ISSN 1845–8319

SPECTRAL MODELLING OF MASSIVE BINARY SYSTEMS: THE EXAMPLE OF LZ CEP

M. Palate, G. Rauw, and L. Mahy

Institut d'Astrophysique et de Géophysique,
Université de Liège, Bât. B5c, Allée du 6 Août 17, 4000 Liège, Belgium
email: palate@astro.ulg.ac.be

Abstract. Despite their importance for many astrophysical processes, massive stars are still not fully understood. Massive binaries offer an attractive way to improve our knowledge of the fundamental properties of these objects. However, some secondary effects are known to generate variations in the spectra of massive binaries, rendering their analyses more difficult. We present here a new approach to the computation of synthetic spectra of massive binaries at different phases of their orbital cycle. Our model starts with the Roche potential modified by radiation pressure and accounts for the influence of the companion star on the shape and physical properties of the stellar surface. We further account for gravity darkening and reflection effects to compute the surface temperature. Once the local gravity and temperature are determined, we interpolate in a grid of NLTE plan-parallel atmosphere model spectra to obtain the local contribution to the spectrum at each surface points. Then we sum all the contributions, accounting for the Doppler shift, and limb-darkening to obtain the total spectrum. The computation is repeated for different orbital phases and can be compared to the observations to determine the best parameters. We illustrate our method through the example of the LZ Cep system (O9III + ON9.7V).

Key words: Stars: massive - Binaries: general - Binaries: spectroscopic

1. Introduction

Some effects linked to binarity complicate the spectral classification and/or the spectral analysis (see e.g., Sana et al. 2005, Linder et al. 2007, and references therein). For instance, the stars in binary systems are not spherical but atmosphere codes currently used to model observed spectra are designed for single spherical stars. In this context, we have developed a novel way of modelling the spectra of binary stars that account for deformations due to tidal effects and partially explain the peculiar effects observed in the spectra. CoMBiSpeC (Code of Massive Binary Spectral Computation) is designed for massive stars but could be modified and extended to low-mass stars. The limitation to massive stars is an initial choice motivated by the fact that these stars are rare, not well-known but important for their surrounding and the galaxies. Moreover, a large fraction of massive stars (at least 50%) are part of binary or multiple system (Sana & Evans 2011 and references therein, Sana et al. 2012).

Non-spherical models were introduced in astrophysics by Russell (1952) to reproduce the light curves of binaries. Kopal (1959) introduced the Roche potential approach that was used by Lucy (1968) and Wilson & Devinney (1971). CoMBiSpeC is based, in a first step, on such models but we have incorporated radiation pressure effects and, of course, the computation of synthetic spectra.

Sect. 2 describes the assumptions, the modelling of the geometry of the stars, and the modelling of the spectra. In Sect. 3, we compare the predicted spectra to the observations and the new parameters found. We provide a summary of our results and future perspectives in Sect. 4.

2. Model

In this paper, we focus on the modelling of circular binary systems. For clarity, we divide the process into two parts, one part involving the surface, gravity and temperature calculation, and a second the spectra calculation. A full description of the model can be found in Palate & Rauw (2012) and Palate et al. (2013). The extension to eccentric orbits and/or asynchronous rotation is fully described in Palate et al. (2013) and consist in the use of the TIDES[1] code (Moreno et al. 1999, 2005, 2011) for the surface and velocity field computation coupled to CoMBiSpeC for the spectral computation.

2.1. Geometrical modelling

In the case of circular systems in synchronous rotation, the stellar surface is an equipotential of the Roche potential. In massive stars, the radiation pressure is very important and acts on the shape of stars, we thus have modified the classical Roche potential by adding the inner radiation pressure (effect on each star's own surface) and the external radiation pressure

[1]Tidal interactions with dissipation of energy through shear.

(effect of the companion) effects. The treatment of the radiation pressure is a complex problem with an extensive literature. Our approach is based on the work of Drechsel et al. (1995) and Phillips & Podsiadlowski (2002) for the treatment of the external radiation pressure and the Howarth (1997) approach for the inner radiation pressure treatment. We refer the reader to these three papers as well as Palate et al. (2013) for the complete demonstrations and discussion.

The effect of the external radiation pressure can be seen as a force that decreases the attraction of the companion. Its treatment therefore consists of scaling the mass of the companion in the Roche potential. The scale parameter $\delta = \frac{F_{rad}}{F_{grav}}$ is computed iteratively for each surface point in a similar way to the reflection effect treatment of Wilson (1990). The modified "Roche" potential can be written

$$\Omega = \frac{1}{r} + \frac{q(1-\delta(r,\varphi,\theta))}{\sqrt{r^2 - 2r\cos\varphi\sin\theta + 1}} + \frac{q+1}{2}\cdot r^2\sin^2\theta - qr\cos\varphi\sin\theta, \quad (1)$$

where $r = \sqrt{x^2+y^2+z^2}$, $q = \frac{m_2}{m_1}$, $x = r\cos\varphi\sin\theta$, $y = r\sin\varphi\sin\theta$, and $z = r\cos\theta$. Here, θ and φ are, respectively, the colatitude and longitude angle in the spherical coordinates centred on the star under consideration.

According to Howarth (1997), the inner radiation pressure can be treated as a simple scaling of the Roche potential and thus, $\Omega_{eff} = (1-\Gamma)\Omega$, with $\Gamma = \frac{\sigma_{Th}}{m_h c}\sigma T^4_{pole}\frac{1}{\|\vec{g}_{pole}\|}$ and where $\frac{\sigma_{Th}}{m_H} \approx 0.036\ \mathrm{m^2kg^{-1}}$, σ_{Th} is the Thomson scattering cross section and σ the Stefan-Boltzmann constant. The stellar surfaces are represented with a discretised grid of 240×60 points (in φ and θ respectively). The local acceleration of gravity is given by the gradient of the Roche potential. The temperature is computed accounting for gravity darkening and following the von Zeipel (1924) theorem

$$T_{\rm local} = T_{\rm pole}\left(\frac{\|\underline{\nabla}\Omega_{\rm local}\|}{\|\underline{\nabla}\Omega_{\rm pole}\|}\right)^{0.25}, \quad (2)$$

We have explicitly made the assumption of a co-rotating system, so that the stars always present the same face to each other. This leads to a local increase in temperature owing to the reflection effect between the two stars. We have followed the approach of Wilson (1990) to treat this effect. Figure 1 displays the gravity distribution at the stellar surfaces.

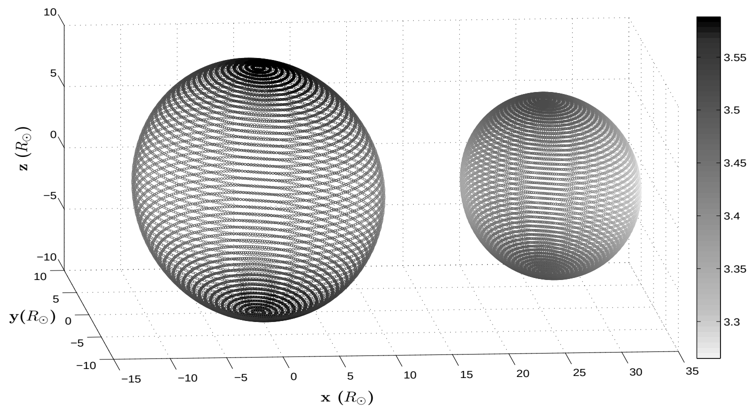

Figure 1: Distribution of $\log(g)$ at the stellar surface (cgs units) for the LZ Cep system computed with radiation pressure effects.

2.2. Spectral modelling

The second part of the algorithm computes the spectrum of the binary by summing the incremental contributions of each surface point. Non-LTE OB star spectral grids (TLUSTY OSTAR2002 and BSTAR2006 grid, Lanz & Hubeny 2003, 2007) are used to compute the integrated spectrum of the star at each orbital phase. The spectral grid is computed for solar metallicity. Each spectrum is defined by two parameters: gravity and temperature. As we know these parameters for each point at the stellar surfaces, we can compute the local contribution to the spectrum. The computation consists of a linear interpolation between the flux of the four nearest spectra in the grid. The appropriate Doppler shift is then applied to the spectrum accounting for the orbital and rotational velocity of the surface element. We multiply the spectrum by the area of the element projected along the line of sight towards the observer and by a limb-darkening coefficient based on the tabulation of Claret and Bloemen (2011). Finally, we sum the contribution to the total spectrum. It has to be stressed that we have assumed that there is no cross-talk between the different surface elements as far as the formation of the spectrum is concerned. Phase zero corresponds to the "eclipse" of the primary by the secondary. Over the first half of the orbital cycle (phase $= [0, 0.5[$), the primary star has a negative radial velocity.

3. LZ Cep

LZ Cep is an O 9III+O 9.7V binary system with an orbital period of 3.070507 days. Its light curve displays ellipsoidal variations that are probably due to the deformation of at least one component. Mahy et al. (2011) recently determined dynamical masses of about 16 $M_{\odot}$ and of about 6.5 $M_{\odot}$ for the primary and the secondary components, respectively. Furthermore, they also found that the secondary is chemically more evolved than the primary. Indeed, the determinations of the CNO and He abundances show a depletion in C and in O whilst N and He are enriched. These results suggested that the secondary component is filling its Roche lobe and transfers its matter to the primary. The secondary thus appears to be a core He-burning object with a thin H-rich envelope.

Table I: Abundances derived by Mahy et al. (2011) compared to the solar abundances (Grevesse and Sauval 1998) used in the CoMBiSpeC model.

Abundances	Primary	Secondary	Solar
He/H	0.1	0.4	0.1
C/H [$\times 10^{-4}$]	1.0	0.3	2.45
N/H [$\times 10^{-4}$]	0.85	12.0	0.6
O/H [$\times 10^{-4}$]	3.0	0.5	4.57

LZ Cep was observed with NARVAL, the spectropolarimeter mounted on the Téléscope Bernard Lyot at the Pic du Midi Observatory in France. This instrument has a spectral resolution of $R = 65000$. The dataset contains ten spectra obtained on a timescale of 14 days between 2009 July 20 and 2009 August 03. These data were automatically reduced with the Libre ESpRIT package (Donati et al. 1997).

Starting from these observations and from solutions derived by Mahy et al. (2011), we have refined the parameters of the stars. We have tried more or less 50 models in various ranges of temperatures and radii. The best agreement between observations and models is summarized in Table II. Figure 2 displays the observed spectrum and the CoMBiSpeC spectrum at phase 0.4. Some differences appear because of normalization errors of the observed spectra (e.g., the H δ and He I λ 4143 lines) and the fact that, the He and CNO abundances of the components of LZ Cep are non-solar while the grid of synthetic spectra used for computation is in solar abundances. Figure 2 (*zoom*) shows this difference for the carbon and nitrogen lines.

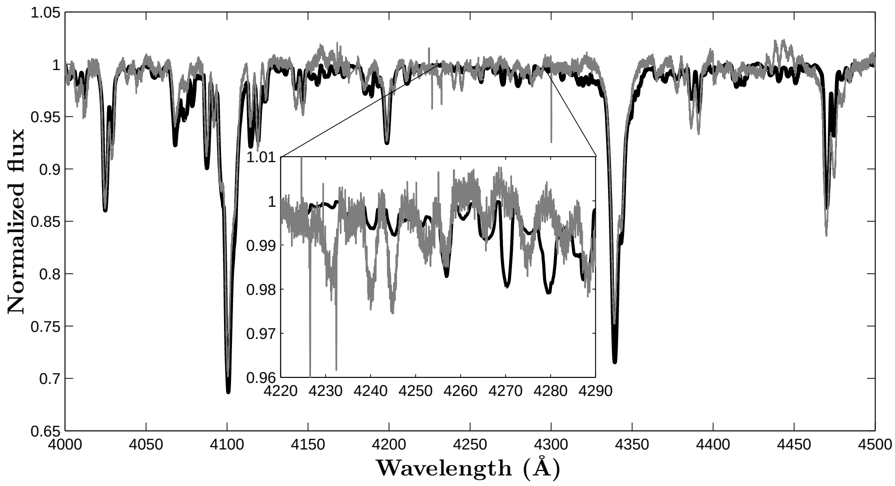

Figure 2: Comparison between observed spectrum (*in grey*) and the corresponding CoMBiSpeC model (*in black*) at phase 0.4. *Zoom:* Abundances difference for the N II $\lambda\lambda$ 4228, 4237, 4242 and O II $\lambda\lambda$ 4276, 4284 lines between observed spectrum (*in grey*) and the CoMBiSpeC model (*in black*).

4. Discussion and conclusion

We have presented the CoMBiSpeC model that is a first step in the spectral modelling of (massive) binaries. It allows us to compute the physical properties on the surface of massive stars in binary systems containing main-sequence O(B) stars. It includes various effects like reflection, radiation pressure, gravity darkening, limb-darkening that allow us to compute the temperature distribution at the stellar surface. Then, we use the TLUSTY OSTAR2002 and BSTAR2006 grids (Lanz & Hubeny 2003, 2007) to compute the spectra of each star of the system as a function of orbital phase. For the first time, the CoMBiSpeC model has been used to refine the solution derived by classical analyses for the LZ Cep system. The example also underlines the improvements that could be done: extension to non-solar abundances, different turbulent velocity, lines affected by stellar winds, cross-talk between the surface elements. However, despite these lim-

Table II: Comparison between the solutions derived by Mahy et al. (2011) and the best solution found with the CoMBiSpeC model.

Parameters	Observations solution 1	Observations solution 2	CoMBiSpeC model solution
Mass_p ($M_\odot$)	15.5 ± 1.0	16.9 ± 1.0	16.9
Mass_s ($M_\odot$)	6.1 ± 1.0	6.7 ± 1.0	6.7
Polar temperature_p (K)	32000(fixed)	32000(fixed)	33500 ± 500
Polar temperature_s (K)	28000(fixed)	28000(fixed)	29500 ± 500
Polar radius_p ($R_\odot$)	10.5 ± 1.2	10.5 ± 1.2	10.0
Equatorial radius_p ($R_\odot$)	13.1 ± 1.2	12.4 ± 1.2	10.91
Maximal radius_p ($R_\odot$)	13.1 ± 1.2	12.4 ± 1.2	10.91
Polar radius_s ($R_\odot$)	6.1 ± 1.2	6.7 ± 1.2	6.7
Equatorial radius_s ($R_\odot$)	6.9 ± 1.2	9.3 ± 1.2	7.33
Maximal radius_s ($R_\odot$)	6.9 ± 1.2	9.3 ± 1.2	8.17

itations and assumptions, the results of the computation are quite encouraging, rendering CoMBiSpeC a promising tool for the analysis of massive binaries.

Acknowledgements

The authors would like to thank Dr. Fabrice Martins who provides the NARVAL spectra. We also acknowledge support through the XMM/INTEGRAL PRODEX contract (Belspo), from the Fonds de Recherche Scientifique (FRS/FNRS), as well as by the Communauté Française de Belgique - Action de recherche concertée - Académie Wallonie - Europe.

References

Claret, A., and Bloemen, S.: 2011, *Astron. Astrophys.* **529**, 75.

Castor, I. C., Abbott, D. C., and Klein, R. I.: 1975, *Astrophys. J.* **195**, 157.

Donati, J., Semel, M., Carter, B. D., Rees, D. E., and Collier Cameron, A.: 1997, *Mon. Not. R. Astron. Soc.* **291**, 658.

Drechsel, H., Haas, S., Lorenz, R., and Gayler, S.: 1995, *Astron. Astrophys.* **294**, 723.

Grevesse, N., Sauval, A.: 1998, *Space Sci. Rev.* **85**, 161.

Howarth, I. D.: 1997, *The Observatory* **117**, 335.

Kopal, Z.: 1959, Close Binary Systems, in The International Astrophysics Series, ed. Ellison, M. A., & Lovell, A. C. B. (Chapman & Hall Ltd., London), 5.

Lanz, T., and Hubeny, I.: 2003, *Astrophys. J., Suppl. Ser.* **146**, 417.

Lanz, T., and Hubeny, I.: 2007, *Astrophys. J., Suppl. Ser.* **169**, 83.

Linder, N., Rauw, G., Sana, H., De Becker, M., and Gosset, E.: 2007, *Astron. Astrophys.* **474**, 193.

Lucy, L.B.: 1968, *Astrophys. J.* **153**, 877.

Mahy, L., Martins, F., Machado, C., Donati, J.-F., and Bouret, J.-C.: 2011, *Astron. Astrophys.* **533**, 9.

Moreno, E. and Koenigsberger, G.: 1999, *Revista Mexicana de Astronomia y Astrofisica* **35**, 157.

Moreno, E., Koenigsberger, G., and Toledano, O.: 2005, *Astron. Astrophys.*, **437**, 641.

Moreno, E., Koenigsberger, G., and Harrington, D. M.: 2011, *Astron. Astrophys.*, **528**, 48.

Palate, M., and Rauw, G.: 2012, *Astron. Astrophys.* **537**, 119.

Palate, M., Rauw, G., Koenigsberger, G., and Moreno, E.: 2013, *Astron. Astrophys.*, **552**, 39.

Phillips, S.N., and Podsiadlowski, Ph.: 2002, *Mon. Not. R. Astron. Soc.* **337**, 431.

Russell, H.N., and Merrill, J.E.: 1952, *Contrib. Princeton Obs.* **23**.

Sana, H., Antokhina, E., Royer, P., et al.: 2005, *Astron. Astrophys.* **441**, 213.

Sana, H., and Evans, C.J.: 2011, *Proceedings of the International Astronomical Union* **272**, 474.

Sana, H., de Mink, S.E., de Koter, A., et al.: 2012, *Science* **337**, 444.

von Zeipel, H.: 1924, *Mon. Not. R. Astron. Soc.* **84**, 665.

Wilson, R.E.: 1990, *Astrophys. J.* **356**, 613.

Wilson, R.E., and Devinney, E.J.: 1971, *Astrophys. J.* **166**, 605.