Extrasolar Planets in Double and Multiple Stellar Systems

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Summary. About 60% of G and K dwarfs belong to double or multiple stellar systems, making these a common environment in which planets may form. Despite this, close binaries have often been rejected from radial-velocity searches for extrasolar planets because they present observational difficulties. Planet formation and survival in binaries is thus a poorly known issue, though interesting in several respects. In particular, stellar duplicity could be used to test planet formation models and possibly identify the main formation mechanism for giant planets. For a few years we have been conducting two observational programmes dedicated to the study of extrasolar planets in binaries. The first one is a radial-velocity search for short-period giant planets in spectroscopic binaries, while the second one is a systematic adaptive optics search for stellar companions to nearby stars with and without planetary companions. In this contribution we first review some observational and theoretical aspects related to extrasolar planets in binaries. We then present some preliminary results from our two observational programmes.

1 Introduction

The study of extrasolar planets in double and multiple stellar systems is a rather new and fast developing facet of the extrasolar planet research field. In this section we present a brief review of some observational and theoretical results related to planets in binaries[1]. The emphasis is not on completeness, but on sketching out the general framework in which current research is taking place.

[1]For conciseness, planets in double and multiple stellar systems will often be referred to as planets in binaries, it being understood that for multiple stellar systems the binary denotes the planet-host star and its nearest stellar companion, or its nearest close pair considered as a unique object for highly hierarchical systems.

1.1 The Observational Perspective

A real interest for planets in binaries emerged only a few years ago. On the one hand, a dozen of planets were then known to orbit the component of a double or triple system, proving that planets can form and survive in certain types of stellar systems. On the other hand, [24] suggested that planets found in binaries may have different properties than planets orbiting single stars. This claim was based on an analysis of the mass-period diagram, emphasizing a paucity of short-period massive planets and the fact that the most massive short-period planets belong to binaries. Hence a possible different mass–period correlation for the two populations (planets in binaries vs planets around single stars), which was found to be highly significant despite the small number of planets in binaries.

The first observational programmes dedicated to the study of extrasolar planets in binaries started around 2001. Radial-velocity searches for planets in spectroscopic binaries (see Sect. 2) and in wide binaries (see Desidera et al., this volume) were thus launched. Some other programmes followed a different approach, namely searching for stellar companions to planet-host stars (see Sect. 3 or [11, 13, 15]). Such an approach is also worth pursuing since a precise knowledge of the multiplicity status of each planet-host star is a prerequisite for any study aiming at comparing the properties of planets found in binaries and around single stars. Many of these observational programmes are still ongoing and only preliminary results are available yet.

Finally, we also studied the eccentricity–period diagram and pointed out that short-period planets found in binaries tend to have a low eccentricity when their period is shorter than about 40 days [6]. That is, the minimum period for a significant eccentricity may be longer for planets in binaries than for planets orbiting single stars. But again, this trend is based on a small sample of planets in binaries, and a larger sample will be needed to settle once and for all whether or not planets found in binaries possess different properties than planets orbiting single stars.

1.2 The Theoretical Perspective

Two major scenarios have been proposed to explain giant planet formation: core accretion and disc instability (see e.g. [2, 18]). Several aspects of planet formation are still poorly known, and it is clear that adding a stellar companion does not simplify the problem. Nevertheless, a few aspects of planet formation in binaries have been studied, on the assumption that the binary was already formed when planet formation began. In such a case, each star may affect a potential circumstellar protoplanetary disc formed around the other component. In close systems, angular momentum transfer between the binary and a (circumstellar) protoplanetary disc will lead to a truncation of the disc's outer radius [1]. Assuming that the protoplanetary disc is still large and massive enough to sustain planet formation, will a planet persist in the long term? Stability zones have been shown to exist in such systems [8], and, generally speaking, if a planet can form in a truncated disc, it is likely to survive in the long term.

The efficiency of forming giant planets in binaries is a less studied and more debated issue. [3] claimed that the presence of a stellar companion located at about 40 AU could favour planet formation via disc instability. On the other hand, [14] showed that planet formation, either via disc instability or via core accretion, is unlikely in binaries with a separation of about 50 AU. More recently, [12] revisited the question and made a more extensive study. Their main conclusions can be summarized as follows: (i) planet formation in massive discs is not possible, whatever the mechanism (core accretion or disc instability), (ii) in intermediate-mass discs, both mechanisms may work, provided cooling is very efficient, (iii) core accretion remains the only viable mechanism in light discs, and (iv) for binaries wider than 120 AU planet formation proceeds very similarly to the isolated case. A very important conclusion can be drawn from these results: fewer planets should be found in binaries with a separation below 100 AU if disc instability is the main formation mechanism [12]. Studying planet formation in binaries may thus be a means of identifying the main formation mechanism for giant planets.

Once a planet has formed, the stellar companion may still affect its evolution. [9] studied the evolution of a Jupiter-mass protoplanet still embedded in a protoplanetary disc and showed that for systems with a separation in the range 50–100 AU both the mass accretion rate onto the planet and the migration rate of the planet are enhanced due to the presence of the stellar companion. These results constitute a first argument in favour of different properties for planets in binaries.

To sum up, even if several aspects of planet formation and survival in binaries are still debated and unclear, models have come up with a few very interesting predictions that could be confronted with observations. For some time, we have been working on gathering observational material to be used to test some of these predictions. Preliminary results from this work are presented in the following sections.

2 Searching for Short-Period Planets in Spectroscopic Binaries

In 2001 we initiated a systematic radial-velocity search for short-period circumprimary giant planets in single-lined spectroscopic binaries (SB1). This programme is aiming at obtaining a first quantification of the frequency of giant planets in close binaries. Our sample of binaries has been selected on the basis of former CORAVEL surveys for G and K dwarfs of the solar neighbourhood [4, 7]. All single-lined spectroscopic binary candidates with a period longer than approximately 1.5 years were retained, providing us with a sample of about 140 binaries covering both hemispheres. For each binary, 10 to 15 high-precision radial-velocity measurements were taken, either with the CORALIE spectrograph (ESO La Silla Observatory, Chile) or with the ELODIE spectrograph (Haute-Provence Observatory, France). The data acquisition phase is now completed and data analysis is under way.

2.1 Data Reduction

Stellar spectra obtained with ELODIE or CORALIE are reduced online. Radial velocities are computed by cross-correlating the measured stellar spectra with a numerical binary mask whose nonzero zones correspond to the theoretical positions and widths of stellar absorption lines at zero velocity. The resulting cross-correlation function (CCF) therefore represents a flux-weighted mean profile of all the stellar lines selected by the mask. For stars with a low projected rotational velocity the

CCF has a Gaussian shape, and the radial velocity is determined by fitting the CCF with a Gaussian function. What we are interested in for the planet search are not the radial velocities themselves but the residual (radial) velocities around the binary orbit. Residual velocities are obtained by subtracting the binary orbit (if known on the basis of CORAVEL data) or a drift (for systems with periods much longer than the duration of the CORAVEL surveys) to the high-precision radial velocities obtained with ELODIE or CORALIE. Note that CORAVEL velocities are used to ensure that the system is a binary and to determine (if possible) its orbit, but they are not directly used to obtain residual velocities. The planet search is based solely on ELODIE or CORALIE high-precision measurements and is carried out by searching for short-period radial-velocity variations in the residual velocities.

2.2 Preliminary Results

The sample used for the final analysis is made of about 100 SB1s. The reduction in the sample size is mainly due to the rejection of CORAVEL SB1s candidates that turned out to be double-lined spectroscopic binaries (SB2) at the higher precision of the ELODIE and CORALIE spectrographs (see Sect. 2.3 for a justification regarding SB2s rejection). Figure 1 shows the residual-velocity variation for all our targets, as quantified by the normalized root-mean-square (rms). Most targets (74%) have a normalized rms close to 1, indicating that no source of radial-velocity variation other than the orbital motion is present. In contrast, some systems are clearly variable (12.5% of the targets exhibit a normalized rms larger than 3), while some others (13.5%) are marginally variable with a normalized rms between 2 and 3. Mean measurement uncertainties indicate that the precision achieved on the radial-velocity measurement for the nonvariable systems is as good as the one commonly achieved by radial-velocity planet searches targeting single stars. The varying systems are, of course, the most interesting ones since the observed variability may be due to a planet orbiting the primary star. Variable and marginally variable systems are currently being analysed in detail as described in Sect. 2.4, but no convincing planetary candidate has been found yet.

2.3 Origin of Observed Radial-Velocity Variations

Does Fig. 1 imply that the frequency of short-period planets in our sample of spectroscopic binaries is quite high? Unfortunately not, for there exist several alternative effects that can produce residual-velocity variations such as the ones observed. The possibilities include: (i) the system is an unrecognized double-lined spectroscopic binary (i.e. a SB2 that happens to be observed when the two correlation peaks are superimposed, thus mimicking a SB1 system), (ii) the primary star is intrinsically variable, (iii) the pair is also a visual binary and there is light contamination from the secondary visual component, and (iv) the system is in fact triple, the secondary itself being a binary.

For visual systems, when the binary separation is close to the diameter of the spectrograph's fiber (2 arcsec for ELODIE and CORALIE) the fraction of light, coming from the secondary, that enters the fiber is variable and depends on the seeing and on the telescope guiding. As discussed in [16], different light contributions produce radial-velocity variations of the cross-correlation function. The amplitude

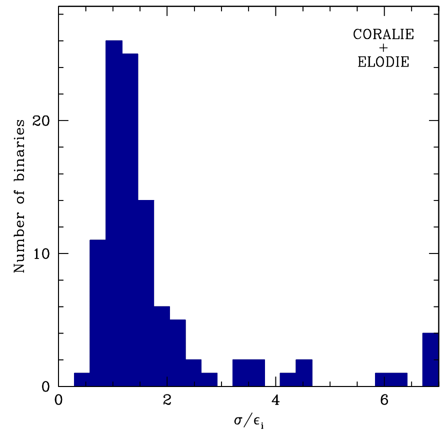

Fig. 1. Normalized residual velocity root-mean-square for all our targets. σ is the rms around a Keplerian orbit or around a drift, and ϵ is the mean measurement uncertainty. Systems with a rms larger than 7 are all gathered together in the last bin.

of the variation strongly depends on the binary magnitude difference, the lower the magnitude difference the stronger the perturbations. This is the reason why we selected single-lined spectroscopic binaries. By considering SB1s we make sure that the magnitude difference is not too small, therefore minimizing the perturbations which are then usually smaller than the photon-noise error.

When the binary is a triple system whose secondary is itself a binary, the secondary spectrum will be varying periodically in time. If the secondary is bright enough, then a shallow and moving secondary CCF will be present, inducing asymmetry variations in the primary CCF, part of which are going to be interpreted as radial-velocity variations (see [20] for further details). Note that such a varying secondary CCF can usually not be detected directly by inspecting the cross-correlation profile since it is very shallow (flux ratio of a few percents), usually very broad (large projected rotational velocity), and is blended with the primary CCF most, if not all of the time (small velocity difference). Such triple systems can be dangerously misleading since they can perfectly mimic the presence of a planet orbiting the primary star, which is precisely what we are looking for.

To differentiate between these effects, tests including analysis of the CCF bisector span, analysis of the CCF parameters and their correlations, cross-correlation with different sets of lines, activity indicators, and photometric data can be used. All these tests are of great help, especially for identifying the cause of the residual-velocity variation observed for the most varying systems, but, in general, the lack of individual radial velocities for the two components is a major drawback.

2.4 Turning SB1s into SB2s Using Multi-Order TODCOR

As just mentioned, identifying the cause of the observed residual-velocity variation is usually not easy. In particular, differentiating between a light body (a planet) orbiting the primary star and a heavier body (a low-mass star or a brown dwarf) orbiting the secondary component may be very tricky using one-dimensional cross-correlation techniques. One way to solve the problem is to use two-dimensional cross-correlation techniques. TODCOR (TwO-Dimensional CORrelation) is such an algorithm developed by Zucker & Mazeh to deal with the difficulties encountered in double-lined spectra when the lines of the two components could not be easily resolved [23]. Assuming the observed spectrum to be the sum of two known templates with unknown Doppler shifts and a given flux ratio, TODCOR calculates the two-dimensional cross-correlation function, whose maximum gives simultaneously the radial velocities of both components. One advantage of TODCOR is its ability to use different templates for the primary and the secondary component, enabling to derive radial velocities for faint secondaries. TODCOR was originally designed to handle single-order spectra, but it is now also working with multi-order spectra [22, 25].

All variable and marginally variable systems from our programme are currently being analysed with TODCOR, trying to obtain the radial velocities of the two components individually. This analysis is still in its early stages, but a few SB1s have already been turned successfully into SB2s or into triple systems. One example is presented in the next subsection.

2.5 HD 223084

According to the Hipparcos catalogue, HD 223084 is a bright ($V = 7.23$) G0 star at a distance of 39 pc from the sun. CORAVEL measurements revealed the star as a long-period SB1 candidate and we consequently included HD 223084 in our planet search sample. A first series of CORALIE measurements exhibited a periodic residual-velocity variation compatible with the presence of a planetary companion orbiting the primary star. Pursuing the observations, tests such as those discussed in Sect. 2.3 began to indicate that the planetary hypothesis was not the best one, and that HD 223084 was probably rather a triple system, the secondary being the variable star (see [5] for a discussion of the one-dimensional radial-velocity analysis). HD 223084 was therefore one of the first candidates for a TODCOR analysis.

Our multi-order TODCOR analyses rely on a template library built from CORALIE and ELODIE spectra. When analysing a binary, we do not select the templates a priori, but rather try different configurations and select the one giving the best results (i.e. lowest rms) for the radial velocities of both components. The flux ratio is a function of the wavelength, and is calculated for the spectral types of the two chosen templates using the spectral energy distribution library by [17].

Applying multi-order TODCOR to our CORALIE spectra of HD 223084 we were able to separate the two components, thus obtaining the individual radial velocities for both components. As we suspected, the B component was found to be a SB1, but looking at the secondary cross-correlation function we occasionally saw a third correlation peak. On some spectra it was thus possible to separate Ba from Bb, turning the B component itself into a SB2. HD 223084 is therefore a triple system made of a G0 star (A) and two M stars (M0–M1 for Ba and M1–M2 for Bb according to the best-fit templates). The outer orbit (AB) is not well constrained since CORALIE data only cover a small fraction of the orbital period, but the inner orbit (Ba-Bb) is well defined. The parameters for this orbit are $P = 202.02 \pm$

0.09 days, $e = 0.272 \pm 0.006$, $K_1 = 16.14 \pm 0.09\,\mathrm{km\,s^{-1}}$, $K_2 = 18.0 \pm 0.4\,\mathrm{km\,s^{-1}}$. The residuals are $\sigma_A = 25\,\mathrm{m\,s^{-1}}$, $\sigma_{Ba} = 494\,\mathrm{m\,s^{-1}}$ and $\sigma_{Bb} = 663\,\mathrm{m\,s^{-1}}$, showing that for this system the precision on the radial velocity of the primary star is degraded, implying a lessened sensitivity for the planet search. But this is not a general truth. For instance, [26] obtained a $10\,\mathrm{m\,s^{-1}}$ precision on the radial velocity of the primary component for the HD 41004 system, which allowed them to find a planet in this close (23 AU) triple system.

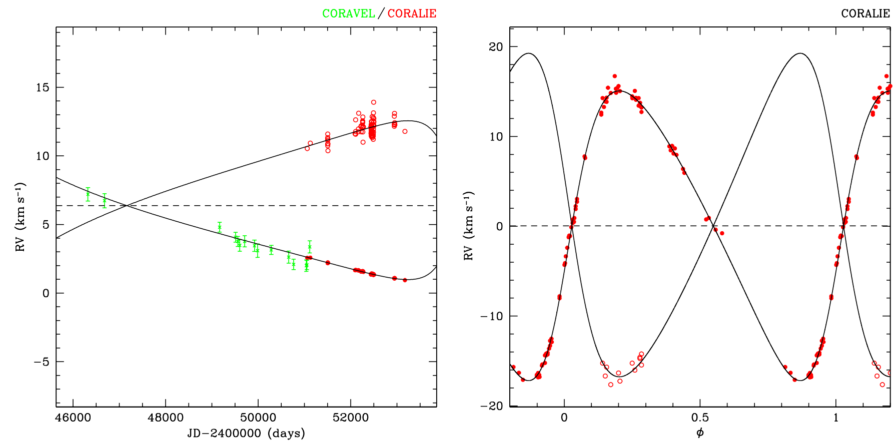

Fig. 2. Left: Radial velocities and tentative orbital solution for HD 223084 AB. CORAVEL data (stars) essentially represent the A component. Radial velocities obtained with TODCOR on the basis of CORALIE observations are shown as dots for the A component and as circles for the B component. **Right:** SB2 orbit for HD 223084 B (see text for orbital parameters). Dots represent Ba and circles Bb.

3 Probing the Multiplicity Status of Nearby Stars with VLT/NACO

Since 2002 we have been carrying out a systematic adaptive optics (AO) search for stellar companions to nearby southern stars with and without planetary companions using the NAOS–CONICA facility [10, 19] at the ESO Very Large Telescope (VLT, Chile). This programme is mainly aiming at characterizing and quantifying the influence of stellar duplicity on planet formation and evolution. But, as a by-product, this survey will also provide us with a precise knowledge of the multiplicity status of many planet-host stars, allowing us to confirm or infirm some of the trends emphasized in Sect. 1.1.

3.1 Programme Description

The programme relies on a sample of 110 dwarf stars of the solar neighbourhood divided into two subsamples. The planet-host star subsample comprises about 50 stars known to harbour at least one planetary companion. The comparison star subsample consists of about 60 stars belonging to our CORALIE planet search sample [21], not showing "large" radial-velocity variations and not known as Hipparcos close visual binaries. Comparison stars have been chosen very carefully, so that we can use them both as statistical references for the scientific analysis, and as point spread function reference stars in the data reduction process. This means that each comparison star has its coordinates, visual magnitude, color and parallax as close as possible to the actual values of one of the planet-host star. Conceptually, comparison stars must not be planet-bearing stars, but in practice this can never be completely known. Selecting comparison stars within the CORALIE planet search sample is one of the best way to approximate the ideal definition. The main reason for choosing a larger comparison star sample is that a few planet-host stars appearing in other published AO surveys will be added to the planet-host star subsample for the final analysis.

The programme strategy consists of searching for stellar companions around each of our 110 targets in order to see whether the binary fraction is the same for the two subsamples. Different binary fractions would indicate that the presence of a stellar companion either favours or inhibits planet formation and/or survival, depending on which subsample has the highest binary fraction.

3.2 Observations

Each star of a pair planet-host star – comparison star is observed in succession, taking unsaturated images through narrow-band filters within the H ($\lambda_c = 1.644\,\mu$m, field of view = $14'' \times 14''$, scale = 13.25 mas/pixel) or K ($\lambda_c = 2.166\,\mu$m, field of view = $28'' \times 28''$, scale = 27.03 mas/pixel) band. Whenever a companion is detected, an additional image is taken in narrow-band filter within the J band for color information. The total integration time is 10–15 min to allow for the detection of almost all stellar companions. Given the large proper motion of most of our targets, second-epoch observations taken after one year usually provide a good test regarding the optical or physical status of the pair. This is of importance since only physical binaries must be considered for the analysis.

3.3 Detection and Detection Limits

The survey itself (i.e. one observation per target) is almost completed, but second-epoch observations are still ongoing. So far we have found 7 companions to planet-host stars and 12 companions to comparison stars. Our detections and detection limits are shown in Fig. 3. In addition, several much fainter companions have been detected, but those have a very high probability of being background stars. The physical or optical status of some of the brightest companions can be assessed by combining our measurements with data from the 2MASS catalogue, but for many pairs this is not feasible since the secondary component is either too close and/or too faint to be listed in the 2MASS catalogue.

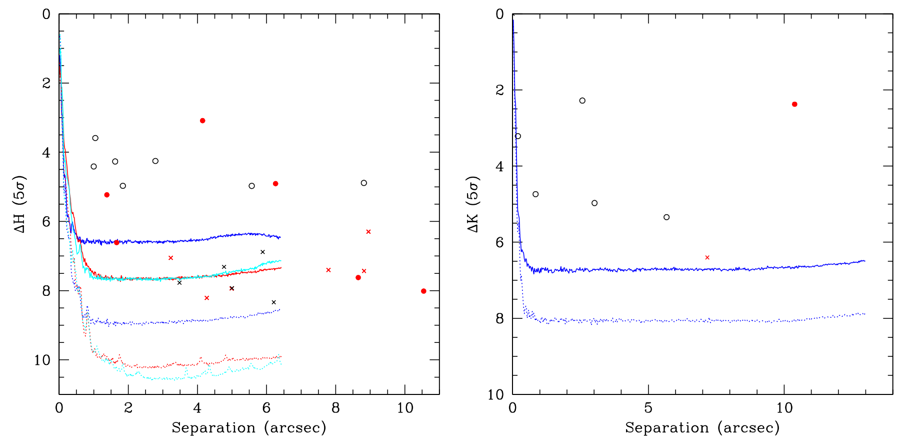

Fig. 3. Detection limits for our 4 observing runs. For each run, the best (dotted line) and worst (solid line) detection curve is given. The survey is preferentially made within the H band, but in case of degraded AO correction the K band is used. The detector of CONICA was changed in the middle of the programme, resulting in better detection curves for the last runs. Dots are companions to planet-host stars, circles are companions to comparison stars. Crosses are much fainter companions with a very high probability of being optical. A few companions were observed in H and in K and are therefore present on both diagrams.

3.4 Effect of Stellar Duplicity on Planet Formation and Survival

Using the available data, a preliminary statistical analysis can be made in order to get a first quantification of the global effect of stellar duplicity on planet formation and survival. The subsamples considered for the statistics comprise 45 planet-host stars and 60 comparison stars from our survey, to which we add 10 planet-host stars from the AO survey by [15]. Only the companions with a projected separation in the range 0.8–6.5″ and located within the most restrictive detection limit for each band (K or H) are considered for this preliminary analysis. Companions with only one measurement but with a high probability of being optical were discarded. Using these subsamples, the binary fraction for planet-host stars is $5.5\pm3.0\%$. For comparison stars the binary fraction is in the range 8.3 ± 3.5–$16.7 \pm 4.8\%$, the uncertainty stemming from the fact that the physical or optical status of several of the bright companions to comparison stars is unknown. But once second-epoch observations will be completed, this binary fraction will be known exactly. For comparison, the binary fraction for field stars can be computed. Using the distributions for nearby stars [4], and the restrictions used for our analysis, the binary fraction for field stars is 11%, in good agreement with our results for comparison stars. Therefore, on the basis of the present results there may be a small difference between the two subsamples, but the two binary fractions may also be compatible within the error bars. In this context, results from second-epoch observations are crucial as they will remove the ambiguity. Furthermore, with the aim of improving the statistics, we are conducting a northern counterpart to our NACO programme using the PUEO–KIR facility at the 3.6-m Canada-France-Hawaii Telescope.

4 Conclusion

The sample of planets found in binaries has almost doubled since 2002, and as of July 2005, 25 of the known planet-host stars were also part of a double or multiple stellar system with a separation in the range 20–6500 AU. Note that this amounts to 31 planets since multiple planetary systems also exist in wide binaries.

Preliminary results from our radial-velocity search for short-period giant planets in spectroscopic binaries indicate that for a large fraction of our targets a precision as good as the one obtained for single stars can be achieved. No convincing planetary candidate has been found yet, but the detailed analysis is in progress.

Globally, stellar duplicity does not favour planet formation for binaries with a separation between 35 and 230 AU. In fact, for this separation range, stellar duplicity could have a negative effect on planet formation and survival. Final results from our adaptive optics programme should soon settle this question.

Regarding the properties of extrasolar planets found in binaries, the new data are, globally, in agreement with the proposed trends. But whether or not planets found in binaries possess different properties than planets orbiting single stars is still an open question.

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