Improving the Gaia planet catch by combining the astrometry with precise radial velocities

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Introduction

Astrometry is a promising technique for exoplanet research. It allows us to determine all the orbit parameters and the accurate mass of the planet. Gaia will be the first space mission to reach astrometric precision capable to detect planetary companions around stars brighter than 15th mag. Astrometry is more sensitive to planets with large periods, in contrast with radial velocities (RV) methods which are more efficient to detect planets with short periods, and deliver only a minimum mass as orbital inclinations cannot be measured. The idea of this study was to combine measurements from both methods, to understand if one can improve the detection of planets with periods too short to be detected solely by Gaia.

The astrometric signature of a planet orbiting around a star is described by seven parameters. With a radial velocities orbit, five parameters can be obtained. If it is known, we only have two parameters left to adjust. In this particular case, the fitting is simplified and weaker astrometric signals can be detected.

Our study aimed to determine what type of planets could be detectable with Gaia when combined with radial velocities measurements, to explore possible programs of RV observations to complement Gaia observations. To compute radial velocities, we considered two high resolution spectrometers: CORALIE and HARPS. CORALIE is installed on the Swiss 1.2-m telescope in La Silla (60 000 resolution). HARPS has a resolution twice better than CORALIE and is installed on the ESO 3.6-m telescope.

1. Method

To simulate planet detections with Gaia, we considered a simplified model. We estimated the amplitude of the signal caused by a planetary companion and compared it to the expected instrumental precisions. If the simulated signal was greater than the detection threshold of the instruments, we considered that the planet could be detected.

The first step of our study was to determine the precision of the instruments. For radial velocities, we assumed an intrinsic instrumental noise of 1 m s^{-1} for HARPS and 3 m s^{-1} for CORALIE. We also considered photon noise as described in [1]. To consider the effect of the resolution of the spectrometers on the estimated RV error, we assumed that the equivalent line width corresponds to a Doppler broadening computed for a stellar rotation speed of 4 km s^{-1} for HARPS, and 8 km s^{-1} for CORALIE.

For Gaia astrometric measurements, we considered the expected precision for a single observation given by Mignard [6]. It is a saw-tooth function depending on the magnitude of the star, in the range of magnitudes from 6 to 12. For fainter stars, it raises with magnitude according to photon noise. The worst precision in the saw-tooth region of the error is reached for magnitudes below 8.8. The influence of this feature will appear in our results. An ongoing effort is made to reduce this effect.

The planet distribution is a debated question (e.g. [3, 5]). To avoid assuming a planet population, we considered different kinds of planets and that each star had a planet. We explored masses in the range between 0.1 and 25 M_{Jup} (Jupiter mass) and periods between 10 and 2000 days. To simplify computations we assumed circular orbits.

For the stellar distribution, we used the Besançon model [7]. We only considered three kinds of stellar objects. A F, a G and late K dwarf stars. Our groups of stars were defined as follows: K stars with an absolute magnitude M_v in the range between 7 and 8.5; G stars M_v between 4.5 and 5; F stars M_v between 3.5 and 4.5.

We computed, for each kind of planet (mass and period), the amplitude of the signal caused by its presence around each star. Then, we counted the stars for which the value obtained was above the detection threshold.

We took into account the location of the stars in the sky. The final precision of Gaia depends on the number of measurements, due to its specific scanning law (described in [6]). The number of observations of a given star depends mostly on the ecliptic latitude (number of measurements varying from 70 to more than 200). We did not consider the dependence on ecliptic longitude as it is dependent on the launch date and shows little variations.

2. Detection criterion

To specify a detection criterion for planets, we defined the detection threshold for each technique and their combination. When only using Gaia, we considered that the signal-to-noise ratio (SNR) limit for astrometric planet detection was 17. This was obtained with a simplified algorithm fitting circular orbits. A similar value (~ 20) was found by Casertano *et al.* [2]. We assumed that a planet could be detected by radial velocity method if the semi-amplitude K_1 of the spectroscopic signal was greater than five times the instrument precision. This threshold corresponds to about 20 measurements per planet, a typical number encountered in planet Doppler surveys. Then, assuming first detection by RV and subsequent combination of astrometric observations, Sahlmann *et al.* [8] showed that a SNR of 7 was enough to fit the astrometric orbit.

3. Results

Our results are organized to address three key questions: (1) what type of planets will be detectable with combined measurements? (2) what will be the lowest mass detectable? (3) which type of stars is best suited for a combined program?

For all kinds of planets considered, we plotted magnitude histograms with stars where planets could be detected. The results were expressed for two cases: (1) when only Gaia measurements are used; (2) when the planet is first detected by RV and then astrometric measurements are combined with spectroscopic data. We can notice on fig. 1 left, that the saw-tooth shape of the precision law affects the results. The lack of detections around magnitude 8 is related to the degradation of the precision for stars with magnitudes below 8.8. Yet, in few cases like Jupiter mass planets with a period of 2000 days orbiting F stars, the use of combined measurements allows detections in this range of magnitudes.

Aside from this effect, when combining data from both techniques, we see in fig. 1 right that there is a drastic increase in detections on the fainter end.

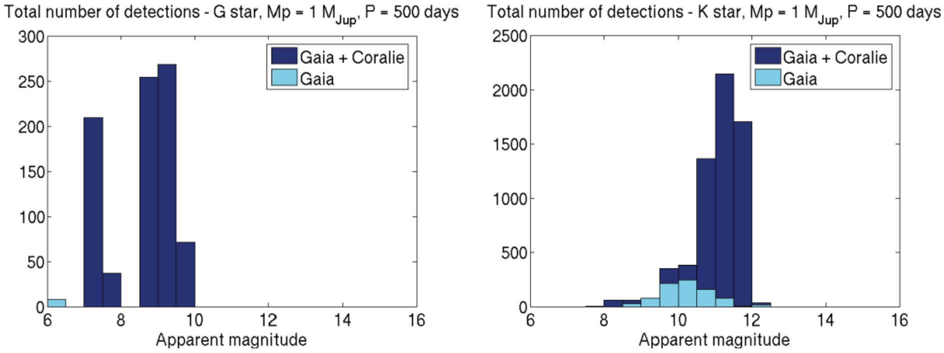

Figure 1: Number of G (left) and K (right) stars with a planet detection in function of their apparent magnitude. We consider here a planet with a Jupiter mass and a period of 500 days.

To study the lowest planet mass that can be found, as a function of orbital period, we considered that we could detect the planet if at least 30 stars (i.e. we assumed a ~3% occurrence rate) could be found in the whole sky, that satisfied the detection criteria.

We decided to compare the lower mass limits for the three considered cases: (1) only Gaia data; (2) CORALIE detections combined with Gaia data; and (3) HARPS detections combined with Gaia data. With only Gaia astrometric measurements, the minimum mass that may be detected is 0.165M$_{Jup}$ and is found at the maximum period, 2000 days (see [2]). When we combine CORALIE RV measurements with Gaia measurements, the improvement, by comparison with the Gaia-only case, is visible on fig. 2 for periods shorter than 400 days. The minimum mass obtained in this range of periods is 0.36 M$_{Jup}$ at 170 days. If we use HARPS instead of CORALIE, we see on fig. 2 a dramatic gain in the minimum mass which is almost constant (~ 0.17 M$_{Jup}$) from 500 to 2000 days.

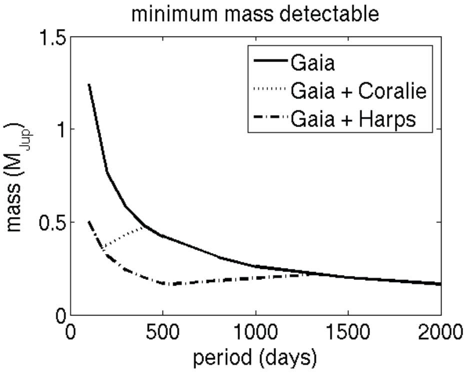

Figure 2: Minimum mass detectable as a function of the period of the orbit with GAIA **solid line**, CORALIE+Gaia **dotted line** and HARPS+GAIA **dashed line**. (For P<200d, CORALIE+Gaia and HARPS+Gaia are superimposed; for P>400d Gaia and CORALIE+Gaia are superimposed; and for P>1300d the 3 curves are superimposed).

The planets with the smallest masses are detected around K stars of apparent magnitude close to 9. This corresponds to a minimum in the saw-tooth error function. For bright stars with magnitudes between 6 and 6.5, the precision is also good but there are not enough K stars to get significant results.

It is worth stressing that an improvement of Gaia's precision for stars with magnitudes close to 8 could lead to a reduction of the lowest detectable mass.

We finally looked at the planets that we could detect with Gaia only when combined with radial velocities data. For each kind of planet considered, we first checked if it could be detected by CORALIE.

Assuming the RV detections, we counted the number of stars around which we could detect the planet with Gaia combined with CORALIE results. Then, we subtracted the cases where Gaia measurements alone were enough to claim detection. We focused on stars brighter than a magnitude 10 as such objects are more adapted to radial velocities observations. Figure 3 shows a plot representing these objects that do require both methods to be characterized. The white region on the top left represents the planets that we cannot detect with Gaia, even if we combine with CORALIE measurements. The white region on the bottom right represents the planets that can be detected with GAIA measurements only.

Those results show that the use of combined measurements enables to complete detections with short periods.

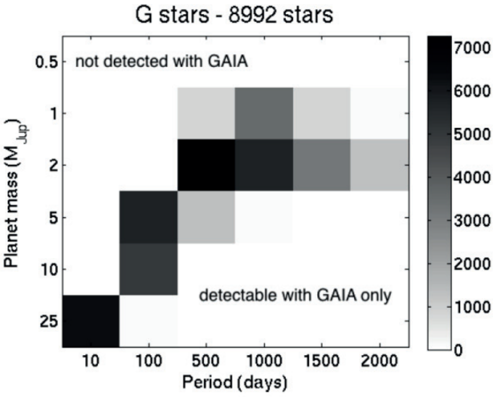

Figure 3: Detectable planets only when combined with CORALIE around G stars with a magnitude <10.

The previous results showed a significant number of possible targets for a radial velocities program combined with Gaia. Due to the galactic stellar distribution and the special Gaia scanning law, there are areas in the sky with a greater number of interesting targets. We tried to locate these regions in order to prepare potential RV survey programs. We calculated, as a function of the position in the sky, the number of stars per square degree, around which we could detect planets only with combined measurements. For the majority of planets in the range considered in this study, the result is the same: the most favorable zone is the intersection between the galactic plane and the ecliptic latitude 45° (region where the number of Gaia measurements is maximal). We plotted this zone in equatorial coordinates (e.g. fig. 4) and we noticed that there is an interesting region in both hemispheres and they are not close enough to the equator to be both observed by a telescope in the southern hemisphere. There are interesting sources for two possible observing programs, one in each hemisphere.

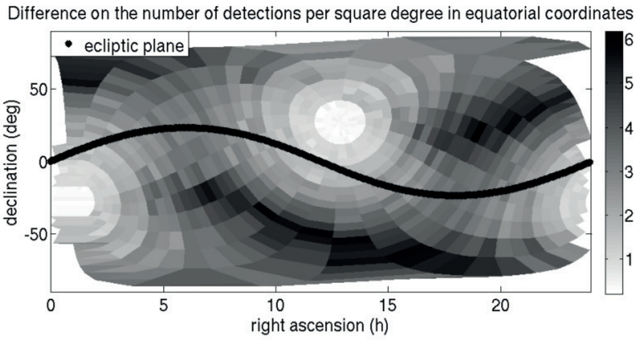

Figure 4: Total number of G stars per square degree, around which we could detect additional planets when combining CORALIE measurements with Gaia measurements, in equatorial coordinates. (Case considered in this figure : M=5M_{Jup}, P=500days)

Conclusion

Our study proved the interest and the potential in combining radial velocities measurements with Gaia measurements. It is interesting to note how the curve of the minimum detectable mass is flat, from P=500 to 2000 days, when using HARPS RV measurements.

The number of Jupiter type planets detectable can be increased using CORALIE. Some of the interesting targets have already been observed (particularly the brighter ones) by the ongoing RV surveys (see [9, 4]). For fainter objects, new observation programs could be started in parallel to the GAIA mission in order to enhance Gaia scientific yield.

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