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Massive binaries as seen with Gaia

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Abstract: *Gaia*, ESA's forthcoming astrometric observatory, will observe a billion stars of our Galaxy, among which thousands of high-mass stars. In this contribution, we study the capabilities of *Gaia*'s spectrometer (RVS) in the context of massive stars, especially the detectability of lower-mass companions to O-type stars. This preliminary study enables us to estimate to what extent *Gaia* will constrain the distribution of the physical and orbital parameters of massive binaries (luminosity, period, mass ratio, eccentricity...).

1 Introduction

Massive binaries are crucial for a robust determination of fundamental parameters of massive stars. Here, we investigate the detection of massive binaries with the radial velocity spectrograph (RVS) of *Gaia*, ESA's forthcoming astrometric mission. To reach this goal, we have used two approaches: one based on a set of binaries with fixed orbital parameters and a second one based on a larger population with an underlying distribution of orbital parameters. The first gave us specific information on the detection of binaries as a function of spectral class. The second is a more statistical assessment of the detection with respect to the mass ratio. We also simulated the capabilities of the astrometric instrument to quantify the impact of the Lutz-Kelker bias (Lutz & Kelker 1973) that affected the *Hipparcos* parallaxes.

2 Gaia

Gaia is ESA's global astrometry mission due for launch in August 2012 with a nominal lifetime of five years. The goal of this mission is to measure the positions, velocities and distances of about one billion stars to create a 3D map of part of the Milky Way. The satellite has two telescopes that share the same focal plane. The 3-in-1 instrument is placed in the unique focal plane composed of 106 CCDs. This instrument has three channels: astrometric, spectro-photometric and spectrometric. The very high precision of the astrometric instrument (up to 7 μas) will help astrophysicists to improve their knowledge in stellar physics, stellar population distribution, exoplanet systems, galactic structure,... The RVS is a medium-resolution ($R \simeq 11500$) near-infrared spectrograph (see Table 1). Its goal is to measure the radial velocity of stars and therefore complete the information of the astrometric instrument (angular position, angular velocity and parallaxes) to characterize completely the motion

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Table 1: Characteristics of the RVS instrument

Wavelength range	$847 - 874$ nm
Accuracy (for late-type stars)	$1 - 10$ kms^{-1}
Resolving power	11500
Spectral resolution	0.075 nm/pixel

of stars. The wavelength range is best suited for G and K stars but includes only a limited number of weak lines in the case of massive (OB-type) stars.

3 Simulations

We simulate the detection of binary systems containing at least one O-star with the RVS. All simulations are done with MATLAB®. We make two distinct simulations but in both cases, the first step is to build synthetic spectra of fake binary systems in the RVS domain. For this purpose, we use a set of eight observed O-star spectra and a grid of thirty-six synthetic spectra of cooler stars from Castelli & Munari (2001) and Munari & Castelli (2000). The spectra are wavelength-shifted according to the orbital elements of the fake binary system. Orbits are supposed circular.

3.1 RVS spectra

In the first case, the orbital elements are fixed. At first, we do not add noise. The masses of the stars are supposed to be known, the inclination of the system takes only three values: $\{0, \pi/4, \pi/2\}$, the period is fixed at ten days and, finally, we only consider the extreme values of the true anomaly[1]. The combination of the spectra of 8 O-stars and 36 non O-stars yields a total of 1440 cases. In the second case, we perform a Monte Carlo simulation for 9 millions binary systems. The latter are generated following the distributions of mass ratios and semi-major axis given by Kobulnicky & Fryer (2007) : $f(q) = C \times q^{0.3}$ where C is a normalization constant. We also assume a uniform distribution of orbital inclinations in the range $[0, \pi]$ radians. The distribution of semi-major axes is also supposed uniform (Kobulnicky & Fryer 2007) and is generated in the range $[13.5R_\odot, 3000R_\odot]$. Again, we only consider the extreme values of the true anomaly. Finally, we add noise to the synthetic spectra.

3.2 Cross-correlation

The resulting simulated spectra are then cross-correlated with two masks (one for the O-star and another one for its companion) and we consider that the binary nature is successfully detected if the cross-correlation peak yields the right radial velocity within the resolution of the RVS (see Fig. 1). Note that the performance of our method is not as good as the procedure that will eventually be used for *Gaia*. To correct for this lower performance, we adopt a larger tolerance on the radial velocity: in our simulations, this tolerance is 25 km s^{-1}, which corresponds to an error of one pixel (low-sampling mode). Although systems with very low radial velocities (either as a result of a low inclination or an unfavorable orbital phase) generally yield a positive cross-correlation with both masks, we discard these cases from our analysis, since in practice, the binarity of such systems can not be established by

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[1] Whilst our simulations consider a "single transit", the results presented below will not change significantly by considering multiple transits, since we have simulated the extreme values of the true anomaly which should provide the best phases for detection of binarity.

Table 2: Characteristics of the ASTRO instrument

Spectral type	Visual Magnitude	Standard deviation of position measurement (μas)
O	< 10	< 7
	< 15	25

these data. Another remark is about the O + O systems. We often found one component of the system but not the second one. This problem comes from the difficulty to find the secondary cross-correlation peak. A more sophisticated method like disentangling could be used to improve the detection of such cases.

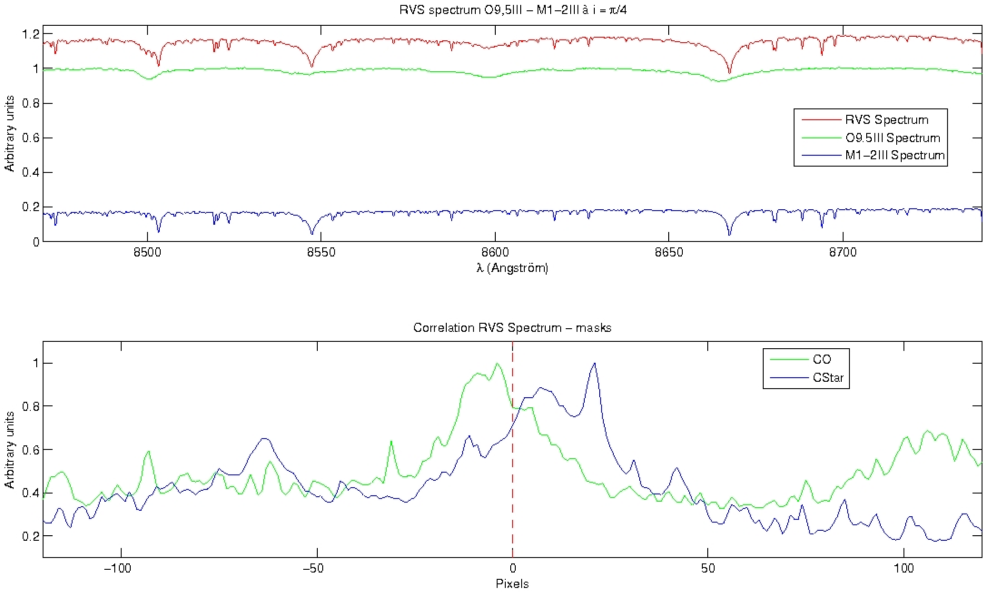


Figure 1: Upper panel: Example of combining spectra of an O9.5 III and an M1-2 pre-main sequence star at an inclination of $\pi/4$. Lower panel: Result of the cross-correlation. The input radial velocities are recovered within the resolution of the RVS.

3.3 Astrometric instrument

Two distinct simulations linked to the astrometric instrument have been done. The first one concerns the calibration of absolute magnitudes. For this purpose, we use the catalogue of Humphreys (1978) of OB-stars and we check whether the error induced by the ASTRO instrument has an impact on the absolute magnitude. The second part of the simulations is linked to the Lutz-Kelker bias (Lutz & Kelker 1973) that affects the *Hipparcos* observations. This bias depends on the ratio σ_{Gaia}/π where σ is the standard deviation of the instrument (see Table 2) and π the observed parallax (we assume that the Humphreys parallaxes are the observed ones). The absolute magnitude and the parallax are connected by the following relation: $M = m - A - d$ with A, the reddening and $d = 5 \times log(1/\pi) - 5$, the distance modulus. For information, the parallaxes given by Humphreys range from 1.5×10^{-4} to 2.9×10^{-3} arcsec.

4 Results and conclusions

The first important result is that the RVS wavelength domain does not allow us to get rid of the common luminosity bias that affects the detection of the companion star. Indeed, binary systems with mass ratios ($M_{companion}/M_O$) below 0.4 will probably not be detected by the RVS, regardless of the luminosity class of the companion (see Fig. 2). The percentages of detections of SB1 and SB2 spectral signatures are given in Fig. 3 below for simulated O + O systems and O + non O systems. As can be seen, the total detection rate will be around 50% (SB1 and SB2 spectral signatures), which is not very good. We also note that high-velocity amplitude systems were actually more difficult to detect. Fortunately these systems are less common than low velocity amplitude systems. The first simulation with a fixed period showed us that the detection rate depends on the luminosity classes of the O-star and its companion. The spectral signatures of O-stars in association with supergiant companions are usually more difficult to detect. The O-star is usually better detected than the companion star. In conclusion, we find that the RVS is not well suited for the study of massive binaries as the near-infrared spectral range, chosen for this instrument, contains only weak lines in the spectra of O-type stars.

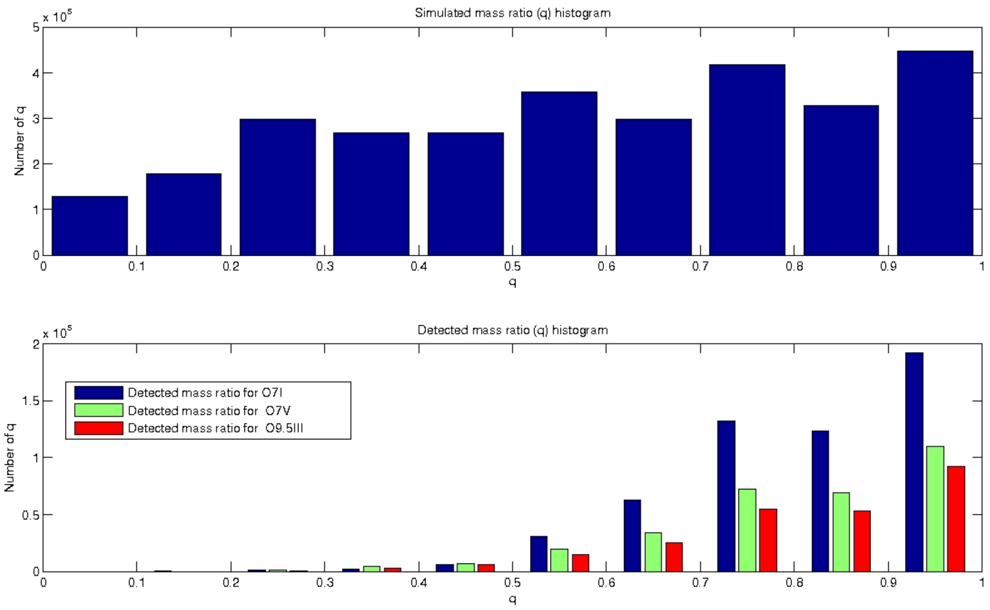
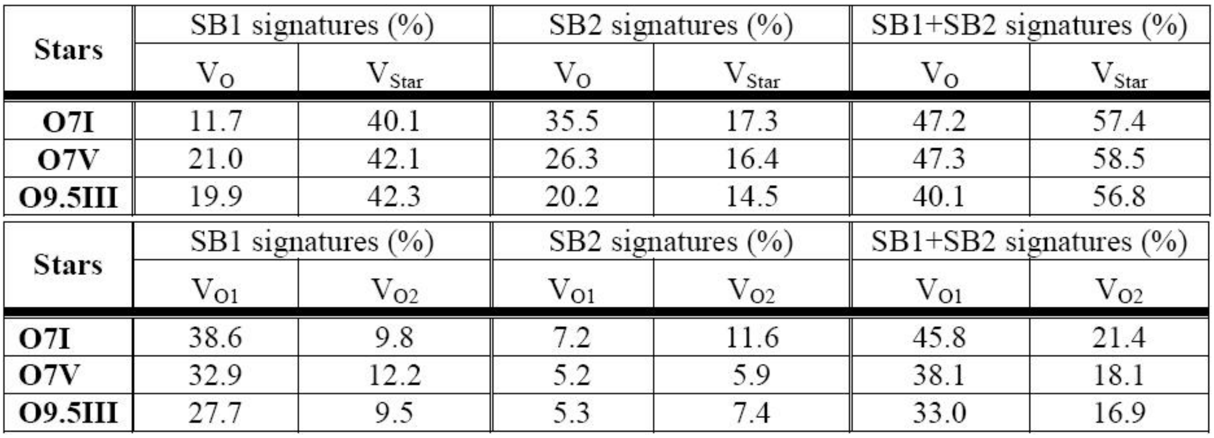


Figure 2: Upper panel: histogram of the simulated mass ratios of the input binary population. Lower panel: histograms of the detected mass ratios for SB2 spectral signatures for three O-star primaries.

The last part of the simulations were related to the astrometric instrument. This instrument will provide parallaxes with unprecedented accuracy that should allow us to obtain a bias-free absolute magnitude calibration for massive stars. For the first part of the simulations, we conclude that the error induced by *Gaia* is indeed negligible. The comparison of our results (catalogue of Humphreys, 1978, + *Gaia*'s error) and the Martins et al. (2005) calibrations showed that the errors introduced by the *Gaia* astrometric instrument are so small that we will be able to distinguish between the different calibrations of O-type star that have been proposed. For the second part of the simulations, the impact of the bias on the determination of the absolute magnitude calibration of O-stars was simulated using the catalogue of Humphreys (1978). We showed that the Lutz-Kelker bias will be negligible (for objects brighter than magnitude 10) thanks to the unprecedented precision of the astrometric instrument. Indeed, the ratio σ_{Gaia}/π is very small, especially for stars brighter than magnitude 10:



Stars	SB1 signatures (%)		SB2 signatures (%)		SB1+SB2 signatures (%)	
	V_O	V_{Star}	V_O	V_{Star}	V_O	V_{Star}
O7I	11.7	40.1	35.5	17.3	47.2	57.4
O7V	21.0	42.1	26.3	16.4	47.3	58.5
O9.5III	19.9	42.3	20.2	14.5	40.1	56.8

Stars	SB1 signatures (%)		SB2 signatures (%)		SB1+SB2 signatures (%)	
	V_{O1}	V_{O2}	V_{O1}	V_{O2}	V_{O1}	V_{O2}
O7I	38.6	9.8	7.2	11.6	45.8	21.4
O7V	32.9	12.2	5.2	5.9	38.1	18.1
O9.5III	27.7	9.5	5.3	7.4	33.0	16.9

Figure 3: Percentages of detections of SB1 and SB2 spectral signatures for three O-star primaries of different luminosity classes. Upper part: O + non O systems. Lower part: O + O systems

the correction on the absolute magnitude is -0.01 at most, and amounts to -0.14 for objects fainter than magnitude 10.

In conclusion, the RVS instrument is not well suited for the study of massive binaries with a detection rate of about 50% even including SB1 signatures. However, the astrometric instrument fulfills its promises to provide a tremendous breakthrough in our understanding of the physics of massive stars.

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