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XVI. Discovery of a planetary system around HD 147018 and of two long period and massive planets orbiting HD 171238 and HD 204313*

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ABSTRACT

We report the detection of a double planetary system around HD 140718 as well as the discovery of two long period and massive planets orbiting HD 171238 and HD 204313. Those discoveries were made with the CORALIE Echelle spectrograph mounted on the 1.2-m Euler Swiss telescope located at La Silla Observatory, Chile. The planetary system orbiting the nearby G9 dwarf HD 147018 is composed of an eccentric inner planet (e=0.47) with twice the mass of Jupiter (2.1 M_{Jup}) and with an orbital period of 44.24 days. The outer planet is even more massive (6.6 M_{Jup}) with a slightly eccentric orbit (e=0.13) and a period of 1008 days. The planet orbiting HD 171238 has a minimum mass of 2.6 M_{Jup}, a period of 1523 days and an eccentricity of 0.40. It orbits a G8 dwarfs at 2.5 AU. The last planet, HD 204313 b, is a 4.0 M_{Jup}-planet with a period of 5.3 years and has a low eccentricity (e = 0.13). It orbits a G5 dwarfs at 3.1 AU. The three parent stars are metal rich, which further strengthened the case that massive planets tend to form around metal rich stars.

Key words. stars: planetary systems – stars: binaries: visual – techniques: radial velocities – stars: individual: HD 147018– stars: individual: HD 171238– stars: individual: HD 204313

1. Introduction

The CORALIE radial velocity planet-search program has been ongoing for more than 10 years (start date:June 1998) at the 1.2-meter Swiss telescope located at La Silla Observatory, Chile. It is a volume limited planet search survey that contains all Hipparcos main sequence stars from F8 down to K0 within 50 pc and has a color-dependant distance limit for later type stars down to M0 (Udry et al. 2000). The fainter targets do not exceed V=10. Among the 1647 stars surveyed with CORALIE, 40 percent of them are measured with a radial velocity accuracy of 6 ms^{-1} or better and 90 percent of the sample is monitored with an accuracy better than 10 ms^{-1}. The remaining 10 percent of the sample have measured at a lower accuracy due to the lower signal to noise ratio and/or to the the widening of the cross-correlation function induced by large stellar rotation velocities. CORALIE went through a major hardware upgrade in June 2007 to increase the overall efficiency whith an net gain in magnitude of 1.5 which allow to survey the fainter part of the sample with an accuracy of 5-6 ms^{-1}.

So far, CORALIE has allowed the detection (or has contributed to the detection) of 54 extra-solar planet candidates. This substantial contribution together with discoveries from various other programmes have provided a sample - as of today - of close to 350 exoplanets that now permit to point out interesting statistical constraints for the planet formation and evolution scenarios (see e.g. Ida & Lin 2004; Marcy et al. 2005; Udry et al. 2007; Udry & Santos 2007; Mordasini et al. 2008, and references therein for reviews on different aspects of the orbital-element distributions or primary star properties).

Concerning the upper part of the planetary mass distribution, it should be noted that a wealth of massive planets have been and is beeing discovered. For instance, 142 of the 350 discovered planets are more massive than 1 M_{Jup} with periods larger than 50 days. Their eccentricity distribution is similar to the binaries and only 18 of them are in multiple giant planet systems. Most of their parent stars are metal rich pointing toward the existence of disk enriched in heavy elements. Interesting enough, the massive planet around the metal deficient star HD 33636 turns out to be a very low mass stars as shown by FGS/HST astrometric observations presented in (Bean et al. 2007). Although not statistically significant, this result show how important astrometric observations are to clarify the nature of those massive planets.

In this paper we report the discovery of a planetary system composed of two massive planets around HD 147018 and of two additional long period and massive planets in orbit around HD 171238, and HD 204313. Three of those planets come in addition to the 54 known planets with periods longer than 1000 days and masses larger than 1 M_{Jup}. The paper is orga-

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* Based on observations collected at the ESO La Silla Observatory with the CORALIE Echelle spectrograph mounted on the Swiss telescope.

nized as follows. In the second section, we discuss the host stars properties. The third section describes the instrumental upgrade of CORALIE, the resulting radial-velocity measurements and the orbital solutions. In section 4, we provide some concluding remarks.

2. Stellar characteristics

Effective temperatures, gravities and metallicities are derived using the spectroscopic analysis of Santos et al. (2000) while the $v.\sin(i)$ is computed using Santos et al. (2002)'s calibration of CORALIE's Cross-Correlation Function (CCF). We also used the improved Hipparcos astrometric parallaxes re-derived by van Leeuwen (2007) to determine the the V-band magnitude using the apparent visual magnitude from Hipparcos (ESA 1997). Metallicities, together with the effective temperatures and absolute V-band magnitudes are used to estimate basic stellar parameters (ages, masses, radii and log g) using theoretical isochrones from Girardi et al. (2000) and a Bayesian estimation method described in da Silva et al. (2006). The web interface for the Bayesian estimation of stellar parameters, called PARAM 1.0 can be found at http://stev.oapd.inaf.it/cgi-bin/param. Resulting Stellar parameters are listed in Table 1.

2.1. HD 147018 (HIP 80250)

HD 147018 is a G9 dwarf with an astrometric parallax of $\pi = 23.28 \pm 0.86$ mas and an apparent V band magnitude of V= 8.30. Our spectral analysis results in an effective temperature of $T_{\rm eff} = 5441 \pm 55$ K and a stellar metallicity of $[Fe/H] = 0.10 \pm 0.07$. Using theoretical isochrones, we finally derived a mass of $M_\star = 0.927 \pm 0.031\ M_\odot$ with an age of 6.36±4.33 Gyr.

2.2. HD 171238 (HIP 91085)

HD 171238 is a G8 dwarf with an astrometric parallax of $\pi = 19.89 \pm 1.15$ mas and an apparent V band magnitude of V= 8.61. Our spectral analysis results in an effective temperature of $T_{\rm eff} = 5467 \pm 55$ K and a stellar metallicity of $[Fe/H] = 0.17 \pm 0.07$. Using theoretical isochrones, we derive a mass of $M_\star = 0.943 \pm 0.033\ M_\odot$ with an age of 4.92±4.11 Gyr.
Eventhough Hipparcos photometry is relatively stable, with a scatter of 0.018 mag in the visible, it should be noted that the star is listed in the General Catalogue of Variable Stars (Samus et al. 2009) as a BY Draconis-type variable. Such variable stars present photometric variability - induced by spot coverage or by chromospheric activity - up to 0.5 magnitude in the visible on time scales ranging from a fraction of a day to 120 days that are likely to affect the velocities. We were not able to derive a value of the $\log\left(R'_{HK}\right)$ index since the star is too faint to conduct a proper spectral analysis with CORALIE, but we were able to averaged 35 CORALIE spectra taken with the Thorium lamp. As shown on Fig.1, a clear Ca II re-emission is seen at $\lambda = 3933.66$ Å revealing the presence of a significant chromospheric activity possibly induced by stellar spots or plagues.

2.3. HD 204313 (HIP 106006)

HD 204313 is a G5 dwarf with an astrometric parallax of $\pi = 21.11 \pm 0.62$ mas and an apparent V band magnitude of V= 7.99. The spectral analysis results in an effective temperature of $T_{\rm eff} = 5767 \pm 17$ K and a stellar metallicity of $[Fe/H] = 0.18 \pm 0.02$.

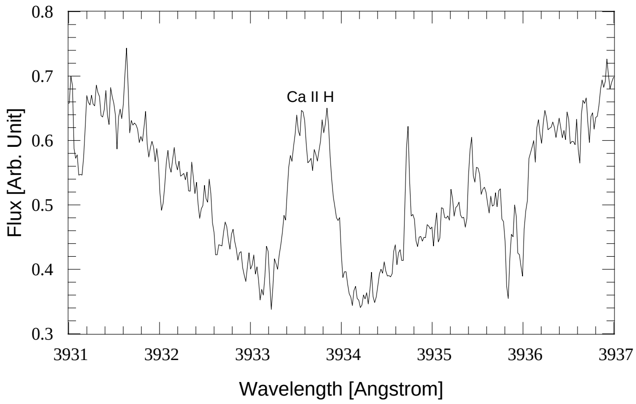

Fig. 1. Ca II H emission region for HD 171238. The large reemission at the bottom of the Ca II H absoption line at $\lambda = 3933.66$ Å is an indicator of chromospheric activity. This region is contaminated by a few thin thorium emission lines. Thorium pollution is too important to display the Ca II K region (around $\lambda = 3968.47$ Å).

Using theoretical isochrones, we derive a mass of $M_\star = 1.045 \pm 0.033\ M_\odot$ with an age of 3.38±2.58 Gyr.

Table 1. Observed and inferred stellar parameters of the planets host's stars presented in this paper. (1) : Parameter derived from Girardi et al. (2000) models. (2) : Parameter derived using CORALIE CCF.

Parameters		HD 147018	HD 171238	HD 204313
Sp. T.		G9V	K0V	G5V
V		8.3	8.66	7.99
$B-V$		0.763	0.74	0.697
π	[mas]	23.28±0.86	19.89±1.15	21.11±0.62
M_V		5.13	5.15	4.61
T_{eff}	[K]	5441±55	5467±55	5767±17
$\log g$	[cgs]	4.38±0.16	4.39±0.14	4.37±0.05
$[Fe/H]$	[dex]	0.10±0.05	0.17±0.07	0.18±0.02
$v\sin(i)^{(2)}$	[kms^{-1}]	1.56	1.48	1.59
$M_\star^{(1)}$	[$M_\odot$]	0.927±0.031	0.943±0.033	1.045±0.033
$\log g^{(1)}$	[cgs]	4.42±0.04	4.43±0.04	4.36±0.04
Age$^{(1)}$	[Gyr]	6.36±4.33	4.92±4.11	3.38±2.58

3. Radial velocities and orbital solutions

3.1. CORALIE upgrade

Triggered by the interest to carry out spectroscopic follow-up on transit candidates fainter than the stars surveyed in our main planet search programme (V<10), we decided to to improve the overall efficiency of the instrument by upgrading CORALIE in June 2007. The fibre link and the cross-disperser optics have been removed and replaced by a new design. The double scrambler has also been removed and the grism/prism cross-disperser component replaced by a series of 4 Schott F2 prisms of 32 deg angle each. The net outcome of this new design is to maintain the spectral range from 381 to 681 nm but with a large efficiency gain of about a factor of 6 (8 below 420 nm) and a spectroscopic resolution of 55 000-60 000 (increased by 10-20%). Those hardware modifications have, however, affected the instrumental zero point with radial velocity offsets that could reach up to ≈ 20 ms^{-1}, depending on the target spectral type. For this reason, we decides to refer to the orginal CORALIE as CORALIE-98 and to the upgraded one as CORALIE-07. The overall instrumental precision was not affected by the upgrate and stays at the 5 ms^{-1} level.

The direct consequence - on our main planet search survey - of the upgrade to CORALIE-07 is to to increase the efficiency of the instrument on bright targets (V<8.5) and to improve the radial velocity accuracy on the fainter part of our sample (28% of the sample, V=8.5-10). Those stars are now monitored with a long term radial velocity accuracy of 5-6 ms^{-1}.

3.2. Two massive planets in orbit around HD 147018

HD 147018 has been observed with CORALIE at La Silla Obervatory since May 2003. Six radial-velocity measurements with a typical signal-to-noise ratio of 25 (per pixel at 550 nm) were obtained with CORALIE-98 leading to a mean measurement uncertainty of 6.1 ms^{-1}, including photon noise and calibration errors. An additional 105 radial-velocity measurements were obtained with CORALIE-07 with a mean signal-to-noise ratio of 52 leading to a mean measurement uncertainty of 3.4 ms^{-1}. An external systematic error of 5 ms^{-1} was quadratically added to the radial velocity uncertainty before performing the period search and the model adjustment. It took more than 1400 days to realize the importance of this target. Indeed, the first 5 measurements only showed a quadratic drift that betrayed the presence of a long period companion. We had to wait the sixth measurement, taken in June 2007, to realize that we missed a planet due to an inadequate temporal sampling (compared to the period and the phase of the planet). In the following months, the presence of a second long period companion, with similar radial velocity amplitude was discovered. It took another one and half year to disentangle the two orbital solutions and to characterize the second planet orbital parameters.

The planetary system consists of two massive giant planets with respective semimajor axis a = 0.24 AU and a = 1.92 AU. The first planet is eccentric with e = 0.469 and a period of P = 44.24 days. It has a minimum mass $m_b.\sin(i) = 2.12$ M_{jup}. The second planet has a much longer period (P = 1008 days) and a minimum mass of $m_c.\sin(i) = 6.56$ M_{jup}. Its orbit is slightly eccentric (e = 0.13) which could betray the presence of interactions between the two massive planets.

Figure 2 shows the CORALIE radial velocities and the the adjusted 2 planet-keplerian model. The residuals to the model show a level of variation of σ = 7.4 ms^{-1}, yielding a reduced χ of 1.28. The orbital elements for HD 147018 b and HD 147018 c are listed in Table 2. Error bars were computed using 5000 Monte Carlo simulations and a confidence interval of 68.3%.

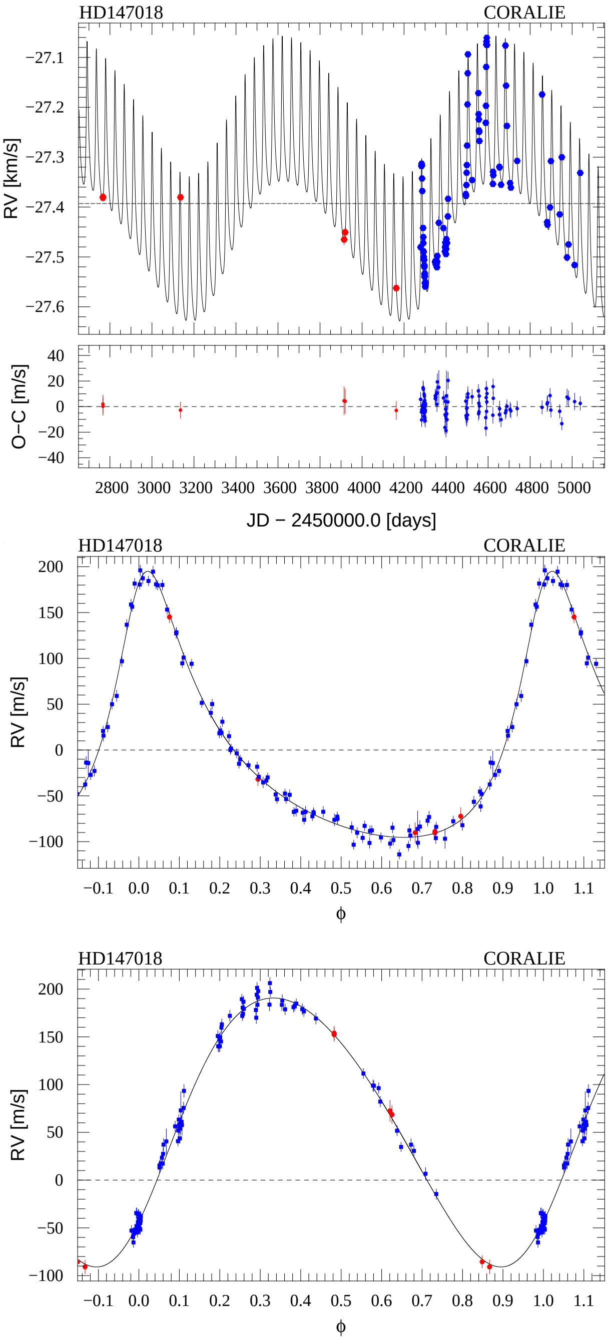

Fig. 2. Radial-velocity measurements of HD 147018 obtained with CORALIE-98 (red) and CORALIE-07 (blue). The top panel presents the observed radial velocities as a function of Julian Date with the best 2-planet-keplerian model (black curve). Residuals show a 7.4 ms^{-1} dispersion. The two bottom figures represent the phase folded radial velocities of HD 147018 b (middle) and of HD 147018 c (bottom).

3.3. A long period and massive planet around HD 171238

HD 171238 has been observed since October 2002. Thirty two radial-velocity measurements with a typical signal-to-noise ratio of 17 (per pixel at 550 nm) were obtained with CORALIE-98 leading to a mean measurement uncertainty of 6.8 ms^{-1}, including photon noise and calibration errors. An additional 65 radial-velocity measurements were obtained with CORALIE-07 with a mean signal-to-noise ratio of 47 leading to a mean measurement uncertainty of 3.6 ms^{-1}. An instrumental error of 5 ms^{-1} was quadratically added to the radial velocity uncertainty before performing the period search and the model adjustment. A clear signature is identified in the periodogram at P = 1523 days (see Fig. 4) which corresponds to a massive planet ($m_b.\sin(i)$ = 2.60 M_{jup}) with a semi-major axis of a = 2.54 AU and with an eccentric orbit (e = 0.40). Figure 3 shows the CORALIE radial velocities and the corresponding best-fit Keplerian model. The orbital elements for HD 171238 b are listed in Table 3.

Table 2. Two planet Keplerian orbital solution for HD 147018 as well as inferred planetary parameters. Confidence intervals are computed for a 68.3% confidence level after 5000 Monte Carlo iterations. ΔT is the time interval between the first and last measurements, χ_r is the reduced χ, G.o.F. is the Goodness of Fit and $\sigma(O-C)$ is the weighted r.m.s. of the residuals around the derived solution. The Julian Date is expressed as JD*=JD-2450 000. C98 stands for CORALIE-98 and C07 for CORALIE-07.

Planet		HD 147018 b	HD 147018 c
γ_{C98}	[kms^{-1}]	-27.343 ± 0.011	
γ_{C07}	[kms^{-1}]	-27.348 ± 0.005	
P	[days]	44.236 ± 0.008	1008±18
K	[ms^{-1}]	145.33 ± 1.66	141.2±4.1
e		0.4686 ± 0.0081	0.133±0.011
ω	[deg]	-24.03± 1.23	-133.1±6.9
T_0	[JD*]	4459.49 ± 0.10	55301±22
$a_1 \sin i$	[10^{-3} AU]	0.5220±0.0057	13.0±0.6
$f_1(m)$	[10^{-9} $M_\odot$]	9.70±0.33	287±30
$m_p \sin i$	[M_{Jup}]	2.12±0.07	6.56±0.32
a	[AU]	0.2388±0.0039	1.922±0.039
N_{mes}		101	
ΔT	[years]	6.22	
χ_r		1.28±0.07	
G.o.F		3.64	
$\sigma_{(O-C)}$	[ms^{-1}]	7.39	

The residuals to the adjusted single planet keplerian model are however quite large for CORALIE (σ = 10 ms^{-1}), yielding a reduced χ of 1.60. In order to explain such a large dispersion, we have conducted a frequency analysis of the residuals. As can be seen on Fig. 4, a significant amount of energy is present around 60 and 160 days. However, no "realistic" keplerian could be adjusted with such periods, discarding the presence of additional jovian planets. Furthermore, as explained in section 2, HD 171238 is a DY Drac variable star that could vary on time scales of 1 to 120 days. The most likely explanation for the large radial velocity dispersion is the presence of stellar spots on the surface of the star which is confirmed by a relatively strong CaII-H re-emission that can be seen in the spectra as illustrated in Fig.1

3.4. A long period and massive planet around HD 204313

HD 204313 has been observed since September 2000. Seventy one radial-velocity measurements with a typical signal-to-noise ratio of 28 (per pixel at 550 nm) were obtained with CORALIE-98 leading to a mean measurement uncertainty of 5.2 ms^{-1}, including photon noise and calibration errors. An additional 26 radial-velocity measurements were obtained with CORALIE-07 with a mean signal-to-noise ratio of 74 leading to a mean measurement uncertainty of 3.2 ms^{-1}. An instrumental error of 5 ms^{-1} was quadratically added to the radial velocity uncertainty before performing the period search and the model adjustment. Radial velocity measurements betray the presence of a long period (P = 1931 days) and massive planet ($m_b.\sin(i)$ = 4.05 M_{jup}) orbiting its parent star at a = 3.08 AU. The orbital elements for HD 204313 b are listed in Table 3. Figure 3 shows the CORALIE radial velocities and the corresponding best-fit Keplerian model. The residuals to the single planet keplerian model show a level of variation (σ = 8.1 ms^{-1}), yielding a reduced χ of 1.24.

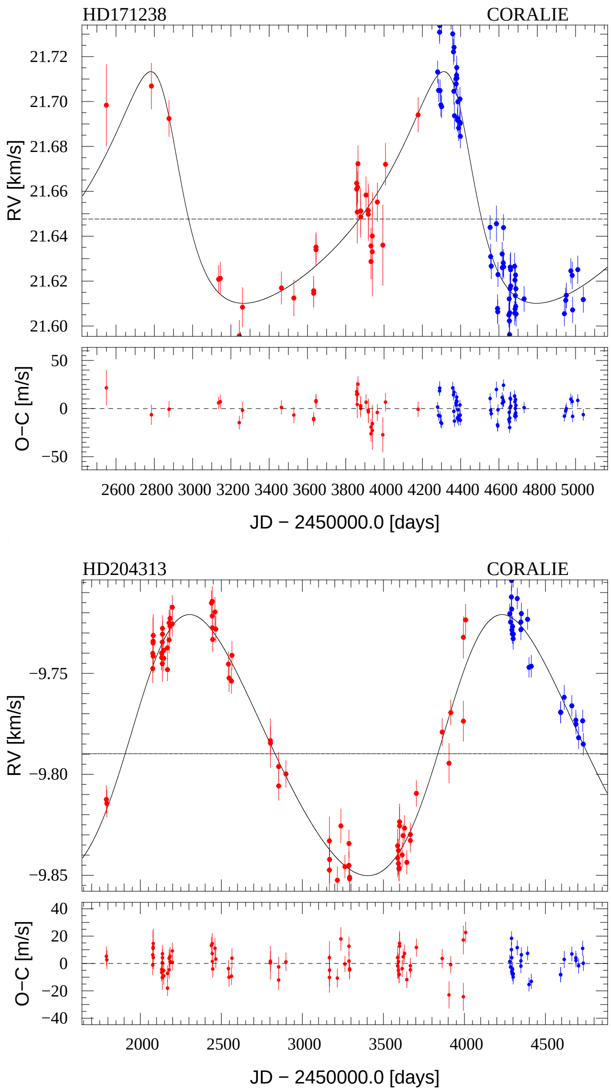

Fig. 3. The two diagrams represent the observed radial velocities as a function of Julian Date obtained with CORALIE-98 (red) and CORALIE-07 (blue) for HD 171238 and HD 204313. The best single-planet keplerian model is represented as a black curve and residuals show a dispersion of 10 ms^{-1} for HD 171238 and of 8 ms^{-1} for HD 204313.

4. Concluding discussion

We have reported in this paper the detection of four extrasolar planet candidates discovered with the CORALIE echelle spectrograph mounted on the 1.2-m Euler Swiss telescope at La Silla Observatory.

– HD 147018 b and HD 147018 c are two massive planets part of the same system with respective masses $m_b \sin i$ = 2.12 M_{Jup} and $m_c \sin i$=6.56 M_{Jup}. The inner planet has a 44.24 day-period and a large eccentricity (e = 0.46) while the outer planet has a 1008 day-period with a low eccentricity.

– HD 171238 b is a long period and massive planet with an eccentric orbit (P=4.14 years, $m \sin i$ = 2.60 M_{Jup}, e = 0.40).

– HD 204313 b is a long period and massive planet with a low eccentricity (P=5.28 years, $m \sin i$ = 4.0 M_{Jup}, e = 0.13).

It is worth to note that the three parent stars are metal rich, which strengthened the case that massive planets tend to form

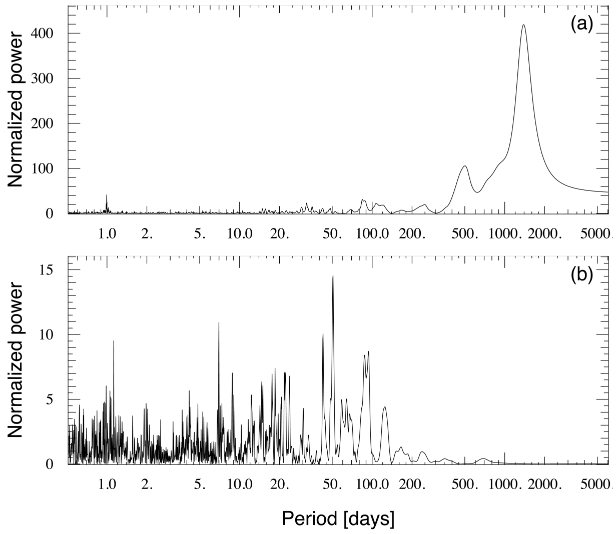

Fig. 4. Periodogram of HD 171238 velocities (a) and of the residuals after substraction of the single planet model (b). A significant amount of energy is detected in the residual's close to a period of 50 days which is probably activity induced.

Table 3. Single planet Keplerian orbital solutions for HD 171238 and for HD 204313 as well as inferred planetary parameters. Confidence intervals are computed for a 68.3% confidence level after 5000 montecarlo iterations. ΔT is the time interval between the first and last measurements, χ_r is the reduced χ, G.o.F. is the Goodness of Fit and $\sigma(O-C)$ is the weighted r.m.s. of the residuals around the derived solution. The Julian Date is expressed as JD*=JD-2450 000. C98 stands for CORALIE-98 and C07 for CORALIE-07.

Parameters		HD 171238 b	HD 204313 b
γ_{C98}	[kms^{-1}]	21.662 ± 0.006	-9.785 ± 0.0018
γ_{C07}	[kms^{-1}]	21.641 ± 0.002	-9.762 ± 0.0031
P	[days]	1523^{+40}_{-45}	1931 ± 18
K	[ms^{-1}]	52.2 ± 1.8	64.8 ± 1.5
e		$0.400^{+0.061}_{-0.065}$	0.131 ± 0.023
ω	[deg]	$47.0^{+9.9}_{-9.8}$	-57 ± 11
T_0	[JD*]	5062 ± 20	3989 ± 62
$a_1 \sin i$	[10^{-3} AU]	6.68 ± 0.32	11.40 ± 0.31
$f_1(m)$	[10^{-9} $M_\odot$]	17.3 ± 2.4	53.2 ± 4.0
$m_p \sin i$	[M_{Jup}]	2.60 ± 0.15	4.05 ± 0.17
a	[AU]	2.54 ± 0.06	3.082 ± 0.055
N_{mes}		96	97
ΔT	[years]	6.82	8.06
χ_r		1.60 ± 0.07	1.24 ± 0.07
G.o.F		7.41	3.09
$\sigma_{(O-C)}$	[ms^{-1}]	10.25	8.11

around metal rich stars as stated by (Santos et al. (2001, 2005); Fischer & Valenti (2005)).
On the statistical point of view, the giant planet mass distribution decreases with a power law, as illustrated on Fig. 5, with no cut-off or change of distribution morphology up to 25-Jupiter-masses. There is no indication in the mass distribution diagram (within 6 AU of the parent star) of the presence of the low mass tail of a possible brown-dwarf mass distribution. The brown dwarf desert is therefore extremely "dry" at the lowest masses within 6 AU. However, with only 26 planets candidates with masses larger than 7 M_{Jup}, one should be carefull not to over-interpret the observations and only a direct measurement of the orbital inclination of each planet candidate will reveal their true nature.

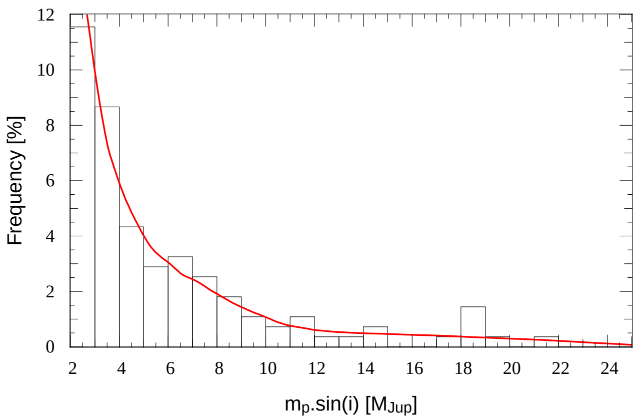

Fig. 5. Frequency distribution of the observed $m_p.\sin(i)$ values for the 117 known exoplanets with masses larger than 2 $M_\odot$ discovered by radial velocities orbiting G&K dwarfs. The underlying $m_p.\sin(i)$ distribution, plotted as a red line, is retrieved using a non-parametric approach with an Epanechnikov adaptive Kernel as described in Jorissen et al. (2001).

Direct measurement of the orbit inclination of massive planet candidates already produced some results. On one hand, Bean et al. (2007), with the HST Fine Guidance sensor, conducted a set of astrometric measurements of HD 33636 at a fraction of milli-arcsecond accuracy. The authors showed that HD 33636 b is not in the planet domain and is indeed an M dwarf. On the other hand and surprisingly enough, the CoRot space mission found a 21.66-M_{Jup} transiting brown dwarf with a 4.26-day period Deleuil et al. (2008).

However, a systematic monitoring of the massive planet candidates will only be possible with the forthcoming dedicated astrometric facilities such as PRIMA (start of operation end of 2009) (Launhardt et al. 2008) and GAIA (Perryman et al. (2001), launch date end of 2011). Those instruments/telescopes will determine the real mass of all massive planets candidates as illustrated by figure 6 and provide statistically reliable numbers about the distribution of massive planets and of brown dwarfs within 6 AU.

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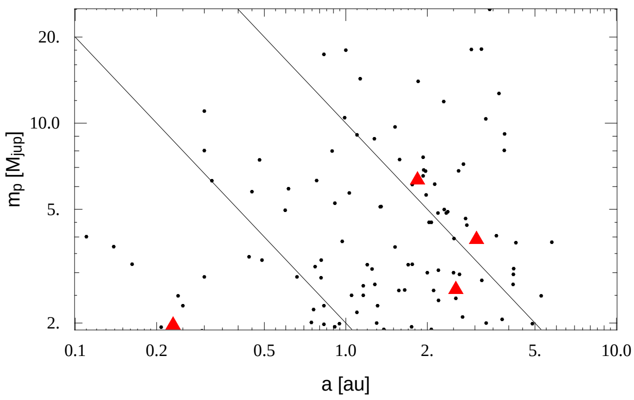

Fig. 6. $m_p.\sin(i)$ vs. separation diagram of the known massive exoplanets orbiting G&K dwarfs and discovered by radial velocities. The two lines correspond to astrometric signatures of 50 μ" and 250 μ" for a 1 $M_{\odot}$ parent star located at 40 pc. The four planets discussed in this paper are represented by triangles. Three of them will be characterized by PRIMA or by GAIA.

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