# A Spectroscopisc's View of Nearby RR Lyrae Stars

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I am greatly honored to be the second Bohdan Paczyński Medal lecturer. Bohdan was a dear friend who left an indelible imprint on my life. He was, as well, an invaluable participant in my early explorations of RR Lyrae spectra, the subject of this lecture. I share the hope of Polskie Towarzystwo Astronomiczne that the Paczyński lecture series will serve to remind present and future astronomers, particularly those who will never have the opportunity to see or hear Bohdan Paczyński in person, of the boisterous enthusiasm, sharp wit, and penetrating insight that he brought to every scientific question, to every conversation, to every social occasion that attracted his attention. To this end I begin with a few memories of Bohdan from the mid 20th century.

## 1 About Young Bohdan Paczyński

*Tell me the tales that to me were so dear,*
*Long, long ago; long, long ago.*
Old English Folk Song

### *1.1 My Introduction to Bohdan*

I first met Bohdan in my office at Lick Observatory in 1962, while he was a graduate student on leave from Warsaw University. I realized that he was smarter than I in the first half-hour of our first conversation. During this conversation I gradually became acquainted with his unforgettable rapid-fire Astrophysical-Journal-English.

### *1.2 Bohdan, The Observer*

Shortly thereafter we began to work together, conducting simultaneous photometric and spectroscopic observations of RR Lyrae stars, an activity that seemed important at that time. Bohdan's good humor lubricated our work. He performed UBV photometry at the 36-inch Crossley reflector, while I made simultaneous observations with the coudé spectrograph of the 120-inch telescope. This cooperation led to a nice paper (Preston & Paczynski, 1964) to which I shall refer later.

### *1.3 Bohdan's Star*

During the afternoon that followed a night of photometry at the Crossley reflector Bohdan came to my office to report that his comparison star for the RRab star TU UMa, was itself variable, a short-period eclipsing binary, and he asked if he could make more observations of it. I said OK unenthusiastically, not appreciating what

Bohdan (Paczynski, 1964) had realized immediately – that BD+30:2163 was destined to become the archetype of a new, important class of contact binaries, the AW UMa stars. These binaries are recognizable by their flat eclipse minima, an indication that one Roche lobe is (uncommonly) much smaller than the other. You can read about the significance of AW UMa in a final paper by Paczyński et al. (2007), accepted by Monthly Notices Royal Astronomical Society on April 3, 2007, just two weeks before Paczyński's death. These two papers about AW UMa are fitting reminders of Paczyński's lifelong interest in the evolution of interacting binary stars. Separated by 44 years, they are the bookends, so to speak, of his scientific life. Today Paczyński is regarded as a leading theorist of his generation, but in 1963 at Lick Observatory he was an indefatigable observer!

## 2 About RR Lyrae Stars

I turn now to my portion of this lecture – what we can learn about RR Lyrae stars from high resolution spectroscopy. In particular, what can we learn from several thousand spectra of several dozen of the brightest, hence nearest, RRab stars collected over the past eight years with the echelle spectrograph of the du Pont 2.5-m telescope at Las Campanas Observatory. I selected for my lecture three relatively unstudied aspects of the structure and evolution of these objects: axial rotation along the horizontal branch (nearing completion), metallicity effects in the RR Lyrae family (in preparation), and shock phenomena in RR Lyrae envelopes (if I live long enough!). Much of what I report here has been learned in the course of long collaborations with Christopher Sneden (University of Texas, Austin) and Merieme Chadid (University of Nice Sophia Antipolis).

### *2.1 Axial rotation along the horizontal branch*

Measurable axial rotation of old main sequence stars is neither observed nor expected in view of what we have long known about chromospheres, winds, and spin-down (Kraft, 1967; Skumanich, 1972). Lucatello & Gratton (2003) set an upper limit of 3 km/s for the observed axial equatorial rotation, Vrotsini, of main sequence stars in globular clusters. Under the simple assumption of rigid rotation with conservation of angular momentum, the axial rotation of such stars should fall to less than 1 km/s, when they evolve to the blue side of the RR Lyr instability strip. However, Nature is full of surprises: Peterson et al. (1996), and subsequently others (see references therein Preston & Chadid, 2013) found rotations of blue horizontal branch (BHB) stars as large as 40 km/s. On the basis of observations collected during the Kepler mission such rotations are now generally attributed to core contraction during antecedent RGB evolution.

If luminosity and angular momentum of a star remain constant during evolution in and near the instability strip, robust horizontal branch theory predicts that $V_{\rm rot} \propto T_{\rm eff}^2$, so from inspection of Fig. 1 approximately 1/3 of the BHB stars should cross the RR Lyrae instability strip between the red arrows with rotations above the upper limit $V_{\rm rot} \sin i < 10$ km/s obtained from spectra of the 27 RRab stars observed by Peterson et al. (1996). None do so. Hence, the conundrum pursued by Preston & Chadid (2013), who only made matters worse by lowering the upper limit of RRab rotation from 10 km/s to 6 km/s by spectral measurements of 29 additional RRab stars.

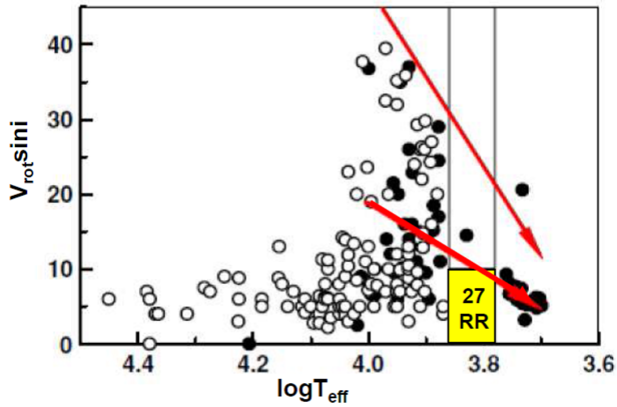


Fig. 1: Values of $V_{\rm rot} \sin i$ for field HB (filled circles) and globular cluster (open circles) stars versus $\log T_{\rm eff}$. Two vertical lines mark boundaries of the instability strip. Box at bottom contains 27 RRab stars. Inclined red arrows are trajectories of stars that conserve angular momentum as they cross the instability strip at constant luminosity.

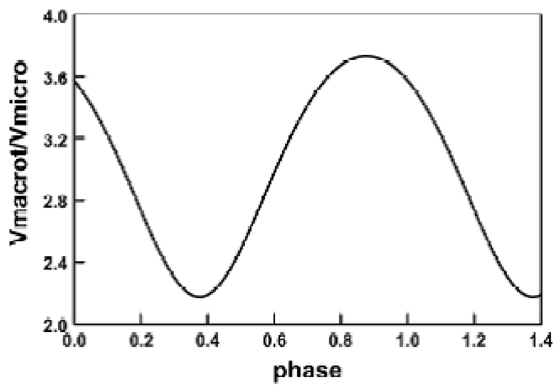


Fig. 2: The average ratio of macroturbulent velocities from Preston & Chadid (2013) and microturbulent velocities from For et al. (2011) for 6 RRab stars is plotted versus pulsation phase.

Macroturbulence and microturbulence in stellar atmospheres are defined as motions of turbulent mass elements with dimensions greater than and less than mean free paths of photons, respectively. Therefore, an observed ratio of macroturbulence to microturbulence is a primitive manifestation of Kolmogorov (1941) spectrum of turbulence. Its behavior during pulsation cycles, shown in Fig. 2, particularly its short-lived minimum, and the very small dispersion of the minimum values of $V_{\rm macrot}$, 6.2 (0.14 km/s, strongly suggest that the minimum is imposed by macroturbulence, not by rotation. The upper limit on $V_{\rm rot}$ must be substantially less than 6 km/s. How much less remains unknown, unfortunately, because the effects of rotation and macroturbulence at the few km/s level cannot be disentangled in spectra with resolution $R = \lambda/\delta\lambda \sim 30000$ (we use the subscript *macrot* to emphasize this limitation). We

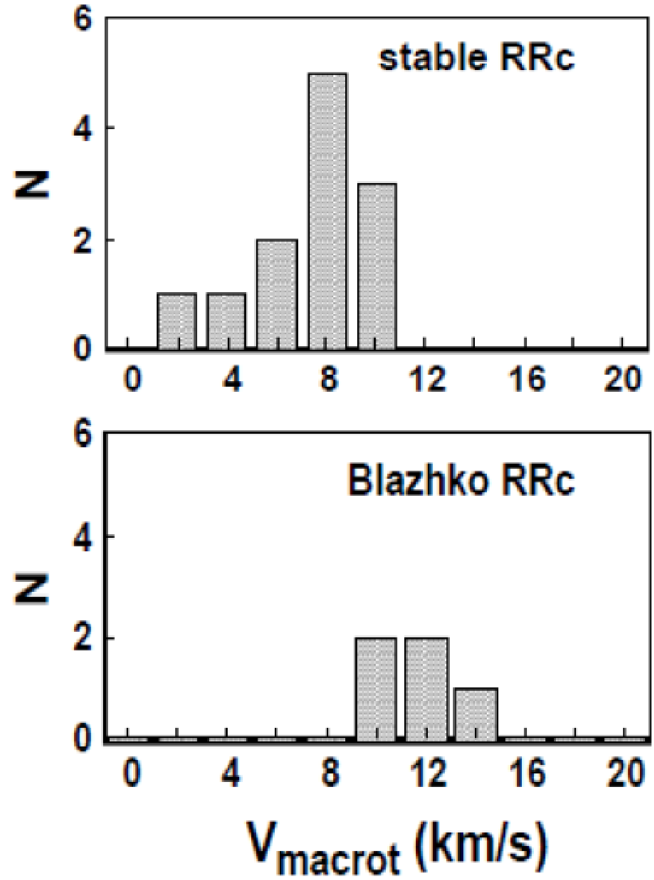


Fig. 3: Distribution of $V_{\text{macrot}}$: upper panel, stable RRc; lower panel, Blazhko RRc with $P_{\text{Bl}} < 11$ . Data are binned at 2 km/s intervals. Numbers along horizontal axes are upper bounds of the bins.

concluded on the basis of available evidence that *most and perhaps all* BHB stars lose angular momentum during passage through the instability strip to the Asymptotic Giant Branch.

The atmospheric angular momentum of the rotating BHB stars in Fig. 1 either sinks to unobservable layers or is ejected from stars during passage through the instability strip. Preston & Chadid (in preparation) try to establish the time scale for disappearance of this spin with measurements of 17 RRc stars that lie between the BHB and RRab domains. We analyzed measurements of equivalent width and FWHM in RRc spectra in the manner described for RRab stars in Preston & Chadid (2013). We imagine two limiting cases. If momentum loss occurs *at the boundary* of the instability strip, the time scale is set by the time required to reach a limit cycle, $\sim$ 1000 P $\sim$ 1 y. If the loss occurs *during RRc evolution*, the time scale could be much longer, $\sim 10^7$ y. The histograms of Fig. 3 derived from measurements of our RRc specra set upper limits of 10 km/s on rotation of stable RRc and a larger value of 14 km/s for 5 RRc Blazhko stars. The $V_{\text{macrot}}$ distributions of the RRab and RRc stars differ markedly. $V_{\mathrm{macrot}}$ values of the RRab stars cluster between 6 and 7 km/s with small dispersion. Those for the RRc stars possess a downside tail that extends to 2 km/s, while values for Blazhko RRc stars extend upward to 14 km/s. All of the latter, with Blazhko periods $< 11$ d (Szczygieł & Fabrycky, 2007), were chosen to have detectable rotational broadening ($> 20$ km/s), if Blazhko periods are periods of axial rotation of these stars: changing aspect produced by axial rotation is one hypothesis advanced to explain the Blazhko phenomenon. I only note in passing that the projected rotational velocities, $V_{\mathrm{rot}} \sin i$, of the five Blazhko RRc stars reported here satisfy the necessary condition $\sin i < 1$ , i.e., our measurements of these particular RRc Blazhko stars *do not falsify* the rotator hypothesis.

One simple way to interpret our results is to suppose that angular momentum loss occurs during evolution of RRc stars in the instability strip, and that small values of $V_{\mathrm{rot}}$ are detectable among them because there is less macroturbulence in the atmospheres of RRc stars than in those of RRab stars. This situation could arise if turbulent motions in RR Lyrae envelopes are correlated with pulsation amplitude. This is an infant field, our conclusions are necessarily speculative, and we look forward to further investigation based on better spectroscopic data.

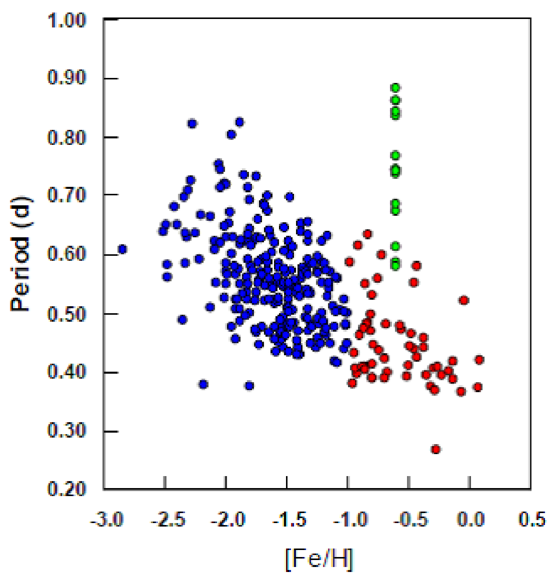


Fig. 4: Pulsation period versus [Fe/H] of Galactic RRab stars. Blue and red symbols denote field stars with [Fe/H] less than and greater than $-1.0$, respectively. Green symbols denote RRab stars in the relatively metal-rich disk globular clusters NGC 6338, NGC 6441, and 47 Tuc.

### *2.2 Metallicity effects in the RRab family*

The first metallicity effect found in the family of RR Lyrae stars is the crude regression of pulsation period on metal abundance (Preston, 1959, 1961) illustrated in Fig. 4. An early indication of this regression was provided by discovery of two spectroscopically normal RRab stars with short periods by Münch & Rivera Terrazas (1946). Shortly

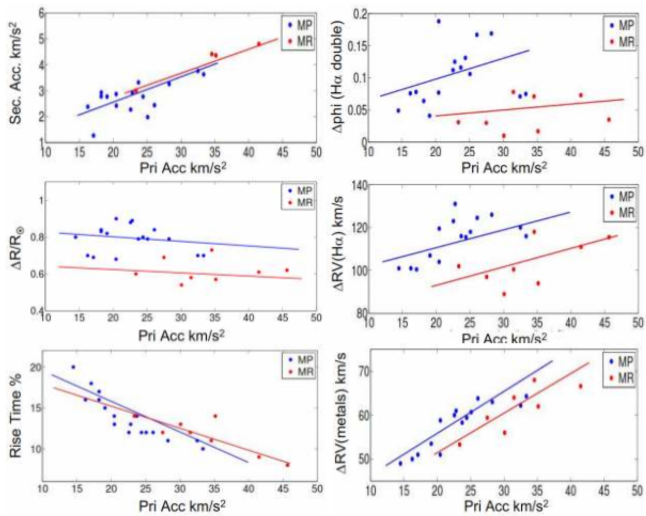


Fig. 5: Top left to bottom right present six observables: secondary acceleration, radius variation, rise time, duration of $H_\alpha$ doubling, $H_\alpha$ RV amplitude, and metal RV amplitude are plotted versus primary acceleration for metal–poor (blue) and metal–rich (red) RRab stars.

thereafter Kukarkin (1949), very likely unaware of the Münch & Rivera Terrazas (1946) observations, called attention to the preferentially low Galactic latitudes of RRab stars with periods less than 0.43 days, a first hint that a different species of RR Lyrae stars inhabits a flattened stellar subsystem of the Milky Way. Subsequent investigations, summarized by Layden (1995), provide abundant evidence that RR Lyrae stars occur in both the halo and the thick disk populations of the Milky Way. This is the second metallicity effect.

All calculations of the structure and evolution of horizontal branch stars predict that luminosity decreases with increasing metal mass fraction $Z$. The modest dependence on $Z$ illustrated in Figure 1 of Tornambe (1987) is reflected in (McNamara, 1997) calibration of extant Baade-Wesselink analyses, $M_V = 0.29$ [Fe/H] $+0.96$. An order–of–magnitude increase in [Fe/H] increases $M_V$ by only 0.3 mag. A successful GAIA mission should settle once and for all the magnitude of this third metallicity effect.

To these "historical" metallicity effects we (Preston, Sneden, & Chadid in preparation) add a collection of distinctions revealed by regressions of various observables provided by high resolution spectroscopy. We use maximum acceleration during primary light rise as our independent variable because it successfully resolves our RRab sample into metal–poor and metal–rich components. This is evident from inspection of blue and red regressions in Fig. 5. Many other regressions can be constructed from various other measured quantities. The regressions chosen for display here suffice to show that metal–poor and metal–rich RRab stars, identified by use of a simple abundance cut near [Fe/H] $= -1$, are distinct species of pulsating stars.

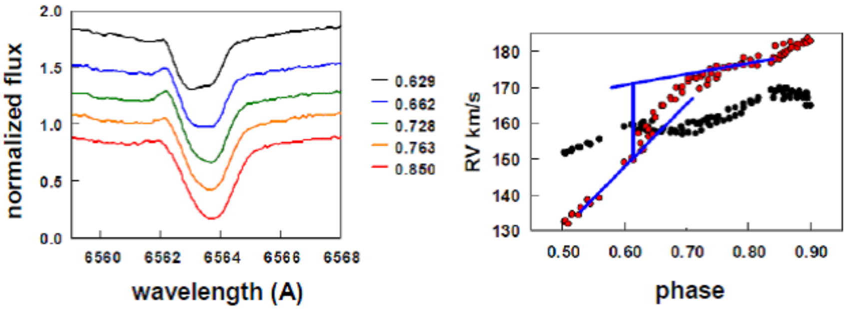


Fig. 6: Left panel: $H_\alpha$ profiles of RV Oct during the ballistic shock. Right panel: radial velocities of metal lines (black symbols) and the unresolved $H_\alpha$ doublet (red symbols). The blue lines indicate our suggested behavior of the two absorption components of the left pane of this Figure.

### *2.3 Shock phenomena*

Emission and line-doubling phenomena arise in a variety of stellar contexts (dMe, T Tauri, Be, Population II cepheids, interacting binaries, stellar explosions). Following the early ideas of Schwarzschild (1952) we attribute hydrogen and helium emission line episodes in RR Lyrae spectra to recombination that follows passages of shocks through atmospheric layers. Such shocks arise naturally in extant model calculations (Wallerstein, 1959; Hill, 1972; Fokin & Gillet, 1997).

Four such emission (shock) episodes can be identified during the pulsation cycles of most RRab stars.

1. The strongest shock, (Sanford, 1949; Schwarzschild, 1952), occurs during primary light rise. It produces the hydrogen and helium emission and double absorption profiles on 0.92<phase <0.10 illustrated in Figures 7 and 9 of (Preston, 2011).

2. Hill (1972) ballistic shock produces the secondary light rise just before minimum light. A violet-displaced $H_\alpha$ emission edge that appears during this shock (Gillet & Crowe, 1988) is accompanied by brief, marginally-resolved line doubling illustrated in the left panel of Fig. 6. The stronger violet-displaced absorption core at phase 0.629 weakens and is replaced by a red-displaced core which dominates at phase 0.728 and thereafter.

3. Red-displaced emission edges at $H_\alpha$ appear during the expansion phases following Shock number 1. These can be seen in profiles 4–8 counting upward in Figure 7 of (Preston, 2011). Adequate phase coverage for two stars permit good estimates of the onset and disappearance of this feature, which lasts for approximately one quarter of the pulsation cycle and ends rather abruptly when the photospheric radii reach their maximum values. The phase intervals for RV Oct and WY Ant are, respectively, 0.17<phase<0.42 and 0.15<phase<0.40. The location of the putative shock that produces this emission is unknown.

4. is identified by the reappearance of helium emission and double-absorption at maximum light, as reported by Preston (2009). The emission is weak but defi-

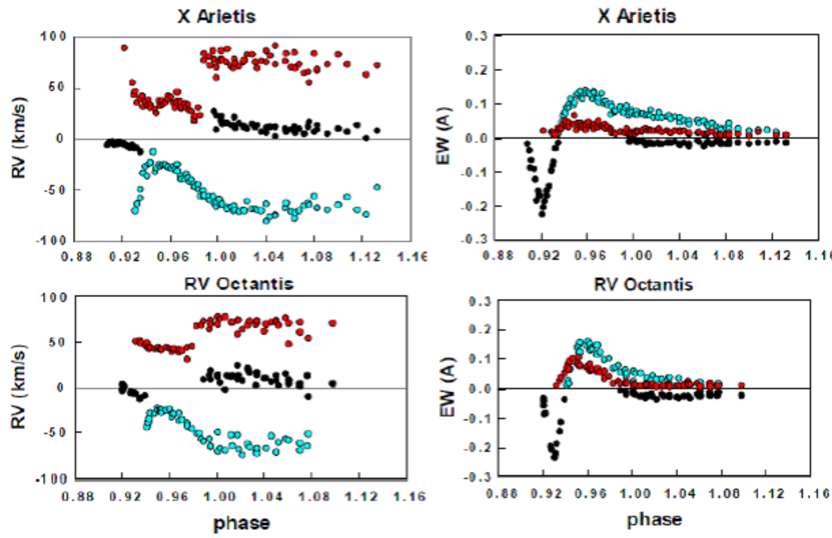


Fig. 7: Helium histories for two RRab stars, X Ari and RV Oct. Left panels: Apparent radial velociies. Right panels: Equivalent widths of violet absorption (blue symbols), red absorption (red symbols), and emission (black symbols). Emission equivalent widths are negative numbers.

nite. I suppose that hydrogen features associated with this shock are masked by strong absorption lines associated with the primary shock. This is pure conjecture on my part. The most surprising aspect of this shock is the abrupt redward velocity shift of the red helium absorption component shortly before maximum light, phase ≈ 0.98, for X Ari and RV Oct that is evident in the left panels of Fig. 7. For most RRab stars this shift is swift, but continuous.

I only speculate that the helium emission attributed to shock number 4 may be a manifestation of transient "coronal" activity suggested by the recent model calculations of Stellingwerf (2013). Were Bohdan Paczyński with us today, I believe that such speculation would please him, if only long enough for him to dismiss it–a good stopping point for this lecture!

Analysis of the myriad of phenomena reported herein present challenges for the future better left to astronomers with backgrounds in physics and mathematics superior to mine. The data themselves comprise my legacy for the next generation.

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