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# The SARG Planet Search

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## 1 Introduction

The search for planets in multiple systems allows to improve our knowledge on planet formation and evolution. On one hand, the frequency of planets in binary systems has a strong effect on the global frequency of planets, as more than half of solar type stars are in binary or multiple systems ([12]). On the other hand, the properties of planets in binaries, and any difference with those of the planets orbiting single stars would shed light on the effects caused by the presence of the companions.

The search for planets in binaries can follow two complementary approaches. The first one is to perform dedicated surveys looking for planets in binary systems. Several programs currently in progress focusing on different types of binaries are described in this book. In this chapter, we describe the first planet search entirely dedicated to binary systems, the survey on-going at TNG using the high resolution spectrograph SARG.

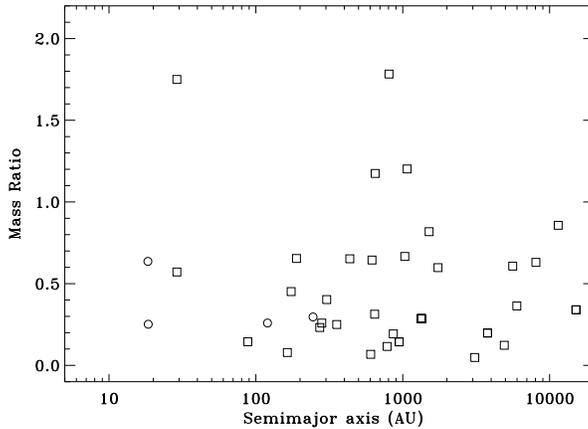
The second approach is to study the binarity of the hosts of planets discovered in general surveys, which include many binary stars in their lists in spite of some selection biases against them. Indeed, the first analysis on the properties of planets in binaries showed the occurrence of some differences with respect to those orbiting single stars ([44], [13]).

In Sect. 2 we summarize our recent work on the statistical properties of planets in binaries. In Sect. 3 we present the second major science goal of the SARG survey, the search for abundance anomalies caused by the ingestion of planetary material by the central star. In Sections 4 to 11 we present the sample, the observing and analysis procedures, and the preliminary results of the SARG planet search. Finally, in Sect. 12 we present some preliminary conclusions on the frequency of planets in binary systems.

## 2 Properties of planets in binary systems

More than 40 planets have been found in binary or multiple systems. An updated compilation was recently assembled by some of us ([5]). We performed a statistical analysis of the properties of planets in binaries and the comparison with respect to those orbiting single stars, based on the planet and stellar parameters listed in the Catalog of Nearby Exoplanets by [3].

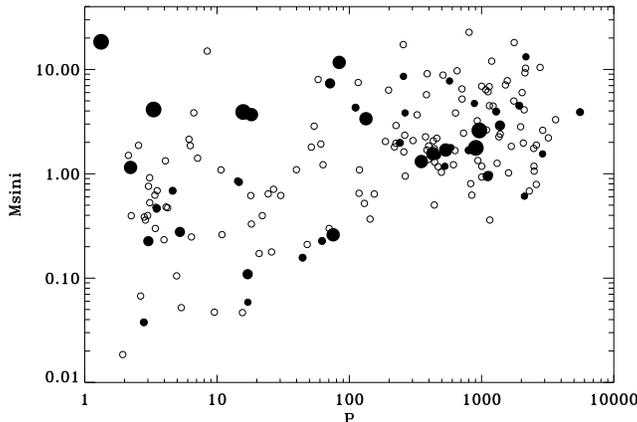
Fig. 1 shows the mass ratio vs semimajor axis for stars with planets in multiple systems. For hierarchical triple systems in which the planet orbits the isolated companion, the masses of the binary companions to the planet host are summed. It results that planets might exist in binaries with very different properties. In some cases (e.g. very low mass companions at a projected separation larger than 1000 AU) the dynamical effects of the companion on the formation and evolution of the planetary system might be very limited, while in the cases of very tight binaries the presence of the planet represents a challenge for the current models of planet formation ([20]).



**Fig. 1.** Mass ratio vs semimajor axis of the binary orbit for stars with planets in binary systems. Open circles represent the pairs for which binary orbit is available, open squares the pairs for which only the binary separation is available. From [5].

To consider the effects of dynamical perturbation by the stellar companion(s) we used the critical semiaxis for dynamical stability of the planet  $a_{crit}$  [22]. We choose  $a_{crit}$  as a reference value because it is a physical quantity that represents the dynamical effects due to a companion on planet formation and stability, including both the orbital parameters and mass ratio.

The critical semimajor axis  $a_{crit}$  was used to divide the sample according to the relevance of the dynamical effects. We define as 'tight' binaries those with  $a_{crit} < 75$  AU and 'wide' binaries those with  $a_{crit} > 75$  AU. The limit



**Fig. 2.** Projected mass vs orbital period of extrasolar planets. Open circles: single stars; filled circles: binary stars. The size of the symbol is proportional to the critical semimajor axis for dynamical stability (larger symbols refer to the tighter binaries). From [5].

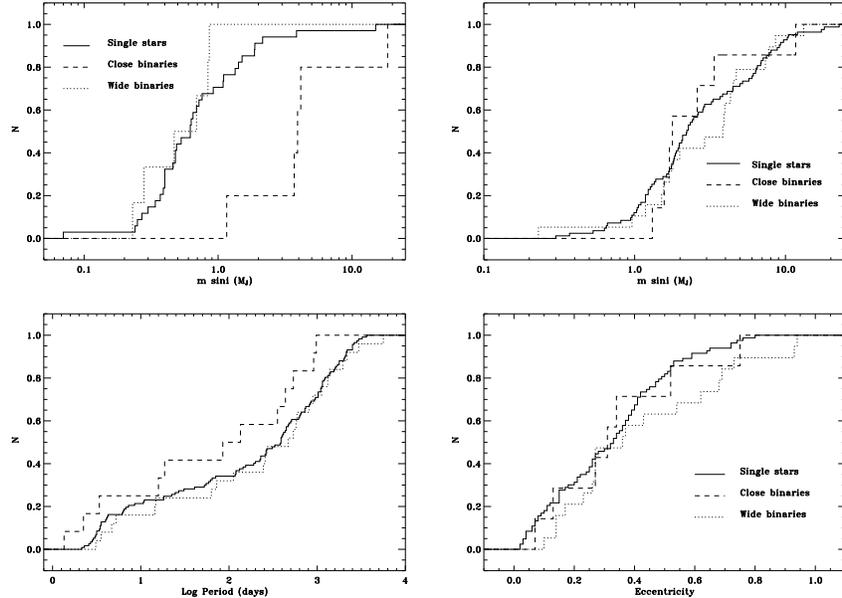
corresponds to a projected separation of about 200-300 AU depending on the mass ratio.

The statistical comparison to test the hypothesis that the parameters of planets (mass, period, eccentricity) in tight and wide binaries and in single stars can be drawn from the same parent distribution was performed using the Kolmogorov-Smirnov test and the Mann-Whitney U test.

The following results were found (see Fig 3):

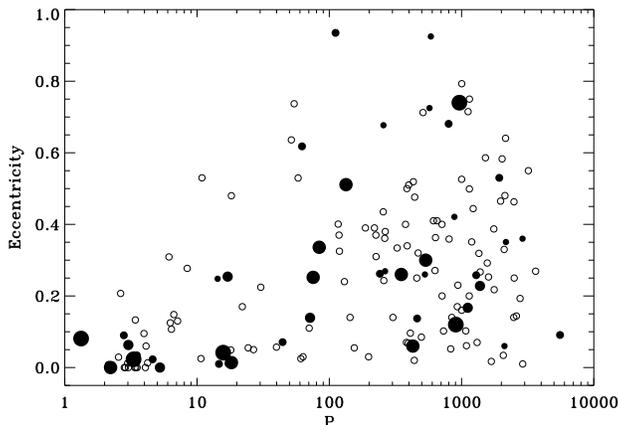
- The mass distribution of short period ( $P < 40$  days) planets in tight binaries is significantly ( $> 99\%$ ) different with respect to that of planets orbiting single stars and components of wide binaries. Massive, short period planets are mostly found in tight binaries (Fig. 2-3). This somewhat resembles the evidence that short-period spectroscopic binaries have in most cases a further companion ([38]).
- The mass distributions of planets in wide orbits in tight and wide binaries and in single stars are not significantly different.
- The differences in period distributions are also not highly significant. However, there is a marginal indication for a lack of long period planets in tight binaries.
- The eccentricity distribution of planets in tight binaries with periods longer than 40 days is not significantly different to those orbiting single stars. On the other hand, there is a marginal indication for a larger eccentricity of planets in wide binaries (Fig. 3-4).
- The occurrence of systems with more than one planet around the components of wide binaries is similar with respect to that of planets orbiting

single stars. No multiple planets have been yet discovered instead around the components of tight binaries, but their small number makes the lack of multi-planet systems not highly significant (probability of 15% of occurring by chance).



**Fig. 3.** Cumulative distributions of planets parameters for planets orbiting single stars (continuous lines); components of wide binaries (dotted lines); components of tight binaries (dashed lines). Upper left panel: mass distribution of planets with period shorter than 40 days. Upper right panel: mass distribution of planets with period longer than 40 days. Lower left panel: period distribution. Lower right panel: eccentricity distribution of planets with period longer than 40 days. Adapted from [5].

We then conclude that planets in close binaries have different characteristics with respect to those orbiting single stars and components of wide binaries. The mass and period distributions of planets in wide binaries instead are not statistically significant different to those of planets orbiting single stars. The only marginally significant difference between planets orbiting single stars and components of wide binaries concerns the planet eccentricity. In any case, high planet eccentricities are not confined to planets in binaries, and the possible differences in eccentricity appears to be limited to the range  $e \geq 0.5 - 0.6$ . This indicates that there are mechanism(s) generating planet eccentricity up to 0.4-0.5 that are independent of the binarity of the planet host, and are characteristic of formation and evolution of a planetary system (e.g.



**Fig. 4.** Eccentricity vs orbital period for planets in binaries (filled circles) and orbiting single stars (empty circles). Different sizes of filled circles refer to different periastron of the binary orbit (larger sizes: closer orbits). From [5].

disk-planet interactions, planet-planet scattering). These probably act during or shortly after planet formation. Further eccentricity enhancements, possibly linked to the presence of a companion, might take place at later epochs. In fact, [35] noted that most high-eccentricity planets orbit old stars (ages  $>5$  Gyr). Mechanisms that require long time scales to modify planetary orbits, such as Kozai oscillations and chaotic evolution of planetary orbits induced by dynamical perturbations then seem favored.

These results indicate that a companion at large separation ( $\geq 500$  AU) probably does not affect too much the planet formation process around one of the components, while the effects of the companions are much more relevant at small separation, causing differences in the physical properties of the planets.

The understanding of the formation mechanism of the planets in close binaries is a key problem. One possibility is that these planets formed before the binary configuration was modified by stellar encounters in the native star cluster ([29]). The alternative is that planets do form in close binaries in spite of the seemingly unfavourable conditions. The exploration of the frequency and properties of planets at intermediate binary separations (100-300 AU), the range of a large fraction of the binaries of the SARG planet search, is important to establish the separation required to show the peculiar features of planet properties.

### 3 Binary systems as a tool to evidence the ingestion of planetary material by the central star

The evidence for a high metal content in stars harbouring planets is becoming stronger as planet discoveries cumulate and suitable control samples are studied using strictly the same procedures ([33], [16]). Two alternative hypotheses have been proposed to explain these observations: either the high metallicity is responsible for the presence of planets, making their formation easier; or the planets are the cause of the high metallicity, because of pollution of metal-rich planetary material onto the (outer region of the) central star ([17]).

Infall of planetesimals on the star during the early phases of planet formation is generally expected on the basis of current models of planet formation. The orbital migration proposed to explain the occurrence of the close-in giant planets found by radial velocity surveys also points to the infall on the star of portions of the proto-planetary disk.

Most of the accretion is expected to take place during the early phases of the evolution of the planetary system. However, when a star is still in the phase of gravitational contraction, its convective zone is much thicker than for main sequence stars (see e.g. [26]). In this case, the metal-rich material should be uniformly distributed by convective mixing over a large portion of the star, resulting in a negligible photospheric chemical alteration even for rather large amounts of accreted material. Late accretion, when the star is approaching or has already reached the main sequence, is likely required to produce observable differences. The ingestion of planets scattered toward the star by dynamical interactions ([25]) might also produce metallicity enhancements at late phases.

Murray and co-workers ([26]) found that the Sun should have ingested some  $2 M_{\oplus}$  of meteoritic material (about  $0.4 M_{\oplus}$  of iron) during its main-sequence lifetime, considering the drop of iron density in the asteroid region and the time distribution of the impact craters. This corresponds to a metallicity enhancement of 0.017 dex. Such a small abundance difference is not detectable when considering a field star, for which no proper reference for the original unpolluted abundance is available. In binary systems and star clusters instead such a reference is provided by the other companion/members of the system. Therefore, the comparison of the chemical composition of wide binaries is a very powerful approach to study the occurrence of planetary pollution, provided that differential abundance analysis with a precision of about 0.02 dex can be obtained.

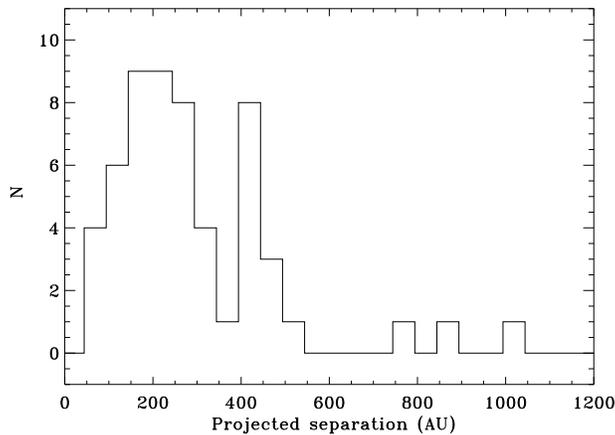
If the high metallicity is the result of planets or planetesimal ingestion ([17]), some systematic difference is expected between members of a binary system with and without planetary companions. On the other hand common metallicity between components should indicate a robust link between metallicity and formation process of planetary systems.

## 4 The SARG sample

With the two science goals identified in Sections 1-3, we started a few years ago a radial velocity (RV) survey of the components of wide binaries. We are using SARG, the high resolution spectrograph of the TNG ([18]), equipped with an iodine cell to derive high precision RVs.

The sample was selected from the Hipparcos Multiple Star Catalog, considering binaries in the magnitude range  $7.0 < V < 10.0$ , with magnitude difference between the components of  $\Delta V < 1.0$ , projected separation larger than 2 arcsec (to avoid contamination of the spectra), parallax larger than 10 mas and error smaller than 5 mas, with  $B - V > 0.45$  and spectral type later than F7. About 50 pairs (100 stars) were selected.

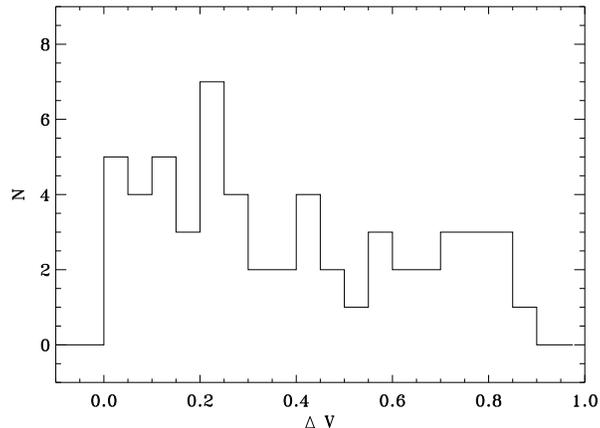
The sample is then formed by wide binaries with mass ratios close to 1. Considering systems with similar components is crucial for the accuracy of the differential chemical abundance analysis. Fig. 5 shows the distribution of the projected separation in AU. For most of the pairs, it results between 50 and 600 AU. Fig. 6 shows the distribution of the V band magnitude difference between the components.



**Fig. 5.** Distribution of the projected separation in AU of the binaries in the sample of the SARG survey.

## 5 Observations

The observations used for the radial velocity determinations were acquired with the SARG spectrograph [18] using the Yellow Grism, that covers the



**Fig. 6.** Distribution of the visual magnitude difference in AU of the binaries in the sample of the SARG survey.

spectral range 4600-7900 Å without gaps, and the 0.25 arcsec slit. The resulting resolution is  $R=150000$  (2 pixels sampling). The iodine cell was inserted into the optical path, superimposing a dense forest of absorption lines used as reference spectrum for the radial velocity determination. Exposure times were fixed in most cases at 15 minutes, to reduce the errors in barycentric correction caused by the lack of knowledge of the exact flux mid time of the exposure. A high signal to noise spectrum without the iodine cell was also acquired for all the program stars, to be used for the abundance analysis (see Sect. 6) and as template for the radial velocity determination (see Sect. 7).

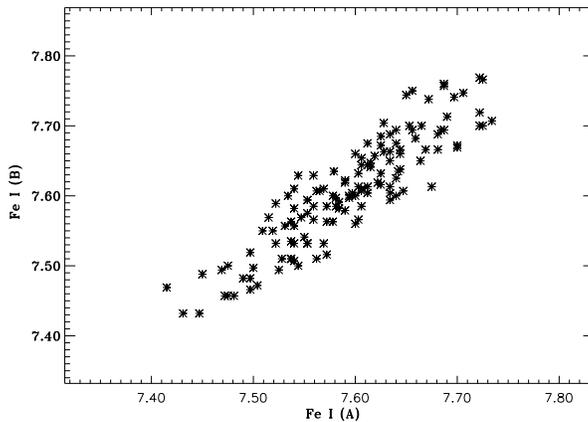
During the observations, the slit was usually oriented perpendicularly to the separation of the components to minimize the contamination of the spectra by the companion. The closest pairs (separation 2-3 arcsec) were observed only in good seeing conditions. In spite of these efforts, some residual contamination of the spectra is present in a few cases. This issue is discussed in Sect. 10. The survey is in progress, up to now we have acquired on average about 15 spectra per star.

## 6 Abundance analysis

The abundance analysis of about half of the pairs of the SARG survey was published in [7] while in [10] we studied 33 pairs of Southern declination observed with the FEROS spectrograph at ESO-La Silla, selected with similar criteria. Taking into account the small overlap between the two samples, we have in hand the results for 50 pairs.

Performing a line-by-line differential analysis (Fig. 7) and exploiting the physical link between the components (same distance from the Sun), we found

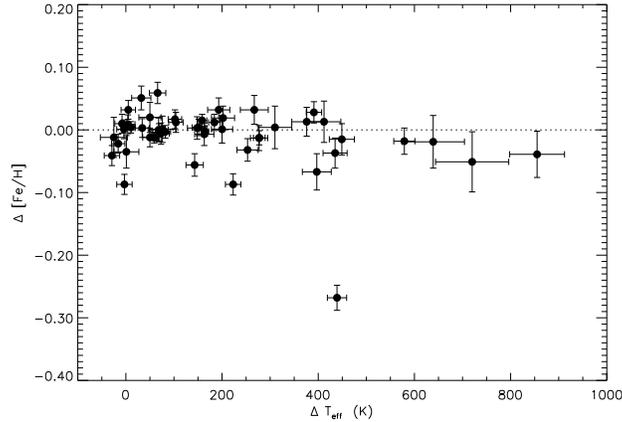
that errors in estimating the difference of iron content between the two components of about 0.02 dex can be achieved for pairs with temperature differences smaller than 300-400 K and slow-rotating components with effective temperatures in the range 5500-6300 K. This is adequate for detailed study of chemical alterations in the external convective layer.



**Fig. 7.** Iron abundance derived for each line of the components of HIP 114914 A and B. A clear correlation is present, indicating that the use of a line-by-line differential analysis significantly reduces the errors on abundance difference between the components. From [10].

Most of the pairs have abundance difference smaller than 0.03 dex (Fig 8). We found one case (HIP 64030=HD 113984) with a large (0.25 dex) abundance difference. The primary of this binary appears to be a blue straggler, and the abundance difference might be due to the peculiar evolution of the star (see Sect. 6.1). A few other pairs show small abundance differences ( $\leq 0.09$  dex). In a few cases these differences suggest the ingestion of a small amount of metal rich material, but in others they are likely spurious, because of the large temperature difference between the components, the high level of magnetic activity, that might cause alterations in the stellar atmosphere or additional errors in our analysis because of intrinsic variability, or possible contamination of the spectra by an additional star in close orbit around one of the components. Some cases of abundance differences involving pairs with warm ( $T_{\text{eff}} \geq 6000$  K) primaries might be due to the diffusion of heavy elements.

Fig. 9 shows the amount of iron accreted by the nominally metal richer component to explain the observed abundance difference. For most of the slow-rotating stars warmer than 5500 K, characterized by a thinner convective envelope and for which our analysis appears to be of higher accuracy, this is similar to the estimates of rocky material accreted by the Sun during its main



**Fig. 8.** Iron abundance difference between the components of pairs as a function of temperature difference for the pairs studied in [7] and [10].

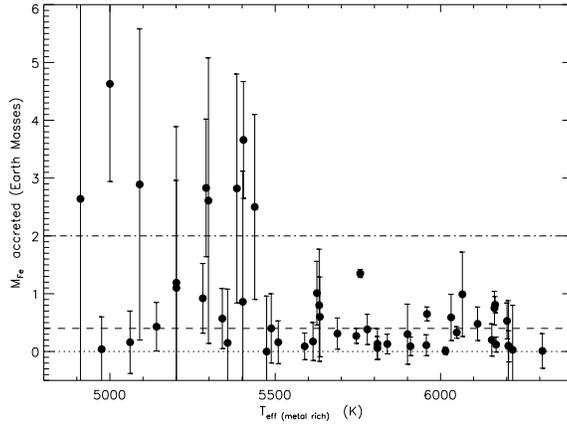
sequence lifetime (about 0.4 Earth masses of iron, [26]). We then conclude that the occurrence of large alterations in stellar abundances caused by the ingestion of metal rich, rocky material is not a common event. For at least 65% of the pairs with components warmer than 5500 K, the limits on the amount of rocky material accreted by the program stars are comparable to the estimates of rocky material accreted by the Sun during its main-sequence lifetime.

### 6.1 The special case of the blue straggler HD 113984

The wide binary HIP64030=HD 113984 is the only pair in our sample that shows a large (about 0.25 dex) iron content difference. The positions of the components on the color magnitude diagram suggest that the primary is a blue straggler. Therefore, the abundance difference may be somewhat linked to the peculiar evolutionary history of the system.

The analysis of additional elements beside iron ([11]) showed that the abundance difference for the elements studied increases with increasing condensation temperature, suggesting that accretion of chemically fractionated material might have occurred in the system. Alteration of C and N likely due to CNO processing is also observed, as expected for the mass transfer process occurring during the formation of the blue straggler. We also showed that the blue straggler component is a spectroscopic binary with a period of 445 days and moderate eccentricity, as typical for field blue stragglers ([30]).

Two scenarios were explored to explain the observed abundance pattern. In the first, all abundance anomalies arise on the blue straggler. If this is the case, the dust-gas separation may have been occurred in a circumbinary disk around



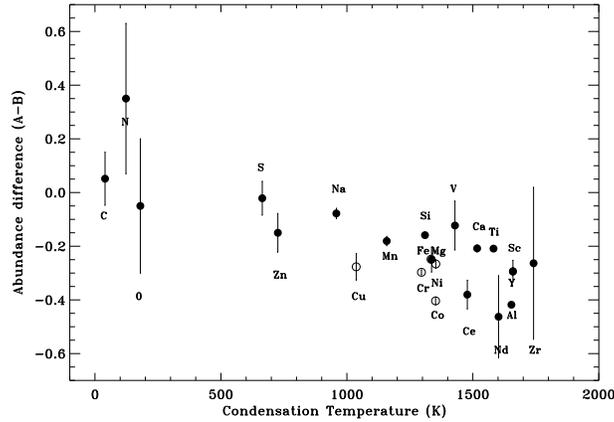
**Fig. 9.** Estimate of iron accreted by the metal-rich component of each pair as a function of its effective temperature, taking into account the mass of the mixing zone as in [26]. The less severe limits at lower effective temperatures are mostly due to the more massive convective zone of cool stars. The horizontal lines show the amount of iron expected to have been accreted by the Sun during the main sequence lifetime ( $0.4 M_{\oplus}$ : [26]), and the amount of iron corresponding to the upper limit on abundance difference between the inner and outer regions of the Sun according to helioseismology ( $2 M_{\oplus}$ : [42]). The mass of meteoritic material is assumed to be about 5.5 times the mass of iron. From [10].

the blue straggler and its expected white dwarf companion, as observed in several RV Tauri and post AGB binaries [41]. In the second scenario, accretion of dust-rich material occurred on the secondary. This would also explain the anomalous carbon isotopic ratio of the secondary. Such a scenario requires that a substantial amount of mass lost by the central binary has been accreted by the wide component.

## 6.2 Abundance difference between components for binary systems with planetary companions

The analysis of 50 pairs shown in Sect. 6 suggests that the frequency of pairs with large alterations in chemical composition is rather small. Therefore, it seems unlikely that the ingestion of planetary material can account for the strong correlation between the frequency of planets and metallicity.

However, none of the stars studied by [7],[10] are known to host planets (most of the pairs of the FEROS sample are probably not being searched for planets). Therefore, it is interesting to consider the abundance difference between the components of binary systems with/without planets. We limit our analysis to pairs with similar components, as errors in differential chemical



**Fig. 10.** Abundance difference for the components of HD 113984 as a function of the condensation temperature. From [11]

abundances becomes larger for large temperature difference (see discussion in [10]).

Among the binary systems with planets, there are five pairs with mass ratio between 0.8 and 1.2. Only for 16 Cyg high-precision differential abundance analysis between the components has been carried out. Laws & Gonzalez [23] found a small abundance difference of 0.025 dex, with the planet-host (the secondary) being more metal-rich, while [36] did not confirm the reality of the small abundance difference.

For the pairs HD 80606/7, HD 99491/2 and ADS 16402 the standard abundance analysis does not reveal significant abundance difference (see Table 1). For HD 20781, the companion of the planet host HD 20782, there are no high-resolution abundance analysis and the abundance difference derived from Strömberg photometry is not significant (errors about 0.1 dex).

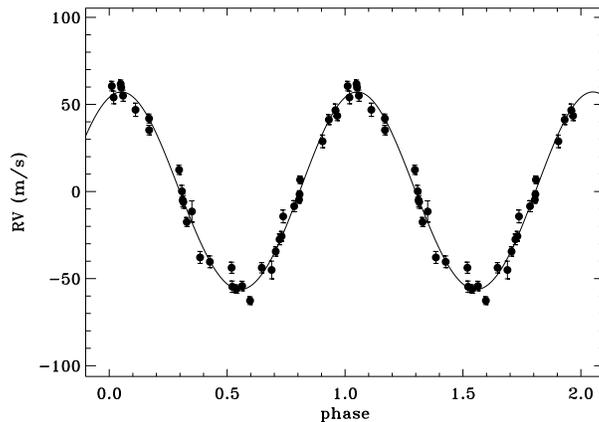
System	Planet host	$\Delta$ [Fe/H]	Ref.
16 Cyg	B	$-0.025 \pm 0.009$	[23]
16 Cyg	B	$0.00 \pm 0.01$	[36]
HD 80606/7	A	$-0.01 \pm 0.11$	[21]
HD 80606/7	A	$+0.002 \pm 0.081$	[37]
HD 99491/2	B	$-0.02 \pm 0.03$	[40]
HD 99491/2	B	$+0.04 \pm 0.13$	[21]
HD 99491/2	B	$+0.076 \pm 0.059$	[37]
HD 20781/2	A	$+0.12 \pm 0.10$	[27]
ADS 16402	B	$-0.01 \pm 0.05$	[1]

**Table 1.** Abundance difference between the components of binary planet hosts with similar components.

Summarizing, there are currently no evidence for large ( $\geq 0.1$  dex) alterations of chemical abundances in the components of binary systems with/without planets. This supports the conclusion of our dedicated study on the abundance difference between the components of binaries that large alteration of chemical abundance caused by the ingestion of planetary material are rare, if any.

## 7 Radial velocities

High precision RVs for the stars in the SARG sample were determined using the AUSTRAL code ([15]) as described in Desidera et al. ([6]). On average we acquired up to now about 15 spectra per star. Typical errors are 2-3 m/s for bright stars observed as standards to monitor instrument performances (Fig. 11) and 3-10 m/s for the  $V \sim 7 - 9$  program stars.



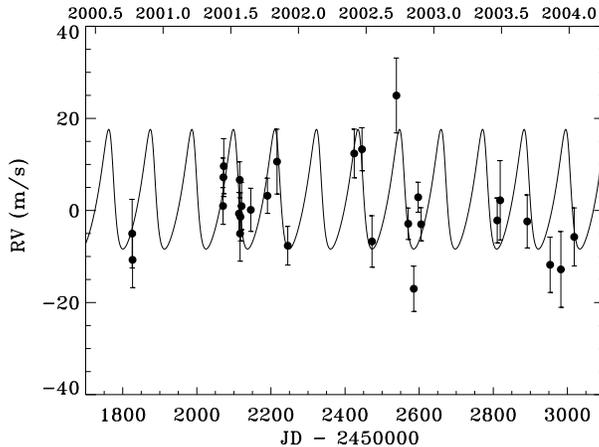
**Fig. 11.** Radial velocities of 51 Peg obtained with SARG phased to the known orbital period.

## 8 Planet candidates and low amplitude variables

The RV time series are being searched for periodic variations as data cumulate. No clear planet detection emerged up to now. A couple of candidates have false alarm probabilities of about 1%, but they are of fairly low amplitude and further data are required for confirmation.

Some further stars show RV variability above internal errors. In most cases this can be explained by stellar activity jitter and residual contamination of the spectra from the companion (see Sect. 10).

One case we investigated in detail is that of HD 219542B. The 2000-2002 data indicated a possible periodicity of 111 days with a significance of about 97% ([6]). However, the continuation of the observations revealed that the RV variations are likely due to stellar activity (see Fig. 12; [8]). In particular, the chromospheric emission measurements indicate that HD 219542 B underwent a phase of enhanced stellar activity in 2002 while the activity level has been lower in both 2001 and 2003.

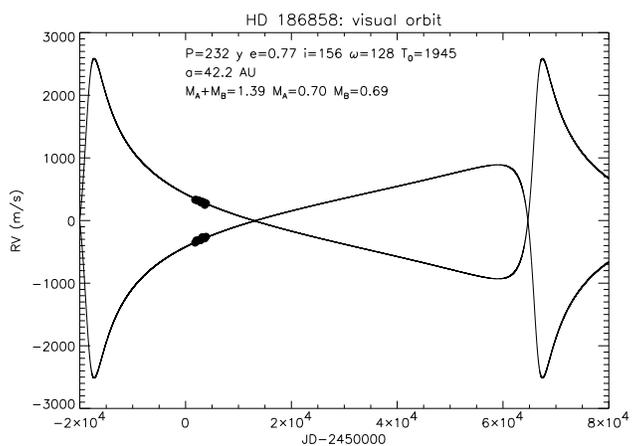


**Fig. 12.** Radial velocity curve for HD 219542 B. The data taken in the 2003 season do not follow the tentative orbital solution previously derived in [6] (overplotted as a solid line). From [8].

## 9 New triple systems and stars with long term trends

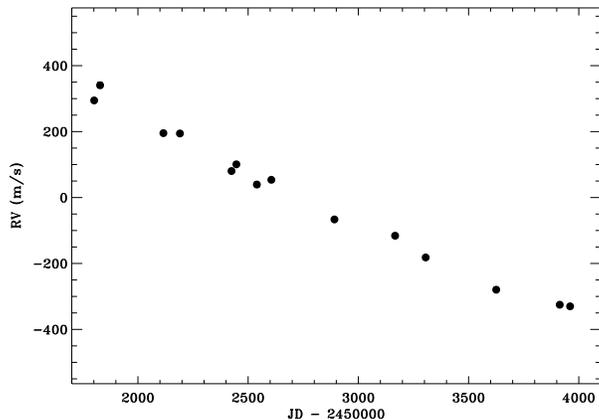
More than 10% of the stars in the sample show long term linear or nearly linear trends. In a few cases the trends are due to the known companion, as trends with opposite sign and nearly the same magnitude are observed for the two components. Fig. 13 shows the case of HD 186858, for which a reliable visual+astrometric solution was presented by [34]. The RV slopes of each components and their absolute RV difference follow very well the orbital solution. The full characterization of the binary orbit and individual masses of the systems we are surveying is useful for the study of the frequency binary systems with/without planets, as described in Sect. 12.

In most cases the trends are due to new low mass, possibly substellar companions orbiting one of the components. One example is shown in Fig. 14. In two cases, the trends show highly significant curvature and the radial velocity curves are compatible with massive planets with period longer than



**Fig. 13.** Continuous lines: predicted RV curve for the components of the binary system HD 186858 according to the visual+astrometric solution derived by [34]. Filled circles: high-precision RV obtained with SARG over 6 years. The RV slopes of each component and their absolute RV difference follow very well the orbital solution.

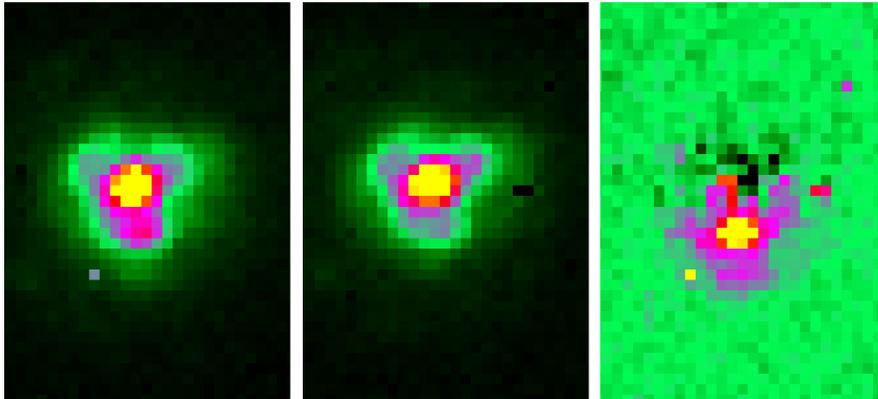
7-10 yr. The continuation of the radial velocity monitoring will reveal the period and nature of these objects.



**Fig. 14.** Radial velocities curve of one of the stars showing a clear linear trend, with a marginal indication for curvature in the last season.

We recently started an adaptive optics program to identify the companions of stars with long term trends using AdOpt@TNG ([4]). Preliminary results

for one object are shown in Fig. 15. The direct identification of substellar objects as companions of stars for which age and chemical composition can be derived would play a relevant role in the calibration of models of substellar objects. It also allows us a better characterization of the orbits and mass ratios of the systems we are monitoring. This point is relevant for the studies of the frequency and properties of planets in binaries as a function of the binary separation or effective gravitational influence.



**Fig. 15.** Adaptive optics identification of a close companion around a star with RV linear trend (Fig. 14): left panel: image the star with RV trend, central panel: image of the wide companion; right panel: difference between the two images. PSF artefacts were removed fairly well, allowing the identification of a close companion at 0.2 arcsec from the star. This is probably responsible for the observed RV trend.

Finally, we also detected a few new spectroscopic binaries among the components of the wide binaries. These systems are then composed by at least three components. Some of these systems are presented in [9].

## 10 Line bisectors: a tool to study stellar activity and contamination

The relevance of activity jitter for the interpretation of the RV data prompted us to develop a tool to measure and possibly to correct for its effect. The differential RV variations induced by stellar activity are due to changes in the profile of spectral lines caused by the presence of spots and/or the alteration of the granulation pattern in active regions. The activity jitter of a star may be predicted by means of statistical relations from its chromospheric emission, rotational velocity or amplitude of photometric variations ([32]; [28]; [43]). Simultaneous determination of RV, chromospheric emission and/or photometry is even more powerful in disentangling the origin of the observed RV variations

Keplerian vs. stellar activity. The measurement of the line profile alterations on the same spectra (ideally on the same spectral lines) represents a direct measurement of the activity jitter. The existence of a correlation between the variations of the RV and those of the line profile is a strong indication for non-Keplerian origin for the observed RV variations.

The study of line profile as a tool to disentangle Keplerian motion and activity jitter is usually performed using a few well isolated lines on high S/N spectra (see e.g. [19]) or by combining the cross-correlation profiles of many spectral lines at moderate S/N ratios with a suitable template mask (see e.g., [31]).

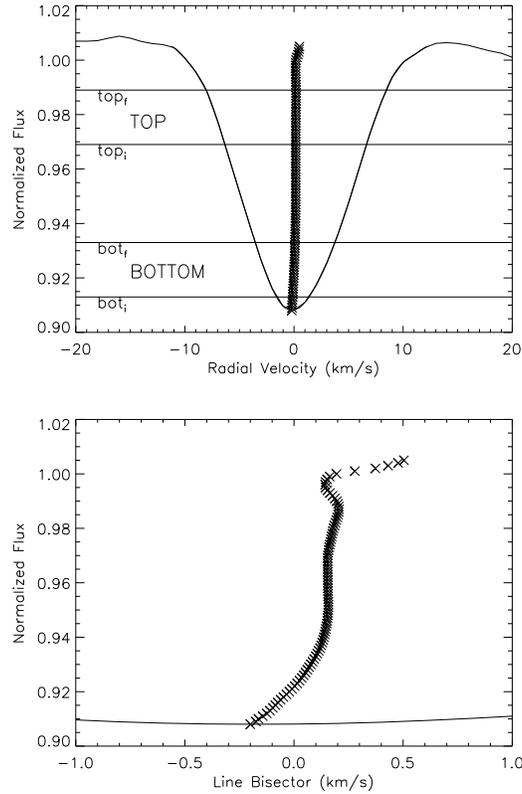
In our case, we followed the latter approach, but we had to handle the complication of having the iodine lines superimposed to the stellar spectra. On the other hand, these lines offer the opportunity to improve the wavelength calibration of the spectra, required for accurate estimates of the line bisectors. The iodine lines were removed by means of a suitable spectrum of a fast rotating early type star with the iodine cell in the optical path. The procedure is described in detail in [24].

The bisector of an absorption line is the middle point of the horizontal segment connecting points on the left and right sides of the profile with the same flux level. The line bisector is obtained by combining bisector points ranging from the core toward the wings of the line. To quantify the asymmetry of the spectral lines and look for correlation with RV it is useful to introduce the bisector velocity span (hereafter BVS, [39]). This is determined by considering a top zone near the wings and a bottom zone close to the core of the lines, which represent interesting regions to study the velocity given by the bisector (see Fig. 16). The difference of the average values of velocities in the top and bottom zones,  $V_T$  and  $V_B$  respectively, determine the bisector velocity span.

The star HD 166435 shows evidence of RV variations, photometric variability and magnetic activity. Furthermore, previous analysis of the variation of the line bisectors revealed a correlation between RV and line bisector orientation ([31]). It was used to test our procedure. As shown in Fig. 17, there is a clear anti-correlation between radial velocity and BVS variations.

The study of line shape is relevant for our program also as a diagnostic for the contamination of the spectra by the wide companion. Contaminated spectra are not easy to handle when analyzing the radial velocity curve. In fact, the internal radial velocity errors are estimates from the scatter of individual chunks on which the spectrum is modeled separately. In case of contamination, all the chunks deviate systematically by a similar amount (our pairs are always formed by similar stars) and then the radial velocity shift might largely exceed the internal errors, causing a spurious but formally highly significant variability.

In the case of contamination, we observe a positive correlation between the bisector velocity span and the radial velocity. The worst case of contamination in our sample occurs for HD 8071B (see Fig. 18). This pair is one of the closest (separation 2.1 arcsec). Furthermore, HD 8071 A is itself a single-lined

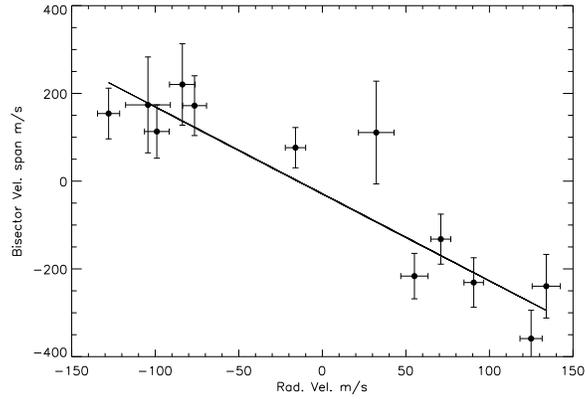


**Fig. 16.** Spectrum of HD 166435. In the top panel we show the normalized cross correlation profile, the line bisector, the top and bottom zones (both with  $\Delta F = 0.02$ ;  $\Delta F = \text{top}_f - \text{top}_i = \text{bot}_f - \text{bot}_i$ ). In the bottom panel we show a zoom of the profile with the RV scale increased to better display the asymmetries of the line bisector. From [24].

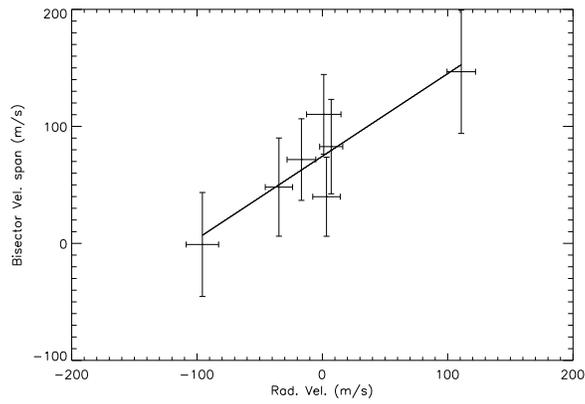
spectroscopic binary with a RV semi-amplitude of about 7 km/s. This causes significant spectra-to-spectra variations of the contamination both in amplitude (because of the variable observing conditions) and wavelength (because of the orbital motion of HD 8071A).

## 11 Upper limits on planetary companions

While no confirmed planet detection emerged up to now from our survey, a detailed analysis of the negative results would allow to constrain the frequency of planets in binary systems. Since we are focusing on a specific type of binaries, wide binaries with similar components at intermediate separations (a few



**Fig. 17.** Radial velocity - line bisector correlation for the active star HD 166435

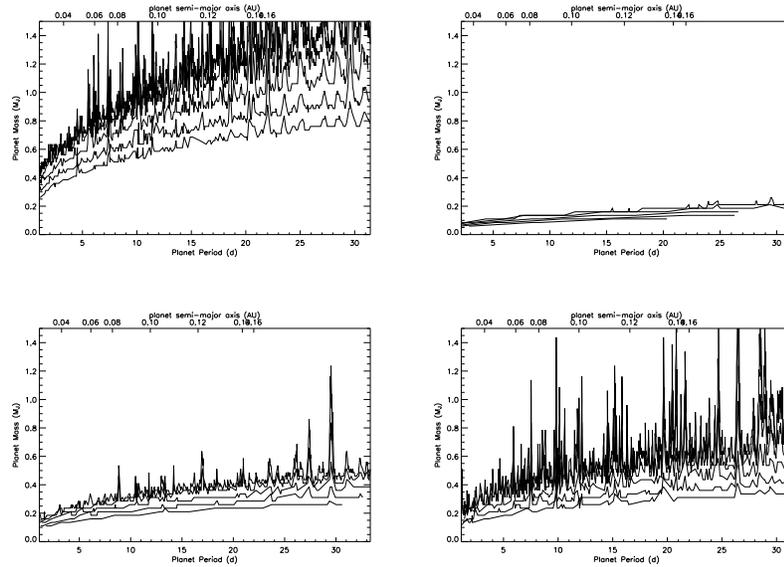


**Fig. 18.** Radial velocity - line bisector correlation for HD 8071B. This is likely due to the contamination by the companion HD 8071A

hundreds AU), such a study is complementary to other studies of planets in binaries.

To this aim, we derived upper limits on the planetary companions still compatible with the observations. Our method, a Montecarlo simulation based on the evaluation of the excess of radial velocity variability caused by the presence of hypothetical planets, allows us a complete exploration of the possible orbital parameters for eccentric orbits (the real case, since most of the known planets are in eccentric orbits). Our approach is described in detail in [6].

Fig. 19 shows the upper limits on planetary companion on short-period circular orbit for four stars representative of our sample. Fig. 20 shows the



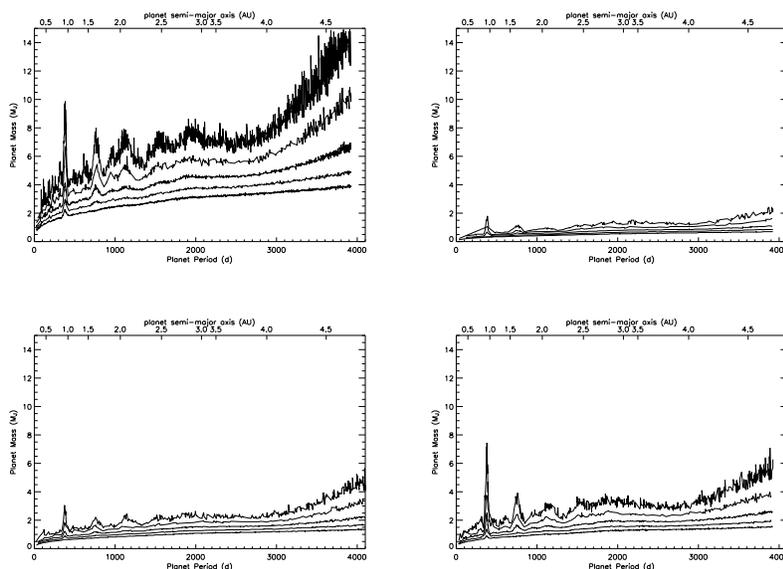
**Fig. 19.** Upper limits on planetary companion on short-period circular orbit for four stars representative of our sample. The different lines refer to the exclusion limits for (from top to bottom) 95%, 90%, 75%, 50%, and 25% of the planets. For the star on the upper-left corner planet detectability is strongly limited by stellar activity. The star in the upper-right corner is the one with the best limits, thanks to the low dispersion of RVs and the large number of measurements. The behaviour of the other two stars is more typical for our survey. The 'noisy' run of exclusion limits with period for the star in the lower-right corner is due to the small number of measurements.

limits for long period planets with eccentricities as large as 0.95. The average limits for the whole sample are shown in Fig. 21.

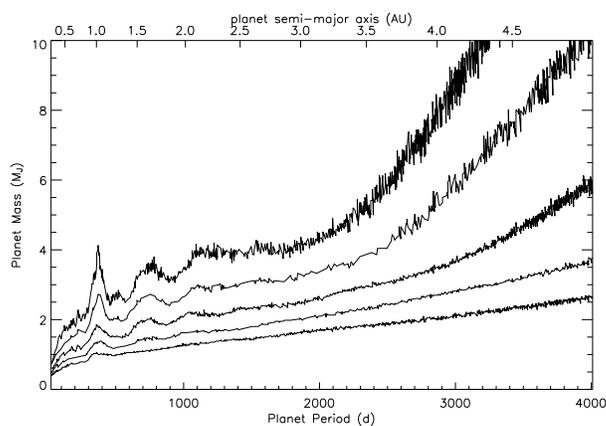
## 12 On the frequency of planets in binary systems

The lack of planets up to now in the SARG sample appears as an indication for a lower frequency of planets in the kind of binary systems we are surveying. Since our sample includes only binaries, a reference sample is needed for a full statistical evaluation. A useful comparison sample is represented by the 'Uniform Detectability' sample identified by [16].

The Uniform Detectability (UD) sample has been built from the full target lists of Lick, Keck and Anglo Australian Surveys (1330 stars), satisfying the requirement of completeness for detections of planets with velocity amplitudes  $K > 30$  m/s and orbital periods shorter than 4 years. Stars that were added



**Fig. 20.** Upper limits on planetary companion on long-period eccentric orbit for the same four stars shown in Fig. 19.



**Fig. 21.** Summary of estimates of exclusion/compatibility of planets in the SARG sample with current data for the stars with at least 10 observations. For each period, the mass corresponding to the exclusion of (from top to bottom) 95%, 90%, 75%, 50%, and 25% of the planets (taking into account planet eccentricity) is shown. The results of individual stars were averaged to produce the plot.

after a planet was discovered by other groups were not included in the sample. However, stars independently present in one of these surveys were considered even if a planet was detected first by another group. Only planets with  $K > 30$  m/s and orbital periods shorter than 4 years were considered for the study of planet frequency. This corresponds to Saturn-mass planets for the shortest periods and Jupiter-mass planets for 4 year orbits.

The UD sample is biased against binaries, as the stars with companions closer than 2 arcsec known at the time of the target selection were excluded. Bonavita & Desidera ([2]) performed a detailed literature search for binarity of the 850 stars in the UD sample, resulting in 202 binary stars in the sample. For some of them, only long term radial velocity and astrometric trends are available.

15 of the binaries in the UD sample have planets, so the global frequency of planets in the UD binary sample is 7.4%. If we consider the single-stars sub-sample, we found that 5.3% of UD single stars have planets (see Table 2). The two frequencies are compatible within their errors. The slightly higher value of the global frequency in the binary sub-sample is probably due to higher completeness level of binary census in stars with planet.

Incompleteness effects are unlikely to deeply modify this picture. Even assuming that the frequency of binaries in the sample is that found by [12] (an upper limit because of the exclusion of binaries with separation less than 2 arcsec) and that all the companions of planet hosts have been already identified, it can be seen that the global frequency of planets in binaries can not be lower by more than a factor of three compared to that of single stars.

The rather large sample size allows us we make some sub-samples with different values of critical semiaxis for dynamical stability of planets ( $a_{crit}$ , see [22] and Sect. 2). All the stars with RV and/or astrometric trend are included in the closest bin, as it is likely that the companion responsible of the trend is at small separation.

$a_{crit}$	$N_{stars}$	$N_{planets}$	$\frac{N_{planets}}{N_{stars}}$
20 AU	89	2	0.022±0.018
20 - 50 AU	18	2	0.111±0.105
50 - 100 AU	24	2	0.083±0.076
100 - 250 AU	26	4	0.154±0.107
> 250 AU	45	5	0.111±0.066
UD Singles sub-sample	647	34	0.053±0.011
Entire UD binary sub-sample	202	15	0.074±0.024

**Table 2.** Frequency of planets in binaries with different values of  $a_{crit}$ . From [2]

We found that there is no significant dependence of the frequency on  $a_{crit}$  except for companion with  $a_{crit}$  less than 20 AU (that corresponds to a separation < 50-100 AU, depending on the mass-ratio of the components). Con-

sidering also the similitude of the mass and period distribution of planets orbiting single stars and components of wide binaries (see [5] and Sect. 2), we then conclude that a wide companion plays a marginal role on the formation and evolution of giant planets.

For the planets in tight binaries, the results are more intriguing. On one hand, there are indications that the properties of planets in tight binaries are significantly different from those of exoplanets orbiting wide binaries or single stars (see [5] and Sect. 2). On the other hand, the frequency of planets in close binaries appears to be lower than that of planets orbiting single stars and components of wide binaries.

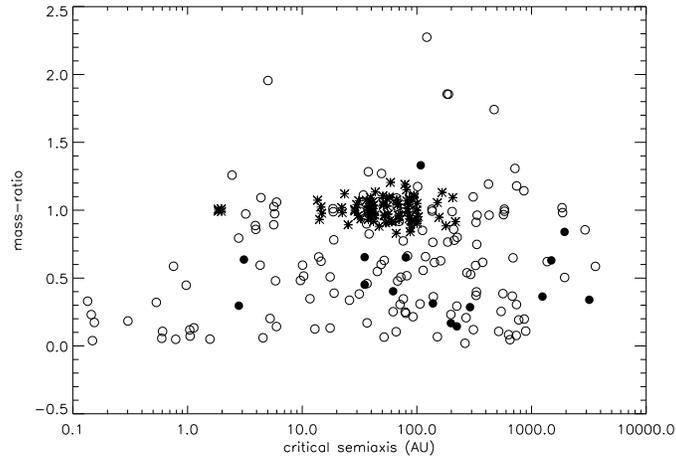
The frequency of planets in close binaries can be used to further investigate how these planets formed and the origin of their anomalous properties. Indeed, [29] showed that the knowledge of the value of the frequency of planets in close binaries<sup>7</sup> should allow to disentangle between two alternative formation scenarii. A low frequency (less than 0.1% but with an uncertainty of about one order of magnitude, so they consider 1% as a limit-value) would be compatible with dynamical interactions that cause the formation of the tight binary after planet formation. While not fully conclusive because of the poor statistics, our results suggests that frequency of planets in close binaries probably is not as low as required to explain their presence only as the results of modifications of the binary orbit after the planet formation. Therefore, it appears that planets do form in tight binaries (separations of the order of 20 AU or even less) in spite of the strong gravitational interactions that might work against.

However, crucial issues still need clarification. There are some hints that the run frequency of planets is not characterized by a continuous decrease when moving to smaller separation: in the full list of planets in binaries by [5] there is only one planet with critical semimajor axis for dynamical stability in the range 10 - 30 AU, while there are 5 planets with  $a_{crit}$  less than 10 AU and 4 planets with  $30 < a_{crit} < 50$  AU. This suggests a bimodal distribution of planet frequency, with a secondary maximum at  $a_{crit} \sim 3 - 5$  AU, but the analysis of the UD sample does not allow us to confirm it because of the small number of binaries with  $10 < a_{crit} < 30$  AU and the lack of binary characterization (orbital parameters, mass ratio) for the stars with only RV and/or astrometric trends.

The targets of the SARG planet search are crossing this range of separation (see Fig. 22), and therefore the completion of the survey, coupled with an estimate of planet detectability homogeneous with that of comparison samples will allow us to better address this issue. The current lack of planets in the SARG survey might suggest a relevant role of the binary mass ratio in the occurrence of planets. A complementary very important approach is represented by a detailed characterization of the binaries in current samples of RV surveys (complete detection of binaries and, when possible, full determination of the orbital elements). The availability of a larger and more complete sample will

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<sup>7</sup> Defined as those binaries with semi-major axis less than 50 AU



**Fig. 22.** Critical semiaxis for dynamical stability for the binaries in the UD sample (filled circles: stars with planets; empty circles: stars without planets) and in the sample of the SARG planet search (asterisks).

allow us to better understand the behaviour of the planet frequency in binaries and, at the same time, to disentangle the questions about the formation of planets in these peculiar environments and especially about the formation mechanisms and the different characteristics of the planets in tight binaries.

## References

1. G.A. Bakos, R.W. Noyes, G. Kovacs et al: ApJ, in press (astro-ph 0609369)
2. M. Bonavita, S. Desidera: A&A submitted (2007)
3. R.P. Butler, J.T. Wright, G.W. Marcy, et al. ApJ **4646**, 505 (2006)
4. M. Ceconi, A. Ghedina, P. Bagnara et al.: Proceedings of the SPIE, Volume 6272, p. 77 (2006)
5. S. Desidera, M. Barbieri: A&A in press (2007)
6. S. Desidera, R. Gratton, M. Endl et al.: A&A **405**, 207 (2003)
7. S. Desidera, R. Gratton, S. Scuderi et al.: A&A **420**, 683 (2004)
8. S. Desidera, R. Gratton, M. Endl et al.: A&A **420**, L27 (2004)
9. S. Desidera, R. Gratton, R.U. Claudi: in *Proc. of ESO Workshop on Multiple Stars Across HR Diagram*, in press (2006)
10. S. Desidera, R. Gratton, S. Lucatello, R.U. Claudi.: A&A **454**, 581 (2006)
11. S. Desidera, R. Gratton, S. Lucatello, M. Endl, S. Udry: A&A, in press (2006)
12. A. Duquennoy & M. Mayor: A&A **248**, 485 (1991)
13. A. Eggenberger, M. Mayor M. S. Udry: A&A **417**, 353 (2004)
14. A. Eggenberger, S. Udry, M. Mayor M. et al.: in *Proc. of ESO Workshop on Multiple Stars Across HR Diagram*, in press (2006)
15. M. Endl, M. Kürster, S. Els: A&A, **362**, 585 (2000)

16. D. Fischer & J. Valenti: *ApJ* **622**, 1102 (2005)
17. G. Gonzalez: *MNRAS* **285**, 403 (1997)
18. R.G. Gratton, G. Bonanno, P. Bruno, et al.: *Exp. Astron.* **12**, 107 (2001)
19. A.P. Hatzes, W.D. Cochran, E.J. Bakker: *ApJ* **508**, 380 (1998)
20. A.P. Hatzes & G. Wuchterl: *Nat.* **436**, 182 (2005)
21. U. Heiter, R.E. Luck: *AJ*, **126**, 201 (2003)
22. M.J. Holman, P.A.. Wiegert: *AJ*, **117**, 621 (2001)
23. C. Laws, G. Gonzalez: *ApJ*, **553**, 405 (2001)
24. A.F. Martinez Fiorenzano, R. Gratton, S. Desidera, R. Cosentino, M. Endl: *A&A*, **442**, 775 (2005)
25. F. Marzari & S.J. Weidenschilling: *Icarus* **156**, 570 (2002)
26. N. Murray, B. Chaboyer, P. Arras, B. Hansen, & R.W. Noyes: *ApJ* **555**, 801 (2001)
27. B. Nordstrom, M. Mayor, J. Andersen et al.: *A&A* **418**, 989 (2004)
28. D.B. Paulson, S.H. Saar, W.D. Cochran, G.W. Henry: *AJ* **127**, 1644 (2004)
29. E. Pfhal & M. Mutherspaugh: *ApJ* **652**, 1694 (2006)
30. G.W. Preston & C. Sneden: *AJ* **120**, 1014 (2000)
31. D. Queloz, G.W. Henry, J.P. Sivan, et al.: *A&A* **379**, 279 (2001)
32. S.H. Saar, R.P. Butler & G.W. Marcy: *ApJ*, **498**, L153 (1998)
33. N.C. Santos, G. Israelian , M. Mayor: *A&A* **415**, 1153 (2004)
34. S. Soderhjelm: *A&A* **341**, 121 (1999)
35. G. Takeda, E.B. Ford, A. Sills, A. et al.: *ApJS*, in press (2007) (astro-ph 0607235)
36. Y. Takeda: *PASJ* **57**, 83 (2005)
37. B.J. Taylor: *ApJS* **161**, 444 (2005)
38. A.A. Tokovinin, S. Thomas, M. Sterzik, S. Udry, S. *A&A* **450**, 681 (2006)
39. C.G. Toner & D.F. Gray: *ApJ*, **334**, 1008 (1988)
40. J. Valenti & D. Fischer: *ApJS* **159**, 141 (2005)
41. H. Van Winckel: *ARA&A*, **41**, 391 (2003)
42. R.A. Winnick, P. Demarque, S. Basu, D.B. Guenther: *ApJ* **576**, 1075 (2002)
43. J.T. Wright: *PASP* **117**, 657 (2005)
44. S. Zucker, T. Mazeh: *ApJ* **568**, L113 (2002)