Mem. S.A.It. Vol. 80, 622

Memorie della

Accounting for convective blue-shifts in the determination of absolute stellar radial velocities

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Abstract. For late-type non-active stars, gravitational redshifts and convective blueshifts are the main source of biases in the determination of radial velocities. If ignored, these effects can introduce systematic errors of the order of ~ 0.5 km s^{-1}. We demonstrate that three-dimensional hydrodynamical simulations of solar surface convection can be used to predict the convective blue-shifts of weak spectral lines in solar-like stars to ~ 0.070 km s^{-1}. Using accurate trigonometric parallaxes and stellar evolution models, the gravitational redshifts can be constrained with a similar uncertainty, leading to absolute radial velocities accurate to ~ 0.1 km s^{-1}.

Key words. Stars: abundances – Stars: atmospheres

1. Introduction

A number of factors get in our way when trying to derive absolute radial velocities of stars from observed wavelengths of spectral lines. In special relativity, the Lorentz factor affects the observed Doppler shifts, making it dependent on the velocity component perpendicular to the line of sight, which is not known a priory. Photons also become redder as they climb out of the gravitational potential of stars; an effect that links the photon's wavelength to the stellar mass-to-radius ratio. Pressure shifts, induced by collisions between the emitter atom or molecule and other perturbers, can also be confused with Doppler shifts. Orbiting companions, planets, and activity cycles are other potential sources of variability in the observed wavelengths. In addition, one needs to disentangle the motion of a star's center of mass from other motions in its envelope and atmosphere related, for example, to convection, pulsation, or rotation.

Recognizing these and other issues involved in the interpretation of observed Doppler shifts of spectral lines, the IAU has recommended that research papers report the 'barycentric radial-velocity measure' (see Lindegren & Dravins 2003). This is a well-defined quantity that can be readily determined from spectroscopic observations alone, and which only includes corrections for the motion of the observer relative to the barycenter of the solar system.

Despite a long list of potential distortions, it is important to underline that for most stars

Send offprint requests to: C. Allende Prieto the majority of these effects amount only to < 0.1 km s^{-1}. *Most stars* are slowly-rotating non-active late-type dwarfs, and for them only two contributors are expected to be important at the level of several tenths of a kilometer per second: surface convection and gravitational redshifts.

The gravitational redshift from the solar photosphere to 1 AU, amounts to 633.5 m s^{-1}, and the same effect on the Earth's gravitational field, reduces it slightly to 633.3[1] m s^{-1}. The gravitational shifts increase slightly for more massive stars along the main sequence, but are of course much smaller for giants, and much larger for white dwarfs (see Dravins et al. 1999). To predict the gravitational redshift, one needs an estimate of the mass-to-radius ratio of the emitting star. When accurate trigonometric parallaxes are available, such as those from Hipparcos for nearby ($<$ 100 pc) stars, one can use stellar evolution models to determine masses and radii of stars within 8% and 5%, respectively (Allende Prieto & Lambert 1999). For a late-type star, this implies a 10% uncertainty in the estimated gravitational redshift, or about 50 m s^{-1}.

Surface convection induces offsets in the wavelengths of solar spectral lines of up to $\sim$0.5 km s^{-1}. This is the net effect of the upward motion of hot gas (granules) combined with narrower and faster downflows (intergranular lanes). Larger blue-shifts are observed for the spectral lines formed deeper in the photosphere, where convection strengthens (see, e.g., Dravins 1982).

The stronger lines of atomic iron observed in the solar spectrum, with an equivalent width larger than about 200 mÅ, appear free from net convective shifts (Allende Prieto & García López 1998). This fact can be used to empirically correct for such shifts: about two dozen lines measured in the solar atlas of Kurucz et al. (1984) give an average of 623±12 m s^{-1}. Similar patterns are observed in cooler dwarfs, but they are hard to detect in warmer objects due to the relative shortage of strong lines (see Ramírez et al. in these proceedings).

Three-dimensional hydrodynamical models offer another route to predict and correct convective shifts. Asplund et al. (2000a) found an rms scatter of about 50 m s^{-1} between the predicted and observed convective shifts for some 30 Fe I solar lines weaker than 60 mÅ. We expand that work to include an order of magnitude more lines, and evaluate a second solar simulation.

[1] On the surface of the Earth, the gravitational redshift along a height of 45m induces a change of $1/\mu$m s^{-1}, and was measured decades ago using Mössbauer spectroscopy (Pound & Rebka 1960).

2. Hydrodynamical simulations and spectral synthesis

In this work we analyze two independent simulations of solar surface convection from Asplund et al. (2000a,b; hereafter model N) and Wedemeyer et al. (2004; hereafter model G). Both simulations cover approximately a period of 50 minutes of solar time. We used one hundred $50 \times 50 \times 82$ snapshots from model N and nineteen $47 \times 47 \times 112$ snapshots from model G to compute the average emergent spectra.

The spectral synthesis was performed with the code ASSϵT (Koesterke et al. 2008). The mean intensity is computed with short-characteristics and the emergent intensity with long-characteristics. The flux is calculated from 21 rays. Cubic interpolation is used to derive the opacities from a pre-calculated grid in $\log T$ (steps of about 250 K) and $\log \rho$ (steps of 0.25 dex). The equation of state includes the most important molecules and ionization stages for elements up to einsteinium (Z = 99). The continuous opacities are derived from the Opacity Project and Iron Project photoionization cross-sections (see, e.g., Seaton 2005, Nahar & Pradhan 2005). Line opacities are from Kurucz's compilation, available from his web site, upgraded with Van der Waals damping constants from Barklem et al. (2000), when available.

3. Consistency checks

It should be emphasized that our choices of equation of state and opacities for the spectral synthesis calculation are not consistent with

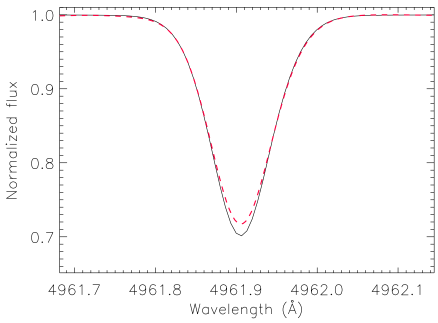

Fig. 1. Profiles for Fe I λ4961 computed with model N and two different 3D synthesis codes: `lte.x` (solid), and ASSϵT (broken line).

Table 1. Predicted Fe I convective blue-shifts for model N and two different synthesis codes

Transition λ (Å)	Residual flux	lte.x shift (km s^{-1})	ASSϵT (km s^{-1})
4918.9940	0.15	+0.351	+0.295
4961.9130	0.70	−0.459	−0.451
5044.2110	0.36	−0.251	−0.271
5006.1190	0.17	+0.279	+0.215
5049.8200	0.19	+0.112	+0.060
5068.7660	0.23	+0.010	−0.027
5076.2640	0.39	−0.276	−0.289
5096.9980	0.30	−0.133	−0.161
5098.6980	0.24	−0.046	−0.085

those used in the hydrodynamical simulations. Inconsistencies of this kind can vary the location of the line formation region and artificially modify the predicted line shifts.

We compared the spectral synthesis for 9 Fe I lines spanning a significant range of equivalent widths using model N and both ASSϵT, and the spectral synthesis code `lte.x` (described by Asplund et al. 2000a and references therein). While the line profiles show an imperfect agreement at a level of a few percent (see the example in Fig. 1), the predicted convective shifts, shown in Table 1, exhibit an rms scatter of 18 m s^{-1} between the two codes, convincing us that systematic differences in the equation of state or opacities were small enough to have a very limited impact on the predicted line shifts. Note that both codes predict positive shifts, i.e. red-shifts, for strong Fe I lines.

In addition, we checked that when using model N to compute the solar spectrum in a limited spectral window between 490 and 510 nm, our closest match of the solar atlas was found with an iron abundance consistent with that derived by Asplund et al. (2000b). Model G would tend to a higher value.

4. Observed vs. predicted line shifts

We have systematically measured Fe I line shifts in spectra computed with model N and model G, as well as in the solar atlas of Kurucz et al. (1984), in the range 400-800 nm. The models were smoothed to a resolving power of about 430,000 (approximately that of the solar atlas), and with a rotation profile for $v_{\rm rot} \sin i$ = 1.88 km s^{-1}. The central wavelengths of lines are determined by fitting third-order polynomials on seven data points around the line minima. We then subtract the wavelength shifts measured in the solar atlas from those measured in the model spectra.

The residuals for both models are displayed in Fig. 2. In agreement with the results of Asplund et al. (2000a), we find that the predictions from model N are excellent for weak lines, but the model predicts smaller blueshifts than observed for lines with equivalent widths stronger than about 60 mÅ. Very similar results are found for model G. Both models predict convective redshifts for Fe I lines stronger than about 200 mÅ, where the observed lines exhibit no convective shifts at all.

By restricting our analysis to lines weaker than 60 mÅ, we examine the residuals and find that their distributions can be approximated by Gaussians with a σ of about 70 m s^{-1}, as shown in Fig. 2. Both distributions are slightly biased, indicating that the predicted convective blueshifts are slightly smaller in the models than observed in the atlas by 30–35 m s^{-1}. Note that these errors are not fully associated with imperfections in the models, but there are uncertainties in the laboratory wavelenghts used, as well as distorting blends which are not accurately predicted.

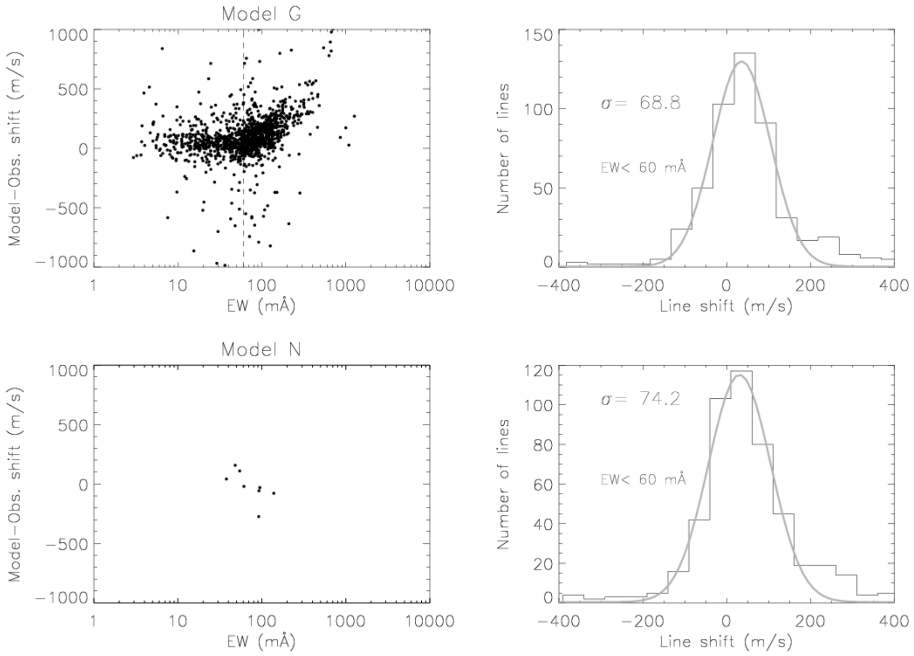

Fig. 2. Differences between the predicted and the observed Fe I line shifts, after subtracting the gravitational shift from the observed solar wavelengths. The right-hand panels show histograms of the residuals restricted to lines weaker than 60 mÅ.

5. Application to Gaia RVS

At the end of the mission, the Radial Velocity Spectrometer onboard Gaia will provide radial velocities for some 10^8 stars down to $V \sim 17$ mag (Wilkinson et al. 2005). The median error in the radial velocities will be about 10–15 km s^{-1}, however, results for bright individual stars, or averages for stellar systems or populations can be much more precise, and should avoid biases due to gravitational or convective shifts.

We have calculated the Gaia spectral window (847–874 nm) for the two solar models discussed above and cross-correlated them, as well as the observed spectrum, with a solar spectrum computed from a static 1D Kurucz model (e.g. Castelli & Kurucz 2003). These tests are carried out at a resolving power much higher than that of the RVS, as at R$\sim$ 11500 achieving a precision better than 100 m s^{-1} is challenging. We find that using a 1D model leads to a systematic error of -263 ± 3 m s^{-1}. Using any of the 3D models the correct zero point is found; the cross-correlation between 3D and 1D models gives offsets of -258 and -279 m s^{-1} for models G and N, respectively.

6. Conclusions

Provided with accurate parallaxes, it is possible to constrain the mass-to-radius ratio of a late-type star to typically 10 %, and gravitational redshifts to $\sim$ 0.050 km s^{-1}. By computing hydrodynamical simulations of surface convection, it is also possible to accurately predict the convective blue-shifts of weak absorption lines to $\sim$ 0.070 km s^{-1}. Therefore, we find that for most non-active late-type stars one can predict the biases in the spectroscopic radial velocities associated with gravitational gravitational and convective wavelength shifts to within $\sim$ 0.1 km s^{-1}.

In the case of Gaia mission, which plans to use cross-correlation templates calculated from one-dimensional static model atmospheres, 3D modeling can be used to correct the RVS radial velocities of late-type stars from convective shifts to within a few tens of m s^{-1}.

Acknowledgements. CAP is grateful to the IAU, a Sociedade Astronômica Brasileira, and UCL graduate school for their generous support. Thanks go also to Katia Cunha for her warm hospitality and to Vivien Reuter for answering inquiries swiftly and with a smile. HGL acknowledges support from EU contract MEXT-CT-2004-014265 (CIFIST).

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