Spectral modelling with interaction effects of the binary system Spica

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Abstract

Massive binary systems are crucial to improve our knowledge of the fundamental properties of massive stars, and synthetic spectra modelling with theoretical stellar atmospheres is commonly used in deriving some of these properties. However, the current stellar atmosphere models are designed for single spherical stars and therefore neglect interaction effects that occur in close binaries. We have developed a combined model that uses the TIDES code for computing the shape and the velocity field and the CoMBiSpeC model for the synthetic spectrum computation. This 2-in-1 model allows us to account for the interactions between the stars. We can now simulate the impact of the binarity on the spectra and refine the physical parameters of the binary systems. This model is presented here through the example of the spectral computation of Spica a double-lined, short-period (4.01452 days) spectroscopic binary (B1.5 IV-V + B3 V) in an eccentric orbit (e = 0.067). In this particular system, the strongest effects due to the binarity appear in the line profile variations and the shape of the radial velocity (RV) curve.

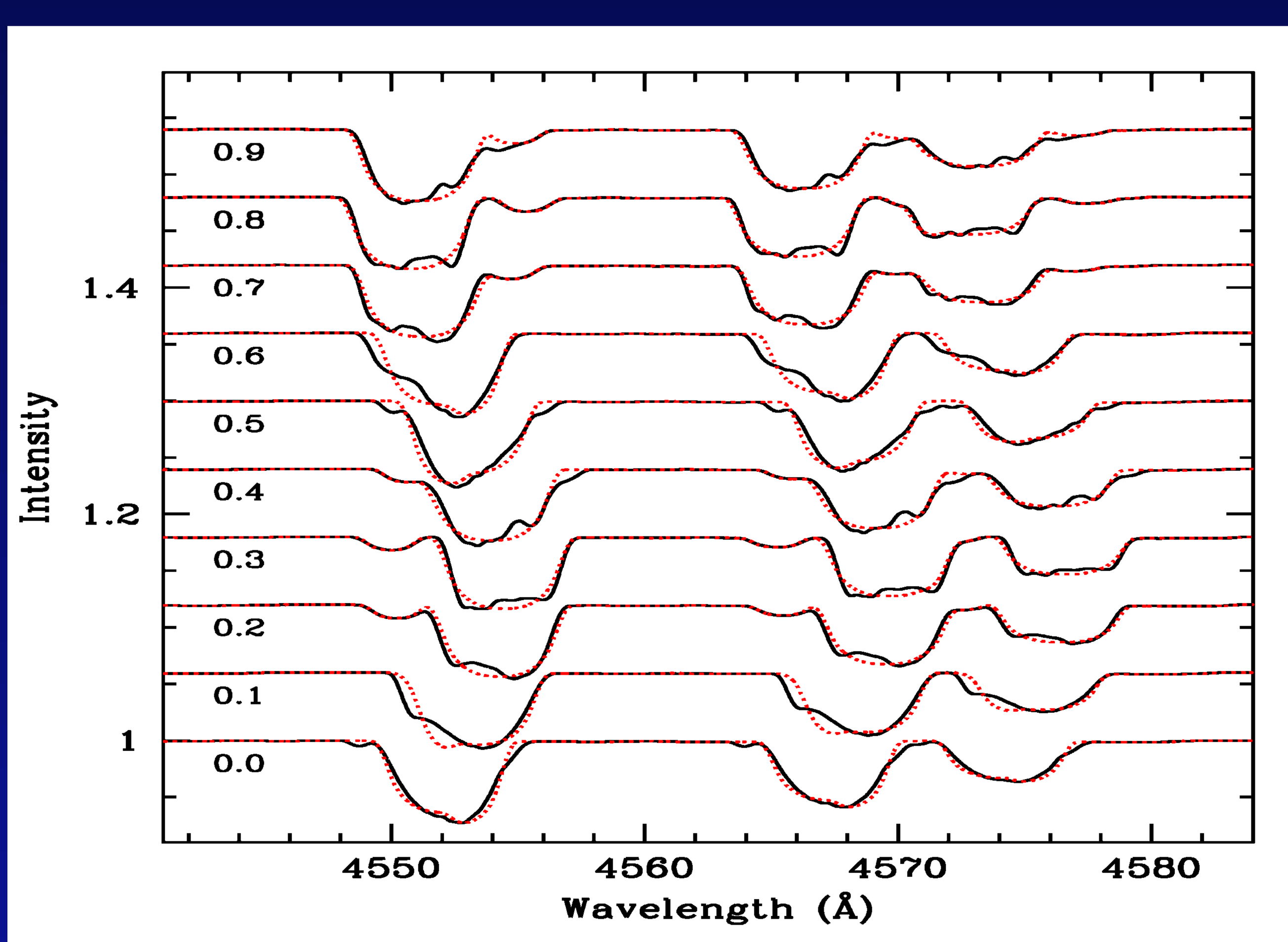

Fig. 1: Spectra perturbed (p) vs. unperturbed (u)

Synthetic primary + secondary combined spectra of the Si III triplet lines from orbital phase, φ=0 (periastron) to 0.9. The p spectra are in dark and the u spectra in red dots. The "bumps" in the primary star's p profiles are evident. They introduce difficulty in properly locating the contribution of the secondary except at φ ~0.3±0.05 and 0.8±0.05 when the lines are clearly resolved.

Model

The deformation and the velocity field of the stellar surface of the stars in the binary system are computed using the TIDES (tidal interactions with dissipation of energy through shear) code (perturbed, p, spectra) or assuming spherical stars (unperturbed, u, spectra). This requires prior knowledge of the stellar masses, radii and rotation velocity, as well as the full set of orbital parameters. The output consists of displacements and velocities (both radial and azimuthal) for each surface element as a function of time (see Moreno et al., 2011, A&A, 528, 48) for a complete description and Harrington et al. (2009, ApJ, 704, 813) for a detailed description of the calculations that were performed for Spica. We use the grid of stellar atmosphere models computed with TLUSTY (Lanz, & Hubeny, 2007, ApJS, 169, 83) to produce NLTE emergent flux spectra with microturbulent speeds, ζ =15 km/s, $T_{eff,1}$ = 22000-25000K, $\log(g)_1$ = 3.75-4.00, $T_{eff,2}$ = 17000-22000, and $\log(g)_2$ = 4.00-4.25. The metallicity of these spectra is Solar and they are not rotationally broadened. Finally, CoMBiSpeC (code of massive binary spectral computation) is used to compute the temperature and gravity distributions and then is used to linearly interpolate and Doppler-shift the spectra to obtain the emergent spectrum for each surface element of the star (projected along the line-of-sight to the observer). The final synthetic spectrum is produced by integration over the entire stellar surface.

Results

The best-matching polar T_{eff} and radii are (primary-secondary) 24000-19500 K and 10.25-6.97 $R_\odot$ (the masses used are 10.25-6.97 $M_\odot$ and the inclination is 60°). The binary interactions significantly affect the shape of the line profiles. Fig.1 compares the Si III triplet line profiles at 10 orbital phases in the p and u spectra. The strong phase-dependent variations in the perturbed profiles are clearly seen and can be described primarily in terms of "bumps" and asymmetries, similar to those present in the observational data (see Fig.2). The same behavior is present in numerous other photospheric absorptions lines and preferentially in lines of intermediate intensity. Strong lines, such as Hγ, undergo weaker perturbations. The line-profile variations introduce an intrinsic uncertainty in the RV measurements which leads to systematic distortions in the RV curve. Fig.3 shows the difference between p and u RV measurements. The maximum semi-amplitudes of δ(RV) range between 6 and 10 km/s, depending on the line. The shape of the p and u RV curves (scaled by a factor 10) for He I λ 5875 is also displayed in Fig.3. This curve shows that the strongest distortion occurs on the ascending and descending branches of the RV curve. The combined effect of these distortions is to skew the RV curve, giving it the appearance of one with a larger eccentricity than that of the actual orbit. For the secondary star, its weaker line-profile variability leads to much smaller deformations and the effect is negligible.

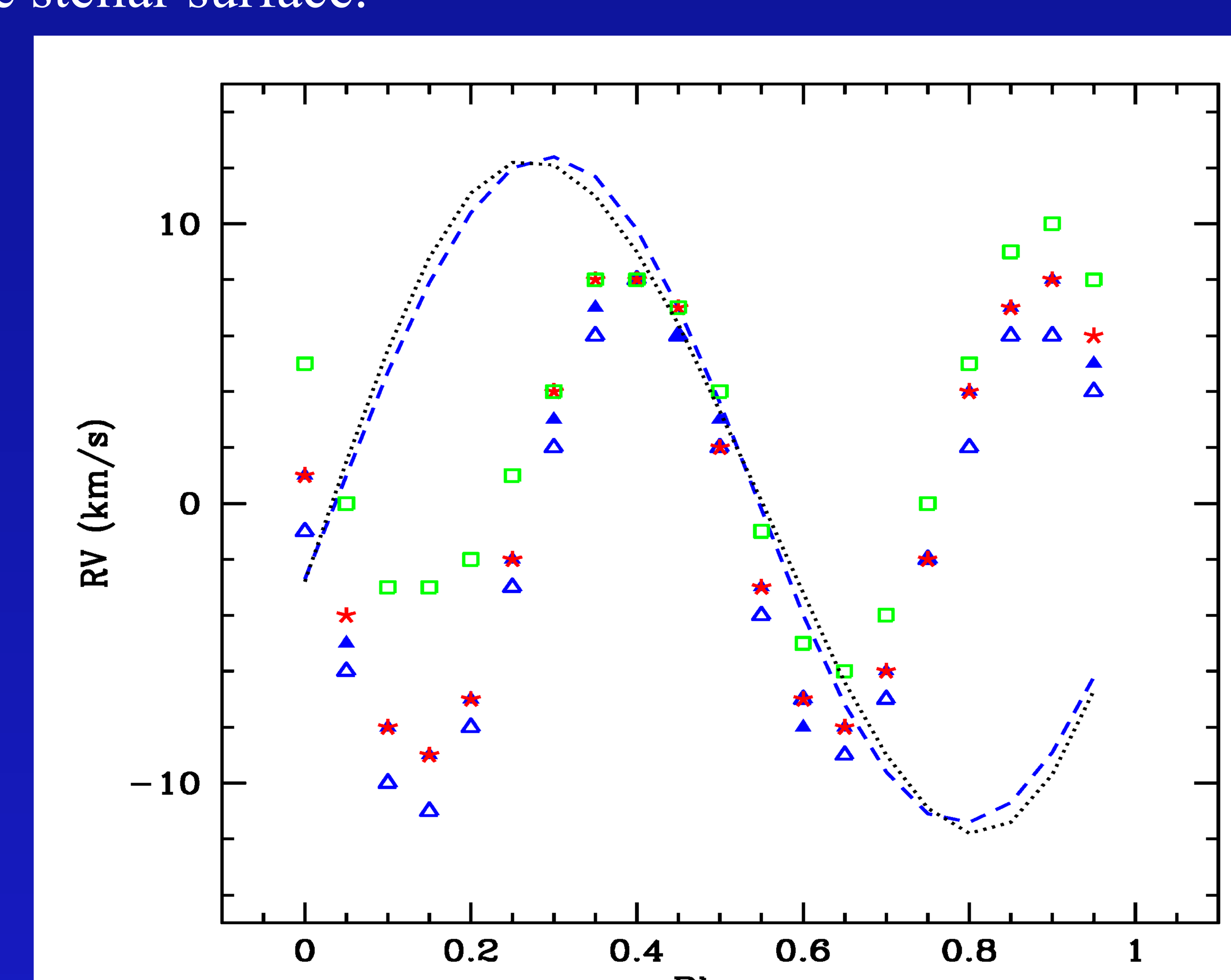

Fig. 3: RV curve of primary star

The difference between RV measurements made on the p and u spectra δ(RV) = RVp-RVu for He I λ 4921 (open triangles), He I λ 5875 (filled-in triangles), Si III λ 4552 (stars) and Hβ (squares). Also shown is the shape of the p (dash) and u (dots) RV curves for He I λ 5875 (scaled down by a factor of 10 for illustration purposes). The perturbation leads to a RV curve corresponding to a more eccentric orbit than the actual one.

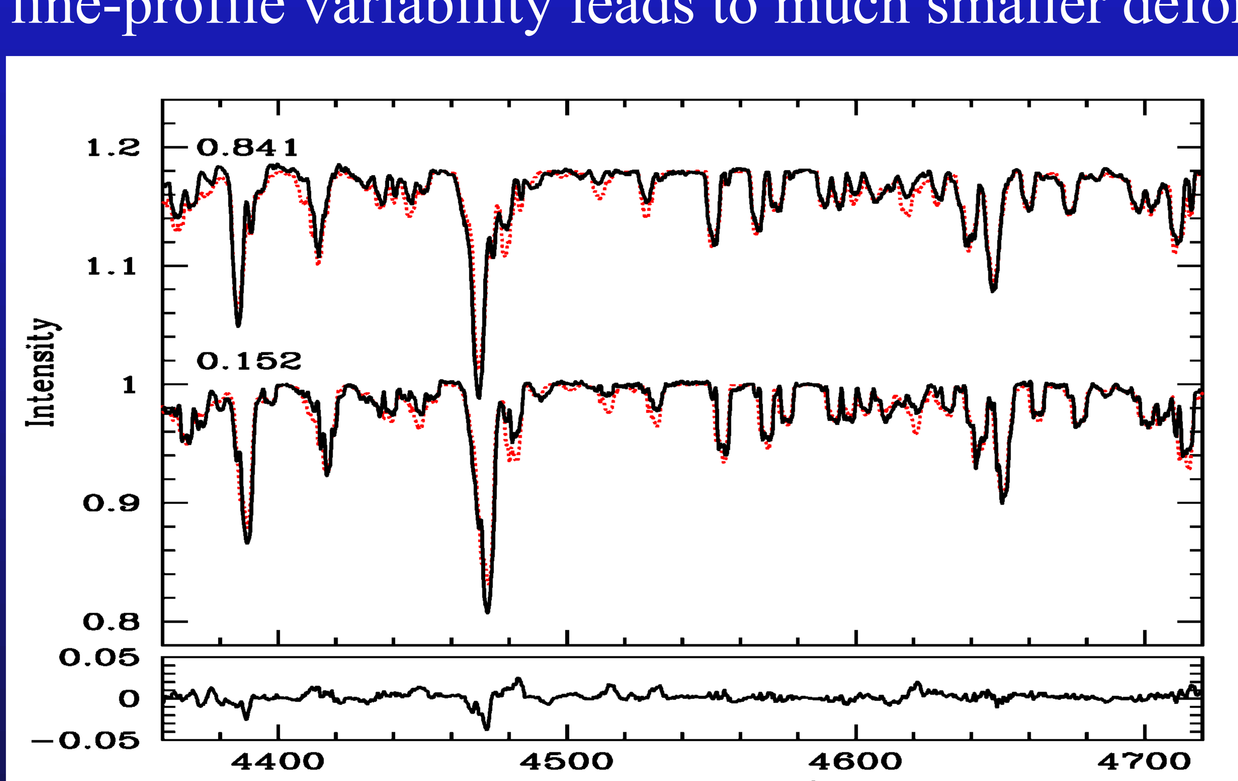

Fig. 2: Best matching model and observations

Comparison of the best-fit CoMBiSpeC model (dots) with Espadons spectra of Spica at orbital phases 0.152 (15 March) and 0.841 (26 March; shifted by +0.2 continuum units). The tracing shown at the bottom is the difference between the 15 March spectrum and its corresponding synthetic spectrum and shows that the fit is good to ~3%.

Conclusions: In the case of Spica, the effects of the binarity (gravity darkening, irradiation by the companion, tidal perturbations) have a small impact on the T_{eff} and log(g) determination. However, because the primary star rotates super-synchronously, perturbations of its surface lead to the formation of bumps in the profiles of lines of intermediate strength. These bumps arise naturally in our calculations without any a priori assumptions regarding non-radial pulsations. The perturbations also lead to radial velocity curve distortion and because the shape of the RV is skewed, a larger eccentricity than the actual value may be inferred. Future work will study systems with parameters that are different from Spica's, where irradiation and tidal deformations are more important, in order to evaluate the uncertainties that are introduced in these cases with the use of single-star atmosphere models.