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# Shock waves and microturbulence in RR Lyrae

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**Abstract.** A time variation of the microturbulence velocity $v_{turb}$ in the atmosphere of RR Lyrae is estimated from a comparison of the observed and theoretical FWHM curves of the Fe II 4923.921 Å absorption line. The theoretical line profiles were obtained using a hydrodynamical RR Lyrae model, discussed in Fokin & Gillet (1997). The estimated value of the $v_{turb}$ varies from 2 to 7 km/s, with a maximum at the phase 0.7. The dominant increase of the $v_{turb}$ seems to be caused by a strong shock, propagating through the line formation region and producing compression of the turbulent gas. Indeed, according to the current theories of the shock/turbulence interaction, the mean density increases, such as revealed by the model, should lead to a certain turbulence enhancement. Yet, the detailed mechanism of such an amplification is to be clarified.

**Key words:** shock waves – turbulence – stars: individual: RR Lyr – stars: oscillations – stars: variables: RR Lyr

## 1. Introduction

Today many works are still devoted to RR Lyrae stars (see Barnes III 1997 or the last conference held in Los Alamos in June 1997). The recent massive photometric surveys (MACHO, EROS, OGLE,...) have provided powerful databases to study some basic physical problems such as the existence of the second overtone (Kovács 1998a) or the dependence of absolute magnitude on metallicity (Bono et al. 1997a, 1997b or Kovács 1998b). Moreover, detailed comparisons between observations and nonlinear pulsating models show that serious discrepancies exist (Kovács & Kanbur 1998). Buchler (1998) gives a general review of the recent advances in nonlinear pulsation theory. In particular, the effect of the convection has been well investigated (Bono & Marconi 1998; Feuchtinger & Dorfi 1998). Since the original approach of Karp (1975) about the coupling between the hydrodynamics and the radiative transport, hydrodynamical models of the pulsation of the atmosphere including shock waves together with the calculation of line profiles and their comparison with high resolution observations are still exceptional (e.g. Fokin & Gillet 1997).

Recently Gillet et al. (1999) suggested that the microturbulent velocity variation in the atmosphere of the $\delta$ Cephei star has two physical origins. The first one is the slow global density variation due to pulsation, and the second one is associated with the shock waves propagating in the atmosphere. In the $\delta$ Cephei atmosphere the effect of the global pulsation prevails, causing the $v_{turb}$ to vary from 2 to 7 km/s at maximum compression. Shocks lead to a smaller turbulence amplification, by about 1.5 to 3 km/s depending of the shock intensity.

An inspection of different theoretical models reveals that the shock waves generation in classical Cepheid, BL Herculis, W Virginis or RR Lyrae stars have many features in common (Fokin & Gillet 1994; Fokin et al. 1996 or FGB hereafter; Fokin & Gillet 1997). In particular, three main shock waves are produced at each pulsation period due to similar physical mechanisms. However, their amplitudes strongly differ from one star to another. For instance, in $\delta$ Cephei the strongest shock amplitude does not exceed 20–25 km/s, while in RR Lyrae the total cumulative shock becomes as high as 140–170 km/s.

A simplified theoretical study of the turbulence amplification by a shock wave in $\delta$ Cephei has recently been given by Gillet et al. (1998). It appears that the best turbulence amplification models, which are based on the adiabatic assumption (weak shocks), predict a too large amplification when the shock Mach number $M$ exceeds 1.5. Unfortunately, an accurate quantitative comparison was not possible in the quoted paper because numerical problems were present at the phase of the strongest atmospheric shock in $\delta$ Cephei ($M = 2.4$). On the contrary, RR Lyrae is known (Fokin & Gillet 1997) to exhibit quite strong shocks up to $M \approx 25$ in the highest part of its atmosphere ($\log \rho = -13$ g/cm$^3$). Thus, RR Lyrae provides a good opportunity to check if the theoretical amplification rate of the turbulence is relevant for nonadiabatic shocks. It would be also interesting to know the real amplification rate which is overestimated by the adiabatic approach.

In Sect. 2 we describe the method used for the reconstruction of the Fe II line profiles. The determination of the turbulent velocity is presented in Sect. 3, and the results are discussed in Sect. 4. We also compare our results with those obtained earlier for $\delta$ Cephei. Finally, some concluding remarks are given in Sect. 5.

## 2. FWHM and turbulent velocity

### 2.1. Line profile modelling

In the present analysis we use the hydrodynamic model RR41 from our previous study (Fokin & Gillet 1997), which reveals the strongest shocks. Its parameters are: $T_{\rm eff} = 7175\,{\rm K}$, $L = 62\,{\rm L}_{\odot}$, $M = 0.578\,{\rm M}_{\odot}$, $X = 0.7$, $Z = 0.002$. These initial parameters are close to standard ones and remain within the uncertainties of the modern evolutionary theory for RR Lyrae stars (e.g. Spite, 1996). Even though the current estimations for the RR Lyrae masses seem to be a little bit higher, probably 0.6–0.7 $M_{\odot}$, this small mass differrence of about 0.05–0.1 $M_{\odot}$ is not critical in view that the present results should be regarded as semi-quantitative.

The details of the numerical calculation and dynamical properties of the model RR41 can be found in the paper mentioned above. In the same paper we already estimated the general effect of the microturbulence on the line profiles. The sets of profiles of the Fe II 4923.921 Å and Ba II 4934.076 Å lines were calculated for two values of the microturbulent velocity, $v_{turb} = 0$ and 5 km/s. We found that the increase of $v_{turb}$ leads to stronger and broader lines.

In order to study the variation of $v_{turb}$ with the pulsation phase, we computed a large set of the Fe II line profiles for different phases, using $v_{turb}$ as a free parameter to get the best fit to the observed FWHM. The method of solution of the transfer equation is the same as in Fokin & Gillet (1997). We adopt three values of the rotational velocity $v_{rot} = 0$, 5 and 10 km/s to test its effect on $v_{turb}$ and assume that this latter is constant at each moment within the whole atmosphere.

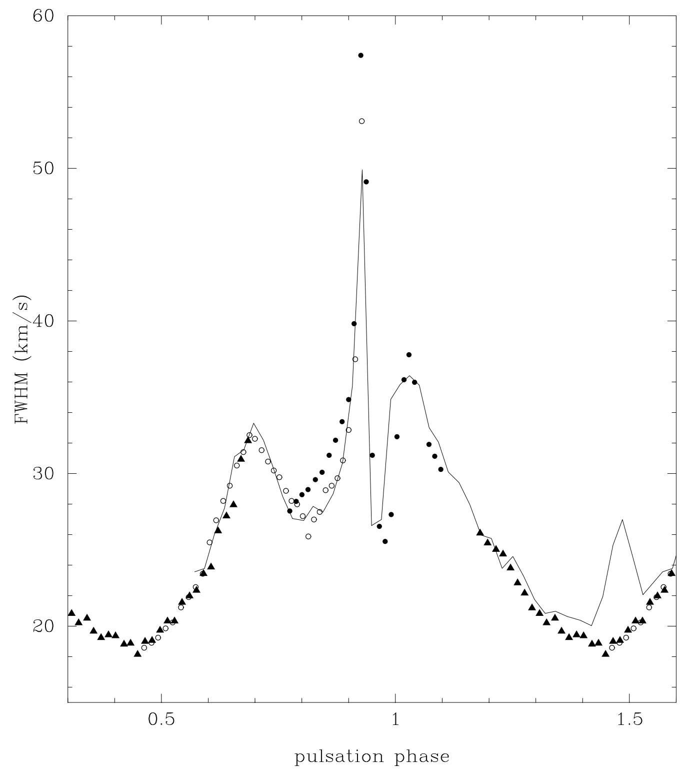


**Fig. 1.** Theoretical fit (full line) to the observed data obtained during 3 nights (black points: 3 August 1994; white circles: 4 August 1994; triangles: 5 August 1994) for the line Fe II 4923.921 Å. The large dispersion of the observed data is probably due to dynamical variations from cycle-to-cycle, since the points represent three consecutive nights of observations. The theoretical curve was obtained by varying $v_{turb}$ as a free parameter

### 2.2. *FWHM curve*

Fig. 1 represents the observed variations of the FWHM with the phase over three consecutive nights (Chadid & Gillet 1997a), together with our theoretical fit obtained with variable $v_{turb}$ for the RR Lyr model RR41 (case $v_{rot} = 0$). Note that the observed FWHM curve slightly varies from one pulsational cycle to another. This effect is mainly due to the poor repetition of the pulsational cycles, most probably caused by the shock propagation. The dispersion is certainly not due to the Blazhko effect because in this case the expected total amplitude of the FWHM variation would be excessively large (the Blazhko period for RR Lyrae is 40.8 days). For this reason we did not try to obtain a detailed fit but a rather general one.

As seen from the figure, the FWHM curve has a complex structure. The inspection of the atmospheric structure and dynamics shows that the principal peak of the FWHM curve occurs exactly during the very short phase of the line doubling induced by a shock. As shown by Fokin & Gillet (1997), this doubling is provoked by the shock s1, emerging at the phase 0.92 rather than by the thermal or turbulent broadening. The height of the narrow FWHM peak at $\varphi = 0.92$ represents the Dopplerian separation of the two components of the splitted Fe II line. On the theoretical velocity curve (Fig. 2), this event corresponds to a drastic velocity inversion after the shock passage. Since the doubling is very short, the peak is very narrow. As shown by our numerical experiences, the intensity of the shock s1, and consequently the amplitude of the Doppler splitting, is very model dependent. Nevertheless, this shock-induced splitting, or broadening, is always much stronger than any physically realistic turbulent broadening. Thus, only a detailed treatment of the observed broadening of *each* line components, can provide the correct value of the turbulence at this phase. Nevertheless, this would be only possible when very high quality observations would be available. We can only suggest that, according to current theories of the turbulence amplification (Gillet et al. 1998), $v_{turb}$ must increase due to compression in the shock. Moreover, because the minimum radius also occurs at the phase 0.92, a part of the FWHM increase is due to the thermal broadening. Nevertheless, as shown by the above discussion, this broadening mechanism remains secondary compared to the shock wave effect.

The reason for the drastic decrease of FWHM after the phase 0.93 seems to be twofold. On the one hand, it is in part related to a very short decrease in the velocity gradient in the line formation region (LFR) after the first shock (s1) passage, at $\varphi \approx 0.92$. Indeed, this shock is very rapid, and crosses the whole LFR in about 0.01P due to high compression degree of the atmosphere. Consequently, the radial velocity behind the front becomes nearly equal everywhere. Because the velocity gradient in the LFR strongly contributes to the line width (FGB), its decrease causes a drop of the FWHM. Note that this local FWHM minimum is yet much higher than the basic minimum at

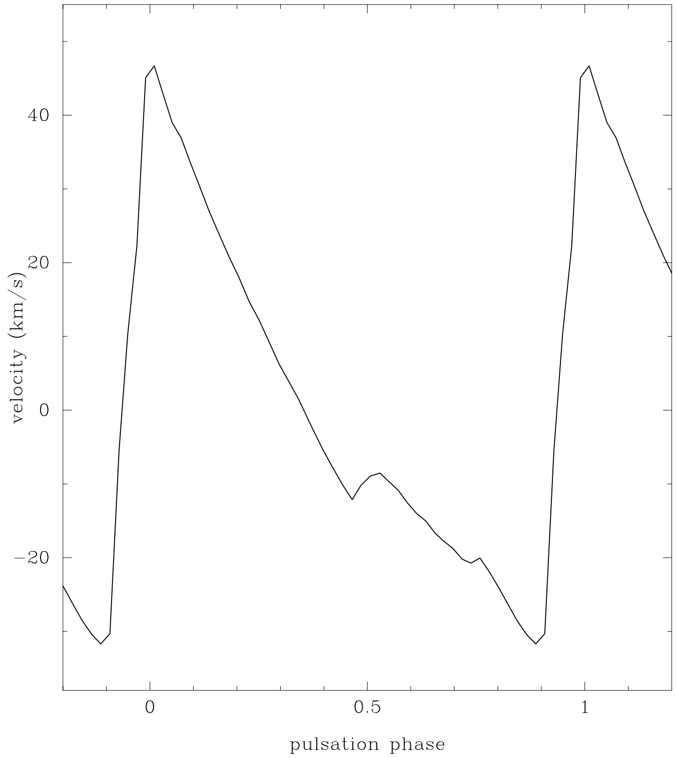


**Fig. 2.** Theoretical velocity curve measured from the minima of the Fe II 4923.921 Å line

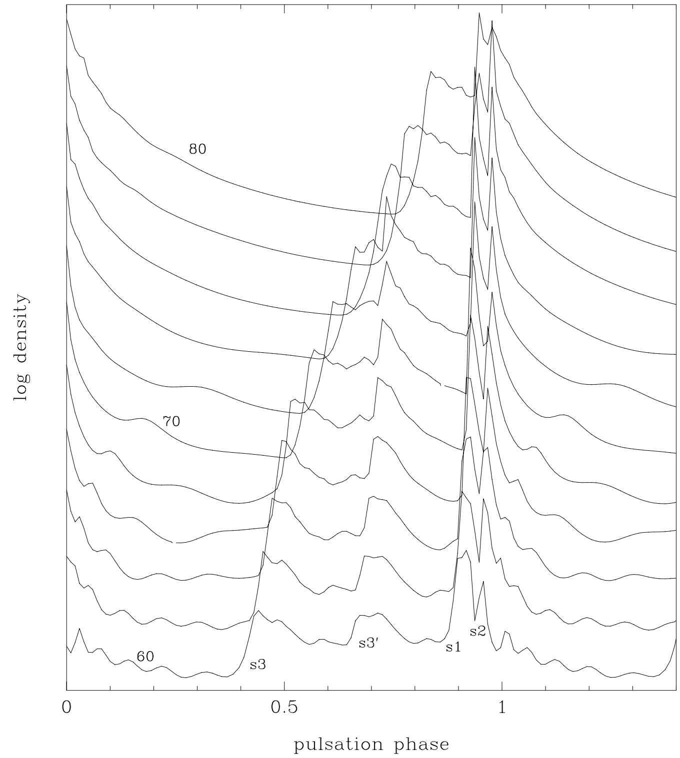


**Fig. 3.** Mass density variation for different mass zones in the hydrodymanical model of RR Lyr (RR41). The photosphere is located between mass zone number 52 and 60 depending on pulsation phase. Here only the part of the atmosphere between mass zone numbers 60 and 80 is shown. The curves are arbitrary shifted to demonstrate the relative behavior of the density for different layers. The shocks are indicated following the notation as in Fokin & Gillet (1997)

the phase 0.45. Shortly after that, the second shock arrives (s2, $\varphi = 0.95$), but it is too weak to produce a perceptible Doppler splitting. The disk integration at this phase also does not contribute much to the FWHM due to relatively low radial velocity in the LFR.

On the other hand, the FWHM depends on the compression state of the turbulent gas. The adiabatic turbulence amplification theories predict an increase of $v_{turb}$ when density increases, and vice versa (see for instance Gillet et al. 1998). As seen from Fig. 3,

fter the first shock (s1) passage, the mass density first rised, quickly decreases due to rapid and homogeneous expansion of the atmosphere after the shock passage. Hence, this atmospheric dilatation during the interval 0.91–0.94, can also contribute to the observed drop of FWHM after the main peak. However, the observed minimum of the FWHM corresponds to the arrival of the second shock s2 (Fig. 3), which also provokes an appreciable compression. Thus, at this moment, we can expect that the turbulent velocity, and consequently FWHM, increase again. Actually, without turbulence enhanced at this phase, the predicted FWHM minimum would be lower. We should note, however, that the value of the calculated FWHM minimum is not only model dependent, but also depends on the accuracy of the description of the physical conditions in the LFR. These conditions strongly vary when the shock propagates through the thin hydrogen ionization zone (see Fokin & Gillet 1997). We must admit that this very rapid phase cannot be satisfactorily calculated in our Lagrangean model. Poor spatial resolution of the H-ionization zone, from one part, and the hypothesis of purely radiative envelope, from the other, lead to unobserved perturbations of the light curve during this phase. Recent studies suggest that an improvement can be achieved either with the inclusion of the convective energy transport (Bono & Stellinwerf 1994), or with increase of the artificial viscosity (Takeuti et al. 1998). Without discussing here this problem, we conclude that $v_{turb}$, calculated from FWHM within the phase interval 0.91–0.94, should be regarded only as indicative.

The second peak, that appears after the phase 1.0, is mainly due to the rapid expansion of the atmosphere. At this moment the integation over the stellar disk alone gives very broad lines which well fit to the observations (the "de Jager" point, see FGB). Between the phases 1.0 and 1.1, FWHM depends on the turbulent velocity only weakly, because the high expansion velocity (about 60 km/s) largely exceeds the sonic velocity (about 7 km/s). Indeed, due to strong dissipation effects, the turbulent velocity should be always subsonic. The discrepancy between the predicted and observed FWHM at this phase is mainly due to the discrepancy in the dynamical characteristics of the model and the real star. Consequently, the value of $v_{turb}$ obtained here for this phase, is rather speculative.

A small theoretical FWHM peak near the phase 1.5 (Fig. 1) coincides with the passage of an early shock (s3), as can be seen from Fig. 3. The Dopplerian broadening, produced by this shock in our hydrodynamical model RR41, is much larger than observed. For this reason, this theoretical peak cannot be eliminated by decreasing of the $v_{turb}$. Evidently, in real RR Lyrae stars this shock must be much fainter than in our nonlinear models. The origin of this shock, as discussed in Fokin & Gillet (1997), is related to a stop of the hydrogen recombination front at the end of the expansion phase. Since in our Lagrangian code this front is poorly resolved with respect to the mass grid, its motion through the mass zones and following physical phenomena are calculated only approximatively. Yet, since the Hillendahl's (1970) pioneering work, there are now strong theoretical evidences that such predicted type of shocks should exist in real stars.

### *2.3. Turbulent velocity variation*

Because the value of the rotational velocity $v_{rot}$ of RR Lyrae is not known, it is a free parameter in our calculation of the FWHM. Nevertheless, high resolution observations of metallic line profiles show that its value is indubitably smaller than 10 km/s. Note that this implies, in the framework of the oscillating oblique magnetic rotator model (Cousens 1983; Chadid & Gillet 1997b), an inclination angle $i$ between the line-of-sight and the axis of rotation close to zero (RR Lyrae would be view almost pole-on) because its expected rotation period would be equal to 40.8 d (the Blazhko's period). Fig. 4 shows the predicted variations of $v_{turb}$ deduced from the FWHM of the Fe II line (Fig. 1) for three three values of the rotational velocity $v_{rot} = 0$, 5 and 10 km/s. The sensibility to $v_{rot}$ is maximum around the maximum radius (phase 0.4) i.e., when the turbulent velocity is minimum. By contrast, it strongly decreases when $v_{turb}$ is maximum (minimum radius). In particular, the variation of $v_{rot}$ does not cancel the two secondary bumps at phases 0.2 and 0.95 and the shape of the main peak centered at the phase 0.7 is conserved. Finally, the general shape of the turbulence curve, given in Fig. 4, seems realistic in the framework in our approach. The influence of the rotational velocity on $v_{turb}$ was already discussed in details by Breitfellner & Gillet (1993).

Keeping in mind the notes made in Sect. 2.2 about the limits of our numerical method, especially in the phase region 0.95–1.1, the $v_{turb}$-curve must be considered in a semi-quantitative manner.

The smallest peak of the observed FWHM curve, seen at $\varphi = 0.7$ (Fig. 1), as shown by our analysis, is entirely due to the increase of the microturbulence. With $v_{turb} = 0$, the theoretical FWHM curve shows only a weak bump two times smaller than observed.

The sharp peak of turbulence at $\varphi = 0.94$ (Fig. 4) occurs just after the minimum radius ($\varphi = 0.92$) and consequently, it is not directly induced by the maximum compression of the atmosphere. As discussed in the previous section, it is probably related to the turbulence amplification caused by the shock s2. Its intensity is certainly not well restituted by our model because a realistic description of the very fast expanding phase of the atmosphere needs a relevant numerical calculation of the hydrogen ionization front which can be only approximative with our Lagrangian approach. A more sophisticated modelling is required to clarify this question.

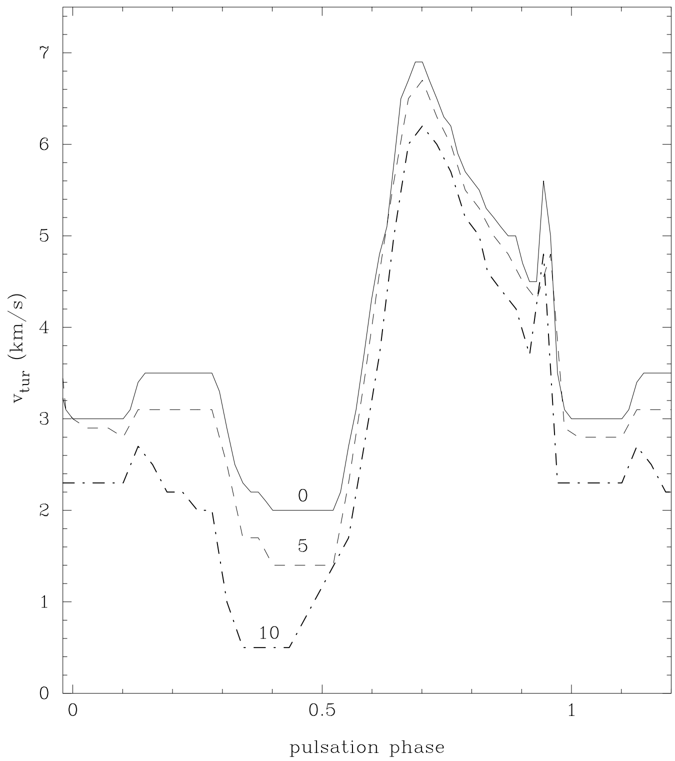


**Fig. 4.** Predicted turbulent velocity variation with phase, deduced from the FWHM theoretical fit with $v_{rot} = 0$ km/s (full line), 5 km/s (dashed) and 10 km/s (dot-dashed)

As seen from the figure, $v_{turb}$ rapidly grows between $\varphi = 0.6$ and 0.7 up to about 7 km/s from its "quiet" level of about 2 km/s ($\varphi = 0.45$). After $\varphi = 0.7$, it decreases slowly until $\varphi = 0.9$, almost linearly with phase. A comparison with the density diagram (Fig. 3) shows that the origin for this turbulence amplification is most probably the density increase due to another shock (s3' in Fokin & Gillet, 1997), which passes early through the LFR, approximately from phase 0.6 until 0.8. It is rapid enough to provoke by $\varphi = 0.7$ the maximum compression in all the line formation region. As a result, at this phase, $v_{turb}$ reaches its maximum, near 7 km/s (Fig. 4).

Due to the considerable extension of the atmosphere of RR Lyrae at the compression phase, deeper layers are more accelerated by gravity than the upper ones. Consequently, the density in the atmosphere generally *decreases* during the global compression phase, as can be seen from Fig. 3. This explains the decrease of $v_{turb}$ after its maximum at $\varphi = 0.7$.

### *2.4. Comparison with $\delta$ Cephei*

A comparison of the $v_{turb}$ curves predicted for RR Lyrae in the present paper, and for $\delta$ Cephei, obtained by Gillet et al. (1999), reveals the same fast turbulence increase at phases 0.6–0.7. Nevertheless, in $\delta$ Cephei, it is much weaker (2.8 km/s), which can be explained by generally fainter shocks in Cepheids.

It is also clear, that the major difference between those two types of stars is that in $\delta$ Cephei the most important mechanism of amplification seems to be related to the global compression of the atmosphere, while in RR Lyrae a shock amplification is the dominant process. The physical origin of this shock (s3') is not clear (Fokin & Gillet 1997) but it seems caused by some effect of the 1H-mode which does not exist in $\delta$ Cephei. Because the Mach number of s3' is relatively large (near 7) compared to ones of shocks in $\delta$ Cephei, it would be interesting to apply the theoretical analysis of turbulence amplification to RR Lyrae, as it was done for $\delta$ Cephei in Gillet et al. (1998). Indeed, as discussed in this last paper, we need to use strong shocks to test the validity of the presently available amplification theories.

## 3. Conclusion

On the basis of reconstruction of the Fe II absorption line profile at 4923.921 Å for different phases of a pulsating nonlinear RR Lyrae model, we estimated the temporal variation of $v_{turb}$ in this line formation region. We found that $v_{turb}$ significantly varies from 2 to 7 km/s. The largest peak of $v_{turb}$ at $\varphi \approx 0.7$ is seemingly provoked by a shock, noted as s3' by Fokin & Gillet (1997). It is not very strong ($\Delta\, v \approx 20$–$30$ km/s), but its effect on the density enhancement in the LFR is considerable. The same shock amplification in $\delta$ Cephei seems less important due to systematically weaker shocks.

It would be interesting to perform the same analysis for several other lines, which form at different atmospheric layers, in order to find out the spatial variation of the mean turbulent velocity.

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