Spectroscopic Properties of a Two-Dimensional Cepheid Model

Valeriy Vasilyev[1,2], Hans-Günter Ludwig[2], Bernd Freytag[3],
Bertrand Lemasle[4] and Marcella Marconi[5]

1. Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
2. Zentrum für Astronomie der Universität Heidelberg, Landessternwarte, Königstuhl 12, D-69117 Heidelberg, Germany
3. Department of Physics and Astronomy at Uppsala University, Regementsvägen 1, Box 516, SE-75120 Uppsala, Sweden
4. Zentrum für Astronomie der Universität Heidelberg, Astronomisches Rechen-Institut, Mönchhofstr. 12-14, D-69120, Heidelberg, Germany
5. INAF -Osservatorio Astronomico di Capodimonte, Via Moiariello 16, I-80131 Napoli, Italy

The chemical composition of Cepheid variables can provide information on the chemo-dynamical evolution of the Galaxy and beyond. The standard method for determining atmospheric parameters and abundances of Cepheids is based on one-dimensional plane-parallel hydrostatic model atmospheres, where convection is treated by Mixing Length Theory. We check the validity of the quasi-static approach against a two-dimensional dynamical Cepheid model computed with CO5BOLD. The spectroscopic investigation of the two-dimensional Cepheid model allowed to derive projection factors and to explain the residual line-of-sight velocity of Galactic Cepheids, long known as the "K-term", by line shifts of convective origin. Moreover, hydrostatic 1D model atmospheres can provide unbiased estimates of stellar parameters and abundances of Cepheids for particular phases of their pulsations.

1 Introduction

Pulsating stars, especially classical Cepheids, play a particular role in astronomy. Due to the existence of a remarkable relation between the pulsational period and luminosity (Leavitt, 1908), they can be used as a step in establishing the extragalactic distance scale (Riess et al., 2016).

Classical Cepheids are young objects and, thus, carry information on the chemical composition of the present interstellar medium. This helps to investigate the accretion history of the Milky Way, and put some constraints on its chemo-dynamical evolution. Especially, Cepheids allow us to measure the metallicity gradients in the Galaxy (Andrievsky et al., 2002; Lemasle et al., 2013; Andrievsky et al., 2016) and in the Magellanic Clouds (see Lemasle et al., this volume). However, the related abundance determinations are based on hydrostatic stellar atmosphere models, whose validity has not been checked in a context of pulsating stars.

2 The Time-dependent Two-dimensional Cepheid Model

Radiation hydrodynamics simulations of a short-periodic Cepheid-like variable star restricted to two spatial dimensions in Cartesian geometry were performed with the CO5BOLD code (Freytag et al., 2012). The radiative transport is non-local but simplified by using the gray approximation.

The run analyzed here starts from initially plane-parallel (except for small disturbances added for breaking the symmetry) and hydrostatic conditions. The model has a nominal effective temperature of $T_{\text{eff}} = 5600\,\text{K}$, a constant depth-independent gravitational acceleration of $\log g = 2.0$, and solar metallicity. The most important feature of the model is the treatment of convective and pulsational motions from first principles. During the initial stages of the temporal evolution of the model, convection is the main dynamical driver. Later on, the model exhibits self-excited oscillations with a period of 2.8 days. Considering the pulsating and non-pulsating phases of the temporal evolution of the 2D model allows us to isolate the influence of convection on its spectroscopic properties. Details of the model and the spectroscopic investigations are presented in Vasilyev et al. (2017a,b).

We took a set of artificial neutral and singly ionized iron lines covering a wide range of excitation potentials (from 1 eV to 10 eV) and line strengths (from 10 mÅ to 130 mÅ). For the given line list, we performed spectral synthesis calculations with the LINFOR3D[1] code (Gallagher et al., 2017) for 150 2D snapshots covering six full pulsational periods, and 99 snapshots taken during the mostly convective, initial phase of the temporal evolution of the 2D model. For each synthetic line, we measured the radial velocity applying three different methods: (i) a Gaussian fit of the whole line profile, (ii) a parabolic fit of the line core below 70% of the continuum level, and (iii) center of mass of a line, given by the first moment of its flux distribution.

3 Interpretation of the *K*-term

The ensemble of Galactic Cepheids shows a residual line-of-sight velocity, long known as the "*K*-term" (Parenago, 1945; Pont et al., 1994). It manifests itself as systematic blue-shift when assuming an axisymmetric rotation model of the Milky Way. Pont et al. (1994) concluded that it can be a result of a statistical effect, an intrinsic effect of Cepheids, or a real dynamical effect of the Galaxy. Nardetto et al. (2008, 2009) performed high-resolution spectroscopic investigations of Galactic Cepheids and derived a *K*-term on a level of $-1.0\,\text{km}\,\text{s}^{-1}$, interpreted as a result of the complex dynamics of the Cepheid atmosphere, pulsations, convective flows, nonlinear physics, and complex radiative transport. Analysis of a Cepheid in a binary system gives a *K*-term of $-1.1\,\text{km}\,\text{s}^{-1}$ (see Pilecki et al., this volume).

Line shifts measured for our synthetic lines averaged over time for the non-pulsating and pulsating phases are shown in the two panels of Fig. 1. Averaged over all spectral lines, we obtain a mean radial velocity of around $-1\,\text{km}\,\text{s}^{-1}$ which does not depend sensitively on the presence or absence of pulsations in the model. Since the main dynamical process during the non-pulsating phase is convection, we conclude that the *K*-term is primarily a result of a convective blueshift, which is well-known in non-pulsating late-type stars. Our evaluation of the *K*-term does not

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[1] http://www.aip.de/Members/msteffen/linfor3d/

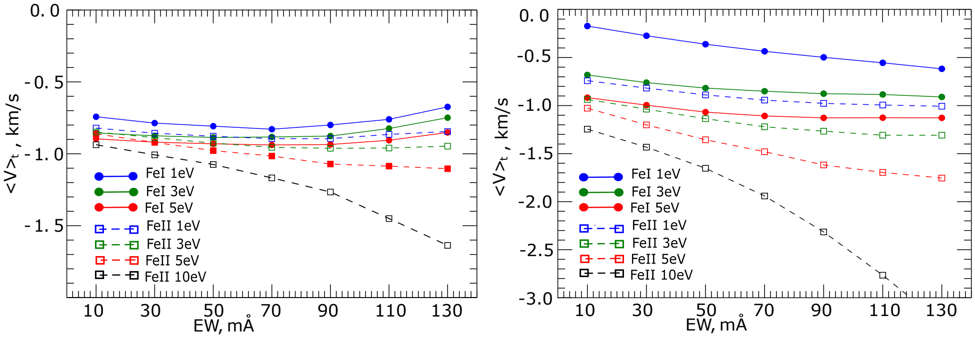

Fig. 1: Temporally averaged radial velocities of synthetic neutral and singly ionized iron lines as a function of the line strength for the non-pulsating (left panel) and pulsating (right panel) phases of the evolution of the 2D model. In the presented case, line shifts were measured by fitting a Gaussian to the whole line profile.

depend on the method of the measurement of the radial velocity and is compatible with recent estimates from observations.

4 Estimation of p-factors

A projection factor, or p-factor, is a key quantity in the Baade-Wesselink method for measurement of distances. The p-factor is the coefficient of proportionality between the spectroscopic radial velocity and pulsational velocity, which is the velocity of layers in the photosphere. The 2D model provides information about the velocity of the optical depth surface at $\tau_R \approx 1$. It allows us to determine the p-factor. Depending on the particular line, the derived projection factors are between 1.23 and 1.27. Our estimates fall in the range of observationally determined p-factors (Nardetto et al., 2009; Mérand et al., 2015; Marconi et al., 2013, see also Pilecki et al., and Nardetto et al., this volume).

5 Biases in the Determination of Atmospheric Parameters with Hydrostatic Models

In this section, we discuss potential biases introduced by applying hydrostatic model atmospheres in the interpretation of Cepheid spectra. For fixed (solar) iron abundance, the equivalent widths of 49 synthetic Fe I and Fe II lines from the 2D model with excitation potentials of 1, 3, and 5 eV were taken as artificial observations. We calculated a grid of 1D LTE hydrostatic plane-parallel stellar atmosphere models covering a wide range of effective temperatures and surface gravities. For the 1D models, we performed spectral synthesis calculations for the same lines as in the 2D case, but additionally varying the microturbulent velocity and iron abundance. Based on the grid of synthetic 1D equivalent widths, we determined gravity, microturbulent velocity, and metallicity, assuming that effective temperature is known since in observations the effective temperature is often obtained by non-spectroscopic means. We fixed the 1D effective temperatures to the values found during the evolution of the 2D model. Surface gravity, microturbulence, and iron abundance were

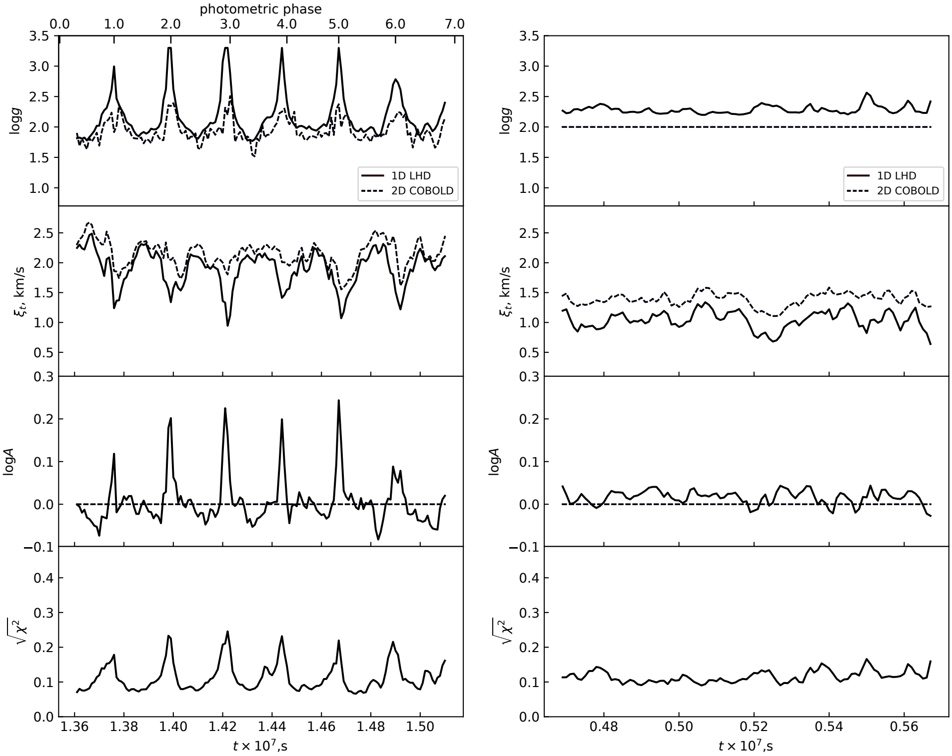

Fig. 2: Results of the determination of the surface gravity, microturbulent velocity, and iron abundance for the pulsating (left panel) and non-pulsating (right panel) phase. The parameters of the 2D model are shown by dashed lines for both phases. Reconstructed parameters using 1D models are shown by solid lines. The relative RMS deviation in line strengths between the 2D and 1D models are shown in the bottom panels.

derived for the pulsating and non-pulsating phases independently at each instance in time by minimizing the sum of relative differences in equivalent widths between the 1D and 2D models. The results are shown in Fig. 2. For the phase of maximum compression, the 1D analysis overestimates surface gravity and iron abundance. However, for a range of photometric phases, $\phi_{\rm ph} \approx 0.3 - 0.65$ corresponding to the maximum expansion and start of compression, the hydrostatic approximation gives an unbiased estimate of the stellar parameters and abundances – at least for the short-periodic model Cepheid investigated here.

6 Summary and Conclusions

We performed a spectroscopic investigation of a time-dependent two-dimensional model of a short periodic Cepheid assuming LTE conditions in the line formation. We conclude that the K-term known for Galactic Cepheids is a consequence of a convective blueshift of lines. Pulsations play a lesser role. We derived theoretical p-factors in a range also obtained observationally. Approximations made in the model, as well as limited statistics, preclude more precise statements here. Estimates of the atmospheric parameters and composition of a Cepheid based on hydrostatic models are potentially biased, but biases can be mitigated by an appropriate choice of the pulsational phase during which observations are taken.

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