Setting a New Standard in the Analysis of Binary Stars
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PHOEBE 2.0 – WHERE NO MODEL HAS GONE BEFORE

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Abstract. PHOEBE 2.0 is an open source framework bridging the gap between stellar observations and models. It allows to create and fit models simultaneously and consistently to a wide range of observational data such as photometry, spectroscopy, spectrapolarimetry, interferometry and astrometry. To reach the level of precision required by the newest generation of instruments such as *Kepler*, GAIA and the arrays of large telescopes, the code is set up to handle a wide range of phenomena such as multiplicity, rotation, pulsations and magnetic fields, and to model the involved physics to a new level.

1 Introduction

The generic goal of many observational studies or campaigns is to extract information from telescope data, and make a comparison with model predictions. This way, we either hope to learn more about the object we are studying, or more about the physics that is involved. In stellar physics, the most basic quantities are the fundamental parameters such as the effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), luminosity (L), mass (M), radius (R), ... These are obvious parameters that come out of stellar evolutionary calculations, or stellar models in general.

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We have also learned that monitoring these quantities with photometers or spectrographs is worthwile, because variability of these quantities informs us about dynamical processes happening on the objects, such as binarity, rotation, spots, pulsations, ...

If we are interested in a detailed comparison of observable quantities with model predictions to learn more about the physics, we need to realize that we almost never observe the model quantities directly. For example, we cannot measure the effective temperature, but need to infer it from multicolour photometry or the detailed study of spectral lines. We cannot measure the total luminosity of the star, because we can only build instruments that are sensitive to a particular wavelength range. We cannot measure radii for the same reason, and we cannot even measure masses because they need to be derived from quantities such as radial velocities in a binary system (which are often on its turn derived from spectral lines in a given wavelength range or from boosting in certain photometric passband). Moreover, we can measure some quantities in many different ways: the radius can be derived from interferometric visibility measurements, from photometric eclipses in binaries, from scaling absolutely calibrated photometry, from solar-like oscillations, ... But it is not guaranteed a priori that all these measurements yield the same value, since they might be measuring *different* radii (radius assuming a limbdarkening law, geometric radius, passband radius, acoustic radius ...). In order to model the system, we need to model the observations as well, and know what exactly we measure. Only then can we hope to combine information extracted from different instruments and methodology, to arrive at a consistent picture that constrains the physics in as much ways as possible.

In these proceedings, we present the new PHOEBE 2.0 open source framework, which is a community driven tool to address these issues.

2 General design in a nutshell

PHOEBE 2.0 is a complete rewrite of PHOEBE 1.0 (Prša & Zwitter 2005), currently in pre-alpha stage. The latter means that all features described below are implemented and are functional on a basic level. Many aspects have been thoroughly debugged and output compared to existing codes, other features are considered more as a proof-of-concept. PHOEBE 1.0 is a tool to model binary light- and radial velocity curves of asynchronously rotating eccentric binaries and includes spots. It is built on top of the Wilson-Devinney code (Wilson 1979), with extensions to address issues on reddening and it introduces heuristic scanning to determine reliable uncertainties on the fitted parameters. A simplex method, a gradient method and the differential corrections method are the basic algorithms behind the fitting procedure.

In PHOEBE 2.0, we decided to rewrite and redesign the basic features of the Wilson-Devinney code. On top of that we extend the Roche formalism to also included single, but (differentially) rotationally deformed objects. We include the treatment of multiple systems by treating them as hierarchically ordered binaries. We include the modelling of optically thick (accretion disks), and provide the possibility to add pulsations. Finally, we add also the treatment of simple magnetic fields (*i.e.* dipole fields).

On the part of generating observables, we add the possibility to synthesize spectral lines, compute absolutely calibrated multicolour photometry for fitting of spectral energy distributions, calculate interferometric visibilities and closure phases, generate on-sky positions for astrometric purposes, and the computation of images.

The fitting framework is currently the least developed, but we added initial support for the Bayesian framework. Therefore, we interface the code with a Metropolis-Hastings algorithm and and affine invariant algorithm. Aside from that, we interfaced the code also with the Nelder-Mead simplex method, the Levenberg-Marquardt gradient method, simulated annealing, Minuit, a full grid search and the possibility to use genetic scanning algorithms.

All this results in PHOEBE 2.0 being both a data modelling tool and a laboratory for experiments in stellar astrophysics. PHOEBE 2.0 continues on the tradition of open source code. The code itself is fully documented and available in a variety of formats at `http://www.phoebe-project.org/2.0/docs`

In the following, we will go into a more details to describe some basic aspects of the code, specifically where it improves upon existing implementations.

3 Improvements and new physics

3.1 Meshing

The discretization of the equipotential surface is done not via squares (*i.e.*, via longitude and latitude), but by triangulating the surface via a marching method (Fig. 1, left panel). This has several advantages. First, the surface is closed, in contrast to square-tiling strategies where vertices of neighbouring squares do not exactly match. Second, the triangles are well-behaved, which means their shape and surface area is independent of the position on the object. Again, this is in contrast to latitudinal/longitudinal gridding, where the resolution around the poles is typically better than at the equator. Finally, the marching method allows to mesh any implicit function, which is beneficial for allowing extensions to different shapes or potentials in the future.

To resolve small transiting bodies (such as main sequence stars eclipsing a giant star, compact stars transiting giants or exoplanets), we introduce a subdivision stage, where eclipsed triangles are divided into 4 equally sized smaller triangles. This step can be repeated until the desired resolution is met (Fig. 1, middle and right panel).

3.2 Atmospheres

The derivation of the intensity of a particular surface element and its aspect angle dependency is most often done by interpolating the passband integrated intensities

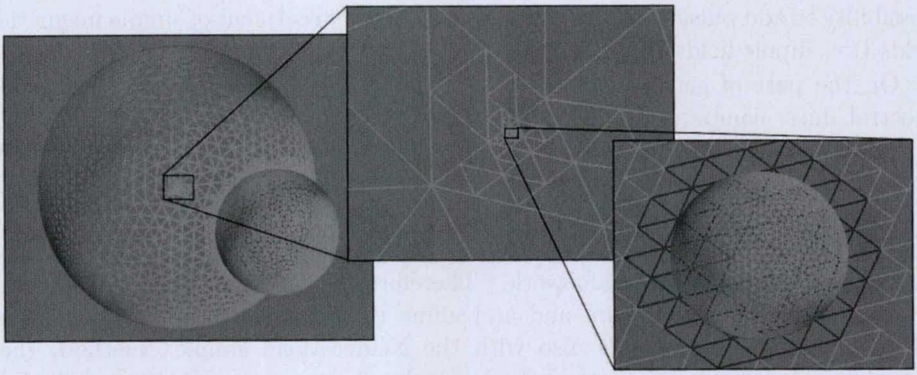

Fig. 1. Triangulated meshes of three bodies, of which the two smaller ones eclipse the larger object. The zoom-ins illustrate the iterative application of the subdivision algorithm to resolve the smallest body.

in a tabulated grid of atmospheres, using $T_{\rm eff}$, $\log g$ and metallicity z as independent parameters. The intensities can thus vary over the surface, because the local effective temperature and metallicity can vary due to the surface deformation. The aspect angle dependency is then implemented by assuming a limb darkening law and one set of coefficients valid on the entire star. This way, the limb darkening coefficients are effectively decoupled from the intensities, and should be considered as some average value over the surface of the star. This can be improved, because we expect that as the local atmospheric quantities change, also the aspect dependency changes. PHOEBE 2.0 accomodates for this effect by allowing also the limb darkening coefficients to vary locally over the surface. Finally, we note that $T_{\rm eff}$, $\log g$ and z are not the only variables which atmospheres are dependent on. For this reason, the design of PHOEBE 2.0 allows interpolation of intensities and limb darkening in any number of parameters. An immediate application is the inclusion of boosting effects (also known as Doppler beaming). Because the specific intensity undergoes a radial velocity shift and change in apparent luminosity when the star is moving towards or a away from the observer, the radial velocity $v_{\rm rad}$ of the object alters intensities and limb darkening coefficents. Including $v_{\rm rad}$ as one of the independent parameters in the interpolation, naturally adds beaming effects to the observables. Another application of allowing extra interpolation parameters is the inclusion of interstellar reddening. Interstellar reddening influences the shape of the specific intensities by an assumed (possibly parameterized) limb darkening law (*e.g.*, Cardelli *et al.* 1989; Fitzpatrick 2004), and thus also has an effect on the local emergent intensities and the passband-integrated limb darkening coefficients (because the influence of reddening is wavelength dependent, even within one passband). Treating limb darkening as a local quantity, eliminates the possibility to easily fit these coefficients, but ensures full consistency between the intensity and the aspect dependency of the intensity. Irrespective of this, PHOEBE 2.0 still supports the assumption of one set of limb darkening coefficients for the entire object. Of course, the inclusion or omission of these effects are dependent on the given system and the precision of the observations.

The code library that PHOEBE 2.0 is based on, includes functionality to generate a custom set of limb darkening coefficients and local normal emergent intensities from a grid of specific intensities. This way, the derivation of the intensities can be optimized based on the needs of the system under study.

Before the intensities can be calculated the local atmospheric parameters need to be derived, specifically the local effective temperature and surface gravity. In the Roche frame, the surface gravity can be derived from the system's geometry and point source masses, but the connection of $T_{\rm eff}$ to these surface gravities is not trivial. Historically, a gravity darkening law of the form

$$T_{\rm eff}^4 = T_{\rm pole}^4 \left(\frac{g}{g_{\rm pole}}\right)^{\beta}, \tag{3.1}$$

is assumed, where in principle the gravity darkening coefficient β is a free parameter. Several prescriptions exist under certain assumptions, *e.g.* those from von Zeipel (1924) and Lucy (1967) Ironically, though gravity darkening arises mainly from the deviation from spherical symmetry, the previously mentioned prescriptions still assume spherical symmetry. Recently, Espinosa & Rieutord (2011) have improved the formalism, removing the need for the gravity darkening coefficient β as a free parameter. This formalism, though highly useful in the treatment of single, rotating stars, becomes hopelessly involved when it is applied to the binary Roche potential. Luckily, Espinosa & Rieutord (2012) provide their results specifically for binaries in a tabulated form, following the parameteric form of Equation (3.1). Although PHOEBE 2.0 still supports the manual setting of the gravity darkening coefficients, it is thus possible to remove it from the set of free parameters. We also note that the gravity brightening coefficient defined by Equation (3.1) is not a passband dependent quantity. Rather, it sets to local conditions such that passband dependent quantities (intensity and limb darkening coefficients) can be derived.

3.3 Irradiation

The implementation of irradiation effects start from the detailed treatment from Wilson (1990), and we expand on this inspired by the work of Budaj (2011). It is important to note that the effect of irradiation can be divided in two components: a fraction of the light from the emitting body (the irradiator) that reaches the other component (the receiver), can be absorbed, and the rest can be reflected. For simplicity, we assume here that the absorbed flux is used in its entirety to heat up the receiver, and call the process the *heating effect*, confusingly called the "reflection effect" by Wilson (1990). The fraction of the absorbed flux with respect to the total incoming bolometric flux is parametrized with the albedo value α, which we dub the "bolometric albedo", to distinguish from passband related effects described below. On its turn, a fraction of the absorbed flux can be used to locally

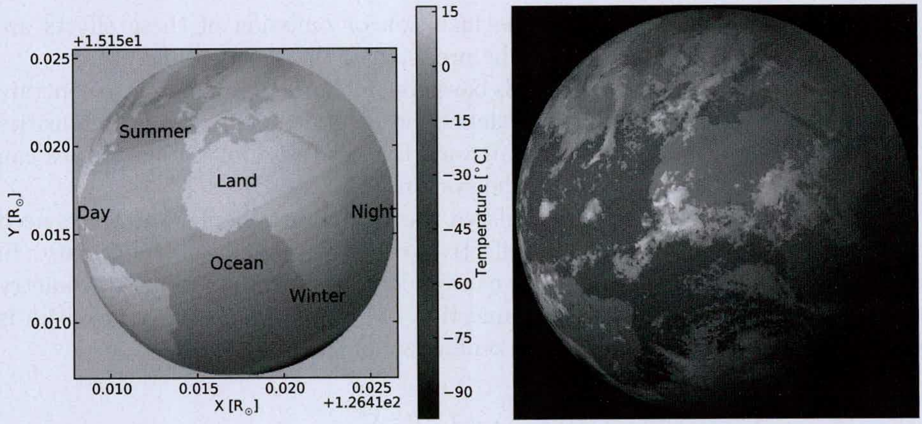

Fig. 2. *Left panel:* a simplified simulation of the heating of the Earth by the Sun. Oceans and lands are assigned different albedo values. The combined effect of this with the inclination and global and latitudinal redistribution of heat, gives rise to different temperatures at the day and night side, land and ocean, and northern and southern hemisphere. *Right panel:* image of the combined effect of heating and reflection in the near infrared, by adding local passband albedos mimicking a cloud pattern.

heat the receiver (parametrized via 1-α_{R}), with the remainder redistributed in one way or another to heat the receiver (α_{R}). Again, a fraction of the redistributed flux can be used to uniformly heat the whole receiver (parametrized via 1-α_{H}), with the remainder (α_{H}) used to heat only in the latitudinal direction, to mimic effects of circulating winds.

PHOEBE 2.0 also deals with the fraction of the flux that is not absorbed by the receiver. The remainder of the flux is indeed scattered off the surface of the receiver (which we call the *reflection effect*). In a first implementation, we assume that the scattering occurs isotropically (so called Lambertian reflection). In contrast to the heating process, we implemented reflection as a passband dependent quantity, and as such it is not parameterized as $1-\alpha$, but assigned its own passband-dependent albedo coefficient α_Λ. To ensure consistency in the definition with the heating coefficients, we define α_Λ such that a value of 1 is equivalent to no reflection (*i.e.* all the flux in the passband is assumed to be used in heating, though there is no strict coupling between α and any of the α_Λ). Thus, the passband albedo can never exceed unity, but can be negative if some flux from outside the passband is reprocessed to fall within the passband. For grey scattering (*e.g.*, electron scattering in radiative atmospheres of massive stars) it is required that $0 \leq \alpha_\Lambda \leq 1$.

Additionally, PHOEBE 2.0 allows to make all the coefficients governing the irradiation effects local properties. This way, it is in principle possible to simulate the effect of water and rocky surfaces on exoplanets (Fig. 2).

We conclude by stating that whatever light you observe is the sum of intrinsic light emitted by a body (possibly heated by a companion), and the light reflected off the body. The relative contribution of the terms is dependent on the type of object and the passband you're observing in. For example, in massive stars, reflection is relatively unimportant, while it is the dominant source of radiation towards the observer for small, close-in rocky planets.

3.4 Dynamics

The kinematics of binary and multiple systems are currently implemented via hierachical nesting of Keplerian orbits. Some of the orbital elements are allowed to vary linearly over time, such as the period, eccentricity and the argument of periastron. The orbits are fully defined in three dimensions, and linear proper motions can be assigned to the entire system. This way, the kinematics can be computed in the plane of the sky, for astrometric purposes. Moreover, an iterative procedure is applied to correct the orbits for light time travel effects, accounting for effects such as Rømer delays in eclipse timings, and eclipse time variations in general.

3.5 Pulsations

Pulsations can be added to a body, assuming the geometry is decoupled from the shape. This means that the computation of the perturbations of the surface is done assuming that the underlying equilibrium quantities are those from a spherical star. Those are then mapped on to the surface of the body under study. Strictly, this restricts the application to bodies for which the rotational deformation is negligible, but the star is allowed to rotate. At this stage, we implement the pulsation treatment including first order effects of the Coriolis force following Zima (2006), and expand up on with the traditional approximation closely following Townsend (2003), which is typically approximately valid up to about half the break-up rotation frequency.

The implementation of pulsations allows to extract information from multicolour photometry to perform mode-identification. Combining the pulsations with the ability to model spectra it is possible to model line-profile variations. Since the spectra generator has access to a library of synthetic line profiles, it is also possible to study line-profile variations of deep (and high signal-to-noise) lines such as Helium lines in massive stars. A combination of the pulsations with binarity, allows eclipse mapping via photometry and spectroscopy. Finally, with the combination of pulsations, binarity and light time travel corrections, PHOEBE 2.0 is capable of simulating also frequency modulations such as explained in detail by Shibahashi & Kurtz (2012).

3.6 Magnetic fields

Magnetic fields are added by assigning magnetic field vectors to each surface element, and include Zeeman splitting during the computations of the spectra (possible using the weak-field approximation). This way, the Stokes I, V, Q and U profiles can be synthesized by approriate summing of all individual profiles on the visible surface of an object. As with the pulsations, the generation of the line profiles can be coupled to a grid of synthetic line profiles, to model deep and high-signal-to noise lines.

4 Conclusion

PHOEBE 2.0 aims to be starting point of a new generation is modelling tools. The wealth of recent and forthcoming instruments give and will give us an increased precision of the measurements, necessitating further development of existing frameworks, more accurate description of "existing" physical phenomena, and inclusion of new effects that were formerly not detectable. The generation of many different types of observations, and the accurate treatment of those observations, allows simultaneous modeling of a variety of data. With every additional type of observations, new and different constraints are given, allowing us to test model predictions in a better and more detailed way.

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