Chapter 2
Probing the Impact of Stellar Duplicity on Planet Occurrence with Spectroscopic and Imaging Observations

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2.1 Introduction

Over the past 14 years, Doppler spectroscopy has been very successful in detecting and characterizing extrasolar planets, providing us with a wealth of information on these distant worlds (e.g., Marcy et al. 2005a; Udry and Santos 2007b; Udry et al. 2007a). One important and considerably unexpected fact these new data have taught us is that diversity is the rule in the planetary world. Diversity is found not only in the characteristics and orbital properties of the ∼340 planets detected thus far,[1] but also in the types of environments in which they reside and are able to form. This observation has prompted a serious revision of the theories of planet formation (e.g., Lissauer and Stevenson 2007; Durisen et al. 2007; Nagasawa et al. 2007), leading to the idea that planet formation may be a richer and more robust process than originally thought.

It is well known that nearby G, K, and M dwarfs are more likely found in pairs or in multiple systems. Specifically, 57% of the G dwarf primaries within 22 pc of the Sun have at least one stellar companion (Duquennoy and Mayor 1991). The multiplicity among K dwarfs is very similar (Halbwachs et al. 2003; Eggenberger et al. 2004b), and among nearby M dwarfs is close to 30% (Fischer and Marcy 1992; Delfosse et al. 2004). Altogether, these figures imply that more than half of the nearby F7–M4 dwarfs are in binaries or in higher order systems. Since these stars constitute the bulk of the targets searched for extrasolar planets via

[1] See the Extrasolar Planet Encyclopedia, http://exoplanet.eu/, for an up-to-date list.

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Doppler spectroscopy, the question of the existence of planets in binary and multiple star systems is fundamental and cannot be avoided when one tries to assess the overall frequency of planets.

From the theoretical perspective, the existence of planets in binary and multiple star systems is not guaranteed a priori as the presence of a stellar companion may disrupt both planet formation and long-term stability. On the other hand, young binary systems often possess more than one protoplanetary disk (Monin et al. 2007 and references therein), meaning that planets may form around any of the two stellar components (circumstellar planets) and/or around the pair as a whole (circumbinary planets). Although theoretically both circumstellar and circumbinary planets should exist (Barbieri et al. 2002; Mayer et al. 2005; Boss 2006; Thébault et al. 2006; Quintana and Lissauer 2006; Haghighipour and Raymond 2007; Quintana et al. 2007; Pierens and Nelson 2007), our present planet search programs are essentially aimed at detecting circumstellar planets, and only these will be considered in this chapter. Our discussion will furthermore be focused on giant planets, which are less challenging to detect by means of the Doppler spectroscopy technique than lower mass objects.

Two different scenarios have been proposed to explain the formation of gaseous giant planets. According to the core accretion model, giant planets form in a protoplanetary disk through the accretion of solid planetesimals followed by gas capture (see, e.g., Lissauer and Stevenson (2007) for a review and references). Despite some remaining uncertainties, this scenario is commonly considered as the favored mechanism to explain the formation of giant planets. An important point in this model is that the protoplanetary cores that give rise to the giant planets may have to form beyond the snow line (i.e., beyond 1–4 AU for solar-type stars) to benefit from the presence of ices as catalysts.

An alternative way to view giant planet formation is to consider that these planets form by direct fragmentation of the protoplanetary disk. This is the so-called disk instability model (see Durisen et al. 2007 and chapter ... for a review and references). Since it is not clear yet whether real protoplanetary disks actually meet the requirements for fragmentation, and whether the fragments will live long enough to contract into permanent planets, the disk instability scenario has remained somewhat speculative. Observational tests that would help characterizing and quantifying the likelihood of forming giant planets by this method are thus desirable.

Regardless of the exact formation process, tidal perturbations from a stellar companion within $\sim$100 AU may affect planet formation by truncating, stirring, and heating a potential circumstellar protoplanetary disk (e.g., Artymowicz and Lubow 1994; Nelson 2000; Mayer et al. 2005; Pichardo et al. 2005; Boss 2006; Thébault et al. 2006). Disk truncation is a serious concern as it reduces the amount of material available for planet formation and it may cut the disk inside the snow line. This is a direct threat to planet formation in binary stars and explains why the naive outlook for planet formation in moderately close binaries is pessimistic.

The impact of disk stirring and heating on planet formation is not so easily understood and requires dedicated simulations. According to Nelson (2000), giant planet formation is inhibited in equal-mass binaries with a separation of 50 AU whatever the formation mechanism, whereas Boss (2006) claims that giant planets are able to form in binaries with periastrons as small as 25 AU. Other studies on the subject concluded that planetesimal accretion is perturbed but remains possible in various binary systems closer than 50 AU (Thébault et al. 2004, 2006), and that the two possible formation mechanisms may yield different predictions as to the occurrence of giant planets in binaries separated by 60–100 AU (Mayer et al. 2005). This last conclusion is particularly interesting since it implies that planets in 60–100 AU binaries might be used to identify the main formation mechanism for giant planets.

Assuming that planets can form in various types of binary systems, another important concern is their survival. The extensive body of literature on this subject can be summarized as follows. For low-inclination planetary orbits ($i \lesssim 39°$), the survival time is primarily determined by the binary periastron. A stellar companion with a periastron wider than approximately 5–7 times the planetary semimajor axis does not constitute a serious threat to the long-term ($\sim$5 Gyr) stability of Jovian-mass planets (e.g., Holman and Wiegert 1999; Fatuzzo et al. 2006). The survival time of planets on higher inclination orbits depends not only on the binary periastron, but also on the inclination angle (Innanen et al. 1997; Haghighipour 2006; Malmberg et al. 2007), meaning that planetary orbits become more easily unstable, even if the semimajor axis is quite large (several hundred of AU). This additional type of instability is due to the so-called Kozai mechanism, which causes synchronous oscillations of the planet eccentricity and inclination (e.g., Kozai 1962; Holman et al. 1997; Mazeh et al. 1997; Takeda and Rasio 2005).

To sum up, if giant planets are to form in binaries with a separation below $\sim$100 AU, then the most sensitive (but also less understood) issue regarding their occurrence in these systems seems to be whether or not these planets can form in the first place. This conclusion is quite appealing as it implies that quantifying the occurrence of planets in moderately close binaries may be a means of obtaining some observational constraints on the processes underlying planet formation. Yet, recent work made to explain the existence of a close-in Jovian planet around HD 188753 A emphasized the alternative possibility that moderately close double and multiple star systems originally void of giant planets may acquire one via dynamical interactions (stellar encounters or exchanges), in which case the present orbital configuration of the system would not be indicative of the planetary formation process (Pfahl 2005; Portegies Zwart and McMillan 2005). Pfahl and Muterspaugh (2006) have tried to quantify the likelihood that a binary system could acquire a giant planet in this way and concluded that dynamical processes could deposit Jovian planets in $\sim$0.1% of the binaries closer than 50 AU. Therefore, to test the possibility of forming giant planets in binaries closer than $\sim$100 AU, one needs not only to detect giant planets in these systems, but above all, to quantify their frequency.

From the observational perspective, the existence of planets in wide binaries and multiple star systems has been supported by observations almost since the first discoveries. In 1997 three planets were found to orbit the primary components of wide binaries HR 3522, HR 5185, and HR 458 (Butler et al. 1997), while another one was discovered around 16 Cyg B, the secondary component of a triple system (Cochran et al. 1997). Three years later, the detection of a giant planet around Gl 86 A (Queloz et al. 2000) brought a clear evidence that Jovian planets can also exist in the much closer spectroscopic binaries, as suggested previously by the possible detection of a giant planet around γ Cephei A (Campbell et al. 1988; Walker et al. 1992; Hatzes et al. 2003). These discoveries rapidly prompted a new interest in the study of planets in binaries, raising the possibility that planets may be common in double and multiple star systems.

When considering planets in binaries, it is important to note that most Doppler planet searches used to be, and still are, strongly biased against binaries closer than $\sim$200 AU. As a consequence, present data from these surveys provide incomplete information on the suitability of $\lesssim$200 AU binaries for planetary systems. Similarly, the actual frequency of planets in these systems remains unconstrained.

Recognizing early the importance and the interest of including binary stars in extrasolar planet studies, we have investigated the impact of stellar duplicity on planet occurrence for a few years. This investigation follows two different approaches. The first one uses Doppler spectroscopy to quantify the occurrence of giant planets in spectroscopic binaries (Eggenberger et al. 2003, 2008b). Combining the results from these surveys targeting moderately close binaries with the results from our "classical" planet searches with ELODIE (Perrier et al. 2003) and CORALIE (Queloz et al. 2000; Udry et al. 2000), we aim at quantifying the occurrence of giant planets in binaries with various separations. The second approach to our study makes use of direct imaging to probe the multiplicity status of nearby solar-type stars with and without planets. This work aims at tracing out the impact of stellar duplicity on planet occurrence and properties in binaries with typical separations between 35 and 250 AU (Udry et al. 2004; Eggenberger et al. 2004c, 2007b, 2008, 2008b).

The outline for this chapter is as follows. In Section 2.2 we present the results from classical Doppler planet searches, whose outcomes constitute the general framework within which lie more specific studies dedicated to binaries. In Section 2.3 we describe how direct imaging can be used to probe the impact of stellar duplicity on planet occurrence and to test whether the frequency of giant planets is reduced in binaries closer than $\sim$100 AU. In Section 2.4 we discuss some preliminary results from our Doppler surveys dedicated to the search for circumstellar planets in spectroscopic binaries. All these results are finally summarized in Section 2.5.

2.2 Results from Classical Doppler Planet Searches

Most of the information gathered to date on planets in binary and multiple star systems[2] has been obtained by "classical" Doppler surveys searching for planets around G and K dwarfs within 100 pc of the Sun (Udry et al. 2007a and references therein). Here, we present and discuss these observational results, together with the selection effects against binary systems that affect classical Doppler planets searches.

[2] For the sake of conciseness, we will henceforth call "planets in binaries" the planets residing either in true binaries or in hierarchical multiple systems.

2.2.1 Selection Effects Against Binaries in Doppler Planet Searches

In a general way, Doppler searches for planets around nearby G and K dwarfs avoid binaries closer than $2''$ to $6''$ (systems that we will call moderately close binaries in this chapter) (Udry et al. 2000; Perrier et al. 2003; Marcy et al. 2005b; Jones et al. 2006), meaning that these programs reject from their samples many star systems closer than $\sim$200 AU. The reason for this discrimination is twofold. First, the naive prospect of finding giant planets in moderately close binaries used to be quite poor and until recently moderately close binaries were not considered particularly interesting targets for planet searches. Secondly, double stars with an angular separation similar to, or smaller than, the size (projected onto the sky) of the spectrograph's fiber or slit present technical difficulties since they cannot be observed as two isolated stars. As explained in Section 2.4, this often complicates the extraction of the radial velocity, rendering classical cross-correlation techniques inadequate to search for planets in certain types of spectroscopic and visual binaries.

When designing our ELODIE and CORALIE planet search programs, we rejected from the main samples all the G and K dwarfs belonging either to "short-period" single-lined spectroscopic binaries ($\lesssim$10 years) or to double-lined spectroscopic binaries[3] (Udry et al. 2000; Perrier et al. 2003). This discrimination was performed in the first place on the basis of former radial-velocity measurements gathered with the two CORAVEL instruments,[4] but additional systems discovered later in the course of our planet programs met the same fate and were rejected as well. However, we kept in the samples single-lined spectroscopic binaries with long periods ($\gtrsim$10 years) since in those systems, not only was the prospect of finding giant planets higher than in double-lined spectroscopic binaries with more massive secondaries, but also the technical difficulties were thought to be minimal.

Our initial policy on wider binaries was less drastic and we kept all visual binaries in our ELODIE and CORALIE samples. However, the data accumulated in the early phases of the CORALIE program showed that radial velocity measurements of primary components of moderately close visual binaries were generally noisier and more variable than expected, suggesting that the secondaries in these systems often contribute to some extent to the recorded flux. Consequently, we flagged as second-priority targets, all the visual binaries closer than $\sim 6''$ and with a magnitude difference $\Delta V \lesssim 4$. These targets are then observed less often than regular single stars.

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[3] Single-lined spectroscopic binaries are systems for which only the spectrum of the primary component is detected, while double-lined spectroscopic binaries are systems for which the spectra of both components are detected. See Section 2.4 for further details on spectroscopic binaries.

[4] The two CORAVEL instruments (Baranne et al. 1979) were used extensively between 1977 and 1998 to monitor the radial velocity of more than 60,000 nearby stars at an intermediate precision (typically 300 $\mathrm{m\,s^{-1}}$) in both hemispheres.

2.2.2 The Sample of Planets in Binaries

Thanks mostly to recent searches for common proper motion companions to planet-host stars (Section 2.3), the number of planets known to reside in binary and multiple star systems has been growing rapidly in the past few years (Patience et al. 2002; Eggenberger et al. 2004, 2007b; Mugrauer et al. 2005, 2006; Chauvin et al. 2006; Raghavan et al. 2006; Desidera and Barbieri 2007) and has now reached to 40 planets in 35 planetary systems. In terms of system architecture, these planets were found in binaries with projected separations between ∼20 and ∼12,000 AU. With few exceptions, all these planets orbit the primary components (Eggenberger et al. 2004; Raghavan et al. 2006; Desidera and Barbieri 2007). This last feature is partly a selection effect, the secondaries being often too faint to belong to the target samples used by Doppler planet searches. Not surprisingly, only a couple of planets were found in binary or multiple systems closer than ∼100 AU. Although some theoretical models predict a shortage of giant planets in binaries closer than ∼100 AU (Nelson 2000; Mayer et al. 2005; Thébault et al. 2006), current Doppler surveys are too severely biased against these particular systems to claim that observations meet theoretical predictions on this point. In particular, the fact that three of the few planets detected in binaries closer than 100 AU were found in systems with separations of about 20 AU likely reflects the selection effects just mentioned in Section 2.2.1. Indeed, for targets within 50 pc and for spectrographs like ELODIE or CORALIE, the separation range between ∼10 and ∼30 AU corresponds to both long-period spectroscopic binaries (that were kept in the samples) and to visual binaries that are compact enough for technical difficulties to remain acceptable if the secondary component is not too bright (see Section 2.4 for details). As a consequence, Doppler planet searches such as the ELODIE and the CORALIE surveys are presently more likely to detect planets in 10–30 AU systems than in $\lesssim$10 AU or in 30–100 AU systems.

The apparent lack of planets in binaries closer than ∼20 AU is also worth noticing. According to theoretical models, the formation of giant planets in binaries closer than ∼20 AU is possible only for low binary eccentricities, if at all (Nelson 2000; Thébault et al. 2004, 2006; Mayer et al. 2005; Boss 2006). Many short-period spectroscopic binaries may then be free from giant planets and the "limit" at ∼20 AU might have a true meaning. Nonetheless, the present observational material does not allow us to rule out the alternative hypothesis that the lack of planetary detections in systems closer than ∼20 AU actually reflects the discrimination against short-period spectroscopic binaries in classical Doppler surveys. On that basis, the question of the closest binaries susceptible of hosting circumstellar giant planets remains open.

To sum up, classical Doppler planet searches have brought observational evidence that circumstellar giant planets do exist in many types of binaries, including spectroscopic systems. Yet, this observational material is incomplete with regard to the closest binaries and we can derive from the present sample of planets in binaries only a minimum value for the fraction of planets residing in double and multiple star systems. This minimum fraction is 21%. Deriving the actual frequency of planets in binaries closer than ∼200 AU and probing the existence of giant planets in binaries closer than ∼20 AU both call for the need of planet search programs capable of dealing with spectroscopic and moderately close visual binaries. Two such programs are presently underway (Konacki 2005b; Eggenberger et al. 2003) and we discuss our own surveys in Section 2.4.

2.2.3 Different Properties for Planets in Binaries?

The first hint that planets found in binaries may possess some distinct properties and characteristics was brought by Zucker and Mazeh (2002). These authors pointed out that planets in binary systems seem to follow a different period-mass correlation than that of planets orbiting single stars. In a similar vein, in 2003, we performed a statistical study considering not only the period-mass but also the period-eccentricity relation (Eggenberger et al. 2004) (see also Mugrauer et al. 2005; Desidera and Barbieri 2007 for more recent studies). As shown in Fig. 2.1, our analysis confirms that the three planets with minimum masses[5] $M_2 \sin i \gtrsim 2\ \mathrm{M_{Jup}}$ and periods $P \lesssim 40$ days all orbit the components of binaries or multiple stars. However, the inclusion, in our sample, of several newly discovered planets with periods longer than 100 days and minimum masses in the range 3–5 M_{Jup}, which were found in

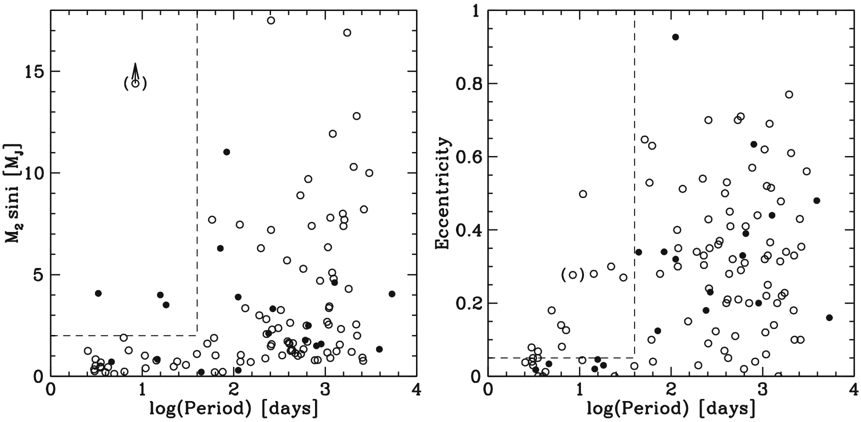

Fig. 2.1 *Left*: minimum mass versus orbital period for all the extrasolar planetary candidates known in 2003. Planets orbiting a single star are represented as *open circles*, while planets residing in binary or multiple star systems are represented as *dots*. The *dashed line* approximately delimits the zone where only extrasolar planets belonging to binaries are found. *Right*: eccentricity versus orbital period for the same planetary candidates as before. The *dashed line* approximately delimits the region where no planet-in-binary is found

[5] In the expression for the minimum mass, M_2 is the true mass of the planet and i is the inclination of the orbit with respect to the tangent plane of the sky.

binaries, decreases the significance of the negative period-mass correlation indicated by Zucker and Mazeh (2002). Yet, marginal signs of this correlation subsist in the form of a shortage of very massive planets ($M_2 \sin i \gtrsim 5\ \mathrm{M_{Jup}}$) on long-period orbits ($P \gtrsim 100$ days).

Our analysis also emphasizes that planets with periods $P \lesssim 40$ days which reside in binaries tend to have low eccentricities ($e \lesssim 0.05$) compared to their counterparts in orbits around single stars (Fig. 2.1). In other words, the minimum period for a significant eccentricity seems larger for planets in binaries ($P \sim 40$ days) than for planets around single stars ($P \sim 5$ days). The statistical significance of this finding is very modest, though, and calls for confirmation.

The two above-mentioned emerging trends are interesting because they might constitute the first observational evidence of two theoretical predictions. For instance, according to Kley (2000) the migration and mass growth rates of a Jovian protoplanet are enhanced when this object is embedded in a circumprimary disk in a 50–100 AU binary system. At the same time, the protoplanet's eccentricity decreases with time due to the damping action of the disk. Taken at face value, these theoretical predictions may provide a nice and self-consistent explanation for the observation that the most massive short-period planets are all found in binaries and have small eccentricities. Yet, the weak point in this reasoning is that the five circumprimary planets with periods shorter than 40 days, reside in systems with very different separations, from ~20 to ~1,000 AU. Kley's conclusions (Kley 2000) may thus apply to some of these systems, but not to all of them.

Another theoretical prediction that might find a first observational evidence in our results is the so-called Kozai migration. This migration process, specific to binaries, results from the coupling of the Kozai mechanism with tidal dissipation (Wu and Murray 2003; Fabrycky and Tremaine 2007). As shown by Takeda and Rasio (2005), if this mechanism has been at work in many planetary systems, it should have produced an excess of low-eccentricity planets. Again, this seems to provide a nice explanation to the observation that short-period planets found in binaries tend to have low eccentricities. The weak point here is that several requirements must be simultaneously met in order for the Kozai mechanism to operate (Holman et al. 1997; Wu and Murray 2003). Kozai migration may thus explain the low eccentricity of some of the five short-period planets found in binaries, but it is unlikely to explain the distinctive characteristics of all of them.

To summarize, the emerging trends seen in the period-mass and period-eccentricity diagrams are potentially interesting and might constitute a first indication that planetary migration can proceed differently in some binary systems than around single stars. To confirm and specify the present observational results, future investigations will have to improve on three points: (1) to increase the present sample of planets in binaries, (2) to systematically probe the presence of stellar companions to the known planet-hosting stars, and (3) to take into account the selection effects against moderately close binaries. We describe in the next two sections our efforts to tackle these issues, aiming at better understanding the impact of stellar duplicity, not only on planet occurrence, but also on planet properties and characteristics.

2.3 Results from Imaging Surveys

The problem of quantifying the impact of stellar duplicity on planet occurrence can be tackled in a somewhat indirect way by comparing the multiplicity among planet-bearing stars to the multiplicity among similar stars but without known planetary companions. Indeed, if the presence of a nearby stellar companion hinders planet formation, or drastically reduces the potential stability zones, the frequency of planets in binaries closer than a given separation (modulo eccentricity and mass-ratio) should be lower than the nominal frequency of planets around single stars. That is, the binary fraction among planet-hosting stars should be smaller than the binary fraction among single stars. Alternatively, if the presence of a nearby stellar companion stimulates planet formation one way or another, planets should be more common in binaries with a specific range of separations (again modulo eccentricity and mass-ratio) than around single stars. The binary fraction among planet-hosting stars should then be larger than the binary fraction among single stars. This indirect approach was first followed by Patience et al. (2002), who probed the multiplicity status of 11 planet-hosting stars and concluded that the companion star fraction among planet-bearing stars is not significantly different from that among field stars. The more than 300 planet-hosting stars known today, and the different conclusions of theoretical studies as to the impact of stellar duplicity on giant planet occurrence, both motivate a new analysis and a reconsideration of the multiplicity among planet-bearing stars.

To quantify the impact of stellar duplicity on planet occurrence and properties in binaries closer than $\sim$200 AU, we initiated in 2002 a large-scale adaptive optics search for stellar companions to $\sim$200 nearby solar-type stars with and without known planetary companions (Udry et al. 2004; Eggenberger et al. 2004c, 2007b, 2008, 2008b). To cover a substantial fraction of the sky, the main program was divided into two subprograms: a southern survey (130 stars) carried out with NAOS-CONICA (NACO) on the Very Large Telescope (VLT), and a northern survey (about 70 stars) carried out with PUEO on the Canada-France-Hawaii Telescope (CFHT). The southern survey has been completed, whereas, at the time of the writing of this chapter, the northern survey was still in progress. We present and discuss in this chapter observational and preliminary statistical results from our southern survey.

2.3.1 Our VLT/NACO Search for Stellar Companions to 130 Nearby Stars with and Without Planets

2.3.1.1 Sample and Observing Strategy

One major limitation that prevents all imaging surveys done to date (Luhman and Jayawardhana 2002; Patience et al. 2002; Mugrauer et al. 2005, 2006; Chauvin et al. 2006; Raghavan et al. 2006; Bonavita and Desidera 2007) to draw robust conclusions on the impact of stellar duplicity on planet occurrence is the absence of a well-defined control sample of non-planet-bearing stars. The use of a controlled sample is essential for two reasons. First, as explained in Section 2.2.1, Doppler planet searches suffer from noticeable selection effects against the closest binaries and these biases must be taken into account to obtain meaningful results. Second, to be rigorous, statistical studies must compare the multiplicity among planet-hosting stars with the multiplicity among similar stars but without planetary companions. To be as rigorous as possible, we included in our NACO survey both a subsample of planet-hosting stars and a controlled subsample of nearby field stars from our CORALIE planet search program showing no obvious evidence for planetary companions from radial-velocity measurements. Proceeding in this way, we had at hand high-precision radial-velocity data that place constraints on the potential giant-planet-bearing status of each comparison star. We matched the target selection criteria for Doppler planet searches, and minimized the corrections related to observational effects.

Our NACO survey therefore relies on a sample of 57 planet-host stars, together with 73 comparison stars (see Eggenberger et al. 2007b for further details on the definition of each subsample). Note that we purposely excluded from our observing list most planet-host stars observed by Patience et al. (2002) and by Chauvin et al. (2006) to avoid repeating existing observations. These stars will be included in our statistical analysis, though, balancing the two subsample sizes to about 70 stars in each subsample (Section 2.3.2). Since most of our targets are within 50 pc, the $13'' \times 13''$ field of view of NACO translates into a projected separation range of a few AU (diffraction limit) to about 325 AU. Recalling the theoretical predictions mentioned in Section 2.1, this means that our survey probes a large fraction of the separation range where the presence of a stellar companion should affect giant planet formation (hence giant planet occurrence) to some degree.

The survey observing strategy consisted of taking a first image of each of our targets (planet-hosting and controlled stars) to detect companion candidates. To distinguish true companions from unrelated background stars, we relied on two-epoch astrometry. Since most of our targets have a proper motion above $0.1''$ year^{-1}, astrometric parameters of bound companions are not expected to vary much over a few years, except for some orbital motion in the closest systems (Fig. 2.2). On the other hand, astrometric parameters of background objects without significant proper motion should vary according to the proper and parallactic motion of the primaries (Fig. 2.2). For relatively wide and bright companion candidates (projected separation $>10''$, magnitude in the K band <14), a pre-existing astrometric epoch could usually be found in the 2MASS catalog (Skrutskie et al. 2006), meaning that only one NACO observation was needed to identify true companions. However, due to the high angular resolution of NACO we could not rely on such preexisting data on a regular basis and we tried to re-observe the targets with companion candidates at a later epoch during the survey.

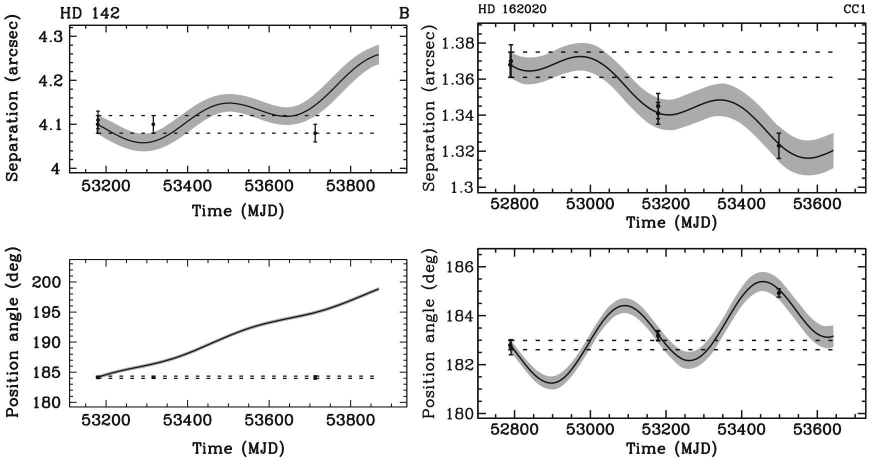

Fig. 2.2 Examples of multi-epoch astrometry from our NACO survey. *Solid lines* depict the evolution of angular separation and position angle for background objects with negligible proper motions. The *gray* zones are the related uncertainties. *Dots* represent our NACO observations and *dotted lines* depict the evolution expected for bound companions without significant orbital motion over the survey time span. The *left panels* show an example of true companion, while the *right panels* show an example of unrelated background star

2.3.1.2 Observational Results

Our NACO survey revealed 95 companion candidates in the vicinity of 33 targets. On the basis of two-epoch astrometry, we identified 19 true companions, 2 likely bound objects, and 34 background stars. The remaining 40 companion candidates (near 16 targets, most of them controlled stars) either lack second-epoch measurements (most of the objects), or have inconclusive astrometric results due to insufficiently sensitive images at one epoch (few objects). Follow-up observations have been carried out and will be used to complete the second-epoch observations.

The bound and likely bound systems identified in our NACO survey are listed in Table 2.1. Among planet-host stars, we discovered two very low mass companions to HD 65216, an early-M companion to HD 177830, and we resolved the previously known companion to HD 196050 into a close pair of M dwarfs. Besides these discoveries, our data confirm the bound nature of the companions to HD 142, HD 16141, and HD 46375. The remaining 11 true companions and the two likely bound objects all orbit control stars. These companions are late-K stars or M dwarfs, and have projected separations between 7 and 505 AU.

As illustrated on Fig. 2.3, the typical sensitivity of our survey enabled us to detect stellar companions down to ~M5 dwarfs at 0.2″, and down to the L-dwarf domain above 0.65″, providing us with a very complete census of the stellar multiplicity among our 130 targets.

Table 2.1 True (*upper portion*) and likely bound (*lower portion*) systems from our NACO survey. We refer the reader to Eggenberger et al. (2007b) for additional information on all these systems

Primary	Sample	Primary spec. type	Secondary	Secondary spec. type	Proj. sep. (AU)
HD 142 A	Planet	G1IV	HD 142 B	K8.5–M1.5	105.1 ± 1.8
HD 7895 A	Control	K1V	HD 7895 D	M2–M5	28.7 ± 0.8
HD 16141 A	Planet	G5IV	HD 16141 B	M1–M4	223 ± 11
HD 24331 A	Control	K2V	HD 24331 B	M4–M6	73.2 ± 1.7
HD 31412 Aa	Control	F8	HD 31412 Ab	M0–M3	7.1 ± 0.3
HD 40397 A	Control	G0	HD 40397 B	M0–M2	58.7 ± 1.7
HD 43834 A	Control	G5V	HD 43834 B	M3.5–M6.5	30.9 ± 0.3
HD 46375 A	Planet	K1IV	HD 46375 B	K9.5–M1.5	345 ± 12
HD 65216 A	Planet	G5V	HD 65216 Ba	M6.5–L0	255.2 ± 6.4
HD 65216 Ba		M6.5–L0	HD 65216 Bb	M7.5–L4	5.7 ± 1.1
HD 70923 A	Control	G0	HD 70923 B	M2–M5	36.9 ± 1.5
HD 78351 A	Control	G8/K0V	HD 78351 B	M1–M4	70.5 ± 2.6
HD 104263 A	Control	G5	HD 104263 B	M2.5–M4.5	68.6 ± 3.2
HD 129642 A	Control	K3V	HD 129642 B	M2.5–M5.5	157.4 ± 5.3
HD 154682 A	Control	G5V	HD 154682 B	M1.5–M4.5	45.3 ± 2.3
HD 177830 A	Planet	K0	HD 177830 B	M2–M5	97.1 ± 4.4
HD 196050 A	Planet	G3V	HD 196050 Ba	M1.5–M4.5	501 ± 22
HD 196050 Ba		M1.5–M4.5	HD 196050 Bb	M2.5–M5.5	19.7 ± 1.0
HD 223913 A	Control	G0V	HD 223913 B	K9.5–M2.5	314.0 ± 5.1
HD 82241	Control	F8V	CC1	M0–M3	16.3 ± 0.4
HD 134180	Control	K3V	CC2	M2.5–M5.5	505 ± 28

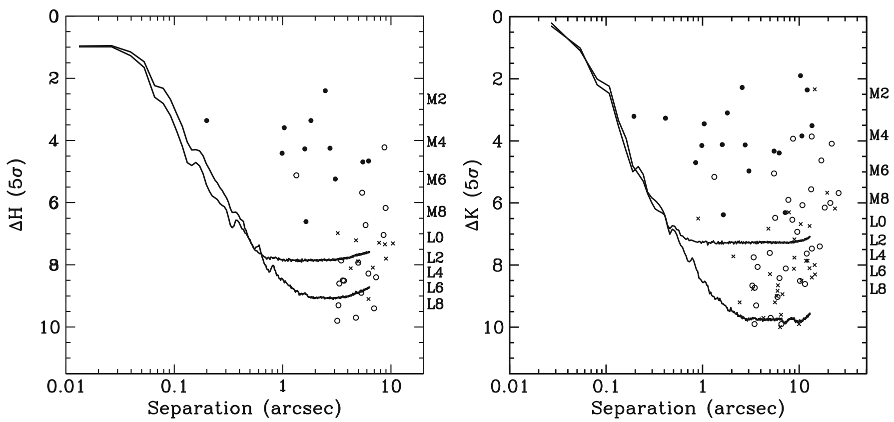

Fig. 2.3 Sensitivity limits and detections from our NACO survey in the H band (*left*) and in the K band (*right*). *Dots* represent bound and likely bound companions, *open circles* represent unbound objects, and *crosses* denote companion candidates with only one astrometric epoch. *Solid lines* are the median detection limits obtained with the two different detectors of NACO (a detector change occurred in the middle of our survey). Labels on the right-hand side of each plot show the relationship between magnitude (narrow-band photometry) and spectral type for companions to a typical old K0 dwarf

2.3.2 The Impact of Stellar Duplicity on Planet Occurrence

The observational results obtained in the context of our NACO survey form an unprecedented data set to study the impact of stellar duplicity on planet occurrence. Indeed, adding to our own results the targets surveyed by Patience et al. (2002) and Chauvin et al. (2006), we have a precise and homogeneous census of the multiplicity status of 73 planet-hosting stars and 66 comparison stars. We present here a preliminary statistical analysis aimed at obtaining a first quantification of the global impact of stellar duplicity on planet occurrence in binaries with mean semimajor axes between 35 and 250 AU.

2.3.2.1 Preliminary Statistical Analysis Based on the NACO Survey

A potentially sensitive issue in estimating the impact of stellar duplicity on planet occurrence is the exact definition of the controlled subsample, especially regarding the non giant-planet-bearing status of these stars. The main issue here is that a small amplitude radial velocity drift can just as well be the signature of a planetary companion as that of a more distant stellar companion. To test the sensitivity of our results to the exact definition of each subsample, we performed our first analysis based on two different sample redefinitions: (i) a loose re-definition where both subsamples were slightly modified except for a homogeneous cut-off at close separation ($\sim 0.7''$) to exclude the few stars with significant radial-velocity drifts; (ii) a more stringent redefinition where both subsamples were limited in distance to 50 pc, and where control stars showing any type of radial-velocity variation (small radial-velocity drifts, short-period variability, ...) were excluded. This additional selection was aimed at keeping in the controlled subsample as little potential planet-hosting stars as possible. Hereafter, the loosely redefined subsamples will be called "full" subsamples, while the more refined subsamples will be called "re-defined".

To quantify the global impact of stellar duplicity on giant planet occurrence, we computed the binary fraction for the four subsamples described above. According to our data, the binary fraction among planet-hosting stars is $5.5 \pm 2.7\%$ (4/73) for the full subsample and $4.9 \pm 2.7\%$ (3/62) for the redefined subsample. For control stars, we obtain binary fractions of $13.7 \pm 4.2\%$ (9/66) and $17.4 \pm 5.2\%$ (9/52) for the full and redefined subsamples, respectively. These results translate into a difference in binary fraction (controlled − planet-hosting) of $8.2 \pm 5.0\%$ for the full subsample and of $12.5 \pm 5.9\%$ for the redefined one. Although the relative errors on these results are quite large due to the small number of available companions, both sample definitions yield a positive difference with a statistical significance of 1.6-2.1σ. In physical terms, this positive difference implies that planets (mainly giant ones) are less frequent in binaries with mean semimajor axes between 35 and 250 AU than around single stars. In other words, stellar duplicity seems to negatively impact the occurrence of giant planets in such binary systems.

To extend the investigation one step further and to seek for a possible trend with mean semimajor axis, we computed the difference in binary fraction for a few bins

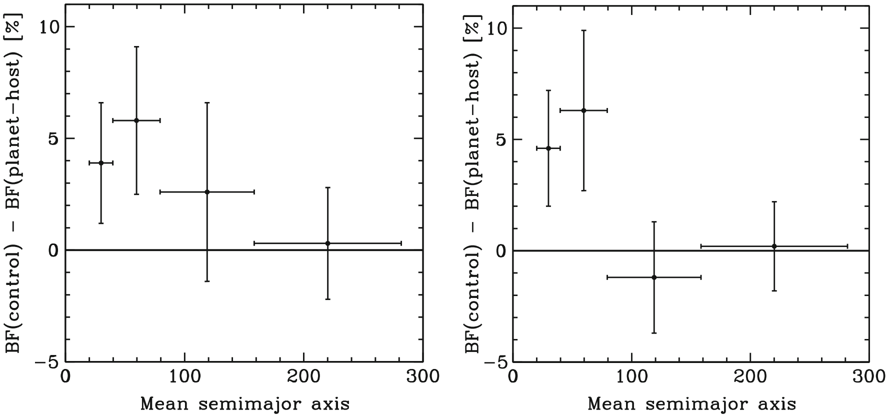

Fig. 2.4 Difference (in per cent) between the binary fraction among control stars and the binary fraction among planet-hosting stars as a function of binary mean semimajor axis. The *left plot* is based on the redefined subsamples, while the *right plot* is based on the full subsamples

in separation between 20 and 280 AU. The results for both the full and redefined subsamples are shown in Fig. 2.4. These two plots show that the difference in binary fraction does not seem to spread uniformly over the range of the semimajor axis studied here. But it seems rather concentrated below ∼100 AU. This result is appealing since it might corroborate the theoretical studies that predict a negative impact of stellar duplicity on planet formation in binaries closer than ∼100 AU. Nonetheless, as partly visible on Fig. 2.4, the small number of true companions available for the statistics still limits our analysis.

Given the range of semimajor axes considered in our analysis, the apparent lower frequency of planets in binaries closer than ∼100 AU is likely to be related to the actual formation of these planets rather than their long-term survival. Recalling the conclusions from theoretical studies, one possible explanation to our observations would be that the disk instability scenario may be a more viable mechanism for the formation of giant planets, and as suggested by Mayer et al. (2005), this mechanism is inhibited in binaries closer than ∼100 AU. However, a weak point in this argument is that Mayer et al. (2005) did not actually study planet formation via core-accretion. The prediction by these authors that the formation of giant planets via core-accretion model proceeds undisturbed in binaries with separations down to ∼60 AU is solely based on the temperature profiles of their simulated disks, whereas additional effects (especially those affecting the relative velocities among planetesimals) may come into play to inhibit planet formation. Our observational results can, however, confirm that core-accretion may in fact be the only formation mechanism for planets, and that its efficiency is reduced in binaries closer than ∼100 AU. This point of view may be consistent with the conclusion by Thébault et al. (2004) who state that planetesimal accretion is possible in the γ Cephei system (semimajor axis of 19 AU), but requires a delicate balance between gas-drag and secular perturbations by the secondary star.

2.3.2.2 Concluding Remarks on the Results from Imaging Surveys

The preliminary statistical results presented above are quite encouraging and already extend beyond what has been done before since the analyses by Patience et al. (2002), Raghavan et al. (2006), and Bonavita and Desidera (2007) could not correct the results for the selection effects against moderately close binaries. By adding about 70 stars to the statistics, the future results from our northern survey will make a valuable contribution to the analysis and will improve the statistical significance of the present results. The completion of the second-epoch measurements from our NACO survey will also strengthen our conclusions.

One point on which all observational studies agree is that if stellar duplicity impacts the formation and/or survival of circumstellar giant planets only in some types of binaries, it will not be easy to identify and quantify this effect in practice. This conclusion may result from practical limitations in the surveys (small sample sizes, difficulty to correct for selection effects, the need for radial-velocity data to ensure that controlled stars are free from giant planets, . . .), but it may alternatively have a more physical origin (e.g., not only binary semimajor axis, but also eccentricity and mass-ratio will likely play key roles in determining the impact of stellar duplicity on planet formation and evolution. Dynamical evolution may also significantly alter the initial distributions of planet-forming material and destroy the imprints of the formation process.). Further advances on both the theoretical and the observational fronts will be needed to specify this point. From the observational perspective, as we will see in the next section, Doppler searches for planets in spectroscopic binaries constitute another avenue to study the impact of stellar duplicity on the occurrence of giant planets in $\lesssim$200 AU binaries.

2.4 Results from Doppler Planet Searches in Spectroscopic Binaries

Nearby binary systems closer than 2–6$''$ can be classified into two categories: true spectroscopic binaries and moderately close visual binaries. True spectroscopic binaries are unresolved systems whose binary nature is known through the periodic translation of their spectra or, more pragmatically, through their periodic variations in radial velocity. Moderately close visual binaries are generally long-period spectroscopic systems as well, but they possess the additional property of being spatially resolved. Strictly speaking, this makes a small difference in terms of data analysis. We will also ignore this here and only consider the spectroscopic nature of all these systems. However, we will distinguish single-lined spectroscopic binaries (SB1s), for which only the spectrum of the primary star is detected, from double-lined spectroscopic binaries (SB2s), for which the spectra of both components are detected. The corollary of this distinction is that for SB1s we can only measure the radial velocity of the primary star, whereas for SB2s we can measure the individual velocities of both components. It should be noted that the classification of spectroscopic binaries into single- and double-lined systems is not absolute and depends on the instrument used for the observations and on the procedure used to analyze the data.

Until 2000–2002, planet searches in binaries closer than 2–6″ ($\lesssim$200 AU) were only of marginal interest. The discovery of two giant planets in the single-lined spectroscopic binaries Gl 86 and γ Cephei (projected separations of 20 AU and 19 AU, respectively Queloz et al. 2000; Hatzes et al. 2003) and the observation that the few most massive short-period planets all orbit the components of double or multiple star systems (Udry et al. 2002; Zucker and Mazeh 2002), changed this point of view and led to an ever-increasing interest for planet searches in moderately close binaries. Despite such an interest, classical Doppler surveys still avoid most 2–6″ binaries. The main issue with these systems is that each stellar component cannot be observed individually. That is, Doppler data of systems closer than 2–6″ consist generally of a composite spectrum made of two (or possibly more) stellar spectra, not of a single stellar spectrum. Obviously, this introduces some complications into the extraction of the radial velocity, rendering classical one-dimensional cross-correlation techniques not well adapted to the search for circumstellar planets in moderately close binaries. The inclusion of spectroscopic binaries into Doppler planet searches thus necessitated the development of data reduction techniques specially designed to extract precise radial velocities from composite spectra.

A rather natural way to analyze composite spectra and to extract precise radial velocities for the individual components of double-lined spectroscopic binaries is to generalize the concept of one-dimensional cross-correlation to that of two-dimensional correlation. This approach was followed some time ago by S. Zucker and T. Mazeh, who developed a two-dimensional correlation algorithm named TODCOR (Zucker and Mazeh 1994). Because we are interested in including spectroscopic binaries in our radial-velocity planet searches, these authors modified their TODCOR algorithm to allow it to work with our ELODIE and CORALIE echelle spectra. This resulted in a new multi-order TODCOR algorithm (Zucker et al. 2003), which has already produced some very interesting results (Zucker et al. 2003, 2004; Eggenberger et al. 2007a, 2008b). We are now using this algorithm extensively to search for planets in spectroscopic and moderately close visual binaries.

We present in this section some results from our ongoing searches for planets in spectroscopic binaries. Our presentation will follow an increasing order of difficulty in terms of radial-velocity extraction. We start with the easiest systems that are single-lined spectroscopic binaries (SB1s) and end with more complicated double-lined spectroscopic ones (SB2s).

2.4.1 Planet Searches in Single-Lined Spectroscopic Binaries

In order to obtain the first quantification of the occurrence of planets in the closest binaries capable of hosting circumstellar planets, we initiated in 2001, a systematic Doppler search for short-period circumprimary planets in single-lined spectroscopic binaries (Eggenberger et al. 2003, 2008b). The prime motivation for this program was the observation that the few most massive short-period planets are all in binaries or multiple systems (Section 2.2.3). The restriction of our survey to SB1s was motivated by two considerations. First, the faintness of the secondary components in these systems gave us good hopes that we could use our standard cross-correlation technique to extract precise radial velocities for the primary components. Second, the prospect of finding giant planets is higher in SB1s than in SB2s with similar separations but more massive secondaries. Our survey for giant planets in SB1s was thus designed as a first exploratory investigation that may be complemented later, in the case of positive results, by an additional survey targeting SB2s.

2.4.1.1 Sample and Observations

Our sample of binaries was selected on the basis of former CORAVEL surveys carried out to study the multiplicity among G and K dwarfs of the solar neighborhood (Duquennoy et al. 1991b; Halbwachs et al. 2003). Basically, we retained all the 140 SB1 candidates with periods longer than $\sim$1.5 years (some of them with well-characterized orbits, others with long-period drifts). Note that CORAVEL velocities have a typical precision of 300 m s^{-1} and thus cannot be used to search for planets. To search for planets in our sample of 140 SB1s we took 10–15 additional high-precision radial-velocity measurements of each system, either with the ELODIE spectrograph (Observatoire de Haute-Provence, France; Baranne et al. 1996; Perrier et al. 2003) or with the CORALIE spectrograph (La Silla Observatory, Chile; Queloz et al. 2000; Udry et al. 2000). Given our initial aim to analyze these high-precision data with standard cross-correlation techniques, we rejected during the observations, the systems that turned out to be SB2s at the higher resolution of ELODIE and CORALIE, as well as the binaries that were resolved within the guiding field of the telescope. After this additional selection, we ended up with 101 SB1s that form the core of our survey.

2.4.1.2 First Analysis Based on One-Dimensional Cross-Correlation

As a first step in the analysis, the spectra obtained with ELODIE and CORALIE were reduced online, and the radial velocities were extracted using our standard cross-correlation pipeline. When searching for planets in binaries, what we are interested in are not the radial velocities themselves but instead the residual (radial) velocities around the binary orbits. The planet search was thus carried out by searching for short-period variations in these residual velocities.

Figure 2.5 shows the distribution of the residual-velocity variations for our 101 targets. These variations are quantified by a normalized root-mean-square (rms), which is the ratio of the external error (i.e., the standard deviation around the orbit or around the drift) to the mean internal error (i.e., the mean of individual photon-noise errors). As shown by Fig. 2.5, most of our targets (74%) have normalized rms close to 1, indicating that no source of radial-velocity variation other than the orbital

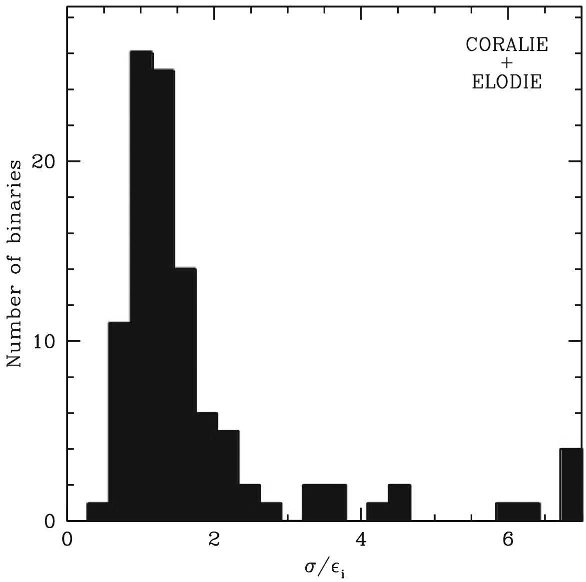

Fig. 2.5 Normalized residual-velocity rms for all our SB1s. σ is the standard deviation around a Keplerian orbit or around a drift, and ϵ_i is the mean measurement uncertainty. Systems with an rms larger than 7 are all gathered together in the last bin

motion is present (see Fig. 2.6 for an example). In contrast, 12.5% of our targets are clearly variable and exhibit normalized rms greater than 3 (see Fig. 2.6 for an example). The remaining systems (13.5%) are marginally variable, with normalized rms between 2 and 3.

In terms of planetary prospects, the most interesting systems are the variable and marginally variable binaries. Nonetheless, the presence of a planetary companion in orbit around the primary star is not the only way to produce residual-velocity variations like those observed. Alternative possibilities include: (i) the primary star is intrinsically variable, (ii) the system is an unrecognized SB2 (i.e., an SB1 when analyzed via one-dimensional cross-correlation, but an SB2 when analyzed via two-dimensional correlation), and (iii) the system is in fact triple and the secondary is itself a short-period spectroscopic binary. Assuming that planets are as common in close binaries as around single stars, we expect to find only one or two planets more massive than 0.5 $M_{\rm Jup}$ and with periods shorter than ∼40 days in our sample. This rough estimation shows that most of the observed residual-velocity variations are probably not related to the presence of planetary companions, but likely stemmed from the binary or multiple nature of our targets. Therefore, to identify the few potential planet-bearing stars among the several variable and marginally variable systems, we must find a way to precisely characterize the cause of the residual-velocity variations.

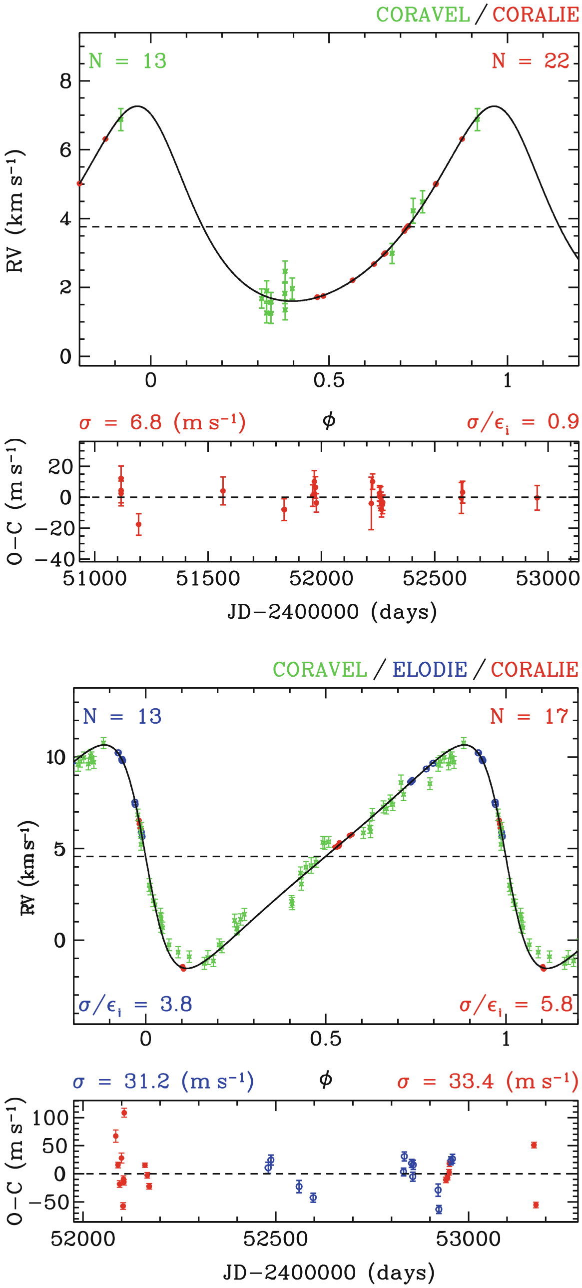

Fig. 2.6 *Top*: example of a binary exhibiting no residual-velocity variation. CORAVEL data are depicted as stars (*large error bars*) while CORALIE data are depicted as *dots*. The *bottom panel* shows the residual velocities (CORALIE data only). *Bottom*: example of a binary with variable residual velocities. This system was exceptionally observed with both ELODIE and CORALIE. Figures on the *top* refer to the ELODIE velocities (represented as *circles*), while figures on the *bottom* refer to the CORALIE velocities (represented as *dots*)

2.4.1.3 Identifying the Origin of Residual-Velocity Variations

Binaries with intrinsically variable primaries can be identified similar to single active stars by considering the chromospheric emission flux in the Ca II H and K lines. Using one-dimensional cross-correlation techniques, identifying triple systems and unrecognized SB2s is feasible in some instances (Santos et al. 2002; Eggenberger et al. 2003, 2008b), but two-dimensional correlation is a much more efficient tool for this purpose. We are thus presently analyzing all the variable and marginally variable systems with the two-dimensional algorithm TODCOR. This work is in progress and only four variable systems have been studied in some detail so far. Of these four systems, two turned out to be triple star systems (see Fig. 2.7 or Eggenberger et al. 2003, 2008b for an example), while the two others turned out to be unrecognized SB2s (see Fig. 2.8 for an example). None of these four systems shows hints of the presence of a circumprimary planet.

2.4.1.4 Preliminary General Results on Planet Searches in SB1s

The present results from our search for circumprimary short-period planets in SB1s show that in most of these systems (74%) the secondary component is so faint (magnitude difference $\Delta V \gtrsim 6$) that it does not contribute significantly to the recorded flux. Doppler data of such systems can be analyzed similar to the Doppler data of single stars and the precision achieved on the measurements of the radial velocities of their primary stars are as good as those of single stars.

In contrast, analyzing the Doppler data of the 26 SB1s that exhibit residual-velocity variations is not straightforward. In many of these systems the secondary component (and also possibly the tertiary component) significantly contributes to the recorded flux ($\Delta V \in [\sim 3, \sim 6]$), rendering the use of two-dimensional correlation mandatory to unambiguously identify the origin of the variations observed, and hence to search for circumprimary planets. Our current results do not enable us to precisely characterize our detection capabilities in terms of circumprimary planet searches, but we estimate that typical precisions on the radial velocity of the primary star range between 10 and 20 $\mathrm{m\,s^{-1}}$. Although these precisions are not as good as for single stars, they remain good enough to search for giant planets.

The preliminary results from our search for circumprimary giant planets in SB1s thus confirm that such a program has grounds for existence. So far, our survey has unveiled no promising planetary candidate, but the data of 22 variable and marginally variable systems remain to be analyzed in detail with two-dimensional correlation. Since contamination effects stemming from the stellar companions are likely to prevail over potential planetary signals, two-dimensional analyses must be completed before concluding on the existence or absence of planets in our sample. All we can say at present is that less than 22% of the SB1s from our sample have a short-period ($P \lesssim 40$ days) giant (minimum mass $\gtrsim$0.5 M_{Jup}) planetary companion. Definitive results from our program will enable us to obtain a much stronger constraint.

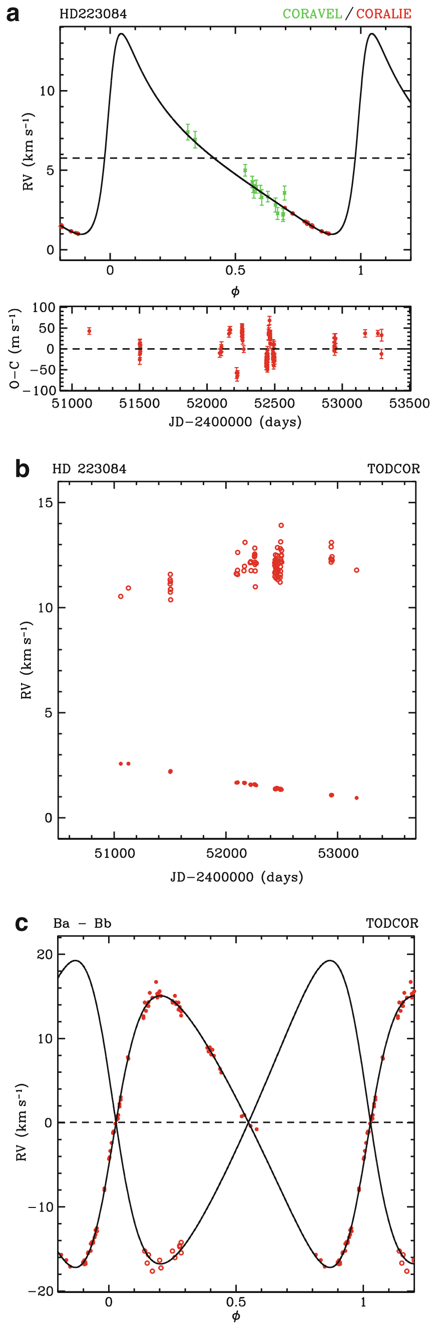

Fig. 2.7 An example of triple system: HD 223084. (**a**) CORAVEL (*crosses, large error bars*) and CORALIE (*dots*) velocities for HD 223084. The binary orbit is tentative and is used only as a proxy to compute residual velocities. The *bottom panel* of Fig. (**a**) shows the residual velocities (CORALIE data only). (**b**) TODCOR velocities for HD 223084 A (*dots*) and HD 223084 Ba (*open circles*) after having removed the 202-day modulation of the Ba–Bb inner pair. (**c**) SB2 orbit for HD 223084 Ba (*dots*) and HD 223084 Bb (*open circles*). This orbit is characterized by a period of 202 days and velocity semiamplitudes of 16.1 and 18 km s^{-1} for components Ba and Bb, respectively

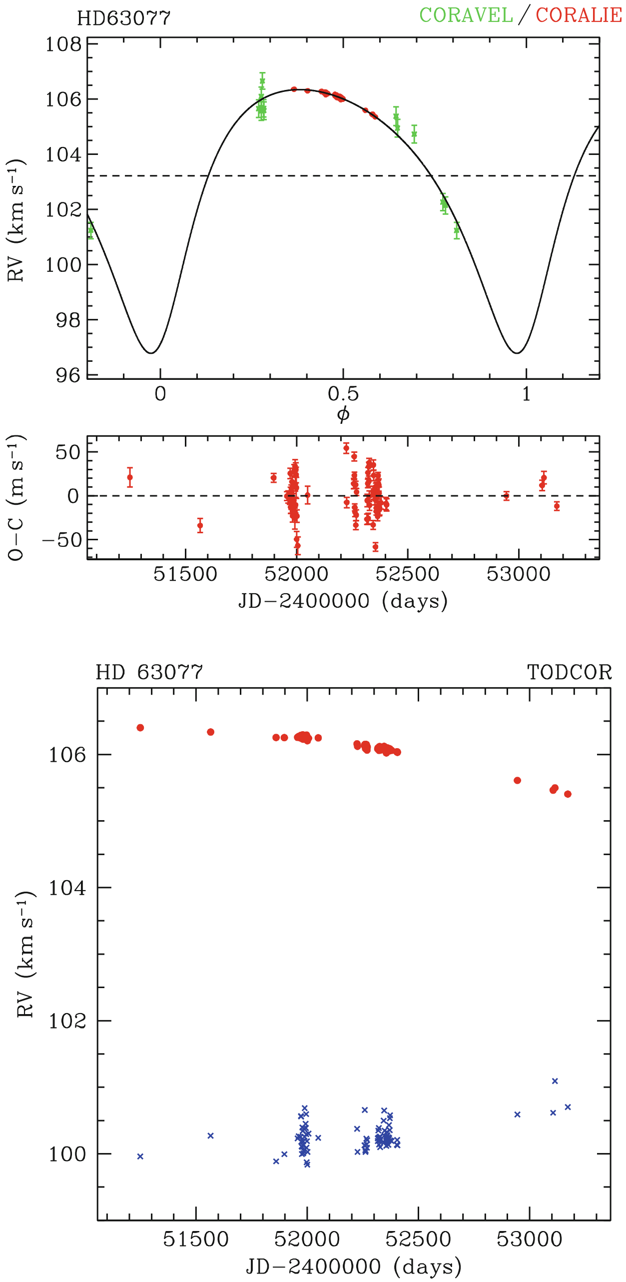

Fig. 2.8 An example of unrecognized SB2: HD 63077. *Top*: CORAVEL (*crosses, large error bars*) and CORALIE (*dots*) velocities for HD 63077. The binary orbit is tentative and is used only as a proxy to compute residual velocities. The *bottom panel* shows the residual velocities (CORALIE data only). *Bottom*: TODCOR velocities for HD 63077 A (dots) and HD 63077 B (*crosses*)

2.4.2 Planet Searches in Double-Lined Spectroscopic Binaries

Double-lined spectroscopic binaries have not been systematically included in any of our observing programs yet, but several of the visual binaries closer than $\sim 6''$ and with magnitude differences of $\Delta V \lesssim 4$ are in fact unrecognized SB2s (i.e., SB1s when analyzed via one-dimensional cross-correlation, but SB2s when analyzed via two-dimensional correlation). To properly analyze the data of these systems and to characterize the feasibility of Doppler searches for circumstellar planets in SB2s, we are presently conducting a series of observational tests and simulations on SB2 systems with various characteristics. To illustrate both the interest in including SB2s in planet searches and the challenges faced by Doppler planet searches in such systems, we present here the results we have obtained for our best-studied case, the triple system HD 188753 (Eggenberger et al. 2007a).

2.4.2.1 The Example of HD 188753

HD 188753 has attracted much attention since July 2005 when Konacki (2005) reported the discovery of a 1.14-M_{Jup} planet on a 3.35-day orbit around the primary component of this triple star system. Aside from the planet, HD 188753 consists of a primary star (HD 188753 A) orbited by a visual companion, HD 188753 B, which itself is a spectroscopic binary with two components HD 188753 Ba and HD 188753 Bb. The visual orbit of the AB pair is characterized by a period of 25.7 years, a semimajor axis of 12.3 AU ($0.27''$ separation) and an eccentricity of 0.5 (Söderhjelm 1999). The spectroscopic orbit of HD 188753 B has a period of 155 days (Griffin 1977; Konacki 2005). What renders this discovery particularly important and interesting is that the periastron distance of the AB pair may be small enough to preclude giant planet formation around HD 188753 A through the canonical planet-formation models (Nelson 2000; Mayer et al. 2005; Boss 2006; Jang-Condell 2007). The discovery of a close-in giant planet around this star has thus been perceived as a serious challenge to planet-formation theories, though the alternative possibility that HD 188753 A might have acquired its planet through dynamical interactions was also pointed out (Pfahl 2005; Portegies Zwart and McMillan 2005).

When observed with ELODIE, HD 188753 reveals itself as an SB2, the spectrum of the faintest component (Bb) being undetectable in most of our observations. Our TODCOR radial velocities for HD 188753 A and HD 188753 Ba are displayed in Fig. 2.9. These velocities confirm that HD 188753 Ba is a spectroscopic binary with a period of 155 days. However, our velocities for HD 188753 A show a steady decrease consistent with the 25.7-year orbital motion of the AB pair, but no sign of the 3.35-day planetary signal as reported by Konacki (2005). Instead, our results indicate that the residuals around the long-period drift are basically noise and the rms of 60 m s^{-1} can be interpreted as the precision we achieve on the measurement of the radial velocity of this star. Monte Carlo simulations run to check our ability to detect the potential planet around HD 188753 A showed that we had both the precision and

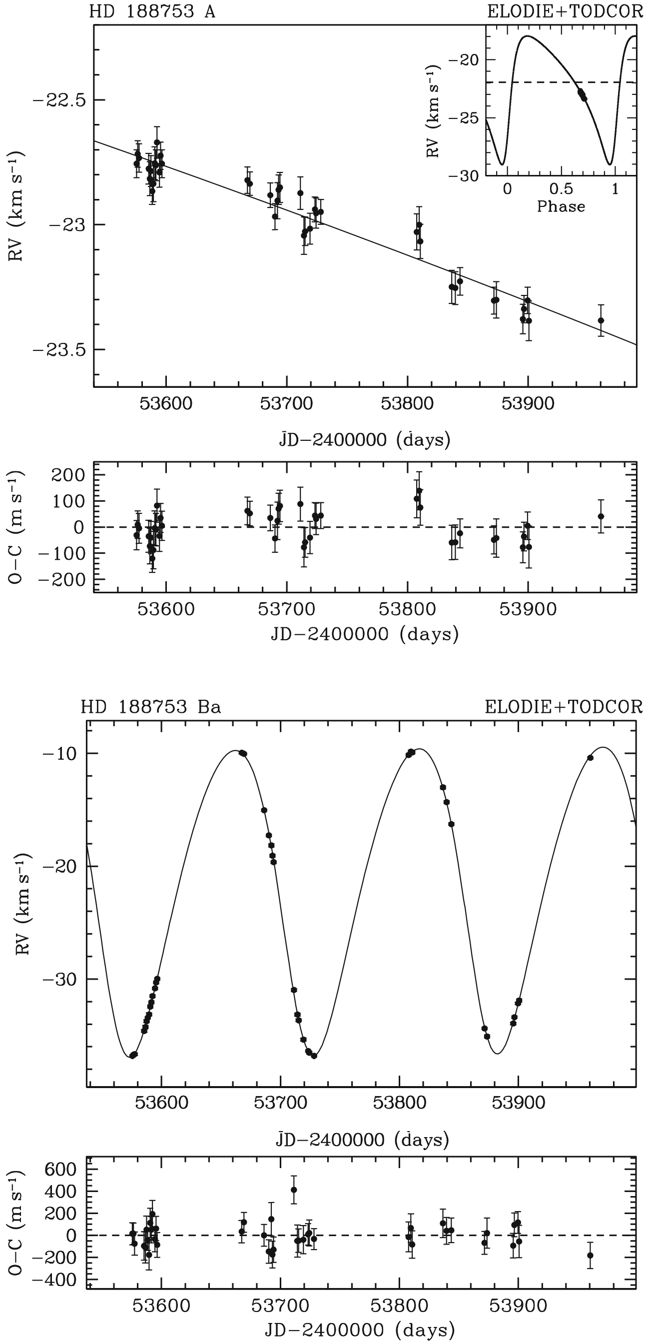

Fig. 2.9 Radial velocities and orbital solutions for HD 188753 A (*top*) and HD 188753 Ba (*bottom*). For component A, the *solid line* represents the 25.7-year orbital motion of the visual pair shown in full in the inset. For component Ba, the orbital solution corresponds to the 155-day modulation and it includes a linear drift to take the 25.7-year orbital motion into account

the temporal sampling required to detect a planetary signal like the one reported by Konacki (2005). On that basis, we conclude that our data show no evidence of a 1.14 M_{Jup} on a 3.35-day orbit around HD 188753 A.

In addition to the question of whether there is or is not a hot Jupiter around HD 188753 A, our analysis of HD 188753 raises several more questions. In particular, the precision of 60 m s^{-1} obtained on the radial velocity of HD 188753 A looks abnormally poor compared to the results presented in Section 2.4.1. The triple nature of HD 188753 may partly explain this result, but it is probably not the primary reason. Rather, the search for circumprimary planets in SB2s seems to require higher quality data (mainly a better spectral resolution) than the search for circumprimary planets in SB1s. Investigations are currently underway to specify this point.

2.4.2.2 Concluding Remarks on Planet Searches in SB2s

Based on our current experience, Doppler searches for circumprimary planets look more challenging in SB2s than in SB1s, even when using two-dimensional correlation. Clearly, considerable work remains to be done to precisely characterize our detection capabilities in spectroscopic binaries with various characteristics and to identify the main factor that limits our precision for each type of system. Nonetheless, including SB2s in planet searches is desirable since these systems are the most susceptible of providing us with interesting constraints on planet-formation mechanisms. Furthermore, SB2s are the potential targets for circumbinary planet searches, which offer a still unexplored research field worth of interest.

2.5 Conclusion and Perspectives

Over the past 5 years, binaries have become increasingly interesting targets of planet searches. On one hand, Doppler surveys have shown that giant planets exist even in spectroscopic binaries (Queloz et al. 2000; Hatzes et al. 2003; Zucker et al. 2004), raising the possibility that planets may be quite common in binary and multiple star systems. On the other hand, theoretical studies have shown that the presence of a stellar companion within ∼100 AU likely affects the formation and subsequent evolution of circumstellar giant planets (Kley 2000; Nelson 2000; Mayer et al. 2005; Boss 2006; Thébault et al. 2006), leaving potential imprints in the occurrence, characteristics, and properties of the planets residing in these systems. The study of circumstellar planets found in binaries closer than ∼100 AU might thus provide a unique means to probe the formation and evolution processes at work in planetary systems.

Imaging surveys searching for stellar companions to the known planet-bearing stars have been very successful, revealing several new binary planet-hosting systems and yielding a precise characterization of the multiplicity status of more than 70 planet-hosting stars (Luhman and Jayawardhana 2002; Patience et al. 2002;

Mugrauer et al. 2005, 2006; Chauvin et al. 2006; Raghavan et al. 2006; Eggenberger et al. 2007b). Additionally, our NACO survey has provided us with the multiplicity among a control sample of about 70 nearby stars showing no evidence for giant planetary companions, and affected by the same selection effects than planet-hosting stars. A preliminary statistical analysis based on our NACO data brings the first observational evidence that the occurrence of giant planets is reduced in binaries closer than ~100 AU (Eggenberger et al. 2008). Given our present knowledge of planet-formation mechanisms, two possible explanations can be put forward to explain this result: either disk instability is a viable formation mechanism that accounts for the existence of a significant number of the planets known presently, or core accretion is the only formation channel but its efficiency is reduced in binaries closer than ~100 AU. Differentiating between these two possibilities will require additional work, both on the theoretical and on the observational sides. Yet, the important point to notice is that observations have caught up with theoretical studies on the investigation of the impact of stellar duplicity on giant planet formation, meaning that some theoretical predictions can now be confronted with observational results.

The recent discoveries from imaging surveys have somewhat decreased the statistical significance of the emerging trends suggesting that short-period planets found in binary and multiple star systems possess distinctive characteristics and properties compared to their counterparts orbiting single stars (Zucker and Mazeh 2002; Eggenberger et al. 2004; Mugrauer et al. 2005; Desidera and Barbieri 2007). The most robust feature in this respect is still the observation that the few most massive short-period planets all orbit the components of binaries or triple stars. Nonetheless, such planets are still sparse and even the most recent statistical studies remain affected by the selection effects against moderately close binaries and by the uncertain multiplicity status of many planet-hosting stars. The combined results from our NACO and PUEO surveys will remove these two last uncertainties to a large extent, allowing for a major reinvestigation of possible differences in the eccentricity distributions of planets found in binaries and around single stars.

Over the past few years, significant effort has been put into extending radial-velocity planet searches to spectroscopic and moderately close visual binaries (Zucker et al. 2003, 2004; Konacki 2005a, 2005b; Eggenberger et al. 2007a, 2008b). In a general way, planet searches in moderately close binaries are still in their early phases and only partial results are available. Current results demonstrate that Doppler searches for giant planets are technically feasible in single-lined and in some types of double-lined spectroscopic binaries. However, the feasibility of planet searches in double-lined spectroscopic binaries with small magnitude differences remains to be characterized and confirmed.

Final results from the presently ongoing planet searches in spectroscopic binaries are awaited with great interest for several reasons. First, Doppler planets searches are the best tool to expand the size of the still limited sample of planets residing in binary and multiple star systems. Second, these surveys constitute the only current possibility to directly probe the occurrence of giant planets in binaries closer than ~200 AU and to characterize the closest systems potentially capable of hosting circumstellar giant planets. In particular, Doppler searches for planets in spectroscopic binaries will provide us with stronger constraints on the reality of the 20-AU "limit" and on its possible interpretation as a minimum separation for considering that a binary possibly harbors a giant planet. Finally, by probing the occurrence of giant planets in binaries closer than $\sim$35 AU, planet searches in spectroscopic binaries will nicely complement the results from our NACO and PUEO surveys. Gathering together the observational results from our imaging and spectroscopic programs, we might then obtain some constraints as to whether most giant planets found in binaries closer than $\sim$100 AU actually formed in these systems or were deposited at their present location through dynamical interactions.

As planet searches progress, the conviction that planets are common objects in the universe continually strengthen. The discovery of planets in environments previously considered as relatively hostile to their existence (spectroscopic binaries, pulsars, ...) has contributed to this development, showing that planet formation is not as easily inhibited as originally thought. In addition to the encouraging results obtained thus far for giant planets, the expectation that terrestrial planets form alongside their Jovian counterparts suggests that discoveries are limited by instrumental sensitivity rather than the availability of planets. Even if the presence of a nearby stellar companion lowers the efficiency of planet formation, theoretical studies support the existence of circumstellar terrestrial planets in many types of binaries (Barbieri et al. 2002; Haghighipour and Raymond 2007; Quintana et al. 2007). Circumbinary planets are also expected to exist around various types of binary systems (Quintana and Lissauer 2006; Pierens and Nelson 2007) and searches for circumbinary planets offer a still unexplored field of investigation for planet hunters. In view of the potential information they can yield on the overall frequency of planets and on the processes underlying planet formation, planet searches in and around binaries are thus not only meaningful but also desirable.

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