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Eclipsing binaries in the era of *Gaia*

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Abstract. The ESA mission *Gaia* is expected to detect a few million eclipsing binaries, most of them hitherto unknown. We present an outline of the processing of these objects in the *Gaia* Data Processing and Analysis Consortium pipeline, with an emphasis on the scientific validation of the software components.

Key words: stars: binaries: eclipsing, surveys

1. Introduction

The advent of large-scale photometric surveys since about three decades ago has led to the detection of an ever-increasing number of eclipsing binaries (EBs) in our Galaxy and in nearby extragalactic systems. This striking boom manifests itself, e.g., in the increase of the number of EBs from 882 in the *Hipparcos* catalog (ESA, 1997) to 11,076 ten years later in the All Sky Automated Survey (ASAS, Paczyński et al., 2006), to half a million another ten years later, in 2016, in the OGLE-4 survey that covers both the Galaxy and the Magellanic Clouds (Pawlak et al., 2016; Soszyński et al., 2016). This list is not exhaustive, but shows the rapid increase in the number of EBs becoming available to the astrophysics community.

The *Gaia* mission, an all-sky astrometric, (spectro-)photometric and spectroscopic survey currently in operation (Gaia Collaboration et al., 2016), will provide the next opportunity to increase the number of known EBs by an order of magnitude. The total number of EBs that will be detected by *Gaia* by the end of its nominal mission (five years of operations) is estimated to be on the order of several million (Eyer et al., 2013), distributed all over the sky. The current extension of the mission beyond its nominal duration by up to five years will allow to both increase the number of EB candidates and to better characterize them. The specific interest of *Gaia*, in addition to its all-sky coverage, lies in the provision of multi-color photometric time series (in the broad optical

G band, the blue G_{BP} band, and the red G_{RP} band) to a precision reaching the milli-magnitude level. Furthermore, *Gaia* will provide astrometric time series and spectrophotometric (BP and RP) epoch data, as well as spectroscopic (RVS) epoch data and radial velocity time series for stars brighter than about $G = 15.5$ mag.

The data downlinked to Earth by the *Gaia* spacecraft is processed by the *Gaia* Data Processing and Analysis Consortium (DPAC). Within this consortium, the detection and processing of EBs is ensured by two Coordination Units (CUs): CU7, responsible for variable source detection, classification and characterization, and CU4, responsible for non-single star processing. Their respective roles in the processing of EBs are described in the next sections.

2. Detection of EBs and geometrical characterization of their light curves

Coordination Unit 7 within the *Gaia* Consortium identifies EB candidates from the classification of all variable objects, and derives their orbital period from their photometric time series (Holl et al., 2013, 2014). Additionally, CU7 characterizes the geometrical properties of their light curves using a two-Gaussian model (Mowlavi et al., 2017). The list of EB candidates is passed to CU4 for the derivation of binary model parameters (see next section).

3. Estimation of EB system parameters

The next step in the processing of an EB takes place in the CU4 Non-Single Stars section, and consists in modeling the observational data, namely the available light curves ($G, G_{\mathrm{BP}}, G_{\mathrm{RP}}$) as well as the radial velocity curve(s) if the object is also detected as a spectroscopic binary, with the aim of extracting the largest possible amount of information about the system given the observational and computational constraints. Depending on the viewing geometry and the physical properties themselves, this information can include the orbital parameters of the EB (inclination, eccentricity, argument of periastron) along with physical properties such as the stellar radii, temperatures and mass ratio.

This is accomplished by adjusting the sought-after parameters to the observational data in a maximum likelihood sense, through the use of an EB simulator capable of generating realistic light and radial velocity curves as a function of these parameters. An overview of this procedure, the *Gaia Eclipsing System Simulator and Solver (GESSS)*, is provided in Siopis & Sadowski (2012).

The massive scale of the data imposes the requirement of an automatic processing. The pipeline software that performs this functionality needs to be tested and validated from a software engineering as well as from a science perspective. This section touches upon the scientific validation part, which tests separately the two components of the software, namely the EB simulator and the optimizer,

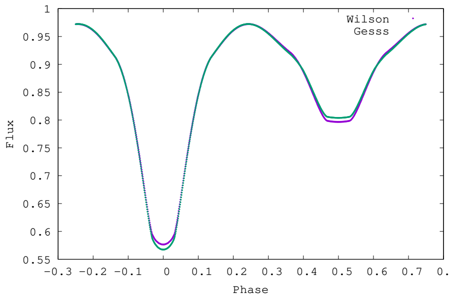

Figure 1. Comparison between the light curves generated at the same 1000 phases by GESSS and by the WD code shows that they overlap almost exactly. They were generated for the same set of physical parameters corresponding to the BW Eri system, shown in arbitrary flux units in Johnson V.

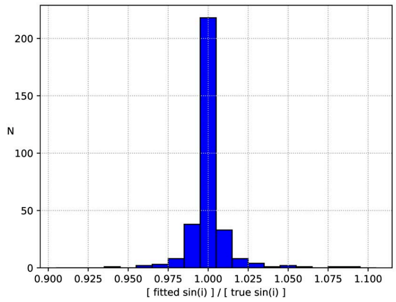

Figure 2. A histogram of the ratio of the fitted $\sin i$ over the true $\sin i$ for the 323 EBs from Terrell et al. (1992), sampled according to the *Gaia* scanning law, and with photometric uncertainties corresponding to those of a $G{\sim}13$ mag object.

the correctness of the former being of course a prerequisite for the correctness of the latter.

3.1. Validation of the EB simulator

The EB simulator calculates flux and radial velocity time series for a given set of input physical parameters. In order to validate the accuracy of the time series, they were compared against the time series produced by the Wilson-Devinney (WD) code (Wilson & Devinney, 1971; Wilson, 1979, 1990) using as input for both GESSS and WD the physical parameters of 323 EBs from Terrell et al. (1992). A black body atmosphere model was used in both GESSS and WD to avoid complications due to differences in the stellar atmosphere models used by default in the two codes. As shown in Fig. 1, the agreement is very good. Moreover, the normalized χ^2 difference between the light curves generated by the two codes remains smaller than $\sim 10^{-5}$ for nearly all 323 EBs in the sample. There is a slight discrepancy around the minima that is visible in some cases, which is due to small differences in the limb darkening coefficients used by the two codes.

3.2. Validation of the optimizer

The optimizer performs a simultaneous adjustment to all available light and radial velocity time series to obtain the best-fit physical parameters for the EB.

The validation of the output is done in a variety of ways, including:

- Fitting synthetic EB observations produced either by the Gaia Object Generator (GOG), which is a CU2 (Simulations) project that approximates a realistic distribution of EB parameters, or internally at CU4 to focus on specific factors (stellar atmospheres, *Gaia* scanning law, data noise, etc.)

- Using real EB data from *Gaia* to perform statistical analyses of large numbers of anonymous objects, or of a small number of well-studied objects.

One type of testing uses again the physical parameters of 323 EBs in Terrell et al. (1992) to generate synthetic light curves of real EBs incorporating various noise levels (thus simulating the effect of varying mean magnitude) and various sampling strategies (uniform vs *Gaia* scanning law). Fig. 2 illustrates the distribution of the ratio of the sines of inclination, $\sin i$, in the calculated solutions over their true values. As $\sin i$ is crucial in determining mass ratios for simultaneously eclipsing and spectroscopic binaries, it is satisfying that the distribution is strongly peaked around unity.

4. Towards *Gaia* Data Releases 3 and 4

The full results of the nominal mission will be available in data release 4 (DR4), planned at earliest for 2024. But a fraction of these EBs will already be published in DR3 during the second half of 2021, thereby providing an early opportunity for the scientific community to study populations of EBs observed by *Gaia*.

The DR3 catalogs will contain the photometric (G, $G_{\rm BP}$ and $G_{\rm RP}$) time series of the published EB candidates, and the processing results of both CU7 (estimated period and geometrical characterization of the light curves) and CU4 (physical parameters for the subset of the sample for which binary system solutions are found).

References

ESA. 1997, *The Hipparcos and Tycho Catalogues* (ESA, Noordwijk, the Netherlands)

Eyer, L., Holl, B., Pourbaix, D., et al., The Gaia Mission. 2013, *Central European Astrophysical Bulletin*, **37**, 115

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al., The Gaia mission. 2016, *Astron. Astrophys.*, **595**, A1, DOI: 10.1051/0004-6361/201629272

Holl, B., Mowlavi, N., Eyer, L., et al., Detecting eclipsing binaries with Gaia. 2013, in EAS Publications Series, Vol. **64**, *EAS Publications Series*, ed. K. Pavlovski, A. Tkachenko, & G. Torres, 399–400

Holl, B., Mowlavi, N., Lecoeur-Taïbi, I., et al., Automated eclipsing binary detection:applying the Gaia CU7 pipeline to Hipparcos. 2014, in EAS Publications Series, Vol. **67**, *EAS Publications Series*, 299–303

Mowlavi, N., Lecoeur-Taïbi, I., Holl, B., et al., Gaia eclipsing binary and multiple systems. Two-Gaussian models applied to OGLE-III eclipsing binary light curves in the Large Magellanic Cloud. 2017, *Astron. Astrophys.*, **606**, A92, DOI: 10.1051/0004-6361/201730613

Paczyński, B., Szczygieł, D. M., Pilecki, B., & Pojmański, G., Eclipsing binaries in the All Sky Automated Survey catalogue. 2006, *Mon. Not. R. Astron. Soc.*, **368**, 1311, DOI: 10.1111/j.1365-2966.2006.10223.x

Pawlak, M., Soszyński, I., Udalski, A., et al., The OGLE Collection of Variable Stars. Eclipsing Binaries in the Magellanic System. 2016, *Acta Astron.*, **66**, 421

Siopis, C. & Sadowski, G., Towards an automated processing of Gaia eclipsing binaries. 2012, in *Orbital Couples: Pas de Deux in the Solar System and the Milky Way*, ed. F. Arenou & D. Hestroffer, 59–63

Soszyński, I., Pawlak, M., Pietrukowicz, P., et al., The OGLE Collection of Variable Stars. Over 450 000 Eclipsing and Ellipsoidal Binary Systems Toward the Galactic Bulge. 2016, *Acta Astron.*, **66**, 405

Terrell, D., Mukherjee, J., & Wilson, R. E. 1992, *Binary stars. A pictorial atlas*

Wilson, R. E., Eccentric orbit generalization and simultaneous solution of binary star light and velocity curves. 1979, *Astrophys. J.*, **234**, 1054, DOI: 10.1086/157588

Wilson, R. E., Accuracy and Efficiency in the Binary Star Reflection Effect. 1990, *Astrophys. J.*, **356**, 613, DOI: 10.1086/168867

Wilson, R. E. & Devinney, E. J., Realization of Accurate Close-Binary Light Curves: Application to MR Cygni. 1971, *Astrophys. J.*, **166**, 605, DOI: 10.1086/150986