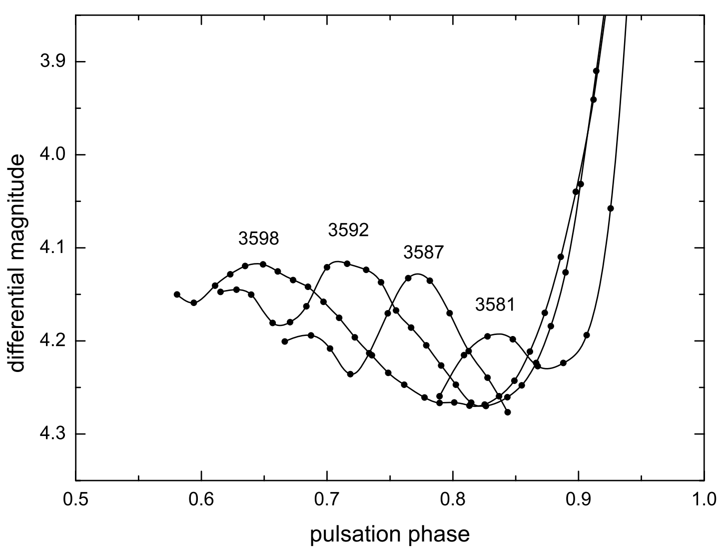

Figure 4.6: Phase diagram of SS For around bump phase for four different nights. Numbers in the figure represent Julian Date - 2450000. Scatter of data points is smaller than the symbols. Lines are spline interpolations of the datapoints and are given for better visibility only.

For our analysis we calculated the Blazhko phase for each of the datapoints and created 20 overlapping phase bins of 0.1 of the period, i.e. 0-0.1, 0.05-0.15 and so on. In each bin the phase and height of the bump maximum were determined. It is obvious that the bump changes from one Blazhko phase bin to the next. At the same time, the peak-to-peak amplitude of the pulsation was measured. In some bins the amplitude could not be measured due to insufficient coverage, but in all bins the phase around the bump is well covered with data. Ten (non-overlapping) phase bins can be seen in Figure 4.7. The results of the analysis of the phase of the bump maximum are plotted in Figure 4.8 together with the peak-to-peak amplitude of the lightcurve.

The following characteristics of the bump behavior can be seen: With the light curve maximum set to phase zero, the bump varies between phase 0.65 and 0.85. This corresponds to 20 % of the pulsation period! The period of the bump variation is equal to the Blazhko period, suggesting that the variations of the bump are directly connected to the Blazhko phenomenon. The curve of the phase variation is non-sinusoidal. It is characterized by a slow progress to earlier phases followed by a quicker motion to larger values. The ε - value which describes the skewness of the curve (see section 1.2) is 0.35, indicating a strong asymmetry. Also, the pulsation amplitudes vary in a non-sinusoidal way during a Blazhko cycle, with the same ε. The earliest phases of the bump maximum occur shortly after minimum pulsation amplitude, while the latest bump phases can be found shortly after Blazhko maximum, i.e. after the pulsation amplitude reached its highest value.

The most obvious question given the discussed results is whether this is a common phenomenon among Blazhko stars or whether SS For is an exception. The data on UV Oct also suggest variations around minimum light as can be seen in the phase diagram of the complete data set. Due to its very long Blazhko period of more than 140 days the data coverage was not sufficient for a detailed analysis like the one performed for SS For. A comparison to another Blazhko star nevertheless was important and we therefore applied the same method to the data of RR Lyr published by Kolenberg et al. (2006). The Blazhko period found in this data set is 38.8 days. On this basis we again calculated the Blazko phase of every data point and created phase bins. The phase of the bump maximum as well as the peak-to-peak amplitude of the pulsation were determined just like in the case of SS For, with comparable results.

The bump before the pulsation minimum of RR Lyr also shows a variation in phase during the Blazhko cycle. The range of this variation, however, is different from SS For. The earliest phase at which the bump in RR Lyr

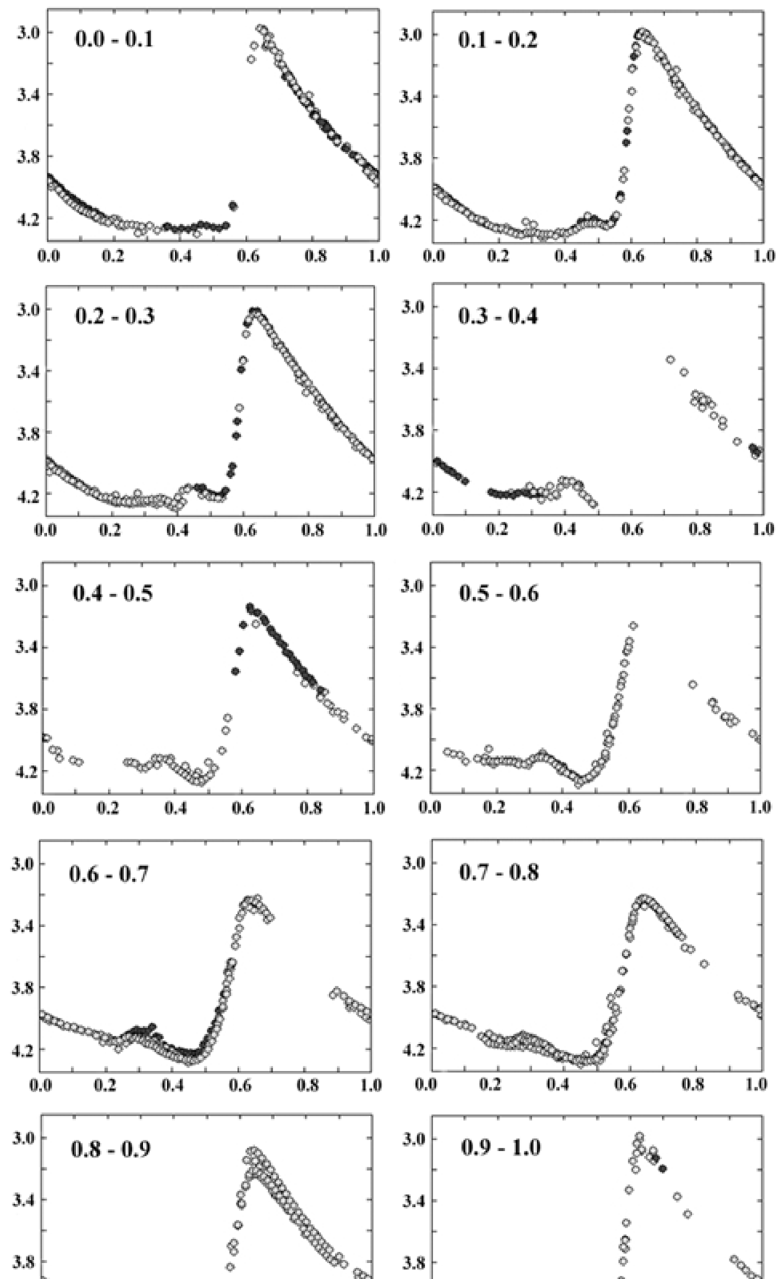

Figure 4.7: Phase bins used for the investigation of the bump before minimum light.

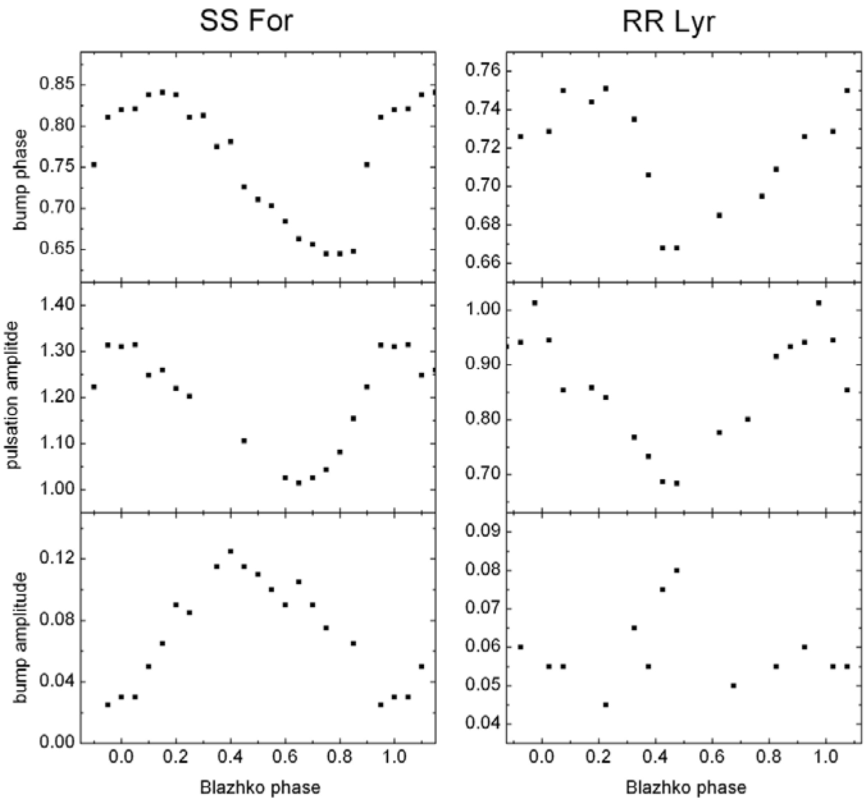

Figure 4.8: Results of the analysis of the bump in the light curves of SS For and RR Lyr. Top panel: phase of the bump with respect to Blazhko phase; middle panel: peak-to-peak pulsation amplitude; bottom panel: strength of the bump.

occurs, is 0.67, the latest 0.75. Zero phase was again defined as the time of pulsation maximum. That corresponds to a variation of 8% of the pulsation period. The interval in which the bump occurs is therefore small compared to the large value of 20% observed in SS For. Again, the smallest value of the bump maximum phase is reached during Blazhko minimum and the highest value during Blazhko maximum. One can therefore conclude that the phenomenon is similar in both analysed stars, but the strength of the effect is different.

In addition to the phase at which the bump occurs, also the distinctiveness of the bump was measured with respect to both the used filters and the Blazhko phase. Concerning the color one can see that the bump is more distinct in the B filter than it is in V. Consequently, the bump is also visible in the B-V color curves of the stars. This was already described by Gillet&

Crowe (1988), among others, and is confirmed by our findings.

Concerning the variation of the bump strength with Blazhko phase, two approaches were used: The first one was to determine the magnitude of the maximum of the bump. This method is slightly biased by the 'motion' of the bump during the Blazhko phase which brings it to different positions on the descending branch of the light curve and therefore influences the brightness of the maximum. The other method was more sophisticated and involved measurements of the brightness on both sides of the bump. The average value was then substracted from the maximum brightness to obtain an unbiased value of the bump 'strength'. Both approaches yielded comparable results. In SS For the bump is strongest during Blazhko minimum and almost disappears during Blazhko maximum. This is also clearly visible in the phase bins. The results for RR Lyr point towards a similar behavior, but the data do not have such a good quality as the SS For data and therefore do not allow a firm conclusion. A distinct bump during Blazhko minimum and a weak bump during maximum would stand in contrast to previous observations by Walraven (1949) and Fringant (1961) who reported the opposite behavior. In any case, it has to be considered that it is a difficult task to find an objective measure for the bump 'strength', because the bump does not only move up and down the descending branch of the light curve, but also varies in width.

Different explanations for the existence of the bump have been proposed by several authors. For Cepheids, a resonance between the fundamental mode and the second overtone is the most widespread model. Not so for RR Lyrae stars. RR Lyrae stars do not fulfill the condition of $P_2/P_0 = 0.5$ that is necessary to explain the bump by a resonance. Two models try to explain the phenomenon in RR Lyrae stars (Gillet & Crowe, 1988): the 'infall' model and the 'echo' model . Both involve shock or compression waves. None of the two has explicitly taken a variation of the bump into account.

It had been suspected for long that shock waves play an important role in RR Lyrae stars. Spectroscopic line doubling in the Balmer and Ca II H and K lines of RR Lyrae stars has already been observed in the middle of the twentieth century. Schwarzschild (1954) explained the phenomenon of line doubling in W Virginis stars with a shock wave separating the atmosphere into inward- and outward- moving layers. The presence of line doubling therefore strongly points towards the presence of shock waves.

The basis for the modern modelling of the bump was provided by Hill (1972). He calculated nonlinear hydrodynamical models of atmospheres in which two shocks formed. His nomenclature 'main shock' and 'early shock' is still in use. Fokin (1992) further refined the models of Hill. According to him a heating of subphotospheric gas might lead to a decrease of the opacity κ and therefore to the observed bump in the light curve.

The 'infall' model, one of the possible explanations for the bump, relies on the work of Hill. It explains the shock wave by fast moving layers that collide with slower, deeper layers during contraction of the star. The 'echo' model, on the other hand, describes a reflection of a shock wave on the stellar core. Both models therefore make a connection between the bump phase and the stellar radius, because the shock waves travel a longer distance to the surface in a larger star than in a smaller star. In the case of the 'echo' model, this correlation was investigated and confirmed by Carney et al. (1992). A relation between the mean (equilibrium) radius of the star and the bump phase, however, makes it hard to explain a variable bump phase.

The 'infall' model, on the other hand, does not connect the bump phase to the equilibrium radius of the star, but rather to the so-called 'expansion radius' which Carney et al. (1992) gave as

$$\Delta R = \int p(v_{\mathrm{rad}} - \gamma)dt$$

v_{rad} is the radial velocity, γ is the γ-velocity and p is the projection factor. If the expansion radius changes during the Blazhko cycle, this would explain the observed bahavior: With a larger expansion radius during Blazhko maximum the bump would be expected to appear later, while during the times of Blazhko minimum when the expansion radius is smaller, the bump would be expected to appear earlier. However, the Blazhko phenomenon is not understood yet, and it is not clear whether the expansion radius actually changes during a Blazhko cycle. In any case, models which try to explain the bump phenomenon should include the possibility of a changing bump phase.

4.7 Fourier parameters

The asymmetric light curve shapes of RR Lyrae stars cannot be described by a single sine frequency. The so-called harmonics, i.e. integer multiples of the pulsation frequency, are necessary to reproduce their light curves. The amplitudes and phases of these harmonics are a quantitative measure of the shape of the light curve. The fit with the pulsation frequency and its harmonics has the following form:

$$m(t) = Z + \Sigma A_k sin(2\pi k f_0 t + \phi_k)$$

During the Blazhko cycle, not only the total amplitude of the pulsation, but also the light curve characteristics of RR Lyrae stars change. Blazhko stars usually show a very non-sinusoidal light curve when they are at the maximum of the modulation cycle and a more sinusoidal curve around the minimum. Therefore, also the values of the amplitudes and phases of the harmonics change during the cycle. They provide a much more objective and quantitative measure for the light curve shape as terms like "less" or "more" sinusoidal. We calculated and compared these parameters for different modulation phases. This was done in the following way:

After obtaining a good Fourier fit of the complete data set, we subdivided the data into subsets of different Blazhko phases Ψ. 10 phase bins were created, ranging from $\Psi = 0.0$ to 0.1, from $\Psi = 0.1$ to 0.2 and so on. For every phase bin, the amplitudes and phases of f_0 and its harmonics were recalculated, while keeping the frequency values fixed. This was done for both stars included in this study: SS For and UV Oct. The results can be seen in the left panels of Figures 4.9 (SS For) and 4.10 (UV Oct). Table 4.5 and Table 4.6 list the values of the amplitudes and phases for each phase bin.

It is obvious that A_1, the amplitude of the fundamental mode, shows a strong change during the Blazhko cycle. At the Blazhko maximum, which was set to occur at $\Psi = 0$ the value of A_1 is -of course- largest, while at Blazhko minimum it reaches its lowest value. The lowest value is as much as 0.16 mag smaller than the maximum in the case of SS For. In UV Oct the difference is slightly larger with the minimum value of A_1 being 0.18 mag smaller than the maximum.

A difference between the two stars can be noted when looking at the other amplitudes A_2, A_3 and A_4. In UV Oct they show parallel behavior with all of them reaching their minimum around Blazhko minimum which indicates a strong change in the total amplitude as all the amplitude components sum up to form the total observed amplitude. In SS For, on the other hand, their changes are smaller and more irregular. The phases show only small changes in both stars.

The errors of amplitudes and phases were calculated in a twofold way. First, their analytical values were calculated and multiplied by two to obtain more realistic values. The formulae for the analytical uncertainties read as follows:

$$\Delta A = 2\sigma\sqrt{\frac{2}{N}}$$

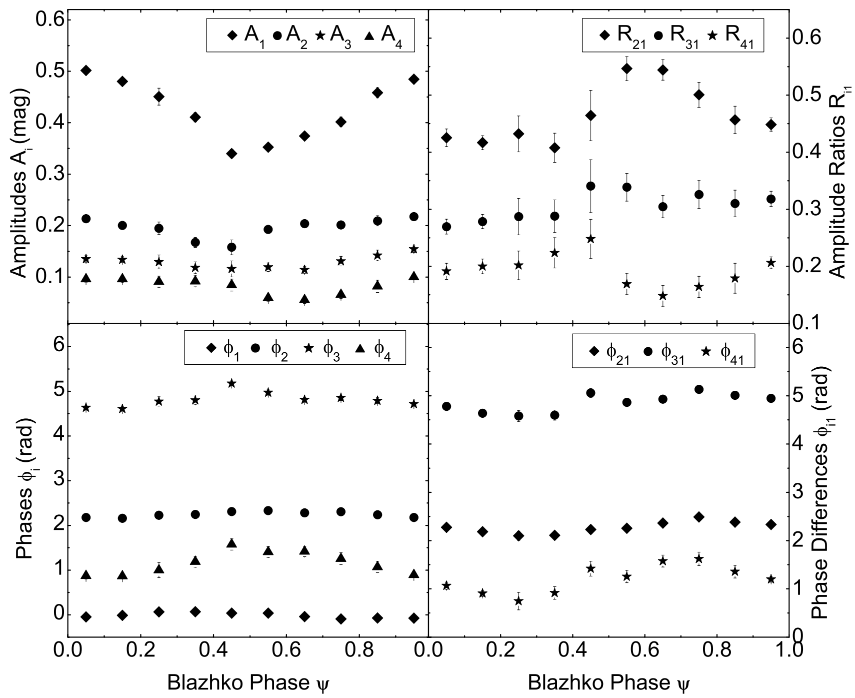

Figure 4.9: SS For: Change of the Amplitudes and Phases of the different harmonics during the Blazhko cycle (left panel) and change of the Fourier-parameters (right panel).

$$\Delta\phi = \frac{\Delta A}{A}$$

Additionally, a Monte Carlo simulation was performed. The errors resulting from the Monte Carlo simulation turned out to be larger and were therefore considered more realistic. Moreover, we multiplied the resulting errors by two, following Handler et al. (2000).

The parameters usually referred to as Fourier parameters, are the *amplitude ratios* and *phase differences* defined as follows:

$$R_{k1} = \frac{A_k}{A_1}$$

$$\varphi_{k1} = \varphi_k - k\varphi_1$$

where A_1 and ϕ_1 are the amplitude and phase of the main pulsation component, and A_k and φ_k are the amplitude and phase of the k^{th} peak in the Fourier spectrum. The errors of the Fourier parameters were calculated as follows:

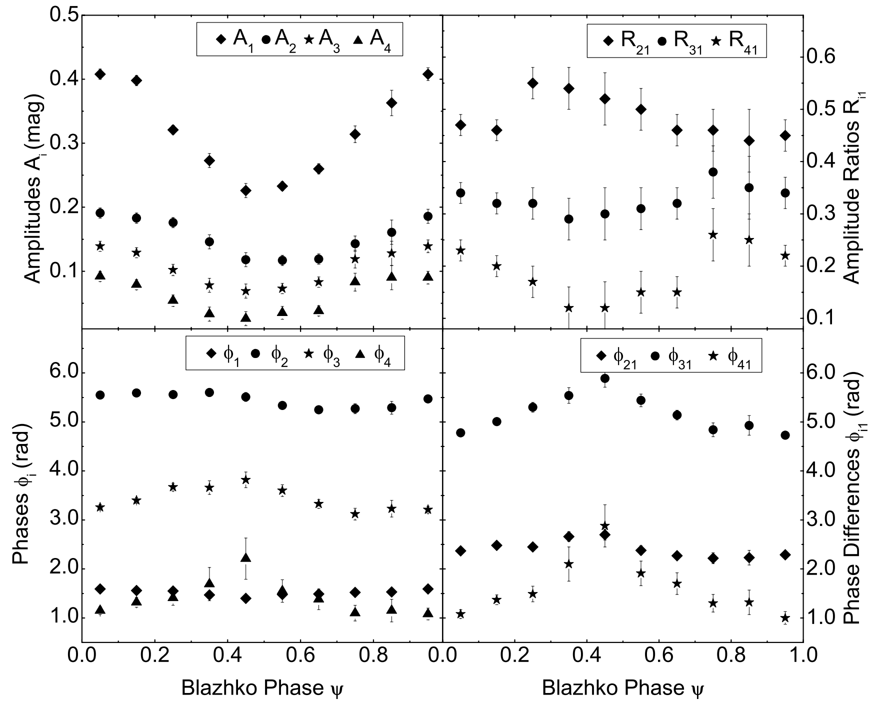

Figure 4.10: Same as Figure 4.9 but for UV Oct

$$\Delta R_{k1} = R_{k1}\sqrt{(\frac{\Delta A_k}{A_k})^2 + (\frac{\Delta A_1}{A_1})^2}$$

$$\Delta\varphi_{k1} = \sqrt{(\Delta\varphi_k)^2 + k(\Delta\varphi_1)^2}$$

The Fourier parameters provide a quantitative measure of the light curve characteristics. Before the 1980s, the shape of the RR Lyrae light curves was mainly discribed in a qualitative way, only using terms like 'dip', 'bump', 'stillstand' or 'shoulder'. The Fourier decomposition, in contrast, provides a more objective description. The amplitude ratios and phase differences are therefore also used to compare the output of hydrodynamical models with observations or, what will later be done in this thesis, to compare Blazhko stars to non-modulated stars (see section 4.7.2).

Simon (1985) was the first to systematically compare the Fourier parameters of a large sample of model RR Lyrae light curves to observational data. He found that for RRc stars, models and observations were in good agreement, and for RRab stars, the amplitude ratios also matched the data. But, the phase differences φ_{21} and φ_{31} of RRab stars deviated dramatically

Bl-Phase	A_1	A_2	A_3	A_4
0.05	0.502 ± 0.006	0.213 ± 0.007	0.135 ± 0.006	0.096 ± 0.007
0.15	0.480 ± 0.006	0.200 ± 0.005	0.134 ± 0.006	0.096 ± 0.006
0.25	0.451 ± 0.017	0.195 ± 0.012	0.129 ± 0.014	0.091 ± 0.011
0.35	0.411 ± 0.009	0.167 ± 0.010	0.118 ± 0.012	0.092 ± 0.011
0.45	0.340 ± 0.008	0.158 ± 0.015	0.116 ± 0.016	0.084 ± 0.012
0.55	0.353 ± 0.007	0.193 ± 0.006	0.119 ± 0.008	0.060 ± 0.006
0.65	0.374 ± 0.005	0.204 ± 0.006	0.114 ± 0.007	0.055 ± 0.007
0.75	0.402 ± 0.009	0.201 ± 0.007	0.131 ± 0.009	0.066 ± 0.007
0.85	0.458 ± 0.010	0.209 ± 0.010	0.142 ± 0.010	0.082 ± 0.012
0.95	0.485 ± 0.005	0.217 ± 0.005	0.154 ± 0.006	0.100 ± 0.005
Bl-Phase	φ_1	φ_2	φ_3	φ_4
0.05	-0.05 ± 0.01	2.18 ± 0.04	4.63 ± 0.06	0.87 ± 0.07
0.15	-0.01 ± 0.01	2.16 ± 0.03	4.61 ± 0.04	0.87 ± 0.06
0.25	0.06 ± 0.03	2.23 ± 0.09	4.77 ± 0.10	1.00 ± 0.17
0.35	0.07 ± 0.03	2.25 ± 0.06	4.80 ± 0.09	1.19 ± 0.12
0.45	0.04 ± 0.04	2.31 ± 0.06	5.18 ± 0.06	1.57 ± 0.13
0.55	0.04 ± 0.02	2.33 ± 0.04	4.97 ± 0.06	1.41 ± 0.12
0.65	-0.04 ± 0.02	2.28 ± 0.04	4.81 ± 0.05	1.42 ± 0.12
0.75	-0.09 ± 0.02	2.30 ± 0.05	4.86 ± 0.06	1.25 ± 0.13
0.85	-0.07 ± 0.02	2.24 ± 0.05	4.79 ± 0.07	1.07 ± 0.13
0.95	-0.08 ± 0.01	2.18 ± 0.02	4.72 ± 0.03	0.89 ± 0.06

Table 4.5: Amplitudes and phases of the harmonics for each Blazhko phase bin for SS For in the V filter.

from the observed light curves. This problem was named the *Fourier phase discrepancy* and remained unsolved for more than a decade. Feuchtinger & Dorfi (1998) finally resolved the discrepancy by including time-dependent radiation and time-dependent convection into their calculations.

We calculated the Fourier parameters and their uncertainties for both stars observed in this study. Their variation over the Blazhko cycle can be seen in the right panels of Figures 4.9 and 4.10 and in Tables 4.7 and 4.8. A strong change during the modulation cycle can be observed for the amplitude ratios as well as for the phase differences in both investigated stars. The ideal model of Blazhko RR Lyrae stars should of course be able to produce matching values at the minimum as well as at maximum of the Blazhko modulation.

Again, it can be noted that the two stars in this study show different behavior. The amplitude ratio R_{21} of SS For, for example, reaches a clear

Bl-phase	A_1	A_2	A_3	A_4
0.05	0.408 ± 0.008	0.191 ± 0.008	0.139 ± 0.008	0.092 ± 0.008
0.15	0.398 ± 0.008	0.183 ± 0.008	0.129 ± 0.008	0.079 ± 0.008
0.25	0.321 ± 0.007	0.176 ± 0.008	0.102 ± 0.009	0.054 ± 0.009
0.35	0.273 ± 0.011	0.146 ± 0.011	0.078 ± 0.011	0.033 ± 0.011
0.45	0.226 ± 0.011	0.118 ± 0.011	0.069 ± 0.011	0.026 ± 0.011
0.55	0.233 ± 0.007	0.117 ± 0.008	0.073 ± 0.008	0.035 ± 0.010
0.65	0.260 ± 0.008	0.119 ± 0.008	0.083 ± 0.008	0.038 ± 0.008
0.75	0.314 ± 0.013	0.143 ± 0.012	0.119 ± 0.014	0.083 ± 0.014
0.85	0.363 ± 0.020	0.161 ± 0.019	0.128 ± 0.019	0.090 ± 0.019
0.95	0.408 ± 0.010	0.186 ± 0.011	0.139 ± 0.010	0.090 ± 0.010
Bl-phase	φ_1	φ_2	φ_3	φ_4
0.05	1.59 ± 0.02	5.55 ± 0.04	3.26 ± 0.06	1.15 ± 0.08
0.15	1.56 ± 0.02	5.59 ± 0.04	3.40 ± 0.06	1.32 ± 0.10
0.25	1.55 ± 0.03	5.56 ± 0.05	3.67 ± 0.08	1.41 ± 0.15
0.35	1.47 ± 0.04	5.60 ± 0.08	3.66 ± 0.14	1.69 ± 0.34
0.45	1.40 ± 0.05	5.51 ± 0.09	3.82 ± 0.16	2.21 ± 0.42
0.55	1.48 ± 0.04	5.34 ± 0.07	3.60 ± 0.12	1.55 ± 0.23
0.65	1.49 ± 0.03	5.25 ± 0.07	3.33 ± 0.09	1.38 ± 0.21
0.75	1.52 ± 0.04	5.27 ± 0.10	3.12 ± 0.12	1.10 ± 0.16
0.85	1.53 ± 0.06	5.29 ± 0.13	3.23 ± 0.17	1.15 ± 0.23
0.95	1.59 ± 0.02	5.47 ± 0.05	3.21 ± 0.07	1.08 ± 0.12

Table 4.6: Same as table 4.5, but for UV Oct

maximum at a Blazhko phase of $\Psi = 0.6$ while in UV Oct R_{21} peaks at $\Psi = 0.25$. Also the phase differences φ_{31} and φ_{41} behave differently for the two stars. Their change is much stronger in UV Oct and their values reach a sharp maximum near the Blazhko minimum while in SS For they change less. It can therefore be seen that the change of Fourier parameters with the Blazhko phase is not necessarily the same for different Blazhko stars.

4.7.1 Metallicity from the light curve

The Fourier parameters are not only a useful method for comparing models with observations and an objective measure of the light curve shape. They can also be used to deduce basic stellar parameters like the metallicity, provided that correlation between the Fourier parameters and the metallicity has been found. Kovacs & Zsoldos (1995) developed such a method, based on the assumption that the characteristics of the light variations depend only on a few basic physical parameters, including the chemical composition.

Bl-Phase	R_{21}	R_{31}	R_{41}
0.05	0.43 ± 0.02	0.27 ± 0.01	0.19 ± 0.01
0.15	0.42 ± 0.01	0.28 ± 0.01	0.20 ± 0.01
0.25	0.43 ± 0.03	0.29 ± 0.03	0.20 ± 0.03
0.35	0.41 ± 0.03	0.29 ± 0.03	0.22 ± 0.03
0.45	0.46 ± 0.04	0.34 ± 0.05	0.25 ± 0.03
0.55	0.55 ± 0.02	0.34 ± 0.02	0.17 ± 0.02
0.65	0.54 ± 0.02	0.30 ± 0.02	0.15 ± 0.02
0.75	0.50 ± 0.02	0.33 ± 0.02	0.16 ± 0.02
0.85	0.46 ± 0.02	0.31 ± 0.02	0.18 ± 0.03
0.95	0.45 ± 0.01	0.32 ± 0.01	0.21 ± 0.01
Bl-Phase	φ_{21}	φ_{31}	φ_{41}
0.05	2.28 ± 0.04	4.78 ± 0.06	1.07 ± 0.07
0.15	2.18 ± 0.04	4.64 ± 0.05	0.91 ± 0.06
0.25	2.10 ± 0.10	4.58 ± 0.11	0.75 ± 0.18
0.35	2.11 ± 0.07	4.60 ± 0.10	0.92 ± 0.13
0.45	2.23 ± 0.08	5.06 ± 0.09	1.42 ± 0.15
0.55	2.26 ± 0.05	4.86 ± 0.07	1.26 ± 0.13
0.65	2.36 ± 0.05	4.93 ± 0.07	1.58 ± 0.12
0.75	2.49 ± 0.05	5.13 ± 0.07	1.62 ± 0.14
0.85	2.38 ± 0.06	5.01 ± 0.07	1.36 ± 0.13
0.95	2.33 ± 0.03	4.95 ± 0.04	1.20 ± 0.06

Table 4.7: SS For: Fourier parameters for each Blazhko phase bin.

On a purely empirical basis, they found a formula that connects the Fourier parameters of a sample of field RR Lyrae stars to their metallicity values known from spectroscopy. The advantage of having a method like this is that it provides a rather easy and accurate way to determine the metallicity. The Fourier parameters are quantities which can be determined with great precision, and photometric data sets can be obtained more easily than sprectroscopic observations, especially for the rather faint RR Lyrae stars.

However, their first approach made use of a large number of Fourier parameters and the deduced relations were of the form of second order polynomials. This made the results rather unstable and sensitive to small changes in the parameters. The method was therefore further improved by Jurcsik & Kovacs (1996, JK96), who found the relation to be linear and who used only the Fourier phase φ_{31} and the period P. This made the method more simple and the results more stable. Their calibration was also based on a larger sample of stars and used more accurate and more recent abundances.

Bl-phase	R21	R31	R41
0.05	0.47 ± 0.02	0.34 ± 0.02	0.23 ± 0.02
0.15	0.46 ± 0.02	0.32 ± 0.02	0.20 ± 0.02
0.25	0.55 ± 0.03	0.32 ± 0.03	0.17 ± 0.03
0.35	0.54 ± 0.04	0.29 ± 0.04	0.12 ± 0.04
0.45	0.52 ± 0.05	0.30 ± 0.05	0.12 ± 0.05
0.55	0.50 ± 0.04	0.31 ± 0.04	0.15 ± 0.04
0.65	0.46 ± 0.03	0.32 ± 0.03	0.15 ± 0.03
0.75	0.46 ± 0.04	0.38 ± 0.05	0.26 ± 0.05
0.85	0.44 ± 0.06	0.35 ± 0.06	0.25 ± 0.05
0.95	0.45 ± 0.03	0.34 ± 0.03	0.22 ± 0.02
Bl-phase	φ_{21}	φ_{31}	φ_{41}
0.05	2.37 ± 0.05	4.78 ± 0.07	1.08 ± 0.09
0.15	2.48 ± 0.05	5.01 ± 0.07	1.37 ± 0.10
0.25	2.45 ± 0.06	5.30 ± 0.10	1.49 ± 0.16
0.35	2.66 ± 0.10	5.54 ± 0.16	2.10 ± 0.35
0.45	2.70 ± 0.11	5.89 ± 0.18	2.88 ± 0.43
0.55	2.38 ± 0.09	5.44 ± 0.13	1.91 ± 0.25
0.65	2.27 ± 0.08	5.14 ± 0.10	1.70 ± 0.22
0.75	2.22 ± 0.11	4.84 ± 0.14	1.30 ± 0.18
0.85	2.23 ± 0.15	4.93 ± 0.20	1.32 ± 0.25
0.95	2.29 ± 0.06	4.73 ± 0.08	1.00 ± 0.13

Table 4.8: UV Oct: Fourier parameters for each Blazhko phase bin.

It is their relation which is used in this study.

The formula they derive to determine the metallicity of fundamental mode RR Lyrae stars reads as follows:

$$[Fe/H] = -5.038 - 5.394P + 1.345\varphi_{31}$$

Blazhko stars, of course, were excluded from the calibration sample, because their light curves and therefore also their Fourier parameters, undergo drastic changes during the Blazhko cycle, as was shown in the previous section. The derived metallicity would therefore depend on the modulation phase in which it was determined. Jurcsik & Kovacs already mentioned that the method is not applicable to peculiar cases like Blazhko variables because the derived values are usually deviant. The question arose, however, if there exists a phase in the Blazhko cycle, at which Blazhko pulsators fit into the general picture of non-modulated RR Lyrae stars in the sense that their metallicity calculated from the Fourier parameters agrees with the spectroscopic value. It is also possible that the mean light curve of Blazhko

SS For	
method	[Fe/H] result
average of the phase bins	-1.18 ± 0.13
value calculated from unmodulated curve	-1.18 ± 0.02
spectroscopic value	-1.09 ± 0.18
UV Oct	
method	[Fe/H] result
average of the phase bins	-1.02 ± 0.18
value calculated from unmodulated curve	-1.14 ± 0.02
spectroscopic value	-1.34 ± 0.18

Table 4.9: Results of the different methods to determine the metallicity of SS For.

variables fulfills this criterion.

We therefore used our Fourier parameters calculated in the previous section to apply the formula of Jurcsik & Kovacs to our stars. For each Blazhko phase bin, of course, we obtained a different value of [Fe/H]. A spectroscopic value was published by Layden (1994) who found the metallicity of SS For to be -1.35. The metallicity vlaues obtained by Layden, however, have to be transformed into a different system (Suntzeff-metallicities) to agree with the values obtained by the JK96 light curve-metallicity relation. The authors give a transformation formula which reads

$$[Fe/H]_S = 0.957[Fe/H]_L + 0.2$$

where $[Fe/H]_S$ are Suntzeff-metallicities and $[Fe/H]_L$ are metallicities measured by Layden (1994). When applying this formula to the metallicity of SS For, one obtains a value of -1.09 ± 0.18.

The values we obtain for the phase parameter φ_{31} for SS For range from 4.58 to 5.13 as can be seen in Table 4.7. The values are in the sinus frame, as required by the formula published by Jurcsik & Kovacs. The resulting metallicities of SS For in the different phase bins range from -1.55 to -0.81 (see Table 4.12). The average value is -1.18, agreeing with the spectroscopic value within the errors. Analyses like this were possible because of the almost complete coverage of the Blazhko cycle. An insufficient coverage would lead to a biased mean curve and would not allow to calculate the metallicities in different Blazhko phase bins. It is also important to obtain full pulsation light curves.

We also tried a different approach using the mean, i.e., unmodulated light curve. The mean light curve was obtained by fitting the data with only f_0 and 8 harmonics, without any side peaks and therefore without a modulation. The φ_{31} value of the unmodulated light curve is 4.856 ± 0.006 and results in a metallicity of -1.18 ± 0.02. The errors were calculated using the equation given by JK96. A comparison of the metallicity values obtained with different methods is given in table 4.9. As the value obtained by us agrees with the spectroscopic metallicity within the errors, the result seems to strengthen the suspicion that the mean light curve of SS For indeed resembles that of an unmodulated RR Lyrae star. For UV Oct, however, the situation is different. Layden (1994) gives a spectroscopic metallicity of UV Oct of -1.61. Again, we used the transformation formula published by JK96 to obtain $[Fe/H]_S$ which is -1.34 in this case. The values obtained by us for φ_{31} range from 4.73 to 5.89 and are listed in table 4.8. The resulting [Fe/H] values at the different Blazhko phases Ψ are listed in Table 4.12 and range from -0.04 to -1.60. The average value therefore is -1.02 which is far from the spectroscopic metallicity of -1.34.

Again, we calculated a mean light curve by fitting the data with only f_0 and 8 harmonics. The phase difference φ_{31} we obtain is 5.076 ± 0.01 and the metallicity therefore is -1.14 according to the formula of JK96. This result does not agree with the spectroscopic metallicity of UV Oct.

4.7.2 Comparison to "normal" RR Lyrae stars

The question at which Blazhko phase, if at any, a modulated RR Lyrae star behaves like a normal, non-Blazhko RRab star has first been adressed in detail by Jurcsik et al. (2002). They found that for Blazhko stars with large amplitude modulation no Blazhko phase corresponds to normal, unmodulated stars. They are always distorted. For their study, the authors used 3 different approaches: one was the one described in the previous section: the calculation of [Fe/H] from the light curve shape and comparison with spectroscopic measurements. The second was to investigate the behavior of Blazhko stars in the photometric amplitude (A_V) - radial velocity amplitude (A_{Vrad}) plane. Non-modulated RR Lyrae stars align along a straight line in this diagram. The third analysis involved the interrelations between the Fourier parameters which were published by Kovacs & Kanbur (1998). It is an analysis like this which is performed in this section.

The interrelations between the Fourier parameters were originally introduced by Jurcsik & Kovacs (1996) to characterize the light curve systematics. They were meant as a qualitative measure to test how well the star in question fits into the light curve systematics of a larger sample. Like the formula for the determination of metallicity, the interrelations were found on a purely empirical basis. To measure the relative accuracy of the derived parameters a deviation parameter D_P was introduced, defined as follows:

$$D_P = |P_{obs} - P_{calc}|/\sigma_P$$

where P_{obs} is the observed parameter, P_{calc} is the value of the parameter calculated with the help of the interrelations, and σ_P is the standard deviation which is provided by the authors for each formula. To find the overall compatibility, the parameter D_m was introduced, which is the maximum of the deviation parameters D_P:

$$D_m = max(D_P)$$

.

Jurcsik et al. (2002) regarded a light curve as normal or undistorted, when both the compatibility criterion is fulfilled *and* the metallicity calculated from the light curve is within an acceptable range from the spectroscopic value. Their selection criteria were $D_m < 2$ and $|\Delta[Fe/H]| < 0.15$ dex. They found that only 3 out of the 21 light curves investigated by them fulfilled these criteria, one of RR Lyrae during its minimum of the 4-year-cycle, and two of RS Boo which is an exceptional star because of its small modulation. They therefore concluded that Blazhko stars with a large modulation never show undistorted behavior.

Following their suit we calculated the Fourier parameters of SS For and UV Oct using the formulae of Kovacs & Kanbur (1998) which are listed here again in Table 4.10. Also the deviation parameters D_P and D_m were determined. The deviation of each parameter in each phase bin, together with the total deviation parameter of each phase bin are listed in Table 4.11.

interrelation	σ_F
$A_1 = 0.611 + 1.406A_2 - 0.099\varphi_{31}$	0.0211
$A_2 = -0.289 + 0.379A_1 + 0.580A_3 + 0.051\varphi_{31}$	0.0118
$\varphi_{21} = -0.296 + 0.991A_1 - 2.047A_3 + 0.507\varphi_{31}$	0.0615
$A_3 = 0.011 + 0.229A_2 + 0.886A_4$	0.0071
$\varphi_{31} = 3.708 + 0.347\varphi_{21} + 0.728\varphi_{41} - 0.137\varphi_{51}$	0.0576
$A_4 = -0.001 + 0.369A_3 + 0.689A_5$	0.0046
$\varphi_{41} = -4.019 + 0.837\varphi_{31} + 0.306\varphi_{51}$	0.0617
$A_5 = -0.002 + 0.381A_4 + 0.710A_6$	0.0027
$\varphi_{51} = 2.673 + 0.924\varphi_{41} + 0.278\varphi_{61}$	0.1221

Table 4.10: Interrelations by Kovacs & Kanbur (1998).

SS For									
Ψ	D_{A1}	D_{A2}	$D_{\varphi 21}$	D_{A3}	$D_{\varphi 31}$	D_{A4}	$D_{\varphi 41}$	D_{A5}	$D_{\varphi 51}$
0.05	3.02	0.84	1.16	1.36	0.01	0.42	0.29	1.61	0.24
0.15	2.24	0.60	1.22	1.14	0.28	0.80	0.15	0.13	0.17
0.25	0.93	0.35	1.77	0.96	1.24	0.94	1.91	0.04	0.88
0.35	0.93	0.19	1.46	1.76	0.10	1.54	0.60	2.42	1.41
0.45	0.38	0.61	2.24	0.86	1.40	0.18	0.06	2.04	0.66
0.55	2.28	2.62	0.27	1.62	0.45	0.46	0.79	3.62	0.44
0.65	1.66	2.82	0.32	1.01	3.28	1.61	3.70	3.85	1.49
0.75	0.75	0.03	0.86	2.17	1.02	2.35	1.45	1.04	1.82
0.85	2.31	1.12	0.37	1.47	0.58	2.31	0.67	0.67	0.26
0.95	2.73	1.61	0.72	0.70	1.40	1.63	1.53	0.05	0.14
UV Oct									
Ψ	D_{A1}	D_{A2}	$D_{\varphi 21}$	D_{A3}	$D_{\varphi 31}$	D_{A4}	$D_{\varphi 41}$	D_{A5}	$D_{\varphi 51}$
0.05	0.05	0.12	2.06	0.32	0.55	0.95	0.52	3.13	0.13
0.15	1.26	0.80	1.64	0.84	0.04	0.32	0.74	1.17	0.20
0.25	0.65	1.22	0.72	0.46	4.35	1.90	4.17	4.05	1.38
0.35	0.24	0.31	0.67	0.65	1.48	1.83	1.50	0.90	2.74
0.45	1.56	1.64	1.20	1.09	0.31	1.30	1.80	0.56	3.35
0.55	0.16	0.22	2.73	0.60	3.12	1.69	1.69	2.19	2.63
0.65	0.47	0.03	2.08	1.49	0.25	1.37	0.91	0.37	1.73
0.75	0.90	0.25	0.07	0.28	0.32	1.40	0.04	1.38	1.01
0.85	0.62	1.06	1.08	0.04	0.46	0.00	0.00	0.95	0.06
0.95	0.22	0.17	1.12	0.85	0.15	0.58	0.70	0.22	0.35

Table 4.11: Deviation parameters for each calculated Fourier parameter in each Blazhko phase.

SS For

Only in one out of 10 phases, D_m lies below 2 and therefore fulfills the criterion of Jurcsik et al. This happens at Blazhko phase $\Psi = 0.25$. At this phase, on the other hand, the metallicity reaches an extreme value of - 1.55 which is far from the spectroscopic value ($|\Delta[Fe/H]| = 0.46$). Inversely, during the Blazhko phase where the metallicity gets closest to the measured value, at the Blazhko phase $\Psi = 0.65$, the deviation parameter reaches its largest value of 3.85. Therefore, we conclude that there is no Blazhko phase in which SS For fulfills both criteria that would be necessary to regard its ligth curve as 'normal'. The resulting deviation parameters D_P are given in Table 4.11, and the calculated metallicities for each Blazhko phase bin Ψ, the difference from the spectroscopic value $\Delta[Fe/H] = |[Fe/H]_{obs} - [Fe/H]_{calc}|$ and the compatibility criterion D_m for each phase can be seen in Table 4.12.

SS For				UV Oct			
Ψ	[Fe/H]	$\|\Delta[Fe/H]\|$	D_m	Ψ	[Fe/H]	$\|\Delta[Fe/H]\|$	D_m
0.05	-1.28	0.19	3.02	0.05	-1.53	0.19	3.13
0.15	-1.47	0.38	2.24	0.15	-1.22	<u>0.12</u>	<u>1.64</u>
0.25	-1.55	0.46	<u>1.91</u>	0.25	-0.84	0.50	4.35
0.35	-1.53	0.44	2.42	0.35	-0.51	0.83	2.74
0.45	-0.91	0.18	2.24	0.45	-0.04	1.30	3.35
0.55	-1.17	<u>0.08</u>	3.62	0.55	-0.65	0.69	3.12
0.65	-1.08	<u>0.01</u>	3.85	0.65	-1.06	0.28	2.08
0.75	-0.81	0.28	2.35	0.75	-1.46	<u>0.12</u>	<u>1.40</u>
0.85	-0.98	<u>0.11</u>	2.31	0.85	-1.34	<u>0.00</u>	<u>1.08</u>
0.95	-1.06	<u>0.03</u>	2.73	0.95	-1.60	0.26	<u>1.12</u>

Table 4.12: Metallicities for each Blazhko phase bin, deviation from spectroscopic value and compatibility criterion for each Blazhko phase bin. The values fullfilling the criteria are underlined.

It has often been suspected that the mean light curve of Blazhko stars might follow the systematics of normal, non-Blazhko RR Lyrae stars. That the metallicity calculated from the mean light curve of SS For agrees with the spectroscopic value within the errors, has already been shown in the previous section. We now also test whether the Fourier parameter interrelations yield correct results for the mean light curve, i.e., whether the compatibility criterion $D_m < 2$ is fulfilled. The mean light curve was obtained by fitting the data with f_0 and 8 harmonics, without any modulation components. The results can be seen in Table 4.13. It gives the values of every calculated parameter and its deviation. The total compatibility D_m is only 1.57, i.e., the compatibility criterion is fulfilled. This seems to be another hint that the mean light curve of SS For might indeed be 'undistorted'.

UV Oct

For UV Oct, four phase bins were found to have a deviation parameter smaller than 2, compared to only one phase bin for SS For. The metallicity values obtained with the ligth curve - [Fe/H] relation of JK96 agree with the spectroscopic result during three different Blazhko phases when applying the criterion that $|\Delta[Fe/H]|$ has to be smaller than 0.15. Other than for SS For, the best results of $|\Delta[Fe/H]|$ can be found in the same phase bins as the best results for D_m. The Blazhko phases for which both criteria are fulfilled are $\Psi = 0.15$, 0.75 and 0.85. This means, that UV Oct shows an "undistorted" light curve during those Blazhko phases according to the definition of Jurcsik et al (2002).

SS For			UV Oct		
parameter	value	D_P	parameter	value	D_P
A1	0.412	0.975	A1	0.325	0.365
A2	0.197	0.237	A2	0.157	0.259
φ21	2.330	1.568	φ21	2.392	0.762
A3	0.122	1.043	A3	0.101	0.600
φ31	4.828	0.483	φ31	5.073	0.060
A4	0.080	1.448	A4	0.064	0.343
φ41	1.174	0.098	φ41	1.508	0.157
A5	0.050	0.723	A5	0.035	0.898
φ51	3.730	0.338	φ51	4.219	0.341
$D_m = 1.568$			$D_m = 0.898$		

Table 4.13: Fourier parameters of the mean light curve, calculated using the interrelation formulae and deviation D_P.

The mean light curve also yields very low deviation parameters, as can be seen in Table 4.13. The total deviation D_m is only 0.898. This is a sign of good agreement of the mean curve characteristics with those of a typical non-Blazhko RR Lyrae stars. On the other hand, however, one has to consider that the metallicity derived from the mean light curve of UV Oct did not agree with the spectroscopic value, as shown in the previous section. The mean light curve of UV Oct therefore cannot be considered undistorted.

Summary and Conclusions

In this thesis the properties of the Blazhko phenomenon have been discussed from an observational point of view, and new photometric results have been presented. Chapter 1 provided some basic information about RR Lyrae stars in general and explained some important terms and diagrams. In Chapter 2 the current knowledge about the photometric phenomenology of the Blazhko effect was summarized. The data obtained in the framework of the Blazhko project centered in Vienna were presented in Chapter 3 together with the data reduction methods and observational techniques which were used. The Analyses which were performed were described in Chapter 4.

High precision photomultiplier photometry was obtained for two southern Blazhko stars. A Fourier analysis was performed for both stars, and the pulsation as well as the Blazhko period could be determined with good accuracy. Also, various features of the light curve and its changes during the modulation cycle were studied in detail. Among these were the calculation of the Fourier parameters for different Blazhko phases and therefore the study of the change in the ligth curve shape. Also, the distinct variations close to minimum light, the so-called bump, were analysed in detail. Also, the stellar metallicity was calculated from the Fourier parameters, and a test was performed, to find out to which extent the ligth curve of the stars observed by us resemble those of non-modulated, "normal" RR Lyrae stars.

When comparing the two stars observed in the framework of this thesis, one can also see that the effect seems to manifest itself in different forms in different stars. The amplitude can show strong changes like in UV Oct or smaller changes like in SS For, the modulation period can be as long as 145 days like it is observed in UV Oct or shorter like the 35 days observed in SS For, just to name a few examples. Also, the test whether the mean light curve of a Blazhko star resembles that of an unmodulated star, yields different results for the two stars analysed in this thesis. On the other hand, there are phenomena which seem to be the same in most or all Blazhko stars. An example would be the decrease of amplitudes with the harmonic order, which is of exponential shape for the harmonics while it is roughly linear for the side lobe frequencies for both observed stars. It can be concluded that a lot can be learned about the Blazhko effect with the means of long-term, high-precision photometry covering both the pulsation and the modulation cycle.

Zusammenfassung und Schlussfolgerungen

Diese Arbeit behandelte das Phänomen des Blazhko Effektes bei RR Lyrae Sternen im Hinblick auf photometrische Beobachtungen. Das erste Kapitel gab einen Überblick über die allgemeinen Eigenschaften de Klasse der RR Lyrae Sterne und erklärte einige wesentliche Grundbegriffe und Definitionen. Im zweiten Kapitel wurde Phänomenologie des Blazhko Effektes besprochen wie sie in der Photometrie zu sehen ist. Der aktuelle Stand der Forschungen und Beobachtungen zu diesem Thema wurde zusammengefasst. Behandelte Aspekte waren unter anderem die Länge des Modulationszyklusses, die Stärke des Blazhko Effektes, seine Abhängigkeit von der Metallizität der betroffen Sterne und die Rate seines Auftretens in verschiedenen Sternsystemen. Im dritten Kaptel wurde die Daten präsentiert die im Rahmen dieser Diplomarbeit beobachtet wurden, und Beobachtungsmethoden sowie die Vorgehensweise bei der Datenreduktion wurden erklärt. Die Analysen wurden die mit den neuen Daten durchgeführt wurden, wurden im vierten Kapitel behandelt.

Zwei südliche Blazhko-Sterne, UV Oct und SS For, wurden im Rahmen dieser Diplomarbeit mehrere Wochen lang photometrisch beobachtet. Aufgrund der verwendeten Beobachtungstechniken und Datenreduktionsmethoden wiesen der Datensätze eine Streuung von nur wenigen Millimagnituden auf. Eine Fourieranalyse ermöglichte die präzise Bestimmung sowohl der Pulsations- als auch der Modulationsperiode. Auch die Eigenschaften der Lichtkurve sowie ihre Veränderungen im Lauf des Modulationszyklusses wurden untersucht. Weiters wurde die Metallizität der untersuchten Sterne aus den Parametern ihrer Lichtkurve berechnet, und auf diese Weise ein Test durchgefhrt, in welcher Blazhkophase die Sterne am ehesten einem "normalen", d.h. nicht modulierten, Stern gleichen.

Durch Vergleich der beiden untersuchten Sterne wird klar, wie unterschiedlich der Blazhko Effekt sich manifestieren kann. Die Modulationsperiode zum Beispiel kann wie bei UV Oct sehr lange sein (145 Tage) oder mit nur 35 Tagen bei SS For wesentlich kürzer. Auch die Amplitude kann sich wie bei UV Oct stark verändern oder weniger stark, wie es bei SS For beobachtet wird. Auch der Test, ob die mittlere Lichtkurve der Blazhko Sterne der eines nicht modulierten, gewöhnlichen, RR Lyrae Stern gleicht, lieferte unterschiedliche Ergebnisse für die beiden untersuchten Sterne. Andererseits gibt es Effekte die scheinbar bei allen Blazhko Sternen gleichermaßen auftreten, wie zum Beispiel die Abnahme der Fourieramlpituden mit der harmonischen Ordnung. Diese ist in beiden untersuchten Sternen exponentiell für die ganzzahligen Vielfachen (Harmonischen) der Grundfrequenz, während sie für die Modulationsfrequenzen etwa ein lineares Verhalten zeigt. Zusammenfassend kann gesagt werden, dass präzise photometrische Beobachtungen, sofern sie über längere Zeit durchgeführt werden und möglichst vollständig sowohl den Pulsations- als auch den Modulationszyklus abdecken, viele Möglichkeiten bieten, den Blazhko Effekt zu untersuchen.

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