From Interacting Binaries to Exoplanets: Essential Modeling Tools
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ROCHE: Analysis of Eclipsing Binary Multi-Dataset Observables

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Abstract. Code *ROCHE* is devoted to modeling multi-dataset observations of close eclipsing binaries such as radial velocities, multi-wavelength light curves, and broadening functions. The code includes circular surface spots, eccentric orbits, asynchronous or/and differential rotation, and third light. The program makes use of synthetic spectra to compute observed *UBVRIJHK* magnitudes from the surface model and the parallax. The surface grid is derived from a regular icosahedron to secure more-or-less equal (triangular) surface elements with observed intensities computed from synthetic spectra for supplied passband transmission curves. The limb-darkening is automatically interpolated from the tables after each computing step. All proximity effects (tidal deformation, reflection effect, gravity darkening) are taken into account. Integration of synthetic curves is improved by adaptive phase step (important for wide eclipsing systems).

The code is still under development. It is planned to extend its capabilities towards low mass ratios and widely different radii of components to facilitate modeling of extrasolar planet transits. Another planned extension of the code will be modeling of spatially-resolved eclipsing binaries using relative visual orbits and/or interferometric visibilities.

Keywords. stars:binaries:eclipsing, stars:binaries:spectroscopic, techniques:interferometric

1. Introduction

The study of eclipsing binaries is the principal way to determine reliable stellar masses, radii, and luminosities needed to test stellar structure and evolutionary models.

The beginning of the realistic interpretation of the light curves (hereafter LCs) of close eclipsing binaries started with the seminal papers of Lucy (1968ab) leading to a plethora of codes in the 1970s (by e.g., Wilson & Devinney, 1971; Mochnacki & Doughty, 1972; Rucinski, 1973; Binnendijk, 1977).

At present, simultaneous solutions of two or more kinds of observations (LCs, radial-velocity (RV) curves, spectral lines profiles, timing variations, and even polarimetric data) are coming into more frequent usage. The morphology of binaries today includes extensions such as non-synchronous rotation, eccentric orbits, or effects of the radiation pressure (Drechsel *et al.*, 1995). Complicated models computing radiation transfer and including accretion disks have been developed (e.g., SHELLSPEC of Budaj & Richards, 2004).

Parameter adjustment uses advantageous methods such as the Levenberg-Marquardt method or Simplex algorithm. Comprehensive overview of close binaries, including determination of orbits and absolute parameters, as well as imaging of stellar surfaces, can be found in Hilditch (2001).

The program most widely used to analyze eclipsing binary data is the Wilson & Devinney (hereafter W&D) code, which was described in a series of papers (for references see Wilson, 1994). A user-friendly interface to the W&D code (PHOEBE) has been developed by Prša & Zwitter (2005). The EBAI project (see Prša *et al.*, 2008) uses artificial intelligence to cope with the enormous increase in the number of LCs of eclipsing binaries resulting from several sky surveys (e.g., OGLE, ASAS, MACHO, NSVS).

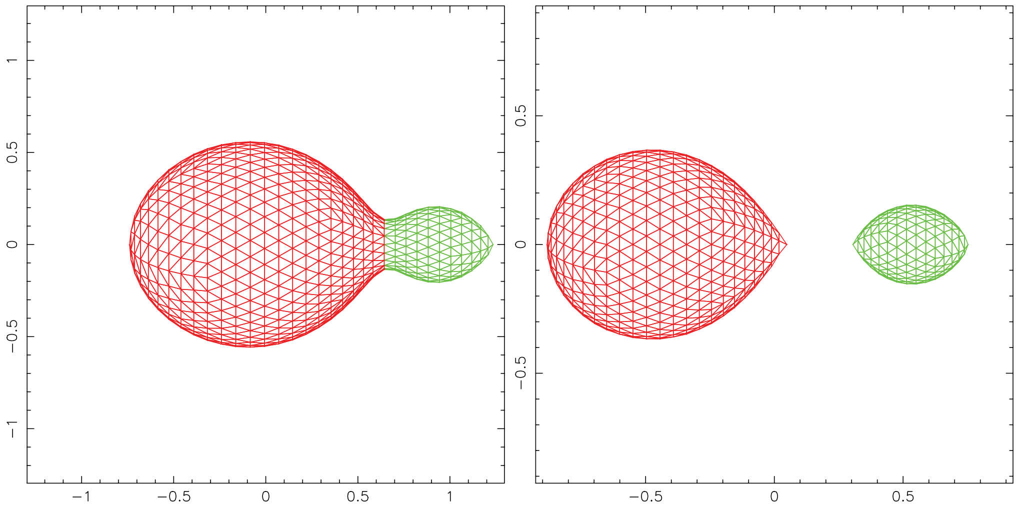

Figure 1. Surface grid based on a regular icosahedron documented in the case of a contact binary (left) and a double-contact binary with the secondary component rotating at break-up velocity with the rotation factor $F = 6$ (right). View from the orbital plane.

2. The ROCHE code

A new code, ROCHE, is based on Roche geometry. In the case of asynchronous rotation and eccentric orbits, the assumptions of Wilson (1979) are used (volume of components is preserved in eccentric orbits). The routines of *ROCHE* are, however, completely independent of the W&D code. It is not planned to add additional structures (such as accretion or circumbinary disks, gas streams) in addition to the binary.

The code uses extensive tables of passband-specific and bolometric limb darkening coefficients of van Hamme (1993). Local passband-specific intensities are interpolated from extensive model-atmosphere tables of Lejeune *et al.* (1997). The model takes into account mutual irradiation of the components and gravity darkening as well. The surface grid is based on the Platonic solid with the largest number of faces - icosahedron. Each of its 20 faces is broken to smaller triangles. In the case of spherical stars, the elements are equal to about 15% (Fig. 1). The relative density of grids for primary and secondary component can be automatically scaled according to the ratio of radii.

The model uses an advanced treatment of the third light: the passband specific third light contributions are taken either independently or it is assumed that the third component is a star. In the latter case, its temperature and radius (with respect to the semi-major axis of the binary) can be optimized.

For the computation of the LCs, the flux from all visible surface points is summed. In the case of the BF synthesis, the summing is done in the RV domain. Intervals of exposures are taken into account when synthetizing BFs. The visibility is tested by the routine based on the principles set by Djurašević (1993). The terminator is modeled by a broken line (the terminator breaks a surface triangular element into a triangle and a quadrangle). The *UBVRIJHK* apparent magnitudes are computed using supplied trigonometric parallax. Modeling of the interstellar reddening/extinction is not included in the current version.

The observables are synthetized in 360 phase points but, in the case of detached eclipsing binaries, the code enables sub-dividing the phase step during the eclipses. Another approach to run the code more efficiently is to use an adaptive phase step, depending on

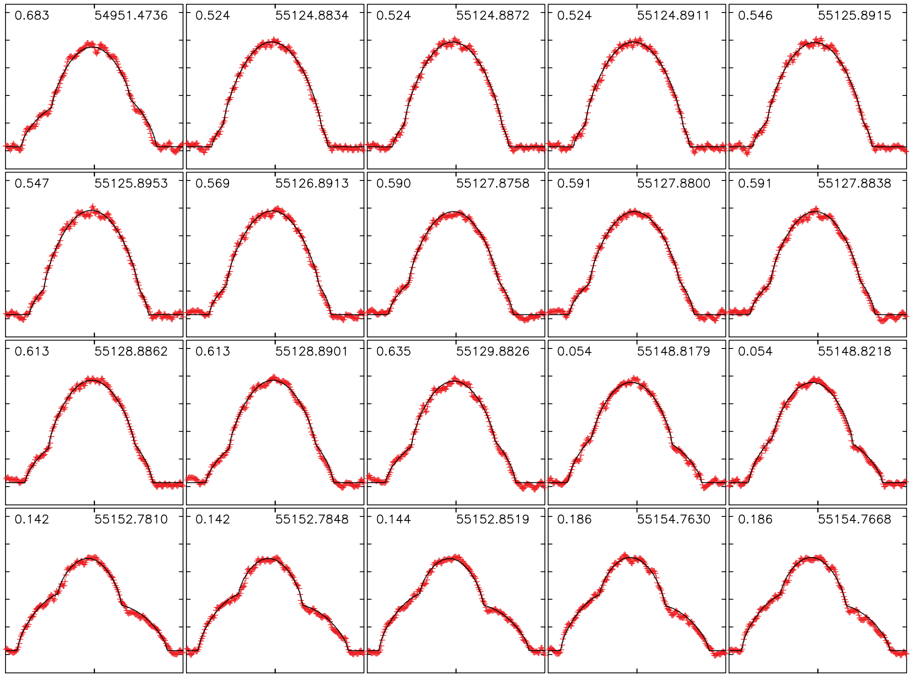

Figure 2. Global fit (black solid line) to BFs (red crosses) of δ Velorum (Pribulla *et al.*, 2011)

the phase derivative of the synthetised LC (yet to be implemented). The observables are then interpolated in the grid of phases.

The code enables simultaneous optimization of up to 7 passband-specific LCs, 2 RV curves, 200 BFs (see Rucinski, 1992), one set of squared interferometric visibilities, and the relative visual orbit (under development).

Optimization is performed using a damped differential correction method. It is possible to perform a grid search for the best χ^2 for a user-defined grid of mass ratios and/or inclination angles.

The code uses the PGPLOT graphic routines, which enables visualization of the input data and fits (or residuals) after each optimization step. Different styles in plotting 3D surfaces including spots can be used. Best fits as well as optimal parameters including standard errors are also automatically saved. A new input parameters file is produced after each computation step.

3. Prospects for further improvements of the code

Although the code has successfully been used to analyze observations of several eclipsing systems (see e.g., case of δ Velorum, Pribulla *et al.* 2011 and Fig. 2; or MOST eclipsing binaries, Pribulla *et al.* 2010) it is still being improved and extended. The code has been extensively tested to synthetize observables for a large range of parameters. The major challenge is its extension to mass ratios below $m_2/m_1 < 0.02$ and ratio of radii below $r_2/r_1 \sim 0.10$. The 3D surfaces are correctly generated by *ROCHE* for the mass ratios down to $q \sim 10^{-5}$, but the major problem poses correct representation of the terminator for systems with components of widely different radii. Modeling LCs and BFs of transiting close-in hot Jupiters assuming Roche model is very important (see Budaj, 2011).

Major challenges in eclipsing-binary data modeling are connected with increasing photometric precision of LCs (CoRoT, KEPLER, MOST, STEREO, SMEI etc.) and

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availability of different sorts of data like interferometry (e.g., VLTI, CHARA), and astrometry (HIPPARCOS, GAIA) providing data showing effects (e.g., Doppler beaming, dynamical tides, or mid-eclipse brightening) that are impossible to reliably detect in the ground-based observations. The present accuracy of *ROCHE* is about 0.001 in intensity for 1000 surface elements.

Two improvements are under development: (i) inclusion of relative visual orbits and (ii) interferometric visibilities. It is planned to add (i) effects of radiative pressure in close binaries with components of early spectral types, (ii) more advanced possibilities in surface mapping, and (iii) timing variations due to unseen third or multiple bodies. The optimization routine, accuracy, and speed of synthesis also require improvements.

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Discussion

P. Zasche: Is the code ROCHE somehow publicly available?

T. Pribulla: Yes, please write to me to get more information about the code.

C. Maceroni: Concerning future improvements: a trivial, but important one, for analysis of Kepler LCs is to include the long integration time (for long cadence data). That is important in some cases as shown by A. Prša. As far as I know, only PHOEBE (A. Přsa) and JKTEBOP (J. Southworth) include that.

T. Pribulla: My code does not take long integration times into account in the case of LC synthesis. The code is developed according to the data which are available and systems that are solved. It should be, however, rather simple to implement the "phase smearing" in the case of LCs.