Modeling the reflection effect with irradiated stellar atmospheres in the sdO+dM eclipsing binary AA Dor

Péter Németh[1], Maja Vučković[2], Roy H. Østensen[3], Steven Bloemen[3] and Péter I. Pápics[3]

[1]Dr. Remeis-Sternwarte Astronomisches Institut, Universität Erlangen-Nürnberg, 96049, Bamberg, Germany
[2]Instituto de Física y Astronomía, Universidad de Valparaíso, 2360102 Valparaíso, Chile
[3]Instituut voor Sterrenkunde, KU Leuven, 3001 Leuven, Belgium
email: `pnemeth1981@gmail.com`

The binary

AA Dor (also LB 3459) is an eclipsing binary discovered 37 years ago (Kilkenny et al. 1978, MNRAS 183, 523) and challenging stellar astronomy ever since. Its light curve (Figure 1) shows deep eclipses and a remarkable reflection effect. Paczyński 1980 (AcA 30, 113) presented the first binary model that is consistent with our current understanding. The system has a hot subdwarf O (sdO) primary and a cool dwarf (dM) companion. The primary heats up the day side of the companion and the varying visibility of the hot spot over the 6 hours orbital period creates the reflection effect. Following the first model atmosphere analysis of the sdO star by Kudritzki et al. 1982 (A&A 106, 254) the binary and orbital parameters have been determined with extensive investigations (e.g. Hilditch et al. 2003, MNRAS 344, 644; Rauch 2000, A&A 356, 665). There is, however, a persistent mystery that could not be answered in the past: the precise nature of the binary members. The mass of the companion is close to the stellar/substellar boundary within error bars. We also lack the accurate atmospheric parameters for the sdO star and a surface gravity discrepancy exists between spectroscopic and light curve analyses.

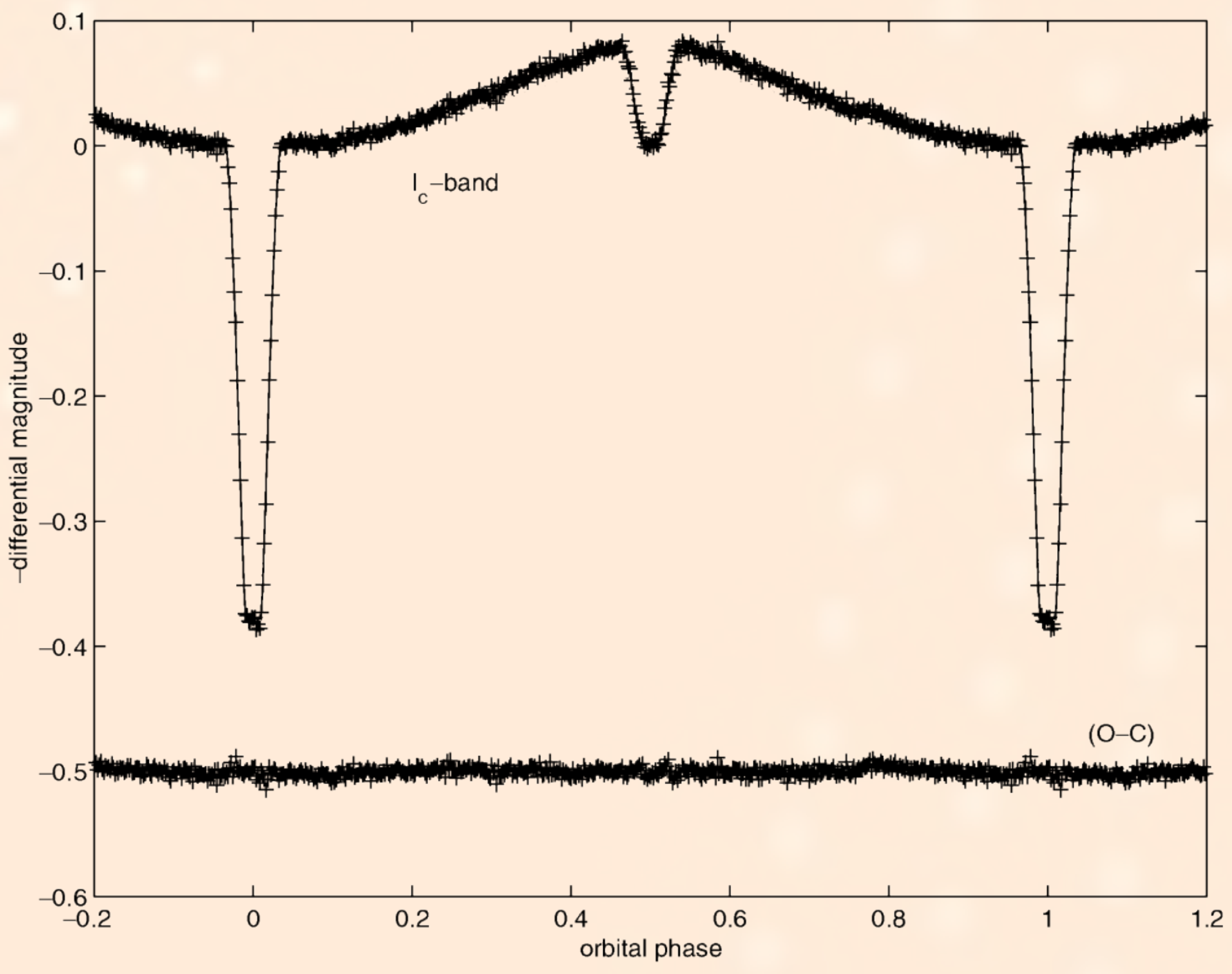

Figure 1: The I_C-band light curve of AA Dor shows a ~0.08 mag reflection amplitude and a full secondary eclipse. (Hilditch et al. 2003).

Most of these ambiguities are due to the extra light from the companion that complicates all analyses. Attempts have been made to observe near the primary eclipse where the reflection effect is negligible, however, this seriously limited the observing feasibility. Meanwhile, the companion mass can be determined from radial velocities and therefore the spectral signatures of the day side are very important. To find the true nature of the binary members we also need to understand the reflection effect.

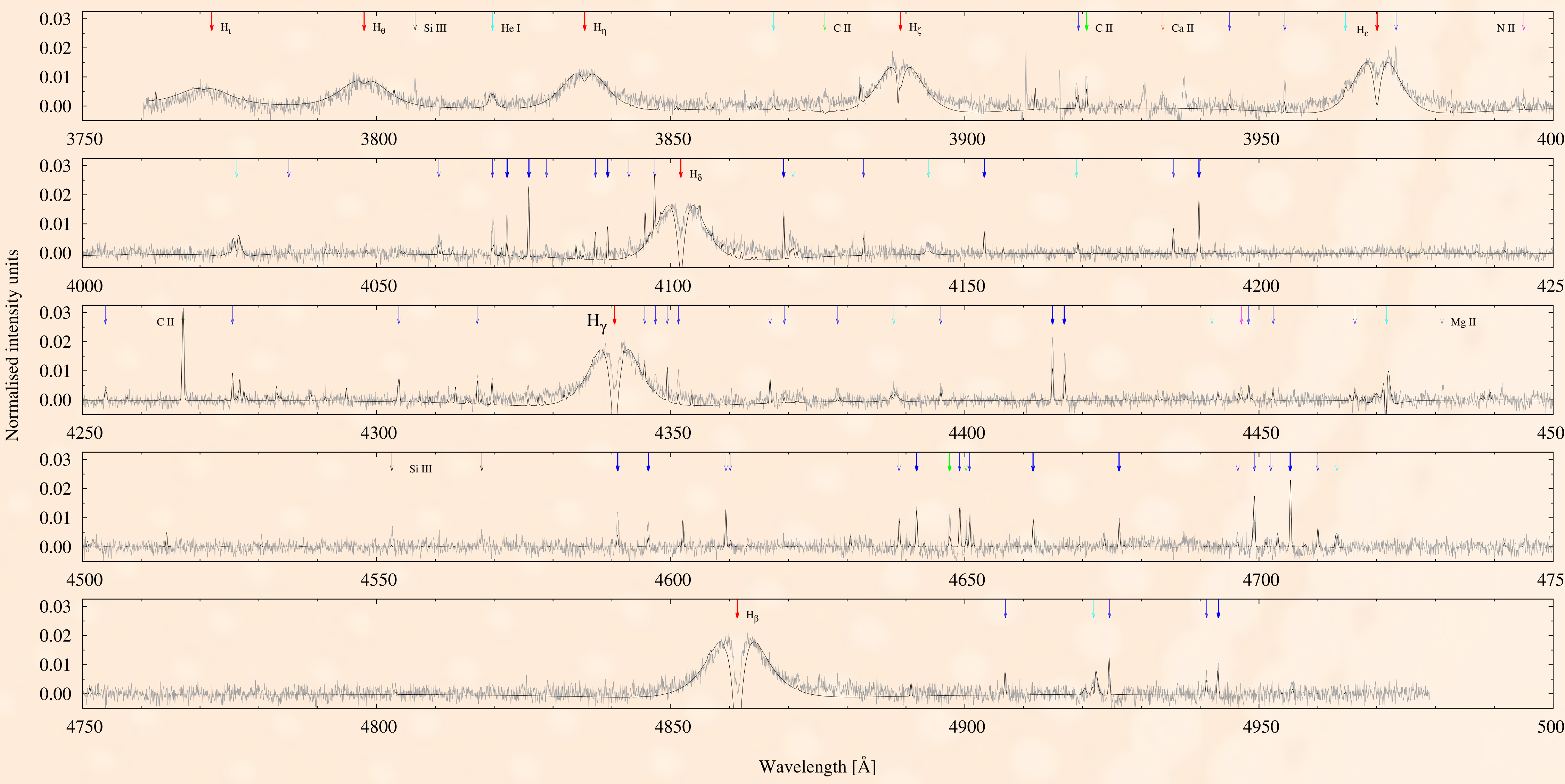

Figure 2: Emission line spectrum of the secondary with the best fit synthetic spectrum of the dM secondary. Lines used in our radial velocity analysis are marked with thick arrows, and weaker lines with possible identifications marked with thin arrows. The color coding on the arrows identifies their species; Balmer lines: red, O II: blue, C II and C III: green, He I: cyan, N II: purple, Si III: black and Mg II: grey. Our synthetic spectrum includes only H, He, and CNO opacities.

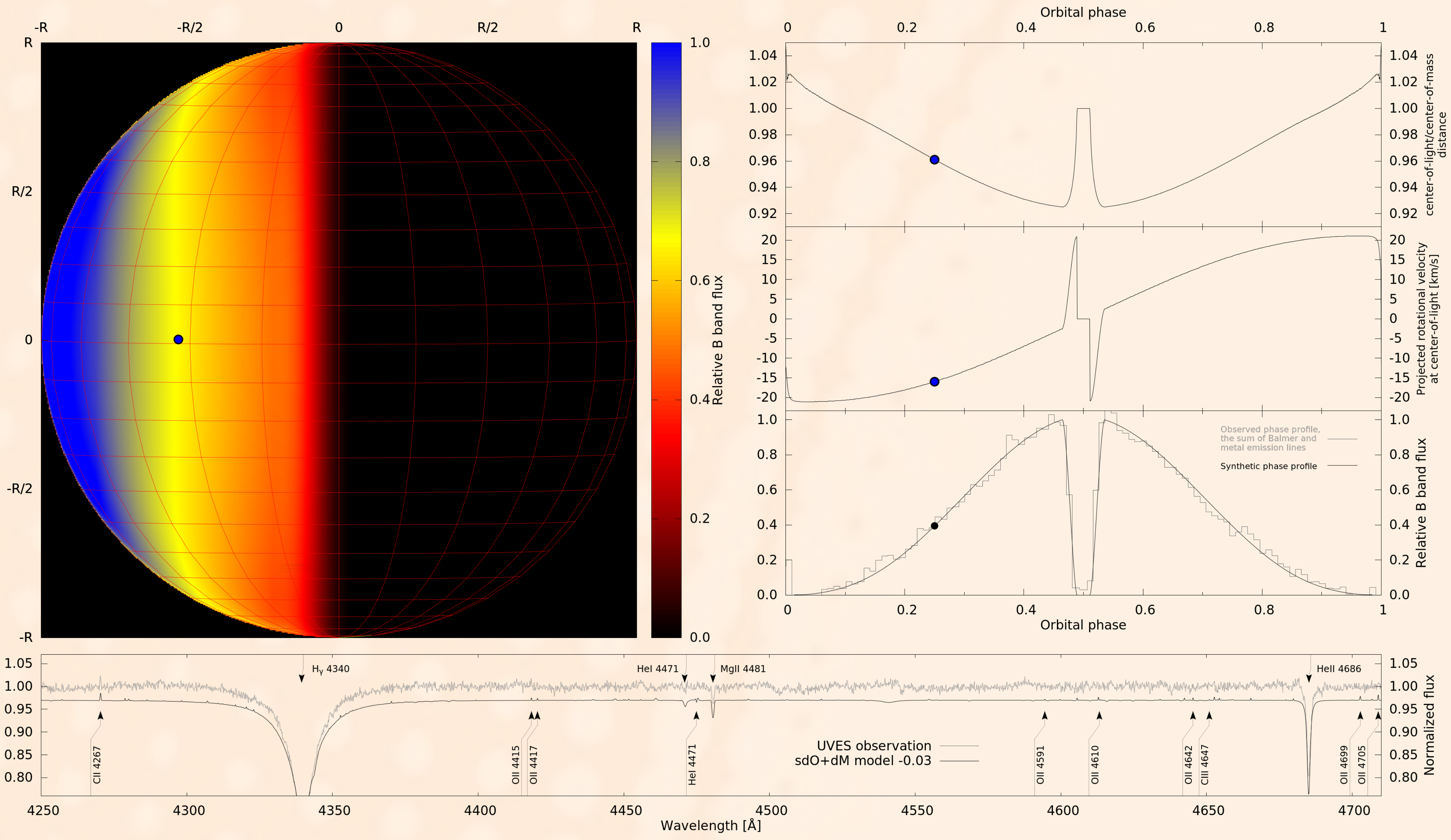

Figure 3: The intensity distribution of the companion at orbital phase 0.25 based on irradiated TLUSTY atmosphere models. The blue point shows the center-of-light. The right panels evaluate the ratio of center-of-light and center-of-mass distances; the Doppler shift of the center-of-light due to synchronised rotation and the total integrated flux. The bottom panel compares the synthetic spectra to the orbital phase resolved UVES observations. The strongest spectral feature of the companion is the C II 4267 Å line.

Eclipsing sdO binaries, like AA Dor are quite rare. Only five are known to date with AA Dor being the brightest, which makes it a unique system and excellent laboratory to develop spectral models, and investigate on cool stellar and planetary atmospheres.

Signatures of the companion

Rauch & Werner 2003 (A&A 400, 277) obtained phase resolved spectroscopy covering one complete orbit of AA Dor with the UVES spectrograph mounted on the VLT. Vučković et al. 2008 (ASPC 392, 199) analysed these data and by combining the 105 spectra they extracted the emission line spectrum of the day side of the companion that we show in Figure 2. The numerous metal emission lines allowed to derive accurate radial velocities: $K_{\rm sdO} = 39$ km s^{-1}, $K_{\rm dM} = 230$ km s^{-1} and masses: $M_{\rm sdO} = 0.45\ M_\odot$, $M_{\rm dM} = 0.076\ M_\odot$, suggesting that the companion is a red dwarf star. Next, we decided to do a model atmosphere analysis for this spectrum to find the conditions on the day side of the companion.

Modeling the day side

We have modeled the dM star with TLUSTY/SYNSPEC (Hubeny & Lanz 1995, ApJ 439, 875) and developed a new version of the steepest-descent iterative spectral fitting procedure XTGRID (Németh et al. 2012, MNRAS 427, 2180) that can directly fit the phase resolved spectroscopy and includes external irradiation. We split the day side of the companion into three concentric irradiation zones around the substellar point. We took the night side temperature to be 3000 K and surface gravity $\log g_{\rm dM} = 5.0$ [cgs] and kept these fixed. The irradiating flux is black-body like in our model with an appropriate temperature for the sdO star (42 000 K). The strength of irradiation was a free parameter, but scaled with the local surface curvature of the companion for each zone.

We found that the companion is heated to 19 000 K in its substellar point and even at 70° away it reaches a temperature of 14 000 K. We combined the specific intensities to reproduce the surface flux distribution and re-calibrated the orbital parameters of the binary by considering the center-of-light of the companion. Figure 3 shows that our model reproduced both the reflection effect and the spectral variations relatively well.

The hot spot must cover at least 95% of the inner hemisphere to reproduce the phase profile. The specific intensities allowed us to evaluate the limb-darkening numerically. Apart from orbital phase ~0.5 we found a moderate limb-brightening. Strongly irradiated extrasolar planets show extended atmospheres. Our models suggest that in the case of AA Dor such an expansion is 0.8% of the dM radius.

Conclusions

We have learned a lot about AA Dor in the past decades and now we can simultaneously reproduce its light curve and spectral variations. Still, AA Dor remains a unique system, one of a kind, as it can teach us new details about irradiated atmospheres in general. We will generalize our models for similar sdO and sdB binaries and include the Roche-geometry for irradiated stars, asynchronous stellar rotation, hot spot asymmetries and parametric circulation models. AA Dor is a benchmark system that can be used to test model predictions. Meanwhile, further observations will be necessary to improve both the orbital phase resolution and the signal-to-noise ratio and make the most out of comparative spectral techniques. Further information on our project is available at: http://stelweb.asu.cas.cz/~nemeth/work/aador

Link to the animated version of Figure 3.

Frontiers of Stellar Spectroscopy, Heidelberg (Germany), 27 - 30 April 2015 — & — Seventh Meeting on Hot Subdwarf Stars and Related Objects, sdOB7, Oxford (United Kingdom), 20 - 24 July 2015