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The CORALIE survey for southern extrasolar planets

XIV. HD 142022 b: a long-period planetary companion in a wide binary[⋆]

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ABSTRACT

We report precise Doppler measurements of HD 142022 obtained during the past six years with the CORALIE echelle spectrograph at La Silla Observatory together with a few additional observations made recently with the HARPS echelle spectrograph. Our radial velocities reveal evidence of a planetary companion with an orbital period $P = 1928^{+53}_{-39}$ days, an eccentricity $e = 0.53^{+0.23}_{-0.18}$, and a velocity semiamplitude $K = 92^{+102}_{-29}$ m s^{-1}. The inferred companion minimum mass is $M_2 \sin i = 5.1^{+2.6}_{-1.5}\ M_{\rm Jup}$ and the semimajor axis $a = 3.03 \pm 0.05$ AU. Only one full orbital revolution has been monitored yet, and the periastron passage could not be observed since the star was too low on the horizon. The eccentricity and velocity semiamplitude remain therefore quite uncertain and the orbital solution is preliminary. HD 142022 is a chromospherically inactive K0 dwarf, metal rich relative to the Sun, and is the primary component of a wide binary. HD 142022 b is thus a new "planet in binary" candidate, and its high eccentricity might be due to secular interactions with the distant stellar companion.

Key words. techniques: radial velocities – stars: individual: HD 142022 – stars: binaries: visual – stars: planetary systems

1. Introduction

The CORALIE survey for southern extrasolar planets has been going on since June 1998. This high-precision radial-velocity programme makes use of the CORALIE fiber-fed echelle spectrograph mounted on the 1.2-m Euler Swiss telescope at La Silla Observatory (ESO, Chile). The sample of stars monitored for the extrasolar planet search is made of 1650 nearby G and K dwarfs selected according to distance in order to have a well-defined volume-limited set of stars (Udry et al. 2000). The CORALIE sample can thus be used to address various aspects of the statistics of extrasolar planets.

Stellar spectra taken with CORALIE are reduced online. Radial velocities are computed by cross-correlating the measured stellar spectra with a numerical mask, whose nonzero zones correspond to the theoretical positions and widths of stellar absorption lines at zero velocity. The resulting cross-correlation function (CCF) therefore represents a flux weighted "mean" profile of the stellar absorption lines transmitted by the mask. The radial velocity of the star corresponds to the minimum of the CCF, which is determined by fitting the CCF with a Gaussian function. The initial long-term velocity precision of CORALIE was about 7 m s^{-1} (Queloz et al. 2000), but since 2001 the instrumental accuracy combined with the simultaneous ThAr-reference technique is better than 3 m s^{-1} (Pepe et al. 2002a). This implies that for many targets the precision is now limited by photon noise or stellar jitter.

After seven years of activity, the CORALIE survey has proven to be very successful with the detection of a significant fraction of the known extrasolar planetary candidates (see the previous papers in this series). As the survey duration increases, new planetary candidates with orbital periods of several years can be unveiled and their orbit characterized. This is the case of the companion orbiting HD 142022: with a period longer than 5 years it has just completed one orbital revolution since our first observation in 1999. This growing period-interval coverage is very important with regard to formation and migration models since observational constraints are still very weak for periods of a few years.

HARPS is ESO's High-Accuracy Radial-Velocity Planet Searcher (Pepe et al. 2002b, 2004; Mayor et al. 2003), a fiber-fed high-resolution echelle spectrograph mounted on the 3.6-m telescope at La Silla Observatory (Chile). The efficiency and extraordinary instrumental stability of HARPS combined with a powerful data reduction pipeline provides us with very high precision radial-velocity measurements,

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[⋆] Based on observations collected at the ESO La Silla Observatory with the CORALIE echelle spectrograph mounted on the Swiss telescope, and with the HARPS echelle spectrograph mounted on the ESO 3.6-m telescope (programme ID 072.C-0488).

Table 1. Observed and inferred stellar parameters for HD 142022 (see text for references).

Parameter	Unit	Value
Spectral type		K0
V	(mag)	7.70
$B-V$	(mag)	0.790
π	(mas)	27.88 ± 0.68
M_V	(mag)	4.93
$T_{\rm eff}$	(K)	5499 ± 27
$\log g$	(cgs)	4.36 ± 0.04
[Fe/H]	(dex)	0.19 ± 0.04
L	$(L_\odot)$	1.01
$M_\star$	$(M_\odot)$	0.99
$v \sin i$	(km s^{-1})	1.20
$\log(R'_{\rm HK})$		−4.97

allowing the detection of companions of a few Earth masses around solar-type stars (Santos et al. 2004). Benefiting from this unprecedented precision, a part of the HARPS Consortium Guaranteed-Time-Observations programme is devoted to the study of extrasolar planets in a continuation of the CORALIE survey, to allow a better characterization of long-period planets and multiple planetary systems. HD 142022 is part of this programme, and the few HARPS measurements obtained so far already contribute to improve the orbital solution based on CORALIE data.

The stellar properties of HD 142022 are summarized in Sect. 2. Section 3 presents our radial-velocity data for HD 142022 and the inferred orbital solution of its newly detected companion. These results are discussed in Sect. 4, showing that the planetary interpretation is the best explanation for the observed velocity variation. Our conclusions are drawn in Sect. 5.

2. Stellar characteristics of HD 142022

HD 142022 (HIP 79242, Gl 606.1 A) is a bright K0 dwarf in the Octans constellation. The astrometric parallax from the Hipparcos catalogue, $\pi = 27.88 \pm 0.68$ mas (ESA 1997), sets the star at a distance of 36 pc from the Sun. With an apparent magnitude $V = 7.70$ (ESA 1997) this implies an absolute magnitude of $M_{\rm V} = 4.93$. According to the Hipparcos catalogue the color index for HD 142022 is $B-V = 0.790$. Using a bolometric correction $BC = -0.192$ (Flower 1996) and the solar absolute magnitude $M_\odot^{\rm bol} = 4.746$ (Lejeune et al. 1998) we thus obtain a luminosity $L = 1.01\ L_\odot$. The stellar parameters for HD 142022 are summarized in Table 1.

A detailed spectroscopic analysis of HD 142022 was performed using our HARPS spectra in order to obtain accurate atmospheric parameters (see Santos et al. 2005, for further details). This gave the following values: an effective temperature $T_{\rm eff} = 5499 \pm 27$ K, a surface gravity $\log g = 4.36 \pm 0.04$, and a metallicity [Fe/H] = 0.19 ± 0.04. Using these parameters and the Geneva stellar evolution code (Meynet & Maeder 2000) we deduce a mass $M_\star = 0.99\ M_\odot$. According to evolutionary models, HD 142022 is an old main-sequence star, in agreement with the K0V spectral type quoted in the Hipparcos catalogue.

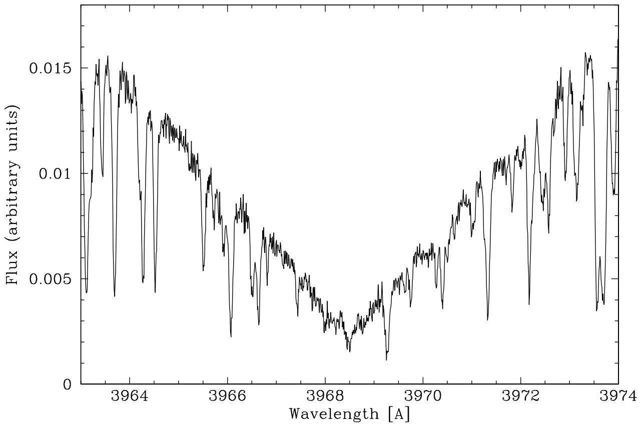

Fig. 1. Ca II H (λ = 3968.47 Å) absorption line region of the summed HARPS spectra for HD 142022.

The cross-correlation function can be used to derive stellar quantities affecting line profiles such as the projected rotational velocity. From the CORALIE spectra we derive $v \sin i = 1.20$ km s^{-1} (Santos et al. 2002). Combining this result to the stellar radius given by the best evolutionary model ($R = 1.15\ R_\odot$) we obtain an upper limit of 48 days for the rotational period.

From the HARPS spectra we can compute the $\log(R'_{\rm HK})$ activity index measuring the chromospheric emission flux in the Ca II H and K lines. This index is a useful estimator of the radial-velocity jitter that can be expected from intrinsic stellar variability. Figure 1 shows the Ca II H absorption line region for HD 142022. No emission peak is visible at the center of the absorption line, indicating a rather low chromospheric activity. This is corroborated by the $\log(R'_{\rm HK})$ value of −4.97, typical of inactive stars.

HD 142022 is part of a wide binary. Its companion, LTT 6384 (Gl 606.1B), is a late-K star about 22 arcsec away and with an apparent magnitude $V = 11.2$. The two stars are listed in the NLTT and LDS catalogs (Luyten 1940, 1979) indicating very similar proper motions. They were also observed by the Hipparcos satellite, but the proper motion of LTT 6384 could not be determined. The apparent separation of the pair, nevertheless, remained close to 22 arcsec from 1920 to 2000 which, given the proper motion of HD 142022 ($\mu_\alpha \cos\delta = -337.59 \pm 0.60$ mas yr^{-1}, $\mu_\delta = -31.15 \pm 0.72$ mas yr^{-1}), is an indication that the pair is indeed a bound system. This conclusion is strengthened by the fact that the CORAVEL radial velocities of the two stars are identical within uncertainties (Nordström et al. 2004). Using the positions given by the Tycho-2 catalogue and its supplement-2 (ESA 1997), we obtain a projected binary separation of 820 AU. This translates into an estimated binary semimajor axis of 1033 AU, using the relation $a/r = 1.26$[1] (Fischer & Marcy 1992).

In the Hipparcos catalogue, HD 142022 is classified as an unsolved variable and is suspected of being a non-single star. Indeed, a Lomb-Scargle periodogram of the Hipparcos

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[1] Strictly speaking, the relation used here to translate the projected separation of a wide binary into a semimajor axis is valid only statistically. It can thus be highly inaccurate for an individual system.

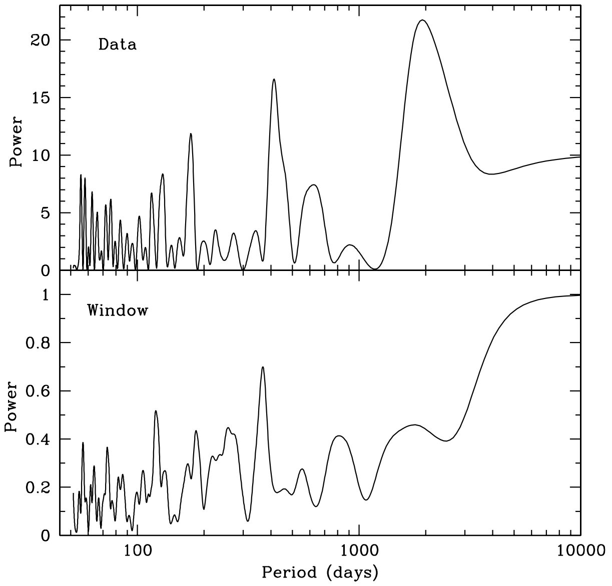

Fig. 2. Lomb-Scargle periodogram of the CORALIE radial velocities for HD 142022 (*top*) and the corresponding window function (*bottom*). The power is a measure of the statistical significance of the signal, not of its true amplitude.

photometry shows no clear signal standing out, but some extra power spread over many frequencies, especially at short period (few days). Performing a detailed study of the Hipparcos photometry for HD 142022 is beyond the scope of this paper, and is not fundamental since the periods involved are much shorter than that of the signal detected in radial velocity. We will nonetheless briefly come back to this issue in Sect. 4, because the potential non-single status of the star may be a concern.

3. Radial velocities and orbital solution

HD 142022 has been observed with CORALIE at La Silla Observatory since July 1999. Altogether, 70 radial-velocity measurements with a typical signal-to-noise ratio of 25 (per pixel at 550 nm) and a mean measurement uncertainty (including photon noise and calibration errors) of 9.7 m s^{-1} were gathered. HD 142022 is also part of the HARPS high-precision radial-velocity programme (Lovis et al. 2005) and, as such, was observed 6 times between November 2004 and May 2005. These observations have a typical signal-to-noise ratio of 90 and a mean measurement uncertainty of 1 m s^{-1}.

The root-mean-square (rms) of the CORALIE radial velocities is 26.3 m s^{-1}, indicating some type of variability. The Lomb-Scargle periodogram of these velocities is shown in Fig. 2. The highest peak corresponds to a period of 1926 days, which is clearly visible in the plot of our radial velocities as a function of time (Fig. 3). Using the expressions given in Scargle (1982), the false alarm probability for this signal is close to 10^{-8}. This low value was confirmed using Monte Carlo simulations, in which data sets of noise only were generated with velocities drawn at random from the residuals around the mean. None of the 10^7 simulated data set exhibited a maximum periodogram power exceeding the observed value, yielding a false alarm probability $<10^{-7}$. Figure 4 shows the CORALIE and HARPS radial velocities phased with a similar period and the corresponding best-fit Keplerian model. The resulting orbital parameters are P = 1928 days, e = 0.53, K = 92 m s^{-1}, implying a minimum mass $M_2 \sin i$ = 5.1 $M_{\rm Jup}$ orbiting with a semimajor axis a = 3.03 AU. The orbital elements for HD 142022 b are listed in Table 2. Since each data set has its own velocity zero point, the velocity offset between the two instruments (HARPS and CORALIE) is an additional free parameter in the fitting process. Note that the first two HARPS measurements are contemporary with the last CORALIE observations (Fig. 3), and the curvature seen in the HARPS data fits perfectly well the CORALIE velocities taken during the previous revolution (Fig. 4). The velocity offset is therefore well constrained though the number of HARPS measurements is small.

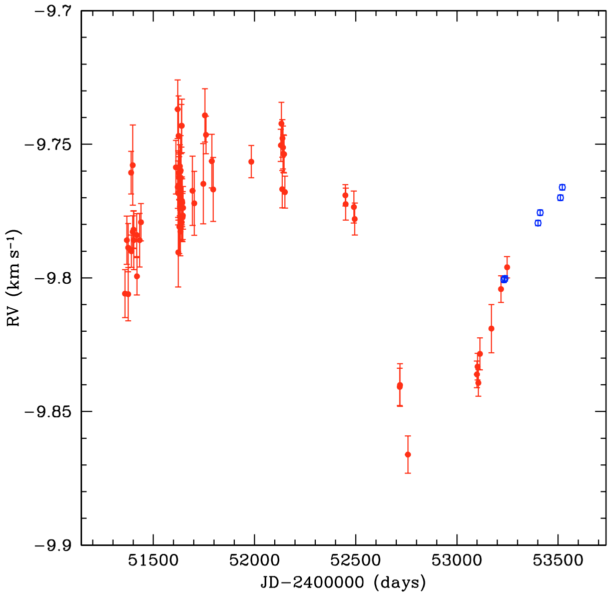

Fig. 3. CORALIE and HARPS radial velocities for HD 142022. CORALIE velocities are shown as dots, HARPS data are plotted as circles. As each instrument has its own zero point, a velocity offset of −8.8 m s^{-1} has been added to the HARPS data (see text for further details). Error bars for HARPS data (1 m s^{-1}) are the same size as the symbols.

As can be seen in Fig. 3, our data span only one orbital period and the phase coverage is very poor near periastron since the star was too low on the horizon to be observed at that time. This is why the orbital eccentricity and the velocity semiamplitude are poorly constrained. The orbital solution is thus preliminary and additional measurements taken during the next revolutions will be needed to obtain more accurate orbital parameters. It should be noted that for such an eccentric orbit the semiamplitude K is strongly correlated with the eccentricity. As our present analysis is more likely to have overestimated the eccentricity, the semiamplitude K might in fact be smaller, implying a smaller minimum mass for the companion. The companion minimum mass is thus very likely to be in the planetary regime, whatever the exact eccentricity.

The uncertainties in the orbital parameters were determined by applying the fitting technique repeatedly to many sets of simulated data. 1000 simulated data sets were thus constructed

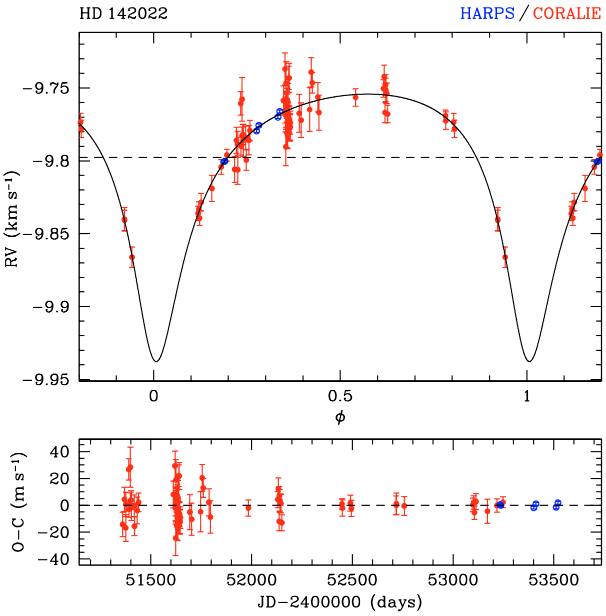

Fig. 4. Phased CORALIE and HARPS radial velocities for HD 142022 (*top*). CORALIE observations are shown as dots, HARPS data are plotted as circles. The solid line is the best-fit orbital solution. Residuals to the Keplerian fit are also displayed (*bottom*). Error bars for HARPS data are the same size as the symbols.

by adding a residual value (drawn at random from the residuals) to the best-fit velocity corresponding to each observing time. For each realization, the best-fit Keplerian orbit was determined. This has been done by using the period obtained from the Lomb-Scargle periodogram as an initial guess for the Keplerian fit. We then used a local minimization algorithm to find the best fit, trying several initial starting values for T, ω and K. The quoted uncertainties correspond to the 1σ confidence interval of the resulting set of values for each orbital parameter.

The rms to the Keplerian fit is 10.8 $\mathrm{m\,s^{-1}}$ for the CORALIE data and 1.4 $\mathrm{m\,s^{-1}}$ for the HARPS measurements, yielding a reduced χ^2 of 1.5. The Keplerian model thus adequately explains the radial-velocity variation, though for both instruments the rms is slightly larger than the mean measurement uncertainties. A periodogram of the velocity residuals after subtracting off the best-fit Keplerian shows no signal with significant power anymore. Furthermore, no changes in stellar line profiles (as quantified by the CCF bisector span, see Queloz et al. 2001) are seen in our data.

4. Discussion

So far, it has been implicitly assumed that the radial-velocity variation observed for HD 142022 stems from the presence of a planetary companion. But it is well known that other phenomena can induce a periodic variation of the radial velocity of a star. Activity related phenomena such as spots, plages or inhomogeneous convection are such candidates. They can however not be put forward to explain the signal observed for HD 142022 since the period is 1928 days, much too long to be related in any way to the rotational period of the star. Stellar pulsations may also cause radial-velocity variations, but no known mechanism could be invoked to sustain large-amplitude long-period oscillations in a K0 main-sequence star. Stellar pulsations can therefore be ruled out as well.

Table 2. Orbital parameters for HD 142022 b.

Parameter	Unit	Value
P	(days)	1928^{+53}_{-39}
T	(JD-2 400 000)	50941^{+60}_{-91}
e		$0.53^{+0.23}_{-0.18}$
γ	$(\mathrm{m\,s^{-1}})$	$-9.798^{+0.007}_{-0.010}$
ω	(deg)	170^{+8}_{-10}
K	$(\mathrm{m\,s^{-1}})$	92^{+102}_{-29}
$M_2 \sin i$	(M_{Jup})	$5.1^{+2.6}_{-1.5}$
a	(AU)	$3.03^{+0.05}_{-0.05}$
Velocity offset (HARPS)	$(\mathrm{m\,s^{-1}})$	$-8.8^{+2.5}_{-2.5}$
N_{meas} (CORALIE+HARPS)		70+6
rms (CORALIE)	$(\mathrm{m\,s^{-1}})$	10.8
rms (HARPS)	$(\mathrm{m\,s^{-1}})$	1.4

The presence of a second and varying faint stellar spectrum superimposed on the target spectrum can also induce spurious radial-velocity variations mimicking a planetary-type signature (see the seminal case of HD 41004, Santos et al. 2002; Zucker et al. 2003). In such a case, the target is the unrecognized component of a multiple stellar system. Given the fact that HD 142022 was suspected of being non-single on the basis of Hipparcos data, this is a possibility to take seriously into consideration. The evolution of the cross-correlation bisector span as a function of radial velocity can be a useful tool in disentangling planetary signatures from spurious radial-velocity signals (Queloz et al. 2001; Santos et al. 2002). For a signal of planetary origin the bisector span is constant whatever the value of the radial velocity, whereas for blended systems it is often correlated with the measured radial velocity (see for example Fig. 3 of Santos et al. 2002). No such correlation is visible for HD 142022. We have also searched for the presence of a second spectrum in our CORALIE spectra using multi-order TODCOR, a two-dimensional cross-correlation algorithm (Mazeh & Zucker 1994; Zucker et al. 2003), but did not find anything convincing. These negative results do not allow us to formally discard the blend scenario, but they render it an unlikely possibility. To sum up, the 1928-day signal observed in our radial velocities for HD 142022 is most likely to be caused by the gravitational perturbation of a planet orbiting the star.

The Keplerian fit to the radial velocities of HD 142022 implies that the stellar orbit has a semimajor axis $a_1 \sin i$ = 0.015 AU. Given the stellar parallax, this translates into an angular semimajor axis $\alpha_1 \sin i$ = 0.41 mas. If the true mass of HD 142022 b were much larger than its minimum mass of 5.1 M_{Jup}, the stellar wobble might be detected in the Hipparcos astrometry. This potential wobble may, however, be partially absorbed into the solution for proper motion and parallax since the orbital period is longer than the 2.7-year duration of the Hipparcos measurements. We searched for an astrometric wobble in the Hipparcos data for HD 142022, but did not find anything significant.

HD 142022 b is one of the planets with the longest orbital period found in a wide binary so far, but its separation of 3 AU is still very small compared to the estimated binary semimajor axis of 1033 AU. HD 142022 b thus orbits well inside the stability zone, whatever the exact orbital parameters of the binary (Holman & Wiegert 1999). The presence of a distant stellar companion may nonetheless cause significant secular perturbations to the planetary orbit. In particular, if the planetary orbital plane is inclined relative to the binary plane, the planet can undergo large-amplitude eccentricity oscillations due to the so-called Kozai mechanism (Kozai 1962; see also Holman et al. 1997; Innanen et al. 1997; Mazeh et al. 1997). The Kozai mechanism is effective at very long range, but its oscillations may be suppressed by other competing sources of orbital perturbations, such as general relativity effects or perturbations resulting from the presence of an additional companion in the system. Regarding HD 142022, we have estimated the ratio $P_{\mathrm{Kozai}}/P_{\mathrm{GR}}$ using Eqs. (3) and (4) of Holman et al. (1997) with the values $e_{\mathrm{b}} = 1/\sqrt{2}$ and $M_{\mathrm{s}} = 0.6\ M_{\odot}$ for the binary eccentricity and secondary component mass, respectively. This yields $P_{\mathrm{Kozai}} = 1.25 \times 10^8$ years and $P_{\mathrm{Kozai}}/P_{\mathrm{GR}} = 0.35$, indicating that Kozai oscillations could take place is this system, since their period is shorter than the apsidal period due to relativistic effects. Although not well constrained, the eccentricity of HD 142022 is clearly quite high, and such a high eccentricity is not surprising if the system undergoes Kozai oscillations.

5. Conclusion

We report a 1928-day radial-velocity variation of the K0 dwarf HD 142022 with a velocity semiamplitude of 92 $\mathrm{m\,s^{-1}}$. From the absence of correlation between stellar activity indicators and radial velocities, and from the lack of significant spectral line asymmetry variations, the presence of a planetary companion on a Keplerian orbit best explains our data. The Keplerian solution results in a $M_2 \sin i = 5.1\ M_{\mathrm{Jup}}$ companion orbiting HD 142022 with a semimajor axis $a = 3.03$ AU and an eccentricity $e = 0.53$. Although HD 142022 b orbits the primary component of a wide binary, its characteristics, including minimum mass and orbital eccentricity, are typical of the long-period planets found so far around G and K dwarfs.

One of the most surprising properties of extrasolar planets revealed by ongoing radial-velocity surveys is their high orbital eccentricities, which challenge our current theoretical paradigm for planet formation. Several mechanisms have thus been proposed to account for eccentric planetary orbits. One of them is the Kozai mechanism, a secular interaction between a planet and a wide binary companion in a hierarchical triple system with high relative inclination. Although the Kozai mechanism can be put forward to explain the high eccentricity of a few planetary companions: 16 Cyg Bb (Holman et al. 1997; Mazeh et al. 1997), HD 80606 b (Wu & Murray 2003) and possibly HD 142022 b, it seems impossible to explain the observed eccentricity distribution of extrasolar planets solely by invoking the presence of binary companions (Takeda & Rasio 2005). According to Takeda & Rasio (2005), Kozai-type perturbations could nonetheless play an important role in shaping the eccentricity distribution of extrasolar planets, especially at the high end. In this regard, ongoing programmes aiming at searching for new (faint) companions to stars with known planetary systems, or aiming at estimating the frequency of planets in binary systems should soon bring new observational material, and enable us to refine our present knowledge.

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