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First detection of a frequency multiplet in the line-profile variations of RR Lyrae: towards an understanding of the Blazhko effect*

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Abstract. All present models for explaining the Blazhko effect are based on the presence of non-radial components. Up to now, however, these components have not been found explicitly in the observational studies, which were all based on photoelectric data. We provide the first detection of a frequency multiplet in the line-profile variations of RR Lyrae. Performing a period analysis on 669 high resolution line profiles obtained with the spectrograph ELODIE at OHP, we clearly detect a multiplet structure, with a separation equal to the Blazhko frequency, around the main frequency and its harmonics. Additional observations are needed to decide about the existence of a quintuplet. The presence of the harmonics of the main frequency in the line profiles indicates the importance of non-linear effects in the pulsation.

The complete understanding of the origin of the Blazhko effect still needs further theoretical modelling and better new observations. Our detection of the frequency multiplet in the line-profile variations is a first essential step towards a decisive confrontation between the theoretical models and the observations.

Key words: stars: oscillations – stars: variables: RR Lyr – stars: individual: RR Lyr

1. Introduction

It is well known that RR Lyrae stars play a very significant role in astrophysics not only because they are standard candles, but also because they are witnesses of the evolution of the universe at young age. At the same time, they are considered to be prototypes of pure radial pulsators. Numerous hydrodynamical studies dealing with their pulsation properties based on the assumption of radial pulsation (e.g. Stellingwerf 1975, Kovács & Buchler 1993, Bono & Stellingwerf 1994). Although rough agreement exists between these computations and the observations, there are further details (e.g. matching of the theoretical light curve to the observations) as well as major questions still to be solved. One of the latter is the mechanism of the amplitude modulation (the so-called *Blazhko effect* – see Szeidl 1988). Since some 20–30% of the RRab stars show such amplitude modulation, it is clear that we cannot claim to understand RR Lyrae pulsations without being able to explain the Blazhko effect.

The detection of non-radial components is of crucial importance to understand the pulsation of the Blazhko stars. Kovács (1994) considered various scenarios for the amplitude modulation within the framework of radial pulsations. He concluded that pure radial mode interactions are highly unlikely to cause amplitude modulation. The question was further discussed in the course of the analysis of RV UMa. Omitting for the time being the very hypothetical role of convection, we are left with three possible explanations of the Blazhko effect (Kovács 1995):

- *The oblique pulsator model*, which assumes that the Blazhko stars have a magnetic field which is oblique to the pulsation axis (a replica of the model proposed by Kurtz 1982 for the roAp stars – see also Cousens 1983 and Shibahashi & Takata, 1995).
- *Dynamical interaction* between the radial fundamental mode and a resonant non-radial mode. In the course of this non-linear interaction a periodic amplitude modulation may occur (e.g. Van Hoolst et al. 1998).
- *Steady resonant pulsation* in the radial fundamental mode together with a non-radial mode of low spherical degree with almost the same period. Contrary to the dynamical interaction, there is only a weak interaction between the two excited modes (almost resonant) and they keep constant amplitudes and phases. The amplitude modulation is caused by the rotation of the non-radial surface patterns, i.e. like for the oblique pulsator model, the amplitude is aspect dependent (e.g. Cox 1993 and Kovács 1995).

All these models are based on the presence of non-radial components. Up to now, however, these components have not

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been found observationally. We remark that all observational studies of Blazhko stars so far are based on photoelectric data. High resolution spectral line profiles, however, are a much better diagnostic to find and identify non-radial pulsation components in pulsating stars. In this respect, RR Lyrae is the only suitable object to detect non-radial components. It is by far the brightest Blazhko star and it has an amplitude difference of about 0.7 mag in the B filter during its Blazhko cycle (Szeidl 1988). Since the non-radial components are able to produce such a big amplitude difference, we expect them to be detectable in the line-profile variations if we have a high enough S/N ratio. Their detection and their identification (degree and azimuthal number) is of utmost importance to find a suitable theoretical explanation of the pulsational behavior of this large group of important variable stars.

In this paper, we provide the first detection of a frequency multiplet in the line-profile variations of RR Lyrae. The paper is organised as follows. In Sect. 2 we briefly describe the observations and the data reduction process. The description and application of methods used for the frequency analysis is presented in Sect. 3. The consequence of the detection of the presence of non-radial components in RR Lyrae is discussed in Sect. 4. Finally, some concluding remarks and our future plans are given in Sect. 5.

2. Observations and data reduction

2.1. Observations

The spectroscopic observations used in this study were obtained with the cross-dispersed spectrograph ELODIE attached to the 1.93-m telescope of the Observatoire de Haute-Provence (Baranne et al. 1996). The detector used is a thinned Tk 1024 CCD, with 1024 x 1024 elements of size 24 μm^2. The observations were obtained during sixteen nights (see Table 1), covering a timespan of 433 days. Six complete pulsation cycles, each observed during two or three consecutive nights, have been monitored. The instrument (Baranne et al. 1996) covers a 3000 Å spectral range from the near ultraviolet to the near infrared with a resolving power $R \simeq 42,000$, a signal-to-noise ratio S/N around 50 for an exposure time between 5–10 mn giving a time resolution around 1% of the pulsation period of 13 h 36 mn.

The pulsation phase has been calculated from the ephemeris given by Chadid & Gillet (1997):

$$\text{HJD(max. light)} = 2,446,654.368 + 0.566839\text{E}, \quad (1)$$

where the maximum of the light (zero phase) and the period are given by Dalmazio (1995) and Zakrzewski (1996) respectively. The Blazhko phase has been determined from the ephemeris given by Chadid & Gillet (1997):

$$\text{HJD(max. light ampl.)} = 2,449,631.312 + 40.8\text{E}. \quad (2)$$

The maximum observed light amplitude which defines the Blazhko zero phase and the Blazhko period were determined by Dalmazio (1995). We note that the closest match between

Table 1. Spectra used for the period analysis. The first column gives the date of the beginning of the night, the second the Julian date, the third gives the phase ψ in the Blazhko cycle, the fourth the number of spectra for each night.

Date	Julian date	Blazhko Phase ψ	Number of spectra
24/06/1996	2450259	15.39	26
25/06/1996	2450260	15.42	29
26/06/1996	2450261	15.44	24
31/07/1996	2450296	16.30	48
01/08/1996	2450297	16.32	51
09/08/1996	2450305	16.52	49
11/08/1996	2450307	16.57	33
05/08/1997	2450666	25.37	30
06/08/1997	2450667	25.39	54
07/08/1997	2450668	25.42	51
08/08/1997	2450669	25.44	43
09/08/1997	2450670	25.47	37
10/08/1997	2450671	25.49	29
29/08/1997	2450690	25.96	47
30/08/1997	2450691	25.98	61
31/08/1997	2450692	26.00	57

Blazhko stars and non-Blazhko stars occurs at the Blazhko phase which corresponds to the largest amplitude (see diagrams in Teays 1993). The Blazhko phases of our observed runs are listed in Table 1. As shown in this table, the obtained spectra do not give a good coverage of the Blazhko cycle.

The amplitude of the Blazhko effect itself varies over approximately a 4-year cycle (3.8 to 4.8 years, Detre & Szeidl 1972). The beginning of this very long cycle corresponds with a minimum of the Blazhko amplitude. The extrapolation of the amplitude maximum of the light curve over a long time interval can be hazardous, because at the beginning of each 4-year cycle a significant phase discontinuity ($0.1 \leq \Delta\psi \leq 0.5$) is observed in the 41-day cycle (Detre & Szeidl 1972). Nevertheless and except during the strongest amplitude 4-year cycle, this discontinuity $\Delta\psi$ remains constant during the whole following cycle. All the spectra we used were obtained during the same magnetic cycle, so we do not have to take into account the phase discontinuity at the beginning of a new 4-year cycle.

2.2. Data reduction

In this study, we have used the profile of the single ionized metallic absorption line Fe II λ 4923.921 Å. Because we need profiles with a signal-to-noise ratio preferably larger than 200, we have added up four successive profiles. The corresponding phase ϕ is the average phase of the four individual profile phases. The ELODIE optimal data reduction of the CCD images was done using the Munich Image Data Analysis System (MIDAS). We have treated the 669 spectra in the same way. A detailed description of the data reduction can be found in Chadid & Gillet (1996a,b, 1997).

2.3. Gaussian fit to the profiles

Using MIDAS we also approached the profiles with a gaussian curve

$$F(v) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(v-\mu)^2}{2\sigma^2}}, \quad (3)$$

with v the velocity corresponding to the wavelength λ in the profile. From the characteristics of the fit (σ and μ) we can easily determine the first three moments of the gaussian curve:

$$M_1 = \mu, \quad (4)$$

$$M_2 = \mu^2 + \sigma^2, \quad (5)$$

$$M_3 = \mu^3 + 3\mu\sigma^2. \quad (6)$$

The moments are one of the diagnostics used for the frequency analysis (see Sect. 3.1). Comparing the moments of the real profiles with the moments calculated for the gaussian fits, we conclude that in the search for periodicities they give the same results. Differences between the real and the gaussian moments occur only at certain phases in the pulsation cycle, when the profiles seriously deviate from the gaussian approximation (e.g. when line doubling occurs due to a shock wave). From now on we do not make use any longer of the gaussian moments.

We also performed a linear filtering procedure on the spectra. Period searches on the filtered spectra and their velocity moments gave identical results as the same analysis on the unfiltered spectra, so we have used the original, unfiltered spectra in our further analyses.

3. Frequency analysis

3.1. Description of the methods

In our frequency analysis we used two period finding techniques, performed on either the variations of the velocity moments of the absorption lines, or on the flux variations as a function of position in the line profile.

The first technique, which will further be referred to as the Moment Period Search (MPS, Telting et al. 1997), consists in searching for periodicity in the change of derived quantities, such as the equivalent width (zeroth order moment M_0 or EW), the apparent radial velocity (first order moment M_1/M_0), the squared line width (second order moment M_2/M_0) and the skewness of the profile (third order moment M_3/M_0). These normalized velocity moments M_n/M_0 (n=1,2,3,...) are obtained by a weighted summation over the normalized flux across the line profile, divided by the equivalent width M_0:

$$M_n/M_0 = \frac{\int (v - v_\gamma)^n (1 - F(v)) dv}{\int (1 - F(v)) dv}, \quad (7)$$

with v_γ the so-called γ-velocity, i.e. the average value of the heliocentric radial velocity of the star over the pulsation cycle, and $F(v)$ the radiation flux. To minimize the influence of the continuum noise in the determination of the moments, the integration is carried out over an as narrow as possible wavelength region.

There are different algorithms for finding frequencies in the observables of variable stars. We have used the CLEAN algorithm as introduced by Roberts et al. (1987) and the PDM method (Stellingwerf 1978). Both methods are based on different basic principles. In the PDM method the data are approached by a mean curve and we examine at which period the dispersion of the data around the mean curve is minimal. This method can be used for all kinds of periodic variations. The CLEAN algorithm is a Fourier technique in which we represent the data by a summation of harmonic components. As a consequence this technique is most useful for purely harmonic data, and deviations from harmonicity give rise to inaccuracies in the determination of the frequencies.

The second technique, referred to as the Intensity Period Search (IPS, Telting et al. 1997), searches for periodicity in the normalized flux of each wavelength bin across the absorption line, resulting in diagrams that give the amplitude and phase of the profile variations as a function of position in the line profile. For this method we used the CLEAN algorithm in two dimensions, since we do not only scan the interval in which we expect to find frequencies, but also the interval of wavelengths along the line profiles.

3.2. Results of the period analyses

We have done several analyses with each technique, MPS and IPS. The first new and important result is that we observe very clearly the presence of the Blazhko period (40.8 d), both with MPS, in the velocity moments, and with IPS, in the spectra. This period corresponds to a frequency f_B of 0.0245 c/d. We do not easily observe this frequency as an isolated frequency in the periodograms, but we find it back as the separation in a multiplet structure around the pulsation frequency f_P (1.7642 c/d) and its harmonics.

3.2.1. Variations in the moments: MPS method

Analyses of the **first moment** with PDM and CLEAN always reveal the pulsation frequency f_P as the principal frequency. The non-linear character of the pulsation in RR Lyrae is derived from the spectra, since we also find back very clearly the harmonics of f_P, surpassing the noise level until the seventh harmonic $8f_P$.

To determine the significance of the presence of the n^{th} harmonic we calculated a harmonic fit to the data according to the following model:

$$M_1/M_0 = C + \sum_{i=1,n} A_i \sin(2\pi i f_P + \psi_i), \quad (8)$$

in which C is a constant term, the A_i represent the coefficients of the terms varying with the multiples of f_P, and ψ_i is the phase corresponding with this variation. The results of these harmonic fits are given in Table 2. For each order n the constant term C and the amplitudes A_i of each order i (i=1,...,n) are given, together with their asymptotic standard error. The last column gives the percentage of the variation which is explained by the fit. The eigth harmonic ($9f_P$) has an amplitude that does

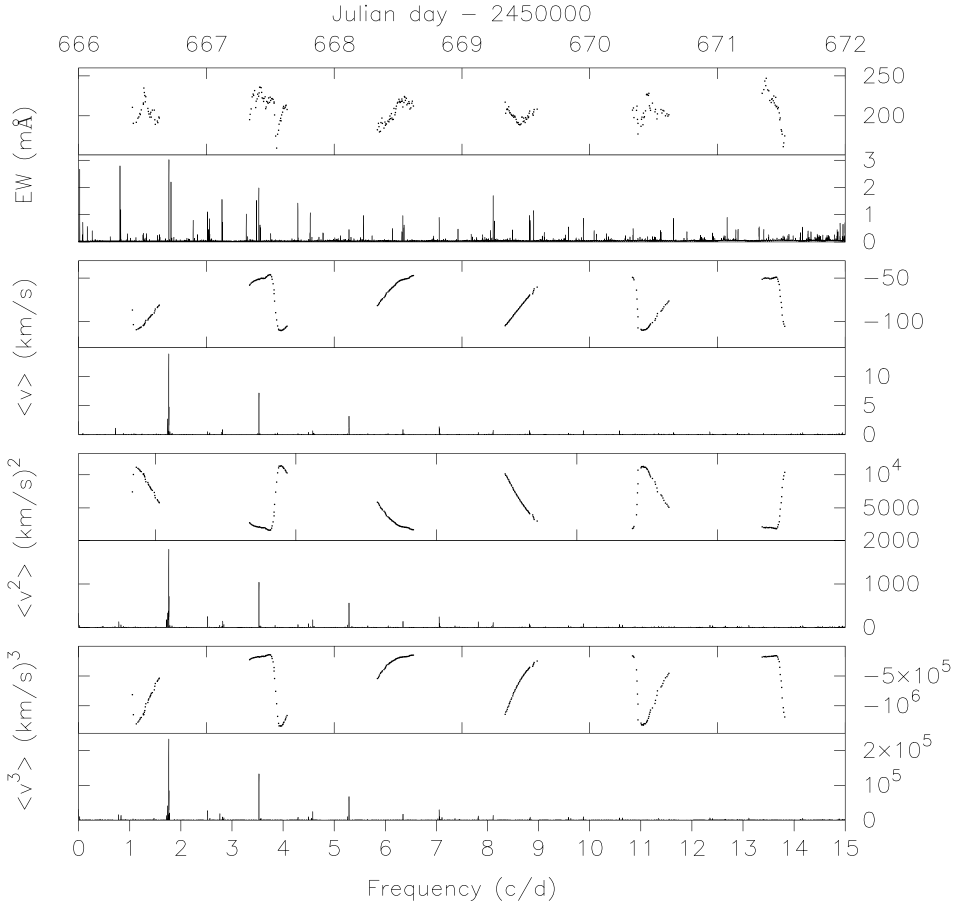

Fig. 1. Variations in EW and the velocity moments for all 669 spectra. In the upper part of each panel we show the variations of the velocity moments (respectively M_0, M_1/M_0, M_2/M_0 and M_3/M_0), for the 6 consecutive nights 5–10 August 1997, while the lower panel displays the corresponding CLEANed periodogram for the respective moments on all 669 data points. The CLEAN analyses were performed in the frequency range 0–15 c/d, with gain 0.3 and a number of iterations equal to 1000, and a step size of 0.0005 c/d. The upper part's abscissa is at the top of the figure and the lower part's abscissa is at the bottom

not significantly differ from zero any more. For that reason we consider the multiples of the main frequency f_P up to the seventh harmonic $8f_P$ to be significantly present in the data. The procedure followed here is similar to a Fourier decomposition on the light curves of RR Lyrae stars performed in many studies, e.g. Simon & Teays (1982), Simon & Clement (1993) and Jurcsik (1998).

Fig. 1 shows the periodogram of a CLEAN analysis on the velocity moments. The second panel shows the resulting periodogram for the first moment. We CLEANed in the interval 0–15 c/d, with a gain of 0.3, the number of iterations equal to 1000 and a step size of 0.0005 c/d. f_P and its harmonics up to $8f_P$ are indicated. The observation of high peaks in the periodogram at the harmonics of f_P illustrates very clearly the non-linear behavior of the pulsation in RR Lyrae. First of all, we observe (see Table 2) that the percentage explained increases considerably for each added harmonic up to the third. Secondly, we observe that in the periodograms of a frequency search in the domain 0–15 c/d, containing f_P and its first seven harmonics, the three highest peaks correspond to f_P, $2f_P$ and $3f_P$. After prewhitening with the latter three frequencies the frequency $f_P - f_B$ appears, the left sidepeak in the triplet structure (see Fig. 1). In other words, after prewhitening with f_P, its first and its second harmonic, the frequency explaining most of the variation is one related to the Blazhko frequency. This shows that the Blazhko effect is clearly present in the line-profile variations.

We have also done about 20 CLEANs in the frequency domain 0–5 c/d, with different values for the gain and number of iterations, and a step size equal to 0.0002 c/d. In our analyses we used different step sizes for numerical reasons. Altering the step size results in different powers, but the position of the frequencies stays the same (Roberts et al. 1987). A representative result is given in Fig. 2, the periodogram of a CLEAN analysis with gain 0.3 and 1000 iterations. Around the main frequency f_P we clearly notice the presence of other frequencies with a large amplitude. Fig. 3 is an enlargement of Fig. 2, between the frequencies 1.66 c/d and 1.86 c/d around f_P. Dashed lines indicate the expected positions of the quintuplet components. We observe two maxima around the main peak, very close to the expected positions of the triplet components $f_P - f_B$ and $f_P + f_B$. They are aliases of the exact triplet frequencies, resulting from the time spacing of the observations, in which a time gap of approximately 400 days occurs, introducing alias frequencies of 1/400 c/d. Using more data, with a more random time sampling, is the best way to discard these alias frequencies, and to observe the present frequencies at their right positions.

A representative result of the PDM analyses we performed on the velocity moments, is shown in Fig. 4, displaying the Θ-statistic for an analysis on the first moment in the frequency domain 0–5 c/d. The numbers of bins and covers respectively were taken 10 and 2, and the step size was equal to 0.0001 c/d. As expected, the deepest minimum is found at the main pulsation

Table 2. Harmonic fits up to the n^{th} order to the first moment M_1/M_0. The order n of the fit is given, followed by the constant term and amplitudes (both in km/s) of each of the periodic terms, as well as the fraction of the variance explained by the fit. Listed below are the amplitudes and the percentage of the variance (f_v) explained for a fit with f_P, its first two harmonics, and the two sidepeaks in the frequency triplet.

n	C	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	fv (%)
1	-71.3 ± 0.4	24.1 ± 0.5									76.0
2	-71.6 ± 0.3	23.5 ± 0.4	9.6 ± 0.4								88.3
3	-71.7 ± 0.2	23.4 ± 0.3	9.4 ± 0.3	5.6 ± 0.3							92.4
4	-71.6 ± 0.2	23.6 ± 0.3	9.3 ± 0.3	5.4 ± 0.3	3.7 ± 0.3						94.3
5	-71.5 ± 0.2	23.6 ± 0.2	9.3 ± 0.2	5.3 ± 0.2	3.7 ± 0.3	2.4 ± 0.2					95.1
6	-71.5 ± 0.2	23.6 ± 0.2	9.4 ± 0.2	5.3 ± 0.2	3.5 ± 0.2	2.4 ± 0.2	1.3 ± 0.2				95.3
7	-71.6 ± 0.2	23.6 ± 0.2	9.3 ± 0.2	5.3 ± 0.2	3.6 ± 0.2	2.4 ± 0.2	1.3 ± 0.2	1.0 ± 0.2			95.4
8	-71.6 ± 0.2	23.6 ± 0.2	9.3 ± 0.2	5.3 ± 0.2	3.6 ± 0.2	2.4 ± 0.2	1.3 ± 0.2	0.9 ± 0.2	0.6 ± 0.2		95.5
9	-71.6 ± 0.2	23.6 ± 0.2	9.3 ± 0.2	5.3 ± 0.2	3.6 ± 0.2	2.4 ± 0.2	1.3 ± 0.2	0.9 ± 0.2	0.6 ± 0.2	0.4 ± 0.2	95.5
	C	A_1	A_2	A_3	$A_{f_P-f_B}$	$A_{f_P+f_B}$					fv (%)
	-72.0 ± 0.2	21.5 ± 0.3	7.8 ± 0.3	4.0 ± 0.3	3.3 ± 0.3						94.2
	-72.0 ± 0.2	21.7 ± 0.3	7.8 ± 0.3	3.9 ± 0.3	2.9 ± 0.4	0.2 ± 0.4					94.3

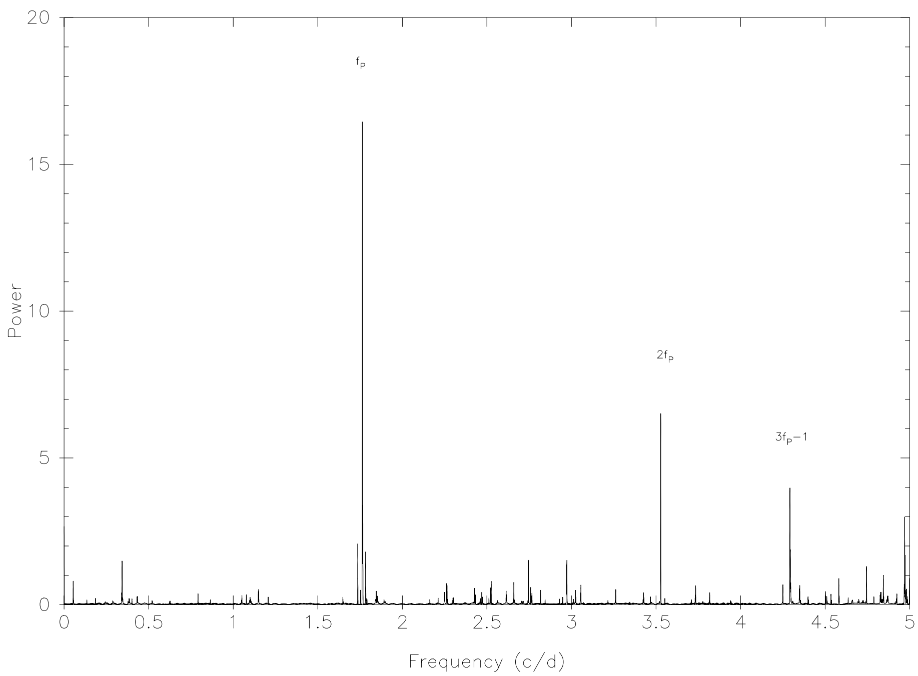

Fig. 2. CLEANed periodogram (from all 669 spectra) for the first velocity moment, with gain 0.3, 1000 iterations and a step size of 0.0002 c/d

frequency. Because no CLEANing with the window function is done, the resulting Θ-statistic suffers much more from aliasing effects than the corresponding CLEAN periodogram. For this reason the multiplet components are hidden among a multitude of 1/400 c/d alias frequencies, but we did find them at local minima in the Θ-statistic. The occurrence of the one day aliases of the main frequency and its harmonics is another consequence of omitting the CLEANing. Another typical feature of the PDM analysis is the appearance of the so-called "subharmonics", i.e. natural fractions of the frequencies present. This explains the peaks at $f_P/2$ and $(2f_P+1)/2$. Because of these effects (aliasing and appearance of subharmonics) the PDM analysis gives an unclear view upon the possible multiplet structure, compared to the CLEAN analyses.

In all our CLEAN analyses we have found frequencies in the close vicinity of or at the exact triplet component values. We always observe the left sidepeak $f_P - f_B$ to have a higher amplitude than $f_P + f_B$. In all the periodograms we also find these patterns recurring around the first harmonic of the radial pulsation, with the same frequency spacing as around the main frequency (see Fig. 2). Also the higher order harmonics of f_P appear to show this triplet structure, but in a less obvious way since their amplitudes are smaller.

Table 1 also lists the amplitudes for a fit with f_P and its first 2 harmonics and the two sidepeaks $f_P - f_B$ and $f_P + f_B$ to the first moment M_1/M_0. We observe that the frequency corresponding to the right sidepeak does not significantly contribute to the fit.

We also performed period analyses on the equivalent width, the second and the third moments of the line profiles. The results are shown in respectively the first, third and fourth panel of Fig. 1. A CLEAN analysis on the **equivalent width** (zeroth order moment M_0) of the 669 profiles does not only show the

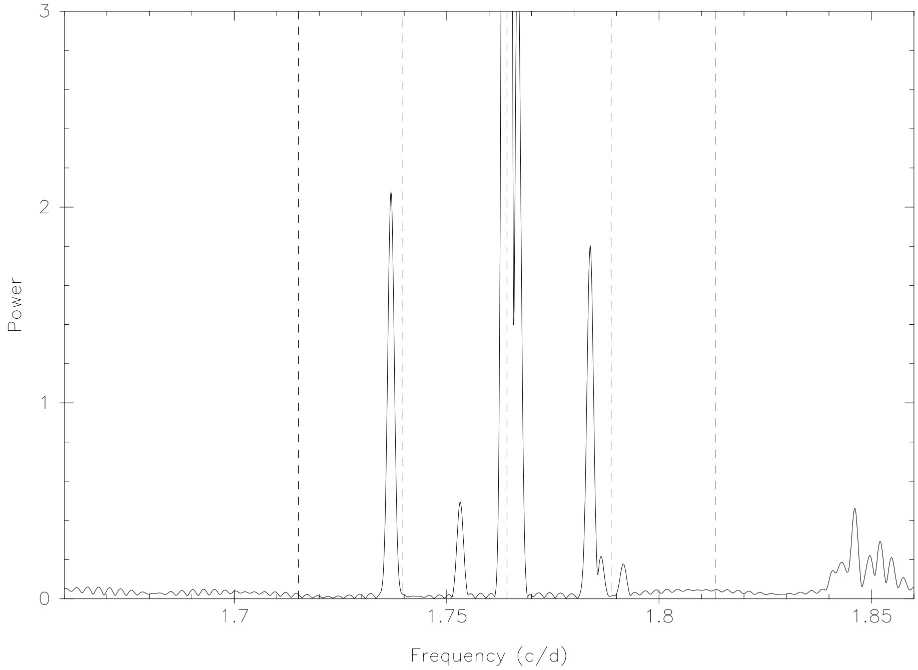

Fig. 3. Enlargement of Fig. 2, between the frequencies 1.66 c/d and 1.86 c/d around f_P. Dashed vertical lines indicate the expected positions of the quintuplet frequencies. The shift of the observed frequencies is caused by aliasing effects

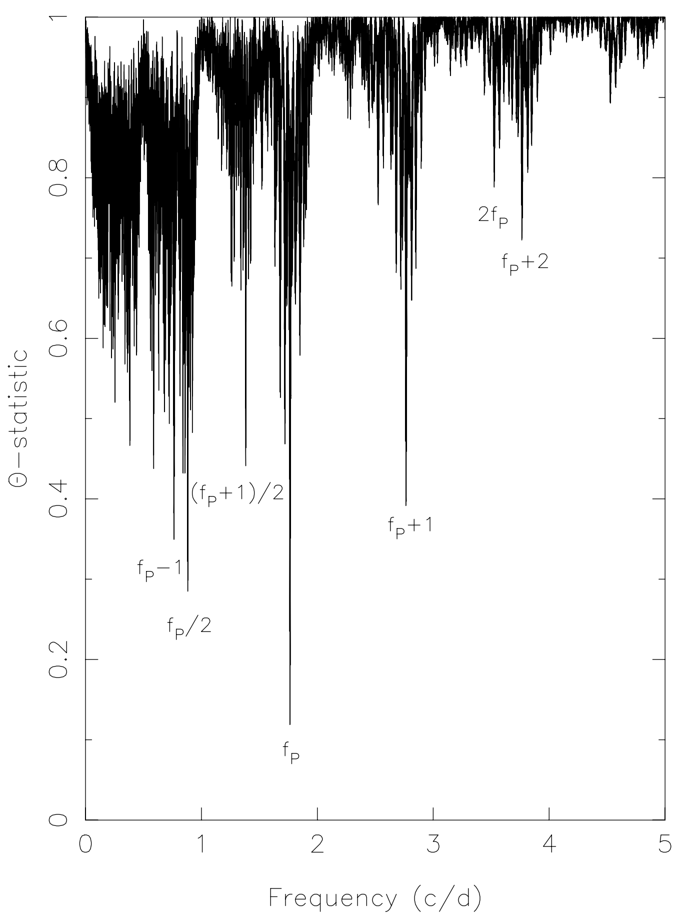

Fig. 4. Resulting Θ-statistic from a PDM analysis on the first moment in the frequency domain 0–5 c/d, with 10 bins, 2 covers and a step size equal to 0.0001 c/d. The radial pulsation causes the most prominent periodicity. Other local minima are labelled on the graph

main frequency, but also yields evidence for the occurrence of the Blazhko frequency itself in the periodogram. We observe a high peak at 0.022 c/d, which is the 1/400 c/d alias of the Blazhko frequency f_B=0.0245 c/d. This aliasing effect, as mentioned above, is caused by the time spacing of the data. Performing a CLEAN analysis with the same parameters on a somewhat smaller dataset, after removing the data showing this 400 days time gap, gives a better approximation for the Blazhko frequency (0.0242 c/d), which remains one of the highest peaks in the periodogram. This implies that the Blazhko frequency is not only present in a multiplet structure, but also appears explicitly in the equivalent width, though it is not obvious in the periodograms of the first three order moments.

A more complete coverage of the whole of the Blazhko cycle will lead to disappearance of the alias frequencies and thus to a better determination of the real ones. Since the zeroth order moment curve is rather noisy for the whole dataset, it is difficult to distinguish relevant frequencies. We did not observe obvious traces of the harmonics of f_P and the triplet structure in the equivalent width.

For the **second and third order moment** we CLEANed in the interval 0–15 c/d, with the same parameters, to allow a comparison with the results presented in the first panel of Fig. 1. These moments also reveal f_P and its harmonics. In both cases the peaks corresponding to the frequencies $2f_P$, $3f_P$ and $4f_P$ are relatively higher, whereas from the sixth harmonic on the frequencies have a lower relative amplitude and tend more towards the noise level.

The Blazhko frequency itself, f_B = 0.0245 c/d, is not found in the period analysis on the first three order moments, contrary to the result for the periodogram of the equivalent width. It is only observable as the separation between the frequencies found around f_P and its harmonics. The occurrence of f_B in a multiplet structure implies that the long-term modulation is caused by a mechanism interacting with the principal frequency (either a magnetic field, or another non-radial pulsation mode).

In varying the parameters of the frequency search codes (the gain and the number of iterations for CLEAN, the number of bins and covers for PDM), we also find some indication for the presence of the frequencies $f_P - 2f_B$ and/or $f_P + 2f_B$ in the data, in about 50% of the cases. Either these frequencies themselves or (more often) their 1-day or 400-day aliases appear above the noise level in the periodograms, i.e. among the peaks surpassing the 3σ noise level. Table 3 lists the results for a CLEAN analysis on the first moment.

This could indicate that they are present, but they are not so obvious as the triplet frequencies. The *triplet* ($f_P - f_B, f_P, f_P + f_B$) or *quintuplet* ($f_P - 2f_B, f_P - f_B, f_P, f_P + f_B, f_P + 2f_B$) structure around the principal frequency and its harmonics is predicted in certain models to explain the Blazhko effect, like the magnetic model by Shibahashi & Takata (1995). Since the distortions of the fundamental radial mode are caused by a dipole magnetic field, the expectation is to see a quintuplet structure for this model. In some (restricted) geometrical configurations we would only see a triplet structure. The amplitude of the quintuplet components $f_P - 2f_B$ and $f_P + 2f_B$ is expected to be smaller than that of the triplet components $f_P - f_B$ and $f_P + f_B$. It is therefore possible that in our data the outer components will be difficult to distinguish from the noise. In the two-dimensional analysis we find comparable evidence for the quintuplet components (see next subsection).

More observations are needed to give a more definitive answer to the question if a quintuplet appears, and, for reasons mentioned above, more data will help us to discard the 400-day aliases which, though they are easily recognized, now still can obfuscate our view on the exact frequencies.

3.2.2. Variation in the normalized flux as a function of position in the line profiles: IPS method

The CLEAN analysis in two dimensions gives more clear results than the MPS. For the same parameters (gain and number of iterations) we have carried out the IPS. A representative result is given in Fig. 5a, showing the periodogram of the frequencies. The curve below the two-dimensional periodogram (Fig. 5c) shows the mean of all the used spectra, and reveals at which wavelengths the line profiles show variation, thus where it is relevant to look for periodicities.

We summed the detected power of the periodograms of the variations across the lines to a one-dimensional periodogram (see Fig. 5b). Comparing this summed periodogram with the periodograms of the velocity moments (MPS, Fig. 2), we observe less peaks in the frequency spectrum. The wavelength range over which the separate periodograms are summed, is kept as small as possible to prevent the noise level from building up (see Fig. 5c). The pattern of frequencies at which variations are seen occurs around the main pulsation frequency, and also around its harmonics. Here we show the pattern as detected around f_P an $2f_P$. Fig. 6a is again an enlargement of Fig. 5a, between the frequencies 1.66 c/d and 1.86 c/d around the main frequency f_P. The corresponding summed periodogram is given in Fig. 6b. Comparing the summed periodogram in Fig. 6b with the one in Fig. 4, we see that the peak at $f_P + f_B$ was more present in the one-dimensional analysis. The relative amplitude of the sidepeaks of the triplet is very different for MPS and IPS. Though in both cases $f_P - f_B$ is most pronounced, the right sidepeak is relatively much lower in the two-dimensional analysis. Another striking feature is that for both components of the triplet the power is observed in the blue part of the profile, and much less pronounced towards longer wavelengths. We have no explanation for this observation.

Table 3. Observed frequencies (in c/d) of spectral line variations in RR Lyrae, and their observed powers resulting from a CLEAN analysis on the first moment in the frequency domain 0–5 c/d, with gain 0.3, 1000 iterations and a step size of 0.0002 c/d. The observed frequencies and powers listed in italics do not appear above the noise level in the periodogram.

	Frequency	Observed	Power
$f_P - 2f_B$	1.7151	*1.7146*	*0.03*
$f_P - f_B$	1.7397	1.7370	2.1
f_P	1.7642	1.7642	16.4
$f_P + f_B$	1.7887	1.7838	1.8
$f_P + 2f_B$	1.8132	*1.8134*	*0.05*
$2f_P - 2f_B$	3.4793	*3.4782*	*0.06*
$2f_P - f_B$	3.5038	*3.5074*	*0.04*
$2f_P$	3.5283	3.5284	6.5
$2f_P + f_B$	3.5528	*3.5530*	*0.21*
$2f_P + 2f_B$	3.5774	*3.5746*	*0.04*

There is yet no evidence for the appearance of a quintuplet structure, but we cannot exclude its existence on the sole basis of our spectra either. The frequencies $f_P - 2f_B$ and $f_P + 2f_B$ appeared in some of the one- and two-dimensional analyses, and since it is very likely that those frequencies have smaller amplitudes than the triplet components, they might not surpass the noise level in the periodograms of most of our frequency analyses. A better coverage of the Blazhko cycle is needed to draw more definitive conclusions about the occurrence of the quintuplet frequencies.

We also searched for the presence of the Blazhko frequency itself, f_B=0.0245 c/d, in the spectra through the IPS. A CLEAN search in the interval 0–0.3 c/d yields a small peak at 0.0254 c/d, but higher peaks in the vicinity of this frequency make it impossible to take this as a proof for the presence of f_B itself. The most reliable argument for the occurrence of the Blazhko frequency was found by MPS on the zeroth order moment (see Sect. 3.2.1). Again, we expect a more complete coverage of the Blazhko cycle to give better evidence.

4. Discussion and future work

The results obtained in these frequency analyses are the first detailed confirmation of amplitude modulation in spectroscopic data of RR Lyrae. This constitutes a fruitful starting point for a

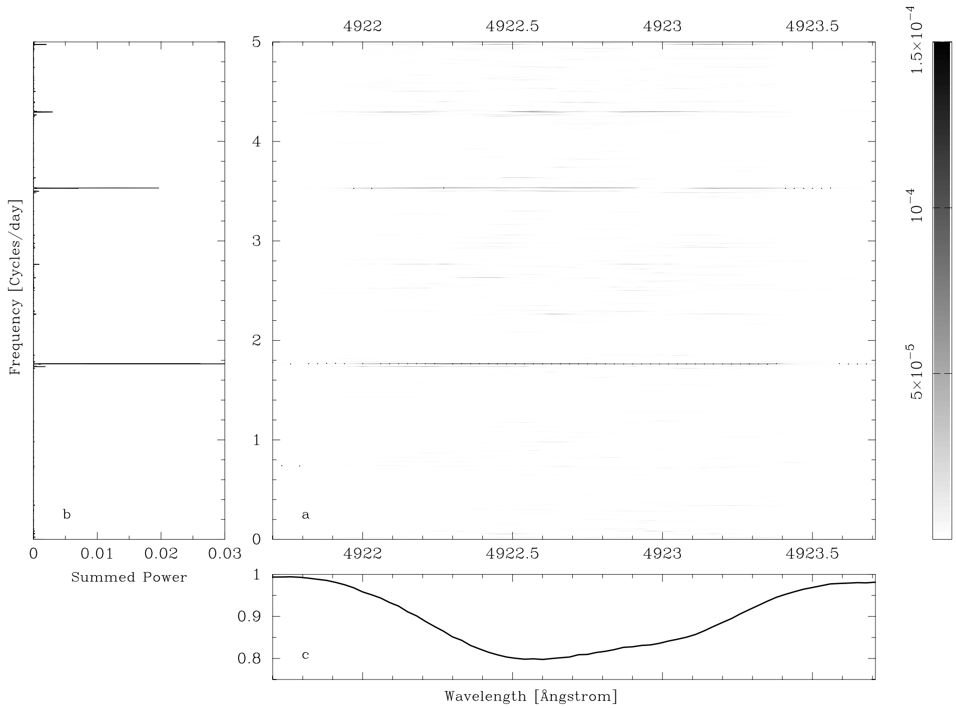

Fig. 5a–c. Fourier periodogram of the flux variations in the Fe II λ 4923.921 Å line, for a CLEAN with gain 0.3, 1000 iterations and a step size of 0.0002. The power as a function of frequency is plotted for each wavelength as a grey-value (panel **a**). The variational power summed over the wavelength range results in a one-dimensional periodogram (panel **b**). Panel **c** displays the mean of the used spectra

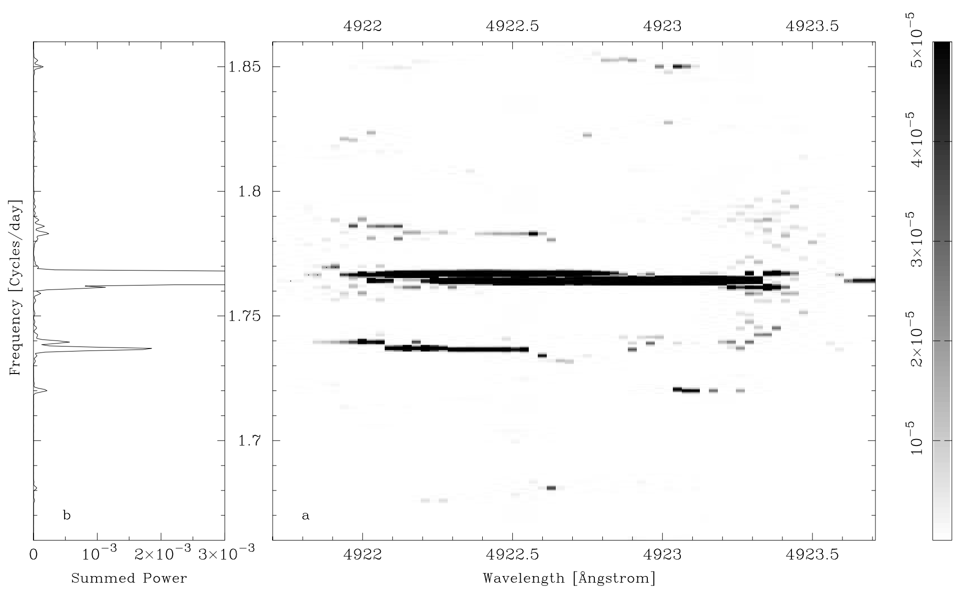

Fig. 6a and b. Enlargement of Fig. 5a and Fig. 5b, between the frequencies 1.66 c/d and 1.86 c/d

further development of the theoretical models about the understanding of the physical origin of the Blazhko effet.

The presence of the magnetic field and the detection of the frequency splitting around the main frequency f_P and its harmonics points towards the magnetic model, which predicts a multiplet structure with a separation equal to the rotation frequency of the star. This hypothesis has been very successful in explaining the frequency spectrum of roAp stars (Kurtz 1982). Almost simultaneously with Kurtz's observational result, a theoretical study of the effect of a weak, constant, axisymmetric magnetic field on linear, adiabatic oscillations of a star was proposed by Biront et al. (1982). Cousens (1983) was the first one to apply the "oblique pulsator model" to RR Lyrae stars while a more recent effort was done by Shibahashi & Takata (1995) who compared their theoretical results to photometric data.

All versions of the oblique pulsator model in use so far are developed in the linear pulsation approach. The effects of the magnetic field and of the rotation are treated as small perturbations, and the effect of the centrifugal force is neglected. This results both in an eigenfrequency shift and in the deformation of the eigenfunction of the radial fundamental mode. The interpretation of the Blazhko effect is as follows: the radial eigenfunction excited by the κ-mechanism is deformed, mainly by the Lorentz force, to have additional non-radial components whose symmetry axis coincides with the magnetic axis. The latter is assumed to be inclined ("oblique") to the rotation axis of the star. As the star rotates, the aspect angle of the non-radial components varies and then these components manifest themselves as the long term modulation of the luminosity variation of RR Lyrae stars. Essential in this model is the dependence of the Blazhko amplitude upon the magnetic field strength. A magnetic field of order one kilogauss is needed for this model. Babcock (1958) detected a variable magnetic field in RR Lyrae with an intensity up to 1.5 kilogauss. Romanov et al. (1987, 1994) confirm this value and found that it presents a periodic variation over the pulsation cycle (13.6 hours) while its average intensity shows a periodic long-term variation corresponding to the Blazhko frequency of 40.8 days. Up to now, these observations have never been confirmed and, due to the importance of these two periodic variations, new observational efforts to confirm them are highly desired, as also emphasized by Teays (1993).

The unambiguous presence of the harmonics of f_P in our data points out the importance of a non-linear treatment of any model proposed as an explanation for the Blazhko effect. In Sect. 3.2 we described two good reasons to perform a non-linear analysis up to the third order: first, the considerable increase of the percentage explained when adding $2f_P$ and $3f_P$ in a harmonic fit to the data, and second the fact that the Blazhko-spaced sidepeak appears in the periodograms as the most important frequency right after f_P and its two first harmonics. These two arguments make us conclude that a generalisation of the present models up to terms in the third order of the displacement, is necessary and will undoubtedly give a much better idea of the validity of those models.

As a next step, we will start to tackle the problem of a detailed modelling of the observed spectra in terms of theoretical models. This continuation of our research requires, on the one hand, a refinement of the magnetic model for RR Lyrae, taking into account the stellar parameters of this star, and non-linear terms up to the third order in the expression for the velocity. On the other hand, the resonance model (Van Hoolst et al. 1998) needs to be further explored. Van Hoolst et al. (1998) found that, at the pulsation amplitudes typical for RR Lyrae stars, the instability of a radial pulsation and the concomitant resonant excitation of some non-radial oscillation modes is very likely. We will investigate whether non-linear resonance can also produce a frequency spectrum like the one we observed in our RR Lyrae profiles.

Furthermore, several elements characterising the observed frequency spectrum, like the phase and the amplitudes of the frequencies, will be used to investigate whether the observed values can be explained within the framework of the different "rival" hypotheses, and to find out which further assumptions in these models are necessary to induce them. If we confirm for instance that the amplitudes of the sidepeaks in the triplet structure are not equal, $f_P - f_B$ always being more prominent than $f_P + f_B$, this inequality can be useful in the identification of certain parameters in the different hypotheses, and also impose restrictions to the models. A non-linear generalisation of the moment method (Aerts et al. 1992) can lead to an identification of the detected non-radial modes.

5. Conclusions

The frequency analyses described in Sect. 3 led us to some important conclusions. The first and by far the most important one is the detection of a multiplet structure in the line-profile variations of RR Lyrae, with a separation equal to the Blazhko frequency around the pulsation frequency and its harmonics. The Blazhko period was already found by Preston et al. (1965) in radial velocity data based on low-resolution spectra. Since all currently accepted models to explain the amplitude modulation involve non-radial pulsation modes, our results are a strong evidence for the presence of non-radial components in RR Lyrae, of which the precise identification is the following step in our work. Furthermore the importance of the harmonics of the main frequency in the periodograms gives a clear view about the non-linearity of RR Lyrae's pulsational behavior.

As already discussed by Kovács (1995), three plausible models, all based on the presence of non-radial components, are presently proposed as an explanation for the Blazhko effect. The oblique magnetic pulsator model for a non-linear radial pulsation mode is compatible with the detected magnetic field as well as the appearance of the frequency splitting around the harmonics of the main frequency. Nevertheless, the observed but not yet confirmed periodic variations of the magnetic field over the pulsation period and those of its average intensity over the Blazhko cycle requires urgent new observations because they would represent strong new observational constraints to models. The magnetic model predicts a quintuplet frequency structure, while at present our data only allow the unambiguous detection of a triplet. The two other models do not require the existence of a magnetic field and as such cannot be confronted with the findings of Romanov et al. (1987, 1994). A dedicated observational effort must be done to re-measure the magnetic field of RR Lyrae.

Our results are in some respect comparable to those obtained by Telting et al. (1997), in their study of the optical line variability of β Cephei. They also observe frequency spacings which they interpret as (multiples of) the rotation frequency of the star.

New spectroscopic high resolution observations with a time basis of at least 6 weeks are necessary to increase our understanding of the frequency spectrum, especially to confirm the presence of a quintuplet. Another reason is that we need to obtain a good value of the intensity of the different frequency peaks and to detect the maximum of harmonics of the main frequency because in each of the proposed models interactions with the radial fundamental mode give rise to the occurrence of selected other frequencies.

Through this exchange between observations, obtained results and theoretical investigations, we hope to be able to select the most probable of the three models (Kovács 1995), and to develop it in further theoretical detail, with the aim of uncovering the physical mechanism behind the amplitude modulation of the Blazhko RR Lyrae stars.

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