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Method of LSD profile asymmetry for estimating the center of mass velocities of pulsating stars

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Abstract. We present radial velocity analysis for 20 solar neighborhood RR Lyrae and 3 Population II Cepheids. High-resolution spectra were observed with either TNG/SARG or VLT/UVES over varying phases. To estimate the center of mass (barycentric) velocities of the program stars, we utilized two independent methods. First, the 'classic' method was employed, which is based on RR Lyrae radial velocity curve templates. Second, we provide the new method that used absorption line profile asymmetry to determine both the pulsation and the barycentric velocities even with a low number of high-resolution spectra and in cases where the phase of the observations is uncertain. This new method is based on a least squares deconvolution (LSD) of the line profiles in order to analyze line asymmetry that occurs in the spectra of pulsating stars. By applying this method to our sample stars we attain accurate measurements (± 2 $\mathrm{km\,s^{-1}}$) of the pulsation component of the radial velocity. This results in determination of the barycentric velocity to within 5 $\mathrm{km\,s^{-1}}$ even with a low number of high-resolution spectra. A detailed investigation of LSD profile asymmetry shows the variable nature of the project factor at different pulsation phases, which should be taken into account in the detailed spectroscopic analysis of pulsating stars.

1. Introduction

RR Lyrae stars are important tracers of galactic dynamics and evolution. Their high luminosity makes them good tracers for investigations of the Galactic halo and of stellar systems outside the Milky Way. Together with the proper motion, the center-of-mass velocity (or barycentric velocity, V_γ) of this type of stars is thus a fundamental parameter that should be derived with the highest possible accuracy. Indeed, the uncertainties associated to the determination of barycentric velocities of RR Lyrae stars constitute a long-standing problem, which also affects the accuracy of RR Lyraes as distance indicators. Several studies have been devoted to the problem (Jeffery et al. 2007; For et al. 2011; Sesar 2012). Briefly, two main methods have been traditionally employed. In the first approach, one relies on a template radial velocity curve, that is shifted and scaled to match the observed radial velocity at a few different phases. This method becomes more accurate when observations covering several phases are available.

Otherwise, the second approach may turn out to be useful: RR Lyraes are observed at a particular phase (usually around 0.5) during a pulsation period, when the observed radial velocity most likely equals the barycentric velocity of the star. However, this solution is not realistically applicable in the case of large surveys, where often there is no possibility to schedule the observations in convenient phases.

In this work, we apply a method which allows to estimate the barycentric velocity of RR Lyrae stars from just a few observations at random phases. The method is based on (i) investigations of the absorption line profile asymmetry that occurs during the radial pulsations and (ii) determination of the absolute value of the pulsation component using line profile bisectors, taking carefully into account limb-darkening effects. We test our method on a sample of solar neighborhood RR Lyraes that was investigated in a previous paper (Pancino et al. 2015) and on densely-spaced observations of RR Lyr (Fossati et al. 2014).

2. Sample of program stars

The analysed sample consists of 20 RR Lyr stars and 3 Population II Cepheids. The stars were observed as part of different observational programs with the SARG echelle spectrograph at the Telescopio Nazionale Galileo (TNG, La Palma, Spain) and with the UVES spectrograph at ESO's Very Large Telescope (VLT, Paranal, Chile). Furthermore, additional archival spectra were retrieved from the ESO archive. The resolving power of the spectra obtained with SARG is $R = \lambda/\delta\lambda \approx 30\,000$ with an average signal-to-noise ratio S/N $\approx$ 50-100 and spectral range from 4000 to 8500 Å. UVES spectra have a higher resolving power, $R \approx 47\,000$, and S/N $\approx$ 70-150 and cover the wavelength range from 4500 to 7500 Å. The observations were performed at random pulsation phases generally three times for each star; however, for some stars we have more observations, or just one. The general information about the program stars are presented in Pancino et al. (2015).

3. Barycentric velocity of pulsating stars

From an observational point of view, the barycentric velocity, V_γ, can be described using the following components:

$$V_\gamma = v_{\rm obs} + v_\odot - v_{\rm puls} \qquad (1)$$

where $v_{\rm obs}$ is the observed velocity of the star along the line of sight, $v_\odot$ is the heliocentric correction, and $v_{\rm puls}$ is the pulsation velocity of the radially pulsating star. We will see in the following sections that the determination of $v_{\rm puls}$ requires a treatment of limb-darkening effects, generally included in the form of a *projection factor*. The sum $v_{\rm obs} + v_\odot$ is the heliocentric radial velocity of the star, $v_{\rm rad}$, at any given phase in the pulsation cycle. In other words, the determination of the barycentric radial velocity of pulsating stars such as RR Lyraes and Cepheids requires — in principle — the determination of two observational quantities: (i) the observed radial velocity (with respect to the heliocentric reference) and (ii) the pulsation component at the moment of the observation or, better, at the specific pulsation phase of the observations (corrected for limb-darkening effects).

4. Method of bisectors

We propose a method for the determination of the barycentric radial velocity that is based on the asymmetry of line profiles in pulsating stars, which vary along the pulsation cycle and thus can also be used to infer the pulsational component of the barycentric velocity. The method, hereafter referred to as *bisectors method* for brevity, allows for an estimate of the barycentric velocity of pulsating stars with a sparse phase sampling, and it works even with just one observation, albeit with a slightly larger uncertainty.

To determine line profiles, we use the LSD method (least-squares deconvolution, Donati et al. 1997) that derives a very high S/N ratio line profile for each spectrum from the profiles of many observed absorption lines, under the assumption that the vast majority of lines have the same profile, and that different line components add up linearly. Depending on the number of used lines, the reconstructed LSD profile can have an extremely high S/N ratio, rarely attainable with RR Lyrae observations on single lines. The original LSD method by Donati et al. (1997) was modified and extended to different applications by several authors. We used the Tkachenko et al. (2013) implementation, and our workflow can be outlined as follows:

1. We compute the LSD profile of each observed spectrum; this also allows for an independent estimate of v_{obs};

2. We compute a theoretical library of LSD profiles, predicting the line profile asymmetries at each pulsation phase, and we compute the bisectors of each of the profiles; one of the example of such grid is presented on top panel of Fig. 1;

3. We compute the bisector of the observed LSD line profile and compare that to the theoretical ones, to determine which pulsation velocity corresponds to the observed asymmetry of the LSD bisector; in our computation, we implement a full description of limb-darkening effects.

Once the observed and pulsational components are known, the barycentric velocity can be trivially obtained from equation (1). The final radial velocity analysis of programme stars is still in progress and final results will be published later, in this paper we presented only the intermediate results.

5. A test on RR Lyrae

In order to test the method, we applied it to the prototype of the RR Lyrae class: RR Lyrae itself. We used the 56 high-resolution ($R = 60\,000$) and high signal-to-noise (100–300) spectra of RR Lyr taken along the whole pulsation cycle, including Blazhko phases, kindly provided by Fossati et al. (2014, private communication). The good phase sampling allows us to test the method thoroughly along the whole pulsation cycle.

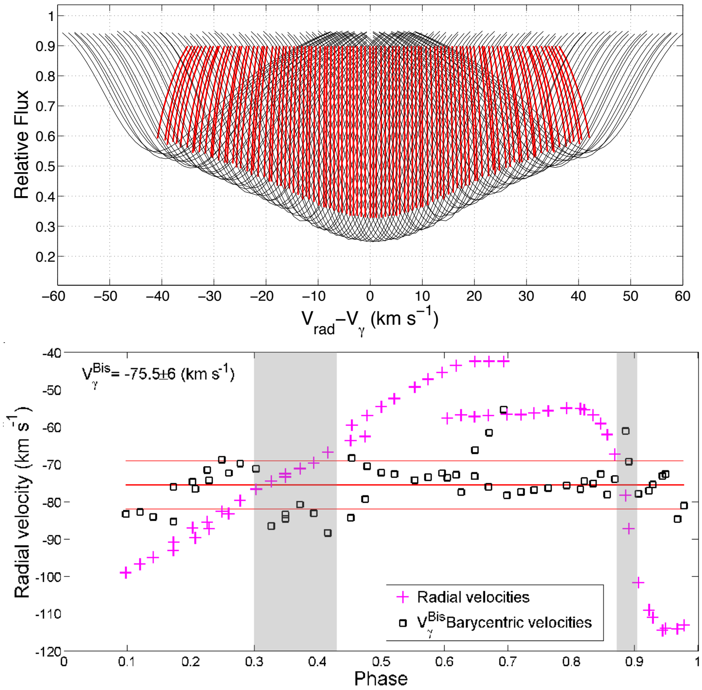

Figure 1. *Top panel:* Example of LSD profiles and bisector computed from model spectra of RR Lyrae with pulsation velocities from -50 to $+50$ km s^{-1}. *Bottom panel:* Barycentric velocities of RR Lyr (black squares - by using method of bisectors) inferred from radial velocities measurements (magenta crosses) at different phases. Grey regions presumably correspond to the phases with low pulsation velocities, that do not affect the line profile asymmetry.

For each spectrum we computed the LSD-profile and the bisectors, deriving both $v_{\rm rad}$ and $v_{\rm puls}$ with the same method used for our programme stars. The results are presented in bottom panel of Figure 1, where the values of the radial velocity and barycentric velocity at different phases are indicated with magenta crosses and black squares, respectively. We finally derived a mean value of $V_{\gamma}^{\rm Bis} = -75.5 \pm 6$ km s^{-1}. However, in the phase ranges 0.2–0.3 and 0.85–0.90, deviations up to 15 km s^{-1} were found. The explanation is as follows: in these phase ranges, the pulsational velocity is small, and our method is not very sensitive to $|v_{\rm puls}| < 5$ km s^{-1}, and also, during the shock phase 0.85–0.90 the absorption iron lines are disappearing, that causes difficulties in the correct determination of line profile asymmetries.

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