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Irregularities in atmospheric pulsations of RR Lyrae stars*

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Abstract. From high spectral resolution observations of the Fe II line at 4923.921Å, it is shown that the star RR Lyrae shows significant differences, both in radial velocity and in line FWHM, from one pulsation cycle to the next. Two explanations are discussed. The first one is the multiperiodic character of the pulsation (Blazhko effect) which was recently detected (Chadid et al. 1999). In this case, the investigated variations would not be irregular but multiperiodic. Nevertheless, the intensity of the multiplet components seem too weak to fully reproduce the amplitude of the observed "irregularities". The second mechanism is a dynamical interaction between the highest atmospheric layers and the deepest ones, which are traversed by strong outward shock waves. Nevertheless, because it is known that the shock wave intensities are modulated by the Blazhko effect, it is not excluded that the multiperiodic behavior of the pulsation can be in part at the origin of the observed variations. New observations are required to determine the exact intensity value of all components. A comparison with a non-Blazhko star would be helpful.

Key words: hydrodynamics – line: profiles – shock waves – stars: variables: RR Lyr – stars: individual: RR Lyr

1. Introduction

In order to provide a detailed analysis of the RR Lyrae instability strip topology, nonlinear pulsating models have been extensively studied (Bono & Stellingwerf 1994). The effect of convection in photospheric regions has also been well studied (Bono & Marconi 1998; Feuchtinger & Dorfi 1998). Nevertheless, all these studies have not considered the detailed structure of the atmosphere, because the number of mass layers above the photosphere was not large enough to calculate line absorption profiles. Consequently, it was not possible to explain high-quality spectra of RR Lyrae that have been obtained with modern CCD-spectrographs such as the ELODIE spectrograph at the Haute-Provence Observatory.

Recently, Fokin & Gillet (1997), using non-linear non-adiabatic pulsating models have explained the line doubling phenomenon observed during very short intervals within some metallic absorption profiles (Chadid & Gillet 1996a). About 40-50 atmospheric mass layers above the photosphere were necessary for modeling the observed profiles. Although, in Lagrangian codes, the spatial resolution of the hydrogen ionization zone is usually too low to compute correctly the rapid variation of the gas parameters, the numerical results explain in a semi-quantitative manner the doubling phenomenon. In addition to this observational test, atmospheric models give a detailed description of the whole atmospheric structure, especially the number and the type of strong shock waves propagating throughout the mass layers. The highest atmospheric regions considered by these models have a relatively low density ($\log \rho = -13$ or $-15\,\mathrm{g/cm^3}$ depending upon the pulsation phase). This means that hydrogen profiles such as Hα can be calculated (Fokin 1992).

Up until now, atmospheric pulsation models of RR Lyrae stars assume that the motion of layers, where metallic and hydrogen lines are formed, are strictly periodic. Although, the luminosity period of bright RR Lyrae stars is known to be constant to within a few seconds over 10 or 20 years, an appreciable fraction of RR Lyrae stars (around 30%) show noticeable variations in the shape of their luminosity and radial velocity curves over a period of about 100 pulsation cycles (This is the Blazhko effect). Consequently, a long term variation in the motion of the atmospheric layers should be expected. This is consistent with the variation of the intensity of the hydrogen line emission over the Blazhko period of RR Lyrae (Chadid & Gillet 1997) because it is directly related to the strength of shock waves.

Does the shock wave strength depend only on the Blazhko phase, or is a variation between two successive pulsation cycles possible? We know from previous studies (Hill 1972; Fokin 1992) that a secondary shock, called *the early shock*, is due to a "collision" between the free-falling outer atmospheric layers and the slower, upwardly moving photospheric layers. This shock has been detected observationally by the presence of a weak hydrogen emission (Gillet & Crowe 1988, Gillet et al. 1989) and by a broadening of the FWHM of metallic lines (Chadid & Gillet 1996b). This indicates that strong perturbations of the pulsation motion are present in the atmosphere and we can expect that dynamical effects, induced by the early shock, are

* Based on observations obtained at the Observatoire de Haute-Provence (France)

not necessary completely relaxed when a new pulsation cycle starts again.

Using high-quality spectral observations, the goal of this paper is to investigate if the pulsation motion in the atmosphere of the brightest RR Lyrae star in the sky, RR Lyrae, is periodic or shows some irregularities. In Sect. 2 we describe the observations of the Fe II (4923.921Å) line profile. The presentation and the discussion of the radial velocity curves are given in Sect. 3 and those concerning the FWHM of the Fe II line in Sect. 4. Finally, a short discussion and some concluding remarks are given in Sects. 5 and 6 respectively.

2. Observations and data reduction

2.1. Observations

The spectroscopic observations were obtained with the ELODIE spectrograph at the 1.93-m telescope at the Observatoire de Haute-Provence (Baranne et al. 1996). This instrument covers a spectral range of about 3000 Å from 3906 Å to 6811 Å and has a resolving power $R \simeq 42,000$. For RR Lyrae, an exposure of 5 to 10 mn, which corresponds to 1% of the pulsation period (13 h 36 mn), results in a signal-to-noise ratio around 50. Therefore, this spectrograph is ideally suited for studying the effect of the pulsation on line profiles, especially for determining the turbulence level in the atmosphere. The spectra, used in this paper, have been recorded during several runs that each lasted two to three consecutive nights. These nights and the corresponding Blazhko phase are listed in Table 1. These Blazhko phases correspond to the mean value over the period of each run.

The pulsation and Blazhko phases have been calculated from the ephemeris given by Chadid & Gillet (1997). The Blazhko phase $\psi = 24.98$ corresponds to the end of the 4-year cycle around September 1994, while the four others Blazhko phases $\psi = 25.40$, $\psi = 15.42$, $\psi = 25.47$ and $\psi = 16.55$ refer to the same and following 4-year cycle.

2.2. Data reduction

In this paper, we have used the profile of a singly ionized metallic absorption line Fe II 4923.921 Å and the correlation profiles of Chadid & Gillet (1996a). The data reduction of the CCD images was done using the Munich Image Data Analysis System (MIDAS). In this study, all the spectra were treated in the same way. A detailed description of the observations and data reduction can be found in Chadid & Gillet (1996a).

Throughout this paper, the pulsation phase is φ, the Blazhko phase is ψ and the average radial velocity over one pulsation period is γ.

2.3. Error estimation

During individual runs, the mechanical, thermal and optical characteristics of the spectrograph did not change. At the beginning of each night, the positioning of the echelle orders on the CCD was calibrated. Consequently, the "zero point" of the spectrograph is never larger than 5 m/s (Naef 1999 private communication). The wavelength calibration was done with a thorium lamp. A thorium arc was taken at the beginning and at the end of each night, except June 24 and 25, 1996 where a thorium arc was also done during the middle of the night. The room that contains the spectrograph is thermally controlled, so wavelength drifts due to temperature variations are very small.

Table 1. The Blazhko phase ψ and their corresponding observing nights.

Blazhko phase ψ	nights
24.98	August 3rd, 4th and 5th 1994
15.42	June 24th, 25th and 26th 1996
16.55	August 9th and 11th 1996
25.40	August 5th, 6th and 7th 1997
25.47	August 8th, 9th and 10th 1997

The main influence on the wavelength stability of the spectrograph is a change in atmospheric pressure, which changes the air refractive index and shifts the zero point of the calibration (100 m/s per mm/Hg). All of the observations were performed in stable conditions, so the wavelength shift during the night was typically around 0.1 pixel, i.e. 50 m/s. There is also a small mechanical flexure of the dewar which moves the echelle orders.

Our main source of error was due to the fact that we determined the radial velocity with only one absorption line (Fe II 4923.921 Å), which was observed with a relatively small signal-to-noise ratio in order to have good temporal resolution. Depending on weather conditions, this ratio is between 40 and 60. A good idea the accuracy is given by the dispersion of the radial velocity between phases 0.2 and 0.5. During this interval the infalling motion of the atmosphere occurs. Consequently, we expect an almost linear variation of the radial velocity and the dispersion of velocities around this straight line gives a good estimate of the accuracy. Depending on the night, it was between 117 and 299 m/s (standard deviation), so the true error is somewhere between these two numbers.

In this paper we compare radial velocity curves over an interval of three years. Observations of standard stars since ELODIE was put into operation at the end of 1993, show that, in normal observational conditions, the fluctuation of the spectrograph "zero point" is between 5 and 10 m/s (Naef 1999 private communication).

3. The radial velocity curve

Figs. 1-5 show the heliocentric radial velocity curves of RR Lyrae during the five Blazhko phases: $\psi = 24.98$, $\psi = 25.40$, $\psi = 15.42$, $\psi = 25.47$ and $\psi = 16.55$. The velocities are determined by fitting a Gaussian to the whole Fe II 4923.921 Å line without taking into account line doubling that occurs just before maximum luminosity (Chadid & Gillet 1996a). As discussed in Sect. 2.3, the accuracy of the measurements is around a few hundred m/s. A good idea of the accuracy is given by the dispersion of points within the phase interval 0.2-0.5. It is quite good for August 3-5, 1994 (Fig. 1) and relatively poor for July 24-26, 1996 (Fig. 3) and August 5-7, 1997 (Fig. 2).

Table 2. Main dynamic parameters at the five Blazhko phases. The first column gives the Blazhko phase ψ, the second the average radial velocity over one pulsation period γ, the third the primary acceleration, the fourth the secondary acceleration and the fifth the radius variation.

Blazhko phase ψ	γ-velocity (km.s^{-1})	primary acc. (cm.s^{-2})	secondary acc. (cm.s^{-2})	$\Delta R/R_{\odot}$
24.98	−71.54	2227	−20	0.87
25.40	−72.42	3484	−60	0.91
15.42	−72.00	3302	−37	0.76
25.47	−72.50	2529	+70	0.92
16.55	−71.34	2193	−47	0.75

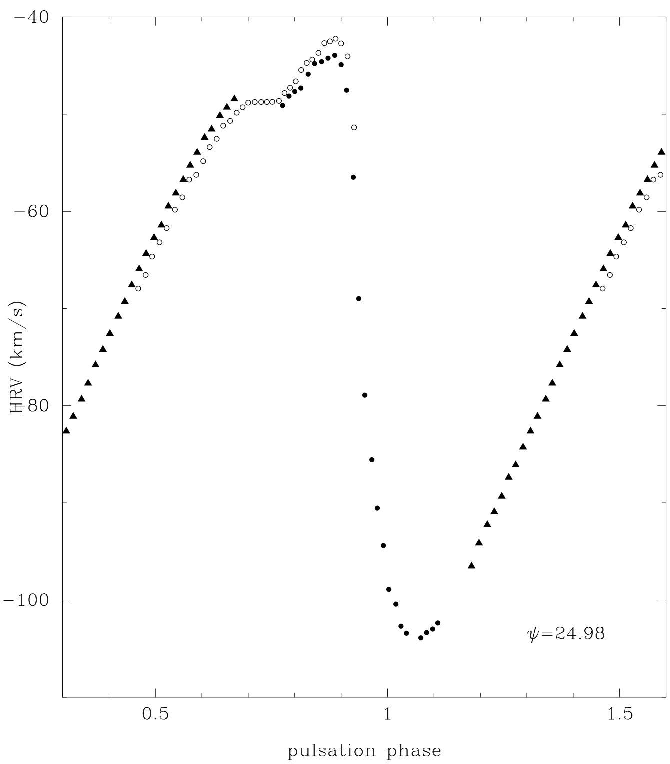

Fig. 1. Heliocentric radial velocities (HRV) obtained during 3 nights (black points: August 3th 1994; white circles: August 4th 1994; triangles: August 5th 1994) for the line Fe II 4923.921 Å. $\psi = 24.98$ is the Blazhko phase.

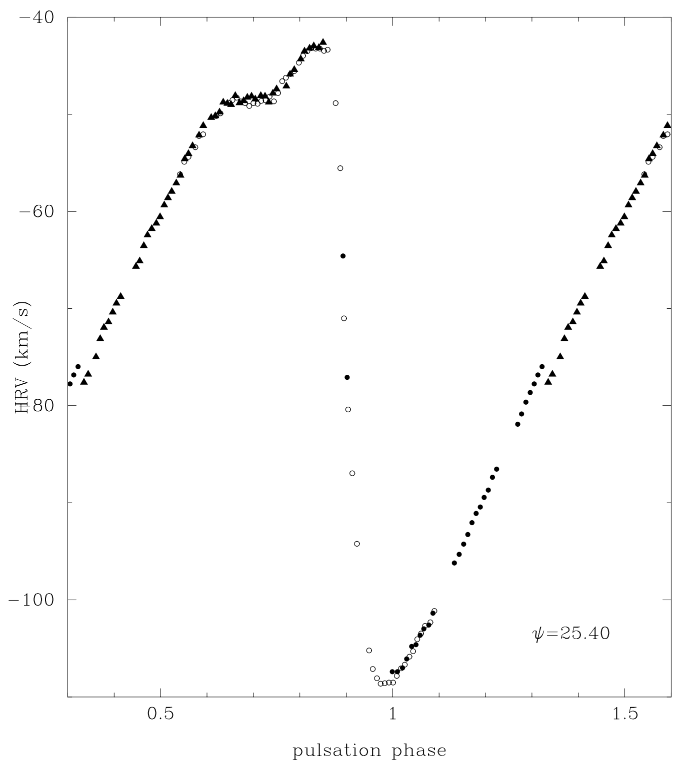

Fig. 2. Same as Fig. 1 for the nights: August 5th 1997 (black points), August 6th 1997 (white circles) and August 7th 1997 (triangles) at Blazhko phase $\psi = 25.40$.

It is clear that a velocity shift is present over the two or three consecutive nights that are required to build up a complete pulsation period. For example, over three nights at $\psi = 25.40$ (Fig. 2), the observed velocity shift is about 4 km/s at the pulsation phase $\varphi = 0.3$, i.e. 7% of the whole pulsation amplitude. This shift can also be smaller ($\psi = 25.47$, Fig. 4). A shift is also visible during the double velocity maximum, which occurs during the pulsation phase interval 0.6-0.8 (Fig. 1), but this is not always the case (Fig. 2). It is difficult to say if all of these variations are due only to the Blazhko effect. Fig. 6 shows an overplot of the five heliocentric radial velocity curves which were fitted with a Fourier series. Although the curve deformations are sometimes large at similar Blazhko phases, for instance at $\psi = 15.42$ and $\psi = 25.40$ curves show completely different shapes, it is difficult to say that they are not connected with the Blazhko effect because it is not a strictly periodic variation.

Table 2 shows the basic dynamical parameters which can be deduced from the integration and derivation of the velocity curves (Chadid & Gillet 1996a). Although the number of observed Blazhko phases is too small to provide any statistical relevant conclusion, there is no well marked correlation with respect to the Blazhko phase. For instance, the primary acceleration seems stronger near $\psi = 25.40$ and $\psi = 15.42$ than at $\psi = 24.98$, but the photospheric extension $\Delta R/R_{\odot}$ appears larger at $\psi = 24.98$ than at $\psi = 15.42$. The variation of the γ-velocity is weak (smaller than 1 km/s) and does not seem clearly connected with the Blazhko effect. Because we have estimated that the standard deviation of the dispersion of radial velocities is between 117 and 299 m/s (see Sect. 2.3), it is not clear that a real variation is present. Moreover, this is not consistent with the result of Struve & Blaauw (1948) who argue for a variation of γ-velocity with a period of approximately 42 days. Consequently, new high quality observations over a complete Blazhko

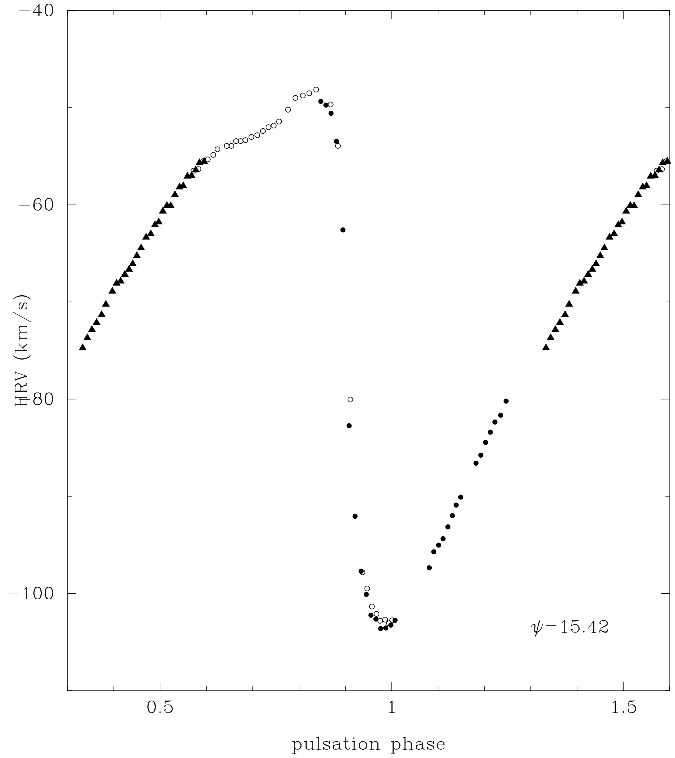

Fig. 3. Same as Fig. 1 for the nights: June 24th 1996 (black points), June 25th 1996 (white circles) and June 26th 1996 (triangles) at Blazhko phase $\psi = 15.42$.

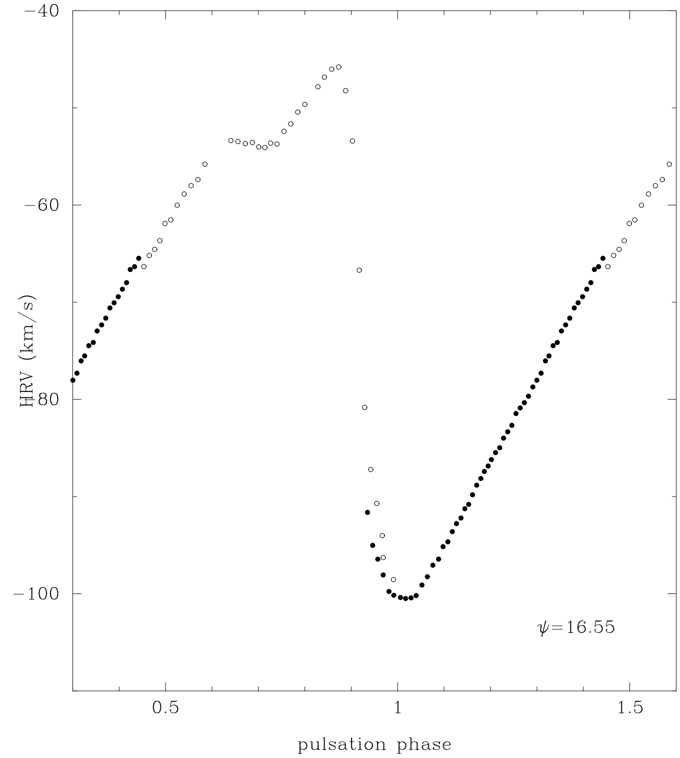

Fig. 5. Same as Fig. 1 for the nights: August 9th 1996 (black points) and August 11th 1996 (white circles) at Blazhko phase $\psi = 16.55$.

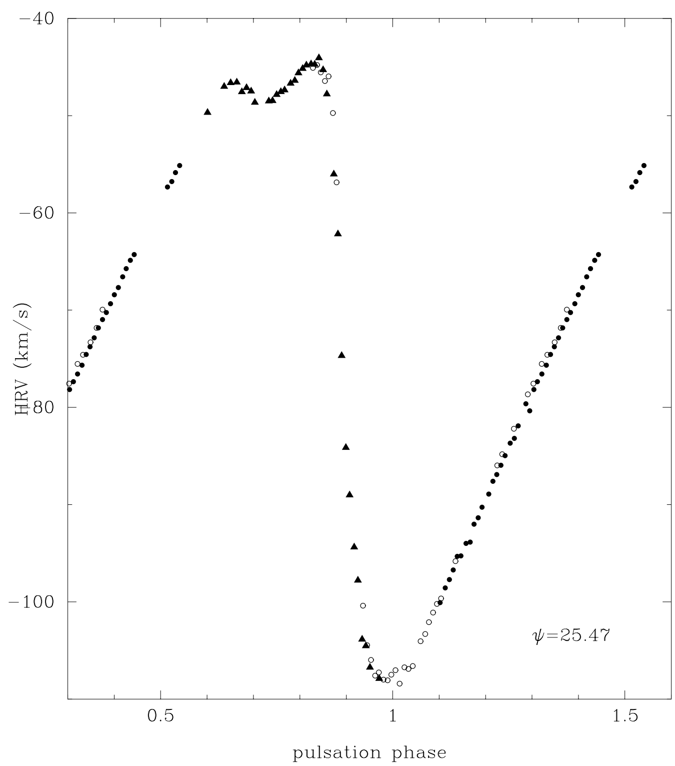

Fig. 4. Same as Fig. 1 for the nights: August 8th 1997 (black points), August 9th 1997 (white circles) and August 10th 1997 (triangles) at Blazhko phase $\psi = 25.47$.

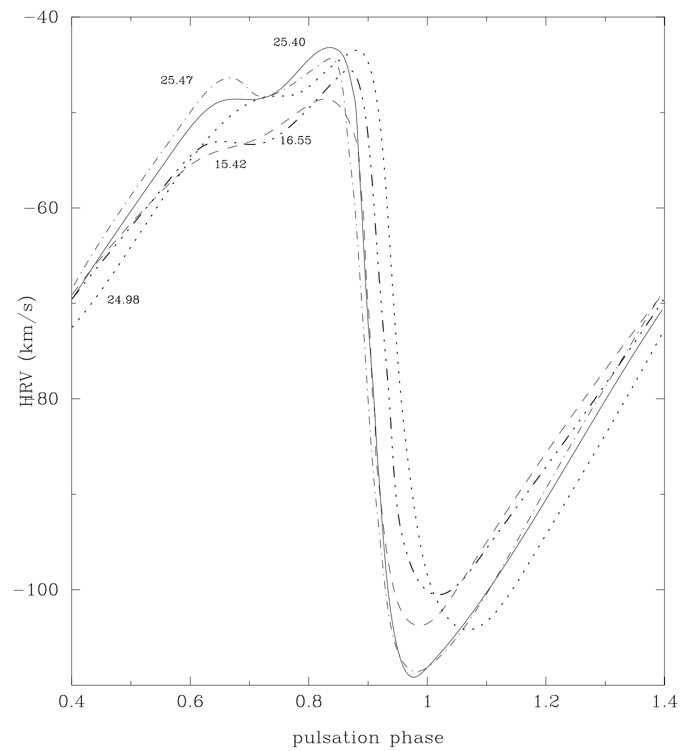

Fig. 6. Superposition of the heliocentric radial velocity curves fitted with a Fourier series at different Blazhko phases. The curves are labeled with the Blazhko phase.

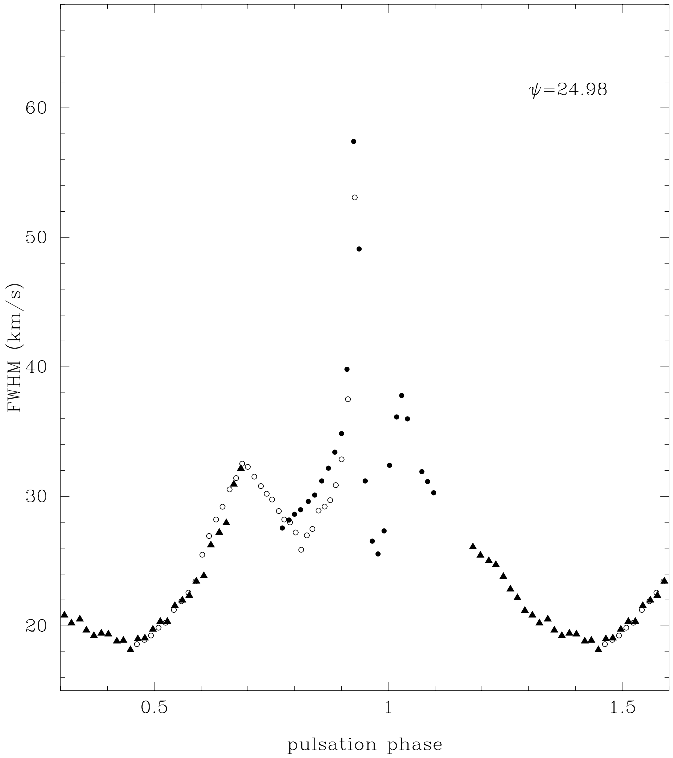

Fig. 7. Variation of the Fe II 4923.921 Å FWHM during 3 nights (black points: 3 August 1994; white circles: 4 August 1994; triangles: 5 August 1994) for the line Fe II 4923.921 Å. $\psi = 24.98$ is the Blazhko phase.

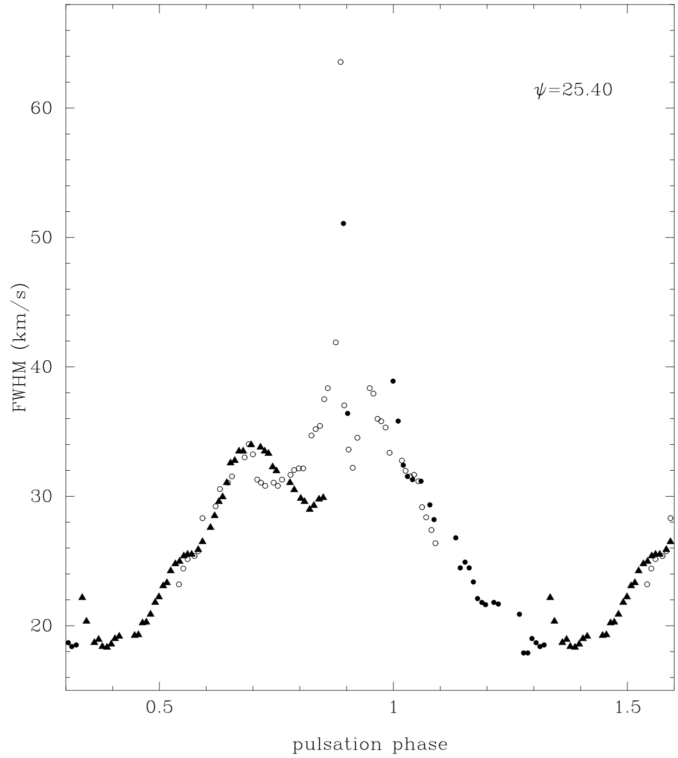

Fig. 8. Same as Fig. 7 for the nights: 5 August 1997 (black points), 6 August 1997 (white circles) and 7 August 1997 (triangles).

period and, if possible, over the same cycle, are required to confirm how the γ-velocity is variable and to determine eventually its amplitude and its period.

4. The FWHM variation

Figs. 7-11 show the observed FWHM of Fe II 4923.921 Å at the Blazhko phases $\psi = 24.98$, $\psi = 25.40$, $\psi = 15.42$, $\psi = 25.47$ and $\psi = 16.55$. To first approximation, the FWHM curves behave similarly, decreasing and increasing together with the pulsation phase and having peaks at the same phases. As previously explained by Fokin et al. (1999), the main peak (phase $\varphi = 0.92$) occurs during the line doubling phenomenon, which is due to a shock passage through the photosphere, the second occurs just after maximum luminosity ($\varphi = 0.00$) and is explained by rotation and pulsation effects, and the last peak ($\varphi = 0.70$), which occurs during secondary acceleration, is due to the propagation of an infalling shock called the "secondary shock"(Chadid & Gillet 1998; Fokin et al. 1999). Thus, the variation of the FWHM of a photospheric absorption line, such as the unblended Fe II 4923.921 Å line, is mainly related to temperature, velocity and turbulence changes occurring in atmospheric layers located just above the photosphere. As shown by Fokin et al. (1996), the variation of the velocity field in pulsating stars, especially when shock waves are propagating in the atmosphere, induces appreciable changes to the FWHM.

A closer inspection of the curves shows that the FWHM curves vary from one night to another, i.e. at least during three consecutive pulsation cycles. For instance, the FWHM shift at $\varphi = 0.80-0.90$ is near 6 km/s at $\psi = 24.98$ and $\psi = 25.40$ and near 10 km/s at $\psi = 25.47$. It clearly appears that the amplitude and the width of the three FWHM peaks are strongly variable from one pulsation period to the next.

5. Discussion

5.1. A multiperiodic origin?

It was recently shown that the presence of a Blazhko effect in RR Lyrae introduces a multiperiodic behavior of the pulsation (Chadid et al. 1999). Indeed, the detection of a frequency triplet structure in the line-profile variations ($f_P - f_B = 1.737$, $f_P = 1.764$, $f_P + f_B = 1.784$ c/d where f_P and f_B are the pulsation and Blazhko periods respectively) points out that the two additional periods can produce cycle to cycle variations. The suspected presence of a quintuplet could be also contribute, at least some part of it but necessary weaker, to this modulation. Nevertheless, the corresponding components need an observational confirmation. Also, the harmonics of the base frequency f_P could have multiplet structure increasing the cycle to cycle variations. Thus, in the framework of this effect, the variations would not irregular but multiperiodic.

Chadid et al. (1999) report the amplitude of the triplet components which are $A_{P-B} = 3.0$, $A_P = 23.2$ and $A_{P+B} = 2.5$ km/s. Taking into account the three first harmonics of the basic frequency together with the two secondary components of the triplet, giving a fraction of the variance explained by the

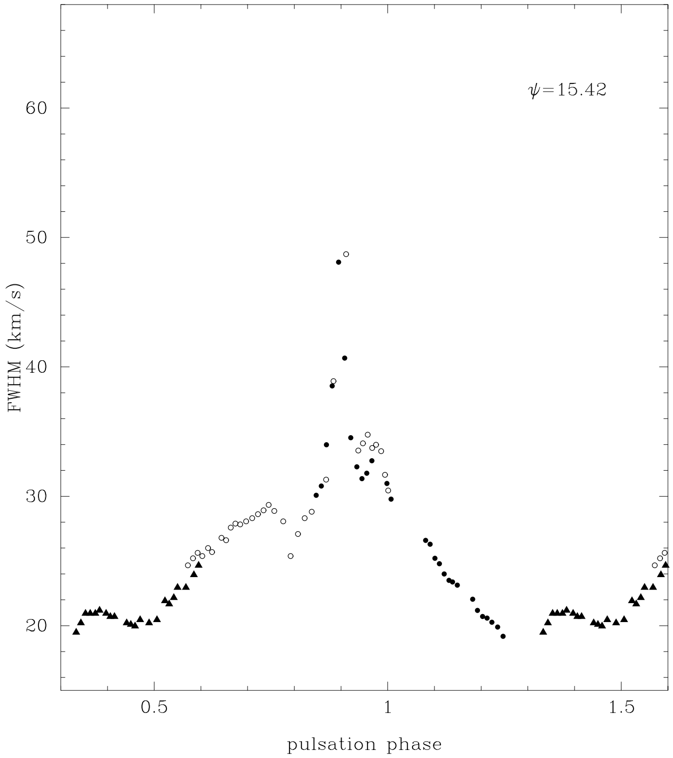

Fig. 9. Same as Fig. 7 for the nights: 24 June 1996 (black points), 25 June 1996 (white circles) and 26 June 1996 (triangles).

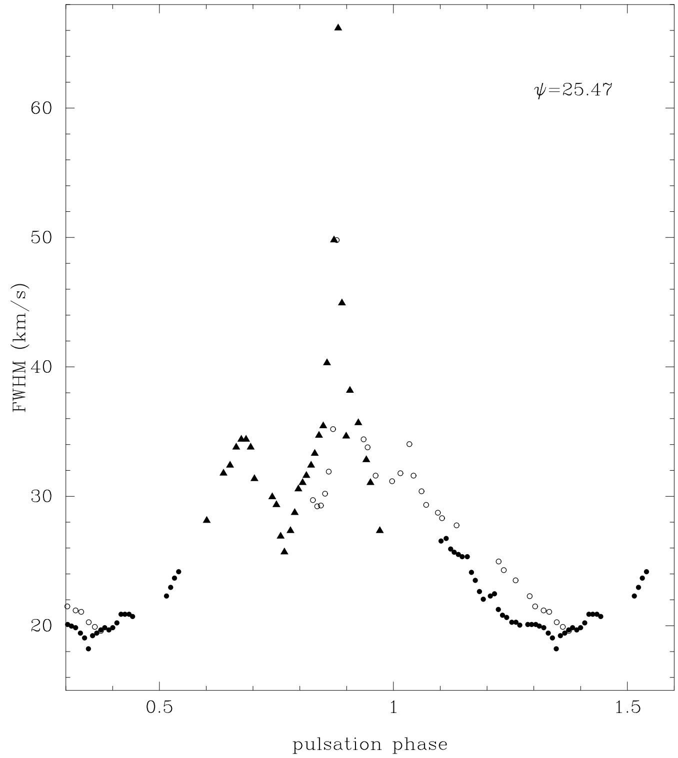

Fig. 10. Same as Fig. 7 for the nights: 9 August 1997 (black points), 10 August 1997 (white circles) and 8 August 1997 (triangles).

fit near 94%, the maximum velocity shift over five pulsation periods (the observation does not exceed three nights) is close or smaller than 1 km/s. This is not large enough because we report a shift up to 4 km/s (see Sect. 3). Nevertheless, it is not possible to conclude because our previous observations (Chadid et al. 1999) were not enough to determine with a good accuracy the component intensities of the triplet and to check if a quintuplet was present or not. New observations are required.

5.2. A dynamical origin?

The radial velocity secondary maximum (φ near 0.62-0.72) is not the same for all curves. It is strongest at the Blazhko phase $\psi = 25.47$, of average strength at $\psi = 16.55$ and weakest at $\psi = 15.42$. It occurs during the bump observed in the luminosity curve, which occurs at $\varphi = 0.70$ and just before the minimum photospheric radius. This is the consequence of the progressive deceleration of the upper atmosphere during contraction. Fokin & Gillet (1997) showed that a shock wave (s3+s4) produces, at this time, an additional local compression of the atmospheric layers in which metallic lines are formed. This shock was called the “early shock” by Hill (1972), who was the first to detect it in his nonlinear pulsating model of RR Lyrae. This dynamical phenomenon induces a secondary photospheric acceleration as observed (see Table 2). Thus, although the motion of layers located just above the photosphere are regular, we can expect that the motion of atmospheric layers well above the photosphere, where the core of absorption lines are formed, will be irregular. These layers, which represent a small part of the total mass of the atmosphere, are strongly affected by supersonic ballistic motion. As a consequence, the subsequent outward propagating shock waves (s1 and s2, see Fokin & Gillet 1997) must be altered. A dynamical coupling, which does not necessarily induce a stationary state, between the motion of atmospheric layers located above the photosphere and those at the photospheric level must be present. This phenomenon, which also includes the interplay with shock waves, could be in part at the origin of the irregularities detected in the radial velocity curves presented in this paper.

As recently shown by Chadid et al. (2000), irregularities in the motion of atmospheric layers in which metallic absorption lines are formed are not large enough to produce a completely decoupled motion between these layers and the photosphere where the continuum and line wings are formed. This is well supported by the fact that the pulsation period deduced from metallic radial velocity curves is close to the broad band photometric period. Thus, the time scale determined from the ballistic motion of the outermost metallic region is certainly not different from the period. Consequently, “irregular” motion means here that some departures may occur at some specific phases of the pulsation instead that it exists a true decoupled motion between the upper envelope of the star, which certainly is present, but it does not concern metallic layers.

Because the FWHM of the Fe II line profile is very sensitive to physical conditions (temperature, velocity field, etc.) within the atmosphere, we must expect that the poor repetitiveness of the FWHM curves reported here can be also due to this dynamical atmospheric process. As demonstrated in Figs. 7-11, the width and the intensity of the first ($\varphi = 0.7$) and the last ($\varphi = 1.0$) peaks are strongly variable. Unfortunately, it is difficult to appreciate the changes to the highest peak ($\varphi = 0.9$), because of the very rapid passage of the shock wave responsible for line doubling. Even the FWHM of the Fe II line, which returns to about the same value (between 18 and 20 km/s) at the maximum radius, does not occur at the same pulsation phase ($\varphi = 0.35 - 0.45$).

5.3. A combined effect?

The multiperiodicity induced variation can be amplified in the upper atmosphere by dynamical effects such as shock wave interactions. Consequently, it is plausible that the two above mentioned effects combine together to produce the observed irregularities. In this case, the investigated variations would be irregular.

6. Conclusion

The observations presented in this paper clearly indicate that important irregularities occur during successive pulsation cycles. In the framework of available observations, which reveal the multiperiodic behavior of the pulsation closely related to the Blazhko effect, it is not yet possible to fully explain the observed "irregularities". In this case, these variations should not be irregular but multiperiodic. New observations are required to confirm that this mechanism is not sufficient. Because there are two strong outward shock waves together with an infalling shock per pulsation period, we suggest that the observed "irregularities" could be also due in part to nonlinear dynamical processes between the motion of the highest and deepest metallic layers when strong shock waves traverse them, which occurs during the bump or the hump. In these conditions, the motion of these layers can be out of synchronization with respect to the photosphere during a small part of the pulsation period. These two mechanisms perhaps combine together to produce the observed variations. New high quality observations of a non-Blazhko RR Lyrae star would be helpful to check if these "irregularities" can occur without the presence of the Blazhko effect.

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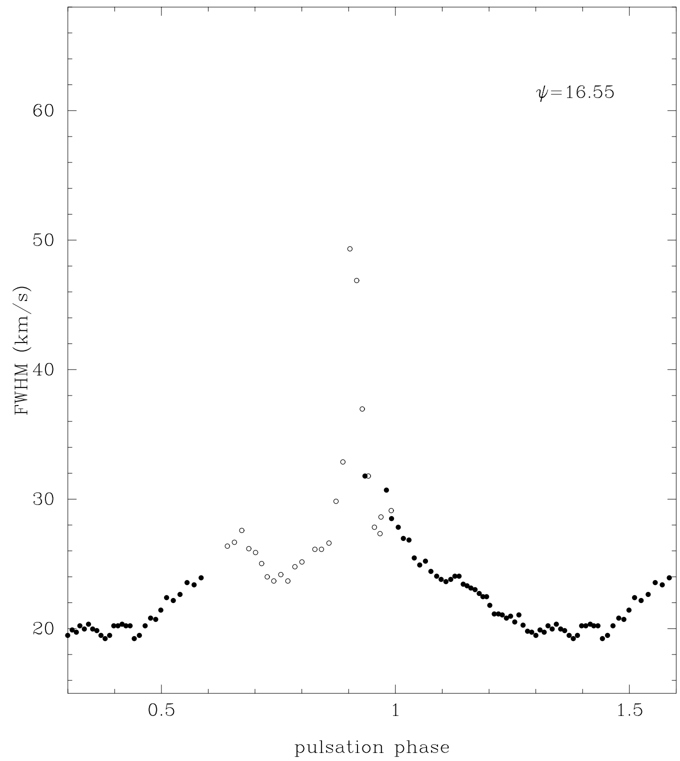

Fig. 11. Same as Fig. 7 for the nights: 9 August 1996 (black points) and 11 August 1996 (white circles).

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