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Spectroscopic binaries in *Gaia*-ESO, *Gaia* and 4MOST surveys

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Abstract. The properties of binary stars are fundamental for understanding star formation and evolution. Spectroscopic binaries (SB) are genuine binaries that probe short to intermediate orbital periods, shedding light on various stellar evolution pathways. We share recent findings from the *Gaia*-ESO Survey regarding stellar multiplicity from a statistical point of view. Additionally, we present the binary content of *Gaia* DR3 and compare *Gaia* NSS SB with the SB9 reference catalogue of spectroscopic orbits. Finally, we provide insights into the detectability of SB within the context of other large spectroscopic surveys, such as 4MOST, which is set to begin operations next year.

Key words: binaries: spectroscopic – techniques: radial velocities – methods: data analysis – methods: statistical

1. Introduction

Why is spectroscopy of binary stars so important? The first argument is related to the fact that the method to detect spectroscopic binaries (SB) is insensitive to the geometrical distance between the system and the observer, as long as the instrument catches sufficient flux; as opposed to visual and astrometric binaries (AB) that can be detected up to 2 kpc (see Fig. 14 of Van der Swaelmen et al. 2023) with the *Gaia* space mission (Gaia Collaboration et al., 2016, 2023b). Similarly, eclipsing binaries (EB) can only be detected if the orbital plane is almost perpendicular to the sky plane. The second argument is related to the fact that SB cover a wide range of periods. Indeed, EB cover periods ranging from 0.1 to some tens day, and AB from 100 to 1 000 days, this latter value being an inherent limitation of the amount of data analysed in *Gaia* DR3. SB nicely bridge the gap from the shortest EB periods to the largest AB periods.

The first historical catalogue of spectroscopic orbits was setup at the beginning of the last century at the Lick Observatory (Campbell & Curtis, 1905). This first version include about 140 SB, but most of them were just detections. The following decades were dedicated to monitoring them and to computing their orbital solutions. The catalogue was continuously updated at the Dominion Astronomical Observatory until its version eight, reaching about 1 500 SB (Batten et al., 1989). Since 2 000, an IAU initiative endorsed the update towards an electronic version of the catalogue managed by Pourbaix et al. (2004). After his last update, the SB9 catalogue contained 5 000 orbits for 4 000 SB, because some systems have several orbital solutions published in literature. The era of large ground-based spectroscopic surveys allow the detection of many new SB. Here we report their detections in three (past, present, and future) large surveys: *Gaia*-ESO, *Gaia* and 4MOST. The reader can refer to Merle (2024) for more details on recent photometric and spectroscopic surveys.

2. The past: *Gaia*-ESO

The *Gaia*-ESO Survey (GES) targeted about 100 000 stars in all stellar populations of the Galaxy (Gilmore et al., 2022; Randich et al., 2022). The final release (GES DR5.1) is publicly available since July 2023. The observing strategy was not tailored for the detection of binaries, but it was possible to detect about 1000 SB1, 430 SB2, a dozen of SB3 and one SB4 (Merle et al., 2017, 2020; Van der Swaelmen et al., 2023). Figure 1 shows the identified SB1 against the GES parent population (left), whereas the right figure shows the SB2, forming a main sequence of twin stars, shifted compared to the main sequence of single stars, because photometrically unresolved, appearing brighter than their single counterpart. The GES SB frequency, after correction for selection biases, is about 12%: 10% for SB1 and 2% for SB2, well in line with the close binary fraction of 15 ± 3 % determined by Moe & Di Stefano (2017). For the sample of SB1, statistical inference of the period distribution was derived, as well as the metallicity-dependence of the binary fraction, which increases at a rate of $\sim 10\%$ per dex of decreasing metallicity. The higher rate in low-metallicity environments is caused by lower gas opacities that favour efficient cooling and fragmentation even on scales lower than 10 au (Bate, 2005). Finally one interesting spectroscopic quadruple has popped up in the GES dataset. Combining archival data (GIRAFFE, UVES) to the data from a new spectroscopic follow-up (HRS/SALT, HERCULES/UCMJO), it was possible to characterise this compact hierarchical 2+2 system. Some of the evolutionary scenarios lead to

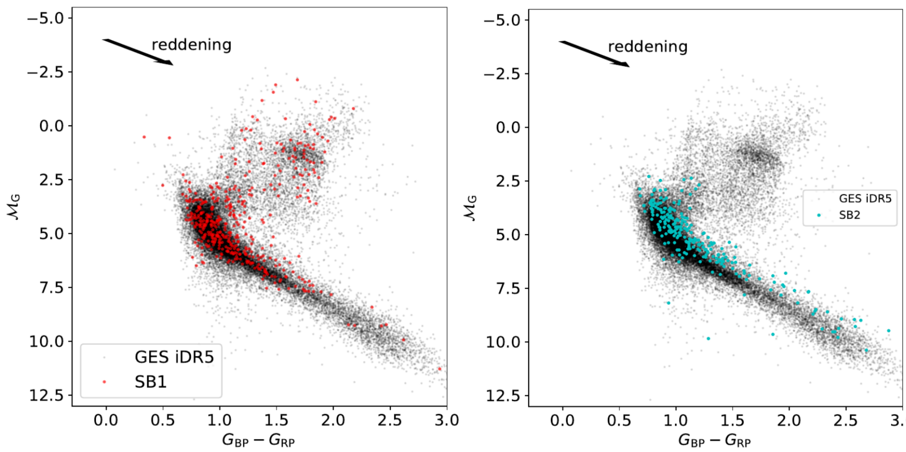

Figure 1. Colour-absolute magnitude diagram of stars in the *Gaia*-ESO Survey with detected SB1 (left panel) and detected SB2 (right panel), using *Gaia* parallaxes and photometry.

the formation of type Ia supernova through a sequence of merger events (Merle et al., 2022).

3. The present: *Gaia*

The ESA *Gaia* mission (Gaia Collaboration et al., 2016, 2023b) started operations in 2013. The 3rd data release (DR3) provided an unprecedented large and homogeneous sample of binary stars, making a quantitative leap in the datasets and orbital parameters for binaries. In *Gaia* DR3, there are 3 sources to explore in term of binarity: (i) the Non-Single Star (NSS) catalogue (Gaia Collaboration et al., 2023a) that contains about 800k binaries, see Fig. 2, (ii) the catalogue of variables that contains about 2 million of eclipsing binaries and more than 6 300 ellipsoidal variables (Eyer et al., 2023), (iii) the Multiple Star Classifier (Creevey et al., 2023) with about 480 million *Gaia* unresolved photometric binaries. The latest should be used with caution, since no validation was performed, but it constitutes an interesting starting point for having rough estimates of effective temperature, gravity and metallicity of individual components.

In brief in NSS, there are about 450k astrometric binaries (AB), 219k SB and 86k eclipsing binaries (EB) as illustrated in Fig. 2. There is a sample of about 58k AB+SB; while the numbers of SB+EB, AB+EB and AB+SB+EB are more anecdotic, still providing an effective number of candidates that will probably serve as a benchmark binary sample.

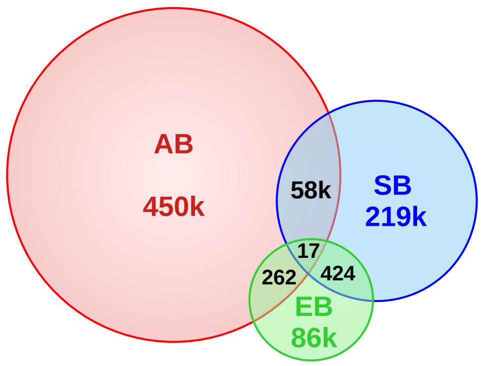

Figure 2. *Gaia* Non-Single Star catalogue content. AB, SB and EB mean Astrometric, Spectroscopic and Eclipsing Binaries. The intersection between AB and SB allows to derive accurate masses for about 20k binaries, reported in the *Gaia* table `binary_masses`.

A careful cross-match of the SB9 with *Gaia* NSS allows to find about 800 common binaries only. This is mainly explained by two reasons: first, the limiting magnitude of the *Gaia* spectrograph for SB is about $G \sim 13$ mag, while reaching ~ 19 mag in SB9; second, the measured orbital periods is limited to about 1 000 d, while reaching 10^5 d in SB9. When comparing the periods, we identified a number of outliers (about 10%) which are investigated in detail in a forthcoming paper (Merle et al., in prep). We can also mention Gosset et al. (2024) who used the SB9 catalogue to validate the *Gaia* NSS SB pipeline.

4. The future: 4MOST

The 4-m Multi-Object Spectrograph Telescope (4MOST, de Jong et al. 2019) is a large ground-based spectroscopic survey on the 4 m VISTA/ESO telescope. The first light is scheduled for 2025. With 2 400 fibres (1 600 in low resolution, $R \sim 6\,000$; and 800 in high resolution, $R \sim 20\,000$) the probing magnitudes will reach 20 (S/N$\sim$ 10 Å^{-1}) and 16 (S/N$\sim$ 100 Å^{-1}) in G band, respectively, in low and high resolution. The accessible range of declinations is $[-80, +20]^\circ$. Such facility will roughly provide about a million spectra a month to analyse, which is considerable and will require automated processes. In this context, the Multiplicity Working Group has developed a cadence strategy for some of the

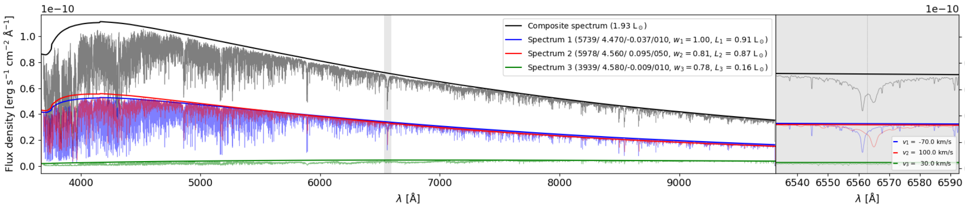

Figure 3. Synthetic composite spectrum of a spectroscopic triple stellar system (grey line)to test the SB detection module implemented in the 4MOST Galactic Pipeline. The primary (blue) and the secondary (red) have similar atmospheric parameters while the third component (green) is almost 2000 K cooler. The panel on the right is a zoom around Hα.

sub-samples to optimise the number of repeated observations. On the one hand, we want a maximum possible time span between required repeats to boost SB1 detection efficiency and, on the other hand, we will follow-up some of the *Gaia* and OGLE (Soszyński et al., 2016) EB and ellipsoidal variables to derive precise stellar masses and radii. In addition, the Detection Of Extrema code (DOE, Merle et al. 2017) is implemented in the 4MOST Galactic Pipeline to ease the detection of SB with two components and more. To test it, we simulate synthetic composite spectra (see the spectroscopic triple star in Fig. 3 as an example), to determine detection efficiency and threshold, as well as precision and accuracy on measured radial velocities. For SB2, the minimum separation between components are about 23 km s^{-1} in high resolution mode and 64 km s^{-1} in low resolution mode. Finally an implementation of a module that will characterise composite spectra with n components is undergoing, following the methodology of El-Badry et al. (2018) and using machine learning approach based on *The Payne* (Ting et al., 2019).

5. Conclusion

In the era of large spectroscopic surveys, many SB candidates are identified, most of them being new discoveries. Nevertheless, follow-up of these candidates is necessary to confirm their multiple nature and characterise their orbital parameters. However, often smaller facilities can follow only the brightest and the most interesting candidates. With the rise of *Gaia*, and new large multi-object spectrographs like 4MOST, we enter a new *industrial* scale where machine learning will be fully exploited to detect and characterise SB, including the most numerous ones having orbital periods beyond a hundred years.

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