The p and $k-$factors of the Classical Cepheid δ Cep

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Probing the dynamical structure of Cepheid atmospheres is of primary importance in order to better constrain the cosmic distance ladder. It is indeed now well-known that the projection factor (or p-factor), that is used in the Baade-Wesselink method of distance determination of Cepheids, is sensitive to the atmospheric velocity gradient and other subtle dynamical effects. Relying on *HARPS-N* high resolution spectroscopic observations, we have measured the atmospheric velocity gradient of δ Cep for the first time, and we found an agreement with the hydrodynamical model of the star. Besides, the mysterious k-term, a residual γ-velocity of the order of $1-2\,\mathrm{km\,s^{-1}}$, seen in *HARPS-N* data of δ Cep, is now physically understood thanks to recently published predicted spectroscopic properties of two-dimensional time-dependent Cepheid models.

1 Introduction

Classical Cepheids are yellow giant and supergiant pulsating stars used as standard candles in the Universe (Riess et al., 2016). The Baade-Wesselink (BW) method is

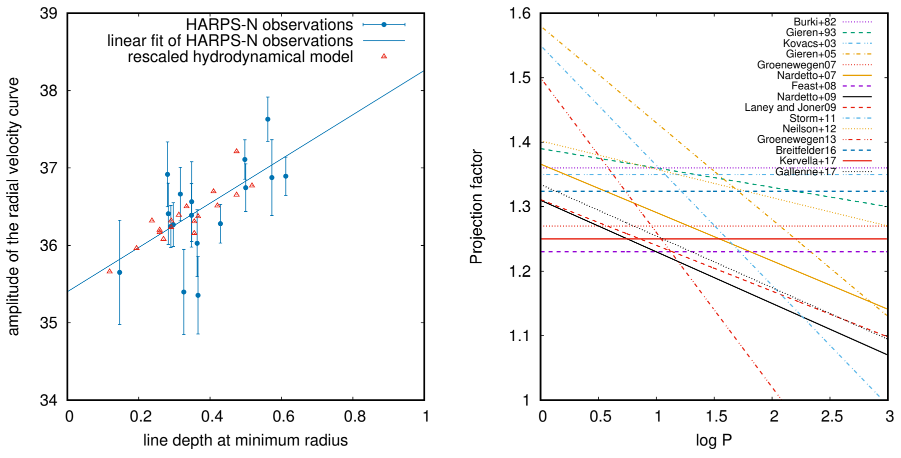

Fig. 1: Left: Amplitude of the radial velocity curves for the 17 metallic spectral lines plotted versus the line depth (at minimum radius) for the rescaled hydrodynamical model (red triangles), and for the *HARPS-N* spectroscopic observations (blue circles). This plot is extracted from Nardetto et al. (2017). Right: The period-projection factor relations from the literature are inconsistent (Burki et al., 1982; Gieren et al., 1993; Kovács, 2003; Gieren et al., 2005; Groenewegen, 2007; Nardetto et al., 2007; Feast et al., 2008; Nardetto et al., 2009; Laney & Joner, 2009; Storm et al., 2011; Neilson et al., 2012; Groenewegen, 2013; Breitfelder et al., 2016; Kervella et al., 2017).

used to determine the distance to Cepheids in the Milky Way and beyond, in the Magellanic Clouds, and consists in combining the angular size variations of the star with its linear size variation. The angular size variation can be determined using infrared surface brightness relations (Storm et al., 2011), interferometry (Kervella et al., 2004), or even a full set of photometric and interferometric data (Mérand et al., 2015, SpectroPhoto-Interferometry of Pulsating Stars or SPIPS approach). The linear size variation is deduced from spectroscopy. The radial velocity curve is first derived from a spectral line profile or a set of spectral line profiles (cross-correlation). The radial velocity curve is then multiplied by a projection factor (or p-factor), which is used to derive the true pulsation velocity curve of the star. Finally, this pulsation velocity curve is time-integrated in order to derive the radius variation of the star. In this approach, the average value of the radial velocity curve is forced to zero before integrating. However, depending on the spectral line considered or the method used to derive the radial velocity curve, the average value of the radial velocity curve is not the same. This effect is related to the so-called k-term of Cepheids.

2 The p-factor of δ Cep from *HARPS-N* Data

Using *HARPS-N* data, Nardetto et al. (2017) derived for the first time the cycle-averaged atmospheric velocity gradient of δ Cep, i.e., the amplitude of the radial velocity as a function of line depth. In order to reproduce all observables, we had to rescale our hydrodynamical model of δ Cep (already published by Nardetto et al. (2004)), by applying a 7.8% increase on the amplitude of the velocity and radius vari-

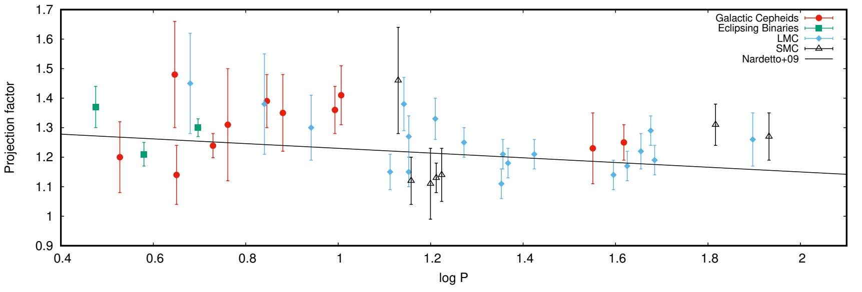

Fig. 2: The inverse BW observational projection factors for Cepheids in the Galaxy (Breitfelder et al., 2016, and references therein), LMC, and SMC (Gallenne et al., 2017) plotted as a function of the period in days. The three values derived from Cepheids in eclipsing binaries are also indicated with green squares (Pilecki et al., 2017, and references therein). The period-projection factor relation from Nardetto et al. (2009) is shown by a black line.

ation curves, which, by definition, left the projection factor unchanged. The observed and modeled atmospheric velocity gradient are plotted in Fig. 1-left. The agreement between observations and the hydrodynamical model shows that our physical understanding of the projection factor is correct, at least for δ Cep. However, there are still disagreements in the derived period-projection factor relations as shown by Fig. 1-right. Strong efforts are now done in order to constrain the p-factors observationally (see Fig. 2).

3 The k-factor

The motion of Cepheids in the Milky Way is confusing and has led to disagreements in the literature. If an axisymmetric rotation of the Galaxy is assumed, Cepheids appear to "fall" towards the Sun with a mean velocity of about $2\,\mathrm{km\,s^{-1}}$. This residual velocity shift has been dubbed the k-term, and was first estimated by Joy (1939) to be $-3.8\,\mathrm{km\,s^{-1}}$. A longstanding debate exists as to whether this phenomenon was truly related to the actual motion of the Cepheids and, consequently, to a complicated rotating pattern of our Galaxy, or if it was the result of effects within the atmospheres of the Cepheids. Nardetto et al. (2008) have shown using spectral line asymmetries that this apparent motion towards us stems from an intrinsic property of Cepheids, and they proposed a method to derive the center of mass velocity of the Cepheids. We know from recent theoretical investigations that the k-term ($k = \frac{-v_0}{p}$) is due to the granulation of Cepheids which creates up- and down-flows of velocity v_0 (Vasilyev et al., 2017). The effect of granulation on the radial velocity curves of several spectral lines is shown in Fig. 3 in the case of δ Cep.

4 Conclusion

The p and k-factors of the prototype of classical Cepheid δ Cep are now physically understood. However, more work is necessary in order to constrain and analyze the period projection factor relation of Cepheids. Moreover, even if the impact of the k-factor is believed to be negligible on the derived distance, further investigations based on 2D time-dependent modeling is necessary in order to confirm it.

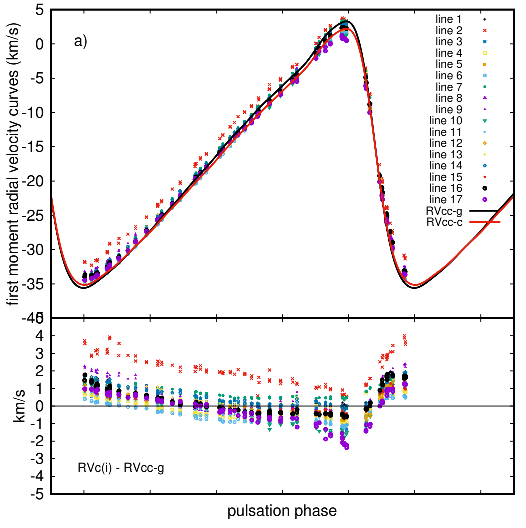

Fig. 3: The first moment radial velocity curves of δ Cep for the 17 unblended spectral lines considered (RV_c(i)) is plotted as a function of the pulsation phase (Nardetto et al., 2017). RV_{cc-g} and RV_{cc-c} are the cross-correlated radial velocity curves as derived from the standard *HARPS-N* pipeline using a Gaussian fit or considering the first moment of the cross-correlated spectral line profile, respectively. We also plot in the sub-panel the individual RV_c measurements minus RV_{cc-g}, so that the γ-velocities become obvious.

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