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Letter to the Editor

Evidence of a sub-stellar companion around HD 47536*

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Abstract. We report evidence of a low-mass companion around the K1III giant star HD 47536. This star belongs to our sample of 83 subgiant and giant stars studied for their radial velocity variations using the FEROS spectrograph at the 1.52 m-ESO telescope on La Silla. We find that the radial velocity of HD 47536 exhibits a periodic variation of about 712 days with a semi-amplitude of 113 m s^{-1}. These variations are not accompanied by variations in either Ca II emission or in the spectral line shapes. A Keplerian orbit due to a sub-stellar companion is thus the most viable explanation for the radial velocity variation. Assuming a moderate stellar mass of $m_1 = 1.1-3.0\ M_\odot$ we obtain a minimum mass for the companion of $m_2 \sin i = 5.0-9.7\ M_{\rm Jup}$, an orbital semi-major axis of 1.6–2.3 AU, and an eccentricity of $e = 0.2$.

Key words. stars: late-type – stars: individual: HD 47536 – technique: radial velocities – stars: planetary systems

1. Introduction

The detection of extra-solar planets has been extended since its first discoveries (Mayor & Queloz 1995; Marcy & Butler 1996). About 100 extra-solar giant planets around solar-type stars have been detected using the precise radial velocity (*RV*) method either by a simultaneous calibration or by the iodine absorption cell technique. Only few planets have been found around giant and subgiant stars due to the intrinsic variability of these objects.

Precise *RV* measurements of K giants started in the late 1980s. Smith HD 4 (1987) reported periodic *RV* variability in Arcturus with a period of 1.84 days. In a sample of 6 cool giants Walker et al. (1989) reported low-amplitude (30–300 m s^{-1}) *RV* variations. It is well known that K giants are multi-periodic with *RV* variability on timescales of days to hundreds of days (Hatzes & Cochran 1998). The short-period variability is due to p-mode oscillations (Hatzes & Cochran 1998; Merline 1997).

The nature of the long-period *RV* variations is still not known with possible explanations including sub-stellar companions, rotational modulation, or pulsations. Planetary companions around the K giants α Tau, α Boo, and β Gem have been suggested before (Hatzes & Cochran 1993), but because the rotation period of K giants can be several hundreds of days (see Choi et al. 1995), or comparable to the long-period *RV* variations, planets around giant stars had not been established with certainty. The discoveries of sub-stellar companions to giants and subgiants: HD 137759 (K2III) by Frink et al. (2002), HD 27442 (K1IVa) by Butler et al. (2001) and γ Cep (K1IV) by Cochran et al. (2002) gave some support to the companion hypothesis for giant stars. In the case of HD 137759 the companion nature of the *RV* variation was almost certain due to the large eccentricity of the orbit, a feature of the *RV* curve most likely explained by Keplerian orbits.

For the past 2.5 years we have conducted a program of precise *RV* measurements of 83 G and K giants occupying the red giant branch (RGB) including the clump region. Here we report on the long-period *RV* variation of the K giant HD 47536. The *RV* measurements were performed using FEROS at the 1.52 m-ESO telescope and CORALIE at the 1.2 m Swiss Euler telescope in La Silla. The resolving power ($R = \lambda/\Delta\lambda$) of the spectrographs are 48 000 (FEROS) and ~50 000 (CORALIE). We demonstrate that the long-period *RV* variation of this giant star is most likely due to a sub-stellar (planetary) companion. This is the second case for which a sub-stellar companion has been found around a giant star of luminosity class III.

2. Observation and data analysis

Observations of HD 47536 started in November 1999 using FEROS. The basic HIPPARCOS stellar properties are given

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* Based on observations collected at the ESO 1.52m telescope at the La Silla Observatory from July 2000 to February 2002 under ESO programs and the ESO-Observatório Nacional, Brazil, agreement.

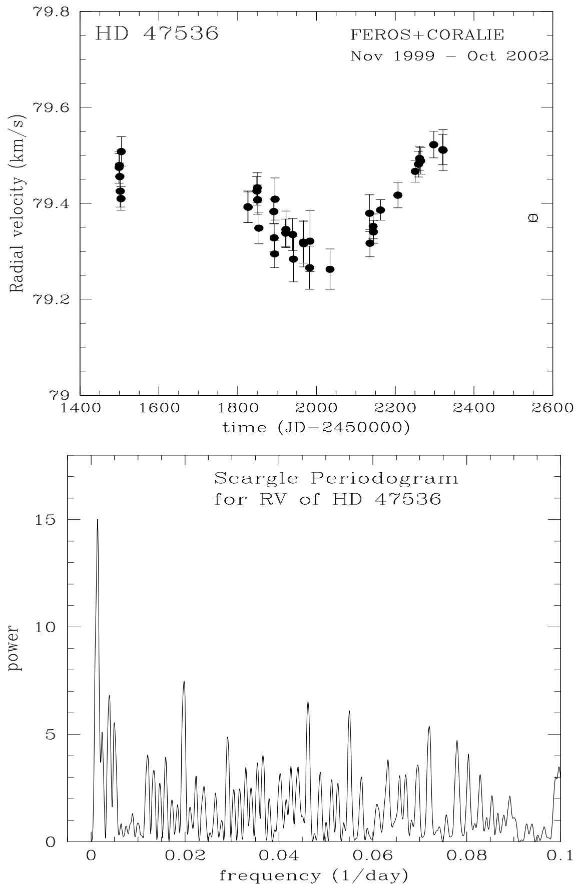

Fig. 1. *RV* variability of HD 47536 and its Scargle periodogram. The dots are FEROS measurements, the single open circle is the CORALIE measurement. The periodic signature of the *RV* variation is shown clearly in the periodogram by the significant power at $\nu = 0.00137$ cycles day^{-1}.

in Table 1. We determined the projected rotational velocity $v_{\rm rot} \sin i$ with the cross-correlation method as described in Queloz et al. (1998) and using the velocity calibration value for FEROS measured by Melo et al. (2001). The angular diameter Θ was taken from the CHARM catalogue (Richichi & Percheron 2002). Stellar *RV* measurements with FEROS were made using a simultaneous Th-Ar calibration technique. With a specified accuracy of 50 m s^{-1} (Kaufer & Pasquini 1998) FEROS was not initially designed for high precision *RV* measurements. Improvements in the FEROS data reduction (Setiawan et al. 2003) and the use of cross-correlation techniques permitted us to achieve a long-term accuracy of better than 25 m s^{-1}. Although this accuracy is not as good as that achieved by other *RV* surveys dedicated to planet searches, it is sufficient for the study of K giants whose *RV* variations were expected to be many tens to hundreds of m s^{-1}.

Until the end of our survey in February 2002 we obtained 38 high signal-to-noise ratio (S/N = 150–200) spectra which were used for determining the *RV*. An additional measurement was taken with CORALIE in October 2002. The *RV* measurements are listed in Table 2.

The data reduction was carried out using ESO-MIDAS. As an end product we obtained 39 one dimensional spectra of each echelle order. The spectra are cross-correlated order by order with a numerical binary template (mask) containing line positions. The template for the Th-Ar was a thorium mask (Baranne et al. 1996) which was then adapted for FEROS (Setiawan et al. 2000), whereas the stellar mask was initially developed for K0 dwarfs. The mean *RV* of our standard star τ Cet measured with FEROS over this period is $-16\,660 \pm 22.8$ m s^{-1}. The CORALIE *RV* value of τ Cet on the night when a spectrum

Table 1. Basic stellar properties of HD 47536.

Spectral type		K1III
m_V	mag	5.25
M_V	mag	−0.17
$B-V$		1.18
$V-I$		1.16
π	mas	8.24 ± 0.56
r	pc	121.36 ± 8.25
$T_{\rm eff}$	K	4380$^{(a)}$
Θ	mas	1.81 ± 0.09$^{(b)}$
R_*	$R_\odot$	23.47 ± 1.97
$v_{\rm rot} \sin i^{(c)}$	km s^{-1}	1.93 ± 0.50
$P_{\rm rot}/\sin i$	days	619.0 ± 168.5

[(a)] Borde et al. (2002).
[(b)] Richichi & Percheron (2002).
[(c)] Determined using cross-correlation method.

Table 2. *RV* measurement table of HD 47536.

HJD −2 450 000	*RV* m s^{-1}	σ_{RV} m s^{-1}	HJD −2 450 000	*RV* m s^{-1}	σ_{RV} m s^{-1}
FEROS			FEROS		
1498.85813	79475.29	33.35	1941.68289	79283.95	47.47
1499.84424	79479.20	24.39	1966.63067	79319.09	43.54
1500.82399	79456.08	28.20	1967.61428	79316.11	48.67
1501.84201	79425.54	33.34	1982.60999	79265.94	45.08
1503.80407	79410.11	24.68	1983.61173	79321.38	63.90
1504.73140	79508.34	30.79	2034.51858	79262.79	42.04
1825.82000	79393.01	32.88	2134.92124	79379.61	38.13
1826.79706	79392.05	31.97	2135.92107	79317.17	28.45
1848.73781	79425.96	29.70	2143.91912	79352.16	25.81
1849.87072	79432.50	31.38	2144.91490	79340.61	23.91
1850.82032	79407.82	30.45	2162.83411	79386.24	21.53
1853.83336	79348.55	32.96	2206.82385	79417.29	26.63
1891.75112	79383.03	25.92	2250.73310	79466.94	22.88
1892.72852	79328.47	29.38	2258.80834	79481.74	26.70
1893.73245	79294.67	28.29	2261.77927	79493.98	24.94
1894.73323	79409.03	43.76	2264.74591	79488.68	27.79
1921.72943	79338.22	28.95	2297.66097	79522.58	27.74
1922.69018	79345.74	38.11	2320.65288	79512.03	31.40
1939.68184	79335.08	33.18	2321.57905	79511.04	42.41
CORALIE					
2549.88550	79369.70	07.62			

of HD 47536 was taken is $-16\,667 \pm 2$ m s^{-1} which is consistent with the FEROS result.

The *RV* measurements of HD 47536 show obvious long-period variability. The standard deviation of this variation is 76 m s^{-1}, or a factor of 3–4 larger than our internal *RV* accuracy. The Lomb-Scargle periodogram (Scargle 1982) of the data (lower panel of Fig. 1) shows a significant power at the frequency $\nu = 0.00137$ cycles day^{-1} ($P = 726.2$ days). The false alarm probability (FAP) of this peak was assessed using Monte Carlo simulations. The measured *RV* values were shuffled keeping the observed times fixed. The Scargle periodogram of this "shuffled" data was then examined to see if it had power exceeding the power of the data periodogram. After 10^5 shuffles there was no instance where the randomized data had power greater than the maximum value in the original periodogram. This establishes that the highest peak in Fig. 1 is significant with a FAP less than 10^{-5}.

3. Chromospheric activity and bisector velocity

We measured the Ca II emission and examined the spectral line shapes to search for other forms of variability that may be correlated with the *RV* variation. This could help establish the nature of the *RV* variation. If the *RV* variation was accompanied by spectral variability with the same period, then this would leave some doubt that a companion is responsible for the *RV* variability.

Figure 2 (upper panel) shows the mean spectrum for the region around Ca II K (solid line) as well as the individual spectra (dotted line). The lack of any variations in the other photospheric lines excludes the presence of systematic effects in the data reduction process. We also computed the "mean absolute deviation" (Walker et al. 1991) as shown in the lower panel of Fig. 2. It shows no significant chromospheric activity in the Ca II K core region.

We searched for variations in the Ca II K emission core by measuring the emission line intensity relative to the intensities of regions in the blue and red wings close to the core which contain no strong absorption features. The upper left panel of Fig. 3 shows these indices plotted against the *RV* measurements. We use only the Ca II K because the Ca II H could be blended by the Hϵ line of the Balmer series. A periodogram analysis of the Ca II data (lower left panel of Fig. 3) also reveals no strong power at the *RV* frequency. We conclude that there is no significant variability in Ca II emission for HD 47536.

We also searched for spectral variations by examining the bisector of the cross-correlation function. This technique was used by Queloz et al. (2001) to establish the spotted nature of the observed *RV* variation for HD 164335. *RV* variations due to spots or other forms of activity should show a correlation with the changes in the spectral line shapes. The correlation of the velocity span of the bisector with *RV* is shown in upper right panel of Fig. 3. The bisector velocity span is constant over the observed *RV* variations. The periodogram of the span measurements (lower right panel of Fig. 3) shows no significant power at the *RV* frequency. In both periodograms the dotted line indicates the frequency of the *RV* variation.

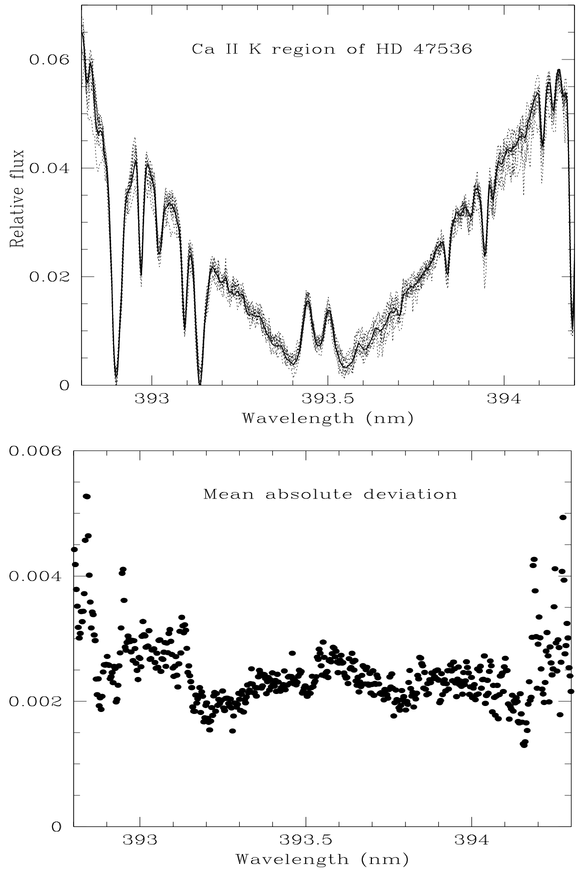

Fig. 2. Upper panel: the Ca II K region of HD 47536. The solid line is the mean spectrum and the dotted lines are individual spectra. Lower panel: mean absolute deviation. No significant variations in the line core are seen.

The analysis of the Ca II line shape data leads us to conclude that rotational modulation is not responsible for the observed *RV* variation. Furthermore, it is unlikely that nonradial pulsations are the cause of the variations since these should also be accompanied by line shape changes which are not seen. The only remaining viable hypothesis is that the *RV* variation is due to a companion.

4. Orbital solution

The orbital solution is shown in Fig. 4 and the orbital elements are listed in Table 3. The orbital period is $P = 712.1$ days. We note that this period is consistent with the rotation period of the star estimated at $P_{\rm rot}/\sin i = 450$–800 days, given by the errors in the radius and $v_{\rm rot}\sin i$. However, since there are no other forms of variability accompanying the *RV* variation it is unlikely that the *RV* period is caused by rotational modulation. The eccentricity is rather low, $e = 0.2 \pm 0.08$, comparable to the eccentricities found in the *RV* variations of other K giants (Hatzes & Cochran 1993).

The determination of accurate masses for giant stars is rather more difficult than for main-sequence stars. In this paper we estimate the mass from the mass distribution for stars in the region around HD 47536 in the HIPPARCOS M_I vs. $V-I$ diagram. For these stars which are not far from the clump

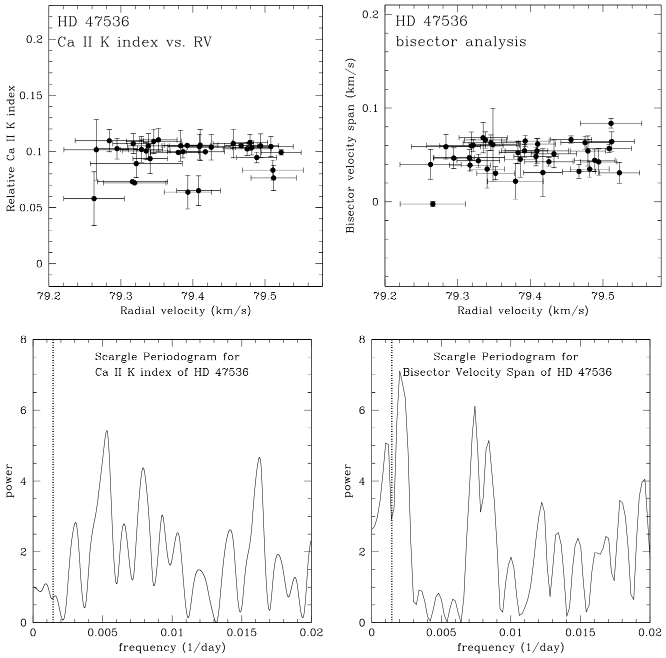

Fig. 3. Activity index, bisector velocity span and their Scargle periodograms for HD 47536. Both activity index and bisector velocity span do not appear to be correlated with the *RV*. The periodograms show no significant powers of significant period which could be similar to the power found in the *RV* Scargle periodogram. The dotted line shows the position of the highest power in the *RV* periodogram.

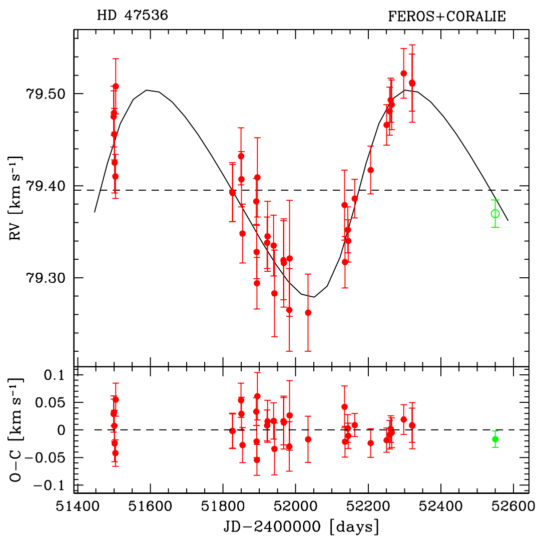

Fig. 4. Radial velocity measurement and the orbital solution for HD 47536. The orbital parameters are presented in Table 3.

region, the mass distribution is similar to that of the clump giants. Observations of red giants in the clump region (see Zhao et al. 2001; Girardi & Salaris 2001) yield an upper limit to the masses of 2.6–3.0 $M_\odot$. This distribution can be also expected for the stars located 1 mag above the clump as shown in Fig. 5 (left). We estimate that the most probable mass for HD 47536 is between 1.0 and 1.5 $M_\odot$ (Fig. 5, right). We use primary masses of $m_1 = 1.1$ and 3.0 $M_\odot$ to compute the minimum companion mass $m_2 \sin i$. For both models we obtain minimum masses

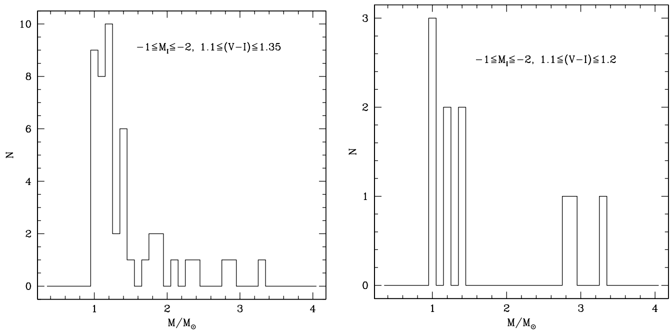

Fig. 5. Left: mass distribution of stars in the region 1 mag above to the clump in the M_I vs. $V - I$ diagram. Right: mass distribution for giants around HD 47536.

Table 3. Orbital parameters for HD 47536.

P	days	712.13 ± 0.31
T_0	JD −2 450 000	1599.36 ± 21.50
e		0.20 ± 0.08
V	km s^{-1}	79.395 ± 0.007
ω_1	deg	260.8 ± 23.7
K_1	km s^{-1}	0.113 ± 0.011
σ(O–C)	m s^{-1}	25.9
reduced χ^2		0.944
$f(m)$	$M_\odot$	0.991×10^{-7}
$a_1 \sin i$	AU	0.722×10^{-2}
with $m_1 = 1.1\ M_\odot$		
$m_2 \sin i$	$M_{\rm Jup}$	4.96
a	AU	1.61
with $m_1 = 3.0\ M_\odot$		
$m_2 \sin i$	$M_{\rm Jup}$	9.67
a	AU	2.25

of 4.96 and 9.67 $M_{\rm Jup}$, as given in Table 3, which is clearly in the planetary mass regime.

5. Conclusion

We observed a long-period (P = 712.1 days) *RV* variation of the K1III giant HD 47536 with a velocity amplitude of 113 m s^{-1}. From the lack of variability in both Ca II and the spectral line shapes a Keplerian orbit is the best interpretation for the long-period *RV* variation of this star. The orbital solution results in companion mass with projected mass between 5.0–9.7 $M_{\rm Jup}$ with an orbital semi-major axis of 1.6–2.3 AU.

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