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The CORALIE survey for southern extra-solar planets

XV. Discovery of two eccentric planets orbiting HD 4113 and HD 156846. ⋆

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ABSTRACT

We report the detection of two very eccentric planets orbiting HD 4113 and HD 156846 with the CORALIE Echelle spectrograph mounted on the 1.2-m Euler Swiss telescope at La Silla. The first planet, HD 4113 b, has minimum mass of $m \sin i = 1.6 \pm 0.2\ M_{\rm Jup}$, a period of $P = 526.59 \pm 0.21$ days and an eccentricity of $e = 0.903 \pm 0.02$. It orbits a metal rich G5V star at $a = 1.28$ AU which displays an additional radial velocity drift of 28 m s^{-1}/yr observed during 8 years. The combination of the radial-velocity data and the non-detection of any main sequence stellar companion in our high contrast images taken at the VLT with NACO/SDI, characterizes the companion as a probable brown dwarf or as a faint white dwarf. The second planet, HD 156846 b, has minimum mass of $m \sin i = 10.45 \pm 0.05$ $M_{\rm Jup}$, a period of $P = 359.51 \pm 0.09$ days, an eccentricity of $e = 0.847 \pm 0.002$ and is located at $a = 1.0$ AU from its parent star. HD 156846 is a metal rich G0 dwarf and is also the primary of a wide binary system ($a > 250$ AU, $P > 4000$ years). Its stellar companion, IDS 17147-1914 B , is a M4 dwarf. The very high eccentricities of both planets can be explained by Kozai oscillations induced by the presence of a third object.

Key words. Stars: planetary systems — Stars: binaries: visual — Techniques: radial velocities — Stars: individual: HD 4113 — Stars: individual: HD 156846

1. Introduction

The CORALIE radial-velocity planet-search programme has been on-going for more than 9 years (since 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 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). Among the 1650 stars surveyed, 40 percent of them have a radial-velocity accuracy of 5 m s^{-1} or better and 90 percent of the sample is monitored with an accuracy better than 10 m s^{-1}, the limitation being mainly due to photon noise. The remaining 10 percent of the sample have a lower accuracy due to the lower signal to noise ratio and/or to the fast rotation of the targets.

So far, CORALIE has allowed the detection (or has contributed to the detection) of 48 extra-solar planet candidates (e.g. Mayor et al. 2004; Ségransan et al. 2007). This substantial contribution together with discoveries from various other programmes have provided a sample of more than 230 exoplanets that now permits us to point out interesting statistical constraints for the planet formation and evolution scenarios (see e.g. Marcy et al. 2005; Udry et al. 2007; Udry & Santos 2007), and reference therein for reviews on different aspects of the orbital-element distributions or primary star properties).

In this paper we report the detection of two of the most eccentric known planets , HD 4113 b and HD 156846 b. Together with HD 80606 b (Naef et al. 2001) and HD 20782 b (Jones et al. 2006), only four of the known planets have eccentricities larger than 0.8. The possible origin of these eccentricitie is still under debate. Suggestions have been made for scenarios which allow the formation of eccentric orbits in a protoplanetary disk of planetesimals (Levison et al. 1998) or gas (Goldreich & Sari 2003). However, the presence of the third body in both HD 156846 b and HD 4113 b suggests that eccentricity pumping might be at work in those two cases (Kozai 1962; Holman et al. 1997; Innanen et al. 1997; Mazeh et al. 1997).

The paper is organized as follows. In Sect. 2 we briefly discuss the primary star properties. Radial-velocity measurements and orbital solutions are presented in Sect. 3. In Sect. 4, we provide some concluding remarks.

2. Stellar characteristics

2.1. HD 4113, (HIP 3391, SAO 192693)

HD 4113 is identified as a G5 dwarf in the Hipparcos catalog (ESA 1997) and has an astrometric parallax, $\pi = 22.70 \pm 0.99$ mas which sets the star at a distance of 44.0 pc from the Sun. With an apparent magnitude $V = 7.88$ this implies an absolute magnitude of $M_V = 4.66$. According to the Hipparcos

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⋆ Based on observations collected with the CORALIE echelle spectrograph on the 1.2-m Euler Swiss telescope at La Silla Observatory, ESO, Chile

Table 1. Observed and inferred stellar parameters for the stars hosting planets presented in this paper. Definitions and sources of the quoted values are given in the text.

Parameters		HD 4113	HD 156846
Spectral Type		G5V	G0V
V		7.88	6.506
$B-V$		0.716	0.557
π	[mas]	22.70 ±0.99	20.41±0.93
M_V		4.660	3.055
$T_{\rm eff}$	[K]	5688±26	6138±36
$\log g$	[cgs]	4.40±0.05	4.15±0.10
[Fe/H]	[dex]	0.20±0.04	0.22±0.05
L	$[L_\odot]$	1.22	4.98
$M_\star$	$[M_\odot]$	0.99	1.43
$v \sin i$	[km s^{-1}]	1.37	4.45
Age	[Gyr]	4.8-8.0	2.1-2.7

catalogue the color index for HD 4113 is $B-V = 0.716$. Using a bolometric correction $BC = -0.136$ (Flower 1996) and the solar absolute magnitude $M_{bol} = 4.746$ (Lejeune et al. 1998), we thus obtain a luminosity $L = 1.22\,L_\odot$. Stellar parameters for HD 4113 are summarized in Table 1.

A detailed spectroscopic analysis of HD 4113 was performed using high signal to noise CORALIE spectra in order to obtain accurate atmospheric parameters (see Santos et al. 2005, for further details). This gave the following values: an effective temperature $T_{\rm eff} = 5688 \pm 26$ K, a surface gravity $\log g = 4.4 \pm 0.05$, and a metallicity [Fe/H] = 0.20 ± 0.04. Using these parameters and the Geneva stellar evolution models (Meynet & Maeder 2000), we derive a mass $M = 0.99\,M_\odot$. According to the Bayesian age estimates of Pont & Eyer (2004), HD 4113 is an old main-sequence star (4.8-8.0 Gyr). From the CORALIE spectra we derive $v \sin i = 1.37$ km s^{-1} (Santos et al. 2002).

2.2. HD 156846 (HIP 84856 , HR 6441, IDS 17147-1914 A)

HD 156846 is a bright, metal-rich and slightly evolved G0 dwarf. The astrometric parallax from the Hipparcos catalogue, $\pi = 20.41 \pm 0.93$ mas (ESA 1997) sets the star at a distance of 49.0 pc from the Sun. With an apparent magnitude $V = 6.50$ this implies an absolute magnitude of $M_V = 3.055$. According to the Hipparcos catalogue the color index for HD 156846 is $B-V = 0.578$. Using the method described in the previous section we derive a luminosity $L = 4.98\,L_\odot$ with a bolometric correction of $BC = -0.049$. Stellar parameters for HD 156846 are summarized in Table 1 as well.

A detailed spectroscopic analysis of HD 156846 gave the following values: an effective temperature $T_{\rm eff} = 6138 \pm 36$ K, a surface gravity $\log g = 4.15 \pm 0.10$, and a metallicity [Fe/H] = 0.22 ± 0.05. Using these parameters and the Geneva stellar evolution models, we deduce a mass $M = 1.43\,M_\odot$. According to the Bayesian age estimates of Pont & Eyer (2004), HD 156846 is a moderately old main-sequence star (2.1-2.7 Gyr).From the CORALIE spectra we derive $v \sin i = 4.45$ km s^{-1}.

HD 156846 is the primary star of a wide binary system (Washington Double Star catalog, hereafter WDS Worley & Douglass 1996) with an angular separaion of $\rho = 5.1''$ and a position angle PA=75 deg. Based on its near infrared magnitude (J=9.405, H=8.92, ie. Cabrera-Lavers et al. 2006) and on the stellar evolutionnary models of the Lyon group (Baraffe et al. 1998), its companion, IDS 17147-1914 B is identified as an early M dwarf of mass $M = 0.59 M_\odot$. Using the positions given in the WDS, we obtain a projected binary separation of 250 AU. This translates into an estimated binary semimajor axis of 315 AU, using the statistical relation $a/r = 1.261$ (Fischer & Marcy 1992).

3. radial-velocity measurements and orbital solutions

3.1. HD 4113

We took 130 spectra of HD4113 from October 1999 to October 2007, yielding radial-velocity measurements with a typical signal-to-noise ratio of 50 (per pixel at 550 nm) with precision of ~ 3.5 m s^{-1}.

Figure 1 shows the CORALIE radial velocities and the corresponding best-fit Keplerian model with a linear drift. The resulting orbital parameters are $P = 526.58$ days, $e = 0.90$, $K = 97.7$ m s^{-1}, imply the presence of a planet of minimum mass $m \sin i = 1.63\,M_{\rm Jup}$ orbiting with a semi-major axis $a = 1.28$ AU. The orbital separation ranges from 0.12 AU at periastron to 2.4 AU at apoastron. Residuals are somewhat larger than the precision of the measurements ($\sigma_{(O-C)} = 8.4$ m s^{-1}), and are probably caused by a combination of stellar jitter and the inadequate modeling of the long period companion.

In addition to the Keplerian signal, the radial-velocity measurements display a 28 m s^{-1} yr^{-1} linear drift with a curvature of over -1.55 m s^{-1} yr^{-2} over a time span of 8 years induced by a companion at a larger separation. Based on the duration and the amplitude of the drift, we are able to make some estimates on the nature of the outer companion of HD 4113. The lowest possible companion mass responsible for the drift has $m \sin i = 10\,M_{\rm Jup}$ which correspond to an orbital period of 11.5 year, an eccentricity of $e = 0.5$ and a radial-velocity semi-amplitude of 150 m s^{-1}. However, this orbital solution is very unlikely since the outer planet-star separation would reach 2.5 AU at periastron which is the separation of the inner planet at apoastron. More realistic solutions therefore have longer periods. For instance, the shortest orbital period for a circular orbit is 22 years and correspond to a probable brown dwarf companion ($m \sin i = 14\,M_{\rm Jup}$) orbiting HD 4113 at $a = 7.9\,AU$. The companion would reach the hydrogen burning limit at a separation of 20 AU with a period of 90 years. Radial velocities allow to conclude that the companion responsible for the observed drift is unlikely to be a planet (orbit stability reasons) but cannot discriminate between a brown dwarf and a stellar companion.

To bring additional constraints on the outer companion's nature we obtained high contrast images of the target using the VLT and its adaptive optics system NACO in differential mode (Montagnier et al. 2007). We did not detect any object within a radius of 2.5 arcsec, which excludes any main sequence stellar companions to HD 4113 down to 0.2 arcsec (about 8 AU), (Montagnier et al., in prep.). We conclude that the companion responsible for the observed drift is likely to be either a faint white dwarf like GJ 86 B (Mugrauer & Neuhäuser 2005; Lagrange et al. 2006) that went undetected in our SDI images or it could be a brown dwarf located between 8 and 20 AU from the parent star with a period ranging from 20-90 years.

3.2. HD 156846

HD 156846 has been observed with CORALIE at La Silla Obervatory since May 2003. Altogether, 64 radial-velocity measurements with a typical signal-to-noise ratio of 75 (per pixel at

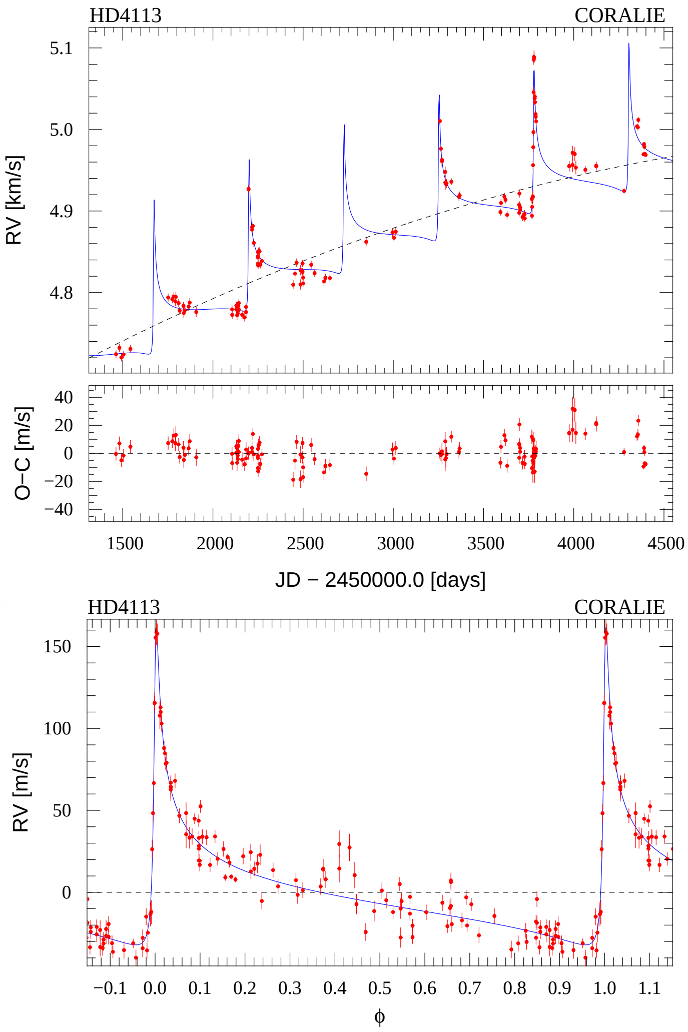

Fig. 1. Radial-velocity measurements as a function of Julian Date obtained with CORALIE for HD 4113 superimposed on the best Keplerian planetary solution (top figure). The residuals are displayed at the bottom of the top figure and the phase folded radial-velocity measurements are displayed on the bottom diagram.

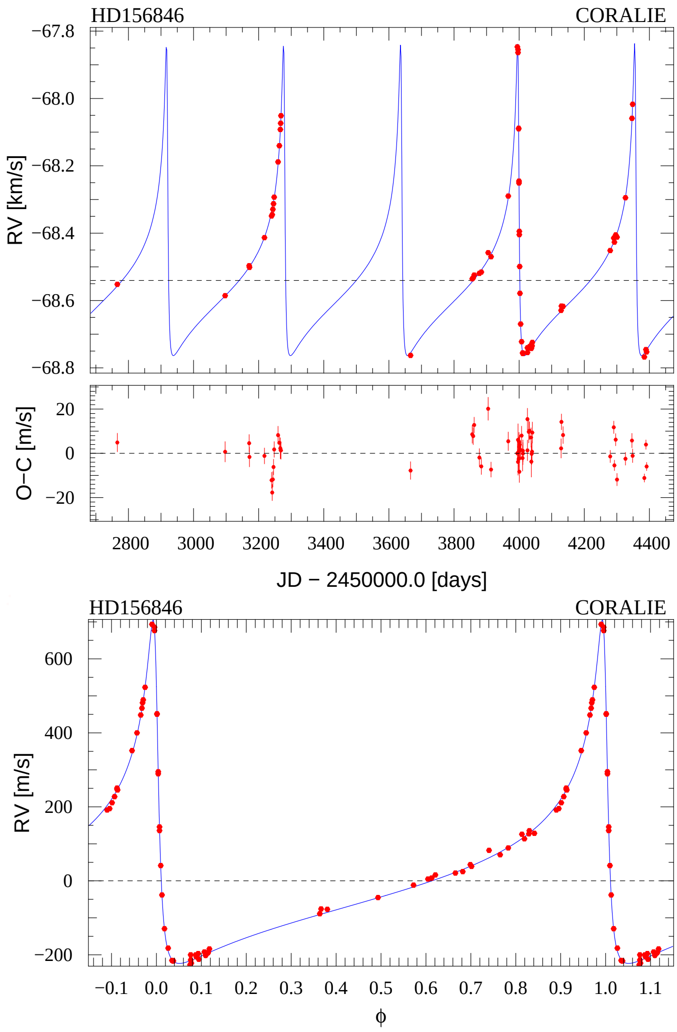

Fig. 2. Same as Fig. 1 for HD 156846.

550 nm) and a mean measurement uncertainty (including photon noise and calibration errors) of 2.8 m s^{-1} were gathered. Figure 2 shows the CORALIE radial velocities and the corresponding best-fit Keplerian model. The resulting orbital parameters are P = 359.50 days, e = 0.847, K = 464 m s^{-1} , implying a minimum mass $m_2 \sin i$ = 10.45 M$_{\rm Jup}$ orbiting HD 156846 with a semimajor axis a = 0.99 AU. The orbital separation ranges from 0.15 AU at periastron to 1.8 AU at apoastron. The orbital elements for HD 156846 b are listed in Table 2. Residuals around the single planet orbital solution are larger than the precision of the measurements ($\sigma_{(O-C)}$ = 7.5 m s^{-1}) which points toward the stellar jitter since the the high eccentricity of HD 156846 b does not leave much room for a short period undetected planet.

4. Discussion & conclusion

In this paper, we have reported the detection of two very eccentric planets orbiting two metal rich G dwarfs - HD 4113 and HD 156846 - for which a third massive body is present in each planetary system. The origin of the wide range of eccentricities in extrasolar planets (represented in Fig. 4 as a e vs. log P diagram) is still under debate, and different scenario have been proposed to explain the largest eccentricities such as the Kozai oscillations (Kozai 1962), chaotic evolution of planetary orbits in multiple systems and formation of eccentric orbits in a protoplanetary disk of planetesimals (Levison et al. 1998) or gas (Goldreich & Sari 2003).

HD 156846 b and HD 4113 b are two of the four most eccentric known planets, together with HD 80606 b (Naef et al. 2001) and HD 20782 b (Jones et al. 2006) with eccentricities larger than 0.85. It should be noticed that the parent stars of these 4 planets are part of wide binary systems (Desidera & Barbieri 2007, for HD 20782 and respective discovery papers for HD80606, HD 4113 and HD 156846) raising the question of the influence of the third body on the planets orbital parameters. It is therefore tempting to investigate the eccentricity pumping scenario a bit further by computing the different time-scales involved.

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 4113 and HD 156846 , we have estimated their Kozai oscillation periods using Eqs (36) of Ford et al.

Table 2. CORALIE best Keplerian orbital solutions for HD 156846 and HD 4113, as well as inferred planetary parameters. Confidence intervals are computed for a 68% confidence level after 10000 montecarlo iterations. *Span* is the time interval in days between the first and last measurements. $\sigma(O-C)$ is the weighted r.m.s. of the residuals around the derived solutions

Parameters		HD 4113	HD 156846
γ	[km s^{-1}]	4.874 ± 0.05	-68.540 ± 0.001
slope	[m s^{-1} yr^{-1}]	27.8 ± 0.3	-
curvature	[m s^{-1} yr^{-2}]	-1.55 ± 0.17	-
P	[days]	526.62 ± 0.3	359.51 ± 0.09
K	[m s^{-1}]	97.1 ± 3.8	464.3 ± 3.0
e		0.903 ± 0.005	0.8472 ± 0.0016
ω	[deg]	-42.3 ± 1.9	52.23 ± 0.41
T_0	[JD-2.45 10^6]	3778.0 ± 0.2	3998.09 ± 0.05
$a_1 \sin i$	[10^{-3} AU]	2.01 ± 0.05	8.15 ± 0.04
$f(m)$	[10^{-9} M$_\odot$]	3.9 ± 0.3	558 ± 9
$m_2 \sin i$	[M$_{\rm Jup}$]	1.56 ± 0.04	10.45 ± 0.05
a	[AU]	1.28	0.9930
N_{mes}		130	64
Span	[years]	8.0	4.45
$\sigma_{(O-C)}$	[m s^{-1}]	8.4	7.7

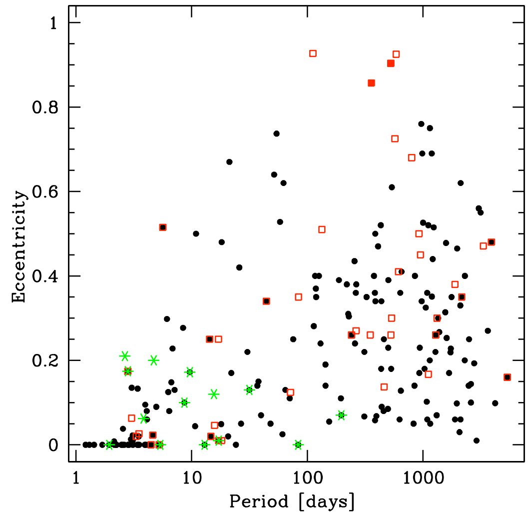

Fig. 3. e vs. log P for the known extra-solar giant planets orbiting dwarf primaries. Filled dots are for planets orbiting single stars and open squares for planets orbiting a component of a multiple stellar system. Green stars correspond to stars hosting Netpune-like planets. HD 4113 b and HD 156846 b are located by filled red squares.

(2000) . This yields to $P_{Kozai} = 5.5\,10^6$ years for HD 156846 and $P_{Kozai} = 6.2\,10^3$ years for HD 4113 which indicates that both planet eccentricity can undergo Kozai oscillations with periods that are many order of magnitude shorter than the age of the systems. We also computed the apsidal precession period due to relativistic corrections to the newtonian equation of motion using Eq. (4) of Holman et al. (1997). This yields $P_{GR} = 1.1$Gyr and$P_{GR} = 7.6$Gyr for HD 156846 and for HD 4113 respectively. This is also several order of magnitude larger that the Kozai oscillation period.

Provided that the orbital planes of the inner planet and the outer companion have different inclinations, the eccentricities of both HD4113 b and HD 156846 b could undergo Kozai oscillations. That would be the most likely explanation for such high eccentricities.

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