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ELODIE metallicity-biased search for transiting Hot Jupiters*

IV. Intermediate period planets orbiting the stars HD 43691 and HD 132406

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ABSTRACT

We report here the discovery of two planet candidates as a result of our planet-search programme biased in favour of high-metallicity stars, using the ELODIE spectrograph at the Observatoire de Haute Provence. One candidate has a minimum mass $m_2 \sin i = 2.5\ M_{\rm Jup}$ and is orbiting the metal-rich star HD 43691 with period $P = 40$ days and eccentricity $e = 0.14$. The other planet has a minimum mass $m_2 \sin i = 5.6\ M_{\rm Jup}$ and orbits the slightly metal-rich star HD 132406 with period $P = 974$ days and eccentricity $e = 0.34$. Additional observations for both stars were performed using the new SOPHIE spectrograph that replaces the ELODIE instrument, allowing an improved orbital solution for the systems.

Key words. stars: individual: HD 43691 – stars: individual: HD 132406 – planetary systems – techniques: radial velocities

1. Introduction

Following the first publications suggesting the metal-rich nature of stars hosting giant planets in close orbits (Gonzalez 1997, 1998), numerous studies on this theme have been published in recent years (Santos et al. 2001, 2004; Fischer & Valenti 2005; Gonzalez 2006). With the increasing number of known planets, statistical studies were able to verify that the frequency of stars hosting a planetary companion is highly correlated with the stellar metallicity. The results show that the probability of finding a close-in giant planet is about 25–30% for the most metal-rich stars ([Fe/H] > 0.3) and only 3% for stars with solar metallicity. The extrasolar planet search biased in favour of high-metallicity stars can thus rapidly lead to the discovery of planets in short-period orbits, the so-called Hot Jupiters ($P < 10$ days), increasing the chances of finding planetary transits. The identification of planets transiting bright stars provides a powerful approach to determine fundamental constraints on the mechanisms of planet formation, the physical properties of the exoplanet, and the geometry of the system.

Based on these assumptions, a few programmes have been initiated with the aim of looking for planets orbiting high-metallicity stars. One of them is the N2K consortium (Fischer et al. 2004), which monitors nearly 2000 main-sequence and subgiant stars. Another project was conducted by our team with the ELODIE spectrograph at the Observatoire de Haute Provence (Da Silva et al. 2006). From a sample of more than a thousand solar-type stars, we selected the most metallic ones after the first measurement to monitor their radial velocities.

Our programme has already yielded the detection of four Hot Jupiters, with periods between 2.2 and 6.8 days and minimum masses between 1.0 and 2.1 $M_{\rm Jup}$, orbiting the stars HD 118203 and HD 149143[1] (Da Silva et al. 2006), HD 189733 (Bouchy et al. 2005), and HD 185269[1] (Moutou et al. 2006).

For the star HD 189733, additional photometric measurements have led to the observation of a planetary transit, making possible the determination of some parameters of the companion, such as mass, radius and mean density (Bouchy et al. 2005; Bakos et al. 2006; Winn et al. 2007). This system is our best result, a very good example of what we expect to obtain with our programme, and revealed to be of particular interest for further studies. Deming et al. (2006) analysed the infrared thermal emission during an eclipse of HD 189733 b using the *Spitzer Space Telescope* (Werner et al. 2004) and determined the brightness temperature of the planet at 16 μm. Knutson et al. (2007), performing observations with *Spitzer* at 8 μm, were able to construct a map of the temperature distribution of HD 189733 b,

* Based on radial velocities collected with the ELODIE spectrograph mounted on the 193-cm telescope at the Observatoire de Haute Provence, France. Additional observations were made using the new SOPHIE spectrograph (run 06B.PNP.CONS) that replaces ELODIE.

[1] The planet around HD 149143 was independently discovered by Fischer et al. (2006) and the one orbiting HD 185269 was also published by Johnson et al. (2006).

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estimating a minimum and a maximum brightness temperature at this wavelength. Fortney & Marley (2007) analysed the mid infrared observations of HD 189733 and suggested a possible presence of water vapor in the atmosphere of the planetary companion. Observations with the *Hubble Space Telescope* have also been proposed in order to perform precise measurements of the size and the orbital inclination angle of HD 189733 b (Pont et al., in preparation).

In this paper, we report the discovery of two new planet candidates resulting from our ELODIE planet search programme biased towards metal-rich stars: a 2.5 Jupiter-mass planet orbiting the star HD 43691 with period $P = 40$ days, and a 5.6 Jupiter-mass planet in a long-period orbit of $P = 974$ days around the star HD 132406. Such results are complemented by additional measurements made using SOPHIE (Bouchy et al. 2006), the new spectrograph that replaces ELODIE.

The radial velocity observations that have led to these results are described in Sect. 2. The observed and derived parameters of the star HD 43691 together with the orbital solution adopted are presented in Sect. 3. The same are presented in Sect. 4 for the star HD 132406. In Sect. 5 we discuss the present and future status of the observational programme.

2. Observations

The HD 43691 and HD 132406 stars are both targets in our "ELODIE metallicity-biased search for transiting Hot Jupiters" survey (Da Silva et al. 2006), conducted from March 2004 until August 2006 with the ELODIE spectrograph (Baranne et al. 1996) on the 193-cm telescope at the Observatoire de Haute Provence (France). In this programme we essentially searched for Jupiter-like planets orbiting metal-rich stars, assuming that such stars are more likely to host giant planets.

After obtaining the first spectrum of HD 43691 and HD 132406, we verified the high metallicity of these stars from a calibration of the surface of the ELODIE cross-correlation functions (Santos et al. 2002; Naef 2003). After three measurements, we could clearly see in both stars a significant radial velocity variation. We therefore conducted follow-up observations with ELODIE, and we obtained 22 spectra of HD 43691 from November 2004 (JD = 2 453 333) to May 2006 (JD = 2 453 872), and 17 spectra of HD 132406 from May 2004 (JD = 2 453 152) to June 2006 (JD = 2 453 900).

The ELODIE instrument was decommissioned in August 2006 and replaced by the SOPHIE spectrograph. Additional measurements were then obtained using this new instrument: 14 spectra of HD 43691 from November 2006 (JD = 2 454 044) to February 2007 (JD = 2 454 155), and 4 spectra of HD 132406 from December 2006 (JD = 2 454 080) to May 2007 (JD = 2 454 230).

With ELODIE, the average signal-to-noise ratio (S/N) calculated from the spectra at λ5500 Å is ~40 for both stars, with a typical exposure time of 20 min. On the other hand, the gain in efficiency of SOPHIE compared to ELODIE is more than one order of magnitude in the high-resolution mode (used for high precision radial-velocity measurements). Typical S/N obtained with SOPHIE are thus 2 times larger than those of ELODIE for exposure times 2–3 times smaller. Table 1 lists the radial velocities of HD 43691 and Table 2 lists those of HD 132406.

Following Zucker & Mazeh (2001), we tried to look for the astrometric signatures of the two orbits in Hipparcos intermediate astrometric data (IAD). HD132406, whose best-fit Keplerian period was close to the Hipparcos mission duration, seemed especially suitable for this kind of analysis. We found no evidence of astrometric signatures. Furthermore, the mass upper limits produced by the IAD are in the stellar regime and therefore do not provide any useful constraint.

Table 1. ELODIE and SOPHIE radial velocities of HD 43691. All values are relative to the solar system barycentre. The uncertainties correspond to the photon-noise errors.

JD − 2 400 000 [days]	*RV* [km s^{-1}]	Uncertainty [km s^{-1}]
ELODIE measurements		
53 333.6255	−29.123	0.011
53 337.6057	−29.098	0.012
53 398.4118	−29.015	0.012
53 690.6694	−28.945	0.013
53 692.6430	−28.962	0.013
53 693.6240	−28.983	0.014
53 714.5653	−28.912	0.014
53 715.5590	−28.903	0.015
53 718.5549	−28.904	0.013
53 719.5681	−28.885	0.010
53 720.5323	−28.853	0.017
53 721.5123	−28.892	0.018
53 722.5237	−28.907	0.015
53 728.4315	−28.969	0.018
53 749.5333	−28.989	0.014
53 750.4982	−28.958	0.014
53 756.4444	−28.840	0.018
53 808.2808	−29.091	0.012
53 809.2850	−29.087	0.009
53 839.3031	−28.960	0.019
53 870.3405	−28.881	0.017
53 872.3456	−28.923	0.020
SOPHIE measurements		
54 044.6274	−28.980	0.003
54 051.6411	−28.830	0.004
54 053.5968	−28.854	0.003
54 078.6009	−29.059	0.004
54 079.4859	−29.040	0.004
54 080.4572	−29.018	0.004
54 081.4440	−28.993	0.003
54 087.4744	−28.858	0.004
54 088.5858	−28.872	0.004
54 089.6137	−28.846	0.004
54 142.4798	−29.064	0.004
54 148.4607	−29.089	0.004
54 151.4010	−29.065	0.004
54 155.4284	−28.981	0.004

In order to derive some of the fundamental stellar parameters, like effective temperature, surface gravity and metallicity, using accurate spectroscopic analysis, we obtained a high S/N spectrum (~130 at λ5500 Å) of HD 43691 with the SOPHIE spectrograph.

3. A planetary companion to HD 43691

3.1. Stellar characteristics of HD 43691

HD 43691 (HIP 30057) is listed in the Hipparcos catalogue (ESA 1997) as a G0 star in the northern hemisphere with visual magnitude $V = 8.03$, color index $B - V = 0.596$, and parallax $\pi = 10.73 \pm 1.16$ mas (a distance of 93 pc from the Sun). The bolometric correction is BC = −0.034, derived from Flower (1996). Using the Hipparcos parameters we derived an absolute magnitude $M_V = 3.18$, which represents a high luminosity for a

Table 2. ELODIE and SOPHIE radial velocities of HD 132406. All values are relative to the solar system barycentre. The uncertainties correspond to the photon-noise errors.

JD − 2 400 000 [days]	*RV* [km s^{-1}]	Uncertainty [km s^{-1}]
ELODIE measurements		
53 152.4773	−37.821	0.010
53 154.4825	−37.837	0.008
53 218.3605	−37.858	0.010
53 520.4238	−37.928	0.013
53 536.4140	−37.875	0.010
53 576.3681	−37.859	0.012
53 596.3805	−37.818	0.014
53 807.6666	−37.727	0.025
53 808.6537	−37.755	0.011
53 809.6643	−37.742	0.011
53 869.5117	−37.779	0.011
53 870.4406	−37.771	0.007
53 873.4386	−37.768	0.009
53 895.4251	−37.757	0.009
53 896.4387	−37.745	0.012
53 899.4286	−37.743	0.019
53 900.4376	−37.770	0.013
SOPHIE measurements		
54 080.7252	−37.718	0.003
54 173.6848	−37.752	0.004
54 187.6332	−37.770	0.004
54 230.5803	−37.790	0.004

G0 star. This suggests that HD 43691 is slightly evolved towards the subgiant branch. Nordström et al. (2004) found a difference of 1.19 mag from the ZAMS, indicating the degree of evolution of this star.

Applying the spectroscopic analysis described in Santos et al. (2004) to the high S/N spectrum of HD 43691 we obtained: $T_{\rm eff}$ = 6200 ± 40 K, log g = 4.28 ± 0.13, and [Fe/H] = 0.28 ± 0.05. From the calibrations of the ELODIE CCF (Santos et al. 2002; Naef 2003), we estimated a slightly smaller but comparable value for the metallicity ([Fe/H] = 0.22 ± 0.05), and a projected rotation velocity $v \sin i$ = 4.7 km s^{-1}.

With these stellar parameters, we estimated the mass and age of HD 43691 using the Geneva models of stellar evolution computed by Schaerer et al. (1993). We found a mass of $M_\star = 1.38 \pm 0.05\ M_\odot$ and an age between 2.0 and 3.6 Gyr, which are in agreement with the determinations done by Nordström et al. (2004): mass $M_\star = 1.38 \pm 0.08\ M_\odot$ and age 2.6 ± 0.5 Gyr. These values are compatible with the star being slightly evolved, especially taking into account the stellar metallicity (Mowlavi et al. 1998). The observed and derived stellar parameters of HD 43691 are shown in Table 3.

3.2. Orbital solution for HD 43691 b

The best Keplerian orbital solution fitted to the radial velocities of HD 43691, using both ELODIE and SOPHIE observations, provides an orbit with period P = 36.96 ± 0.02 days and eccentricity e = 0.14 ± 0.02. With the estimated value for the primary mass of 1.38 $M_\odot$, we obtained a minimum mass $m_2 \sin i$ = 2.49 $M_{\rm Jup}$ and a separation of 0.24 AU for the planetary companion. The solution includes a velocity zero-point of the two datasets as a free parameter, and the difference between them is $\Delta_{\rm S-E}$ = 23 ± 4 m s^{-1}. For this solution, we estimated a false alarm probability of 1.3×10^{-5} using the approach described in Horne & Baliunas (1986).

Table 3. Observed and estimated parameters of HD 43691 and HD 132406. Some of the stellar parameters of HD 43691 were obtained from spectroscopic analysis while those of HD 132406 come from calibrations of the ELODIE CCF.

	HD 43691	HD 132406	
Spectral type	G0 IV	G0 V	
V	8.03	8.45	
$B-V$	0.596	0.65	
π	10.73 ± 1.16	14.09 ± 0.77	[mas]
M_V	3.18	4.19	
BC	−0.034	−0.062	
$T_{\rm eff}$	6200 ± 40	5885 ± 50	[K]
$M_\star$	1.38 ± 0.05	1.09 ± 0.05	$M_\odot$
age	2.0–3.6	6.4 ± 0.8	Gyr
log g	4.28 ± 0.13		
[Fe/H]	0.28 ± 0.05	0.18 ± 0.05	
$v \sin i$	4.7	1.7	[km s^{-1}]

In the top panel of Fig. 1 we plot the radial velocities of HD 43691 and the Keplerian fit adopted using the two sets of measurements. The middle panel shows the residuals around the solution. The weighted rms around the solution is $\sigma_{\rm E}$ = 17.5 m s^{-1} for ELODIE, $\sigma_{\rm S}$ = 9.0 m s^{-1} for SOPHIE, and $\sigma_{\rm ES}$ = 10.0 m s^{-1} for the whole dataset. The bottom panel shows the phase-folded radial velocities. Table 4 lists the adopted orbital elements, together with the inferred planetary parameters.

3.3. Low chromospheric activity for HD 43691

The radial velocity variations observed for a star can also be the result of physical events in the stellar atmosphere rather than the presence of an orbital companion. For example, spots on the surface of an active star can change the observed spectral-line profiles and induce periodic variations in the measured radial velocities. By analysing the line-bisector orientations one can distinguish which of these situations is the real origin of the variations (Queloz et al. 2001).

The analysis of the line-bisector orientations, or bisector inverse slope (BIS) value, of HD 43691 shows that there is no correlation between the BIS values and the derived radial velocities (Fig. 2, top panel). Thus the observed variations in radial velocity are not induced by stellar activity and rotation (as is the case for HD 166435 in Queloz et al. 2001). The observed behaviour of the line bisectors also indicates that the radial velocity variations do not result from contamination by the light of a late-type binary companion (see e.g. the case of HD 41004 in Santos et al. 2002). Such variations are thus most probably due to the presence of a planetary companion orbiting HD 43691.

The chromospheric activity level can also be verified by means of the reemission in the core of Ca II absorption lines (e.g. λ3968.5 Å). By observing the respective spectral region in the high S/N spectrum of HD 43691 obtained with SOPHIE (Fig. 2, bottom panel), we can note that this star is not active. Since this line is located in the blue part of the spectral domain, where the flux is appreciably lower, this kind of inspection requires a high S/N spectrum, which is much better achieved by the higher efficiency of SOPHIE.

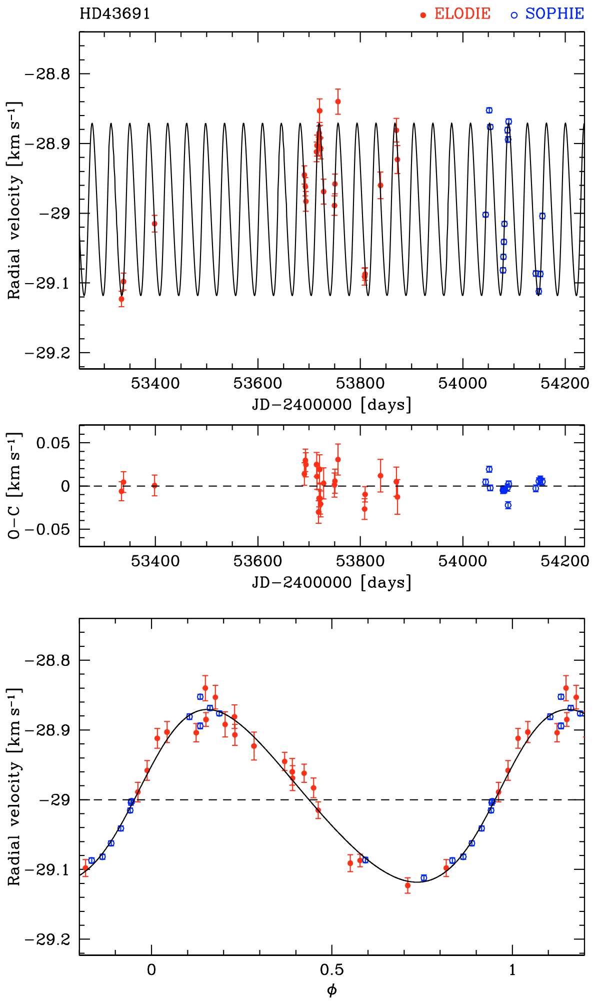

Fig. 1. *Top*: ELODIE and SOPHIE radial velocities of HD 43691 plotted together with the best Keplerian solution that fits the combined measurements. *Middle*: Residuals around the solution, with $\sigma_E = 17.5$ m s^{-1} for ELODIE, $\sigma_S = 9.0$ m s^{-1} for SOPHIE, and $\sigma_{ES} = 10.0$ m s^{-1} for the combined data points. *Bottom*: Phase-folded radial velocities with the best Keplerian solution. Error bars represent the photon-noise errors.

4. A long-period planet orbiting HD 132406

4.1. Stellar characteristics of HD 132406

HD 132406 (HIP 73146) is listed in the Hipparcos catalogue as a G0 star with visual magnitude $V = 8.45$, color index $B - V = 0.65$, and parallax $\pi = 14.09 \pm 0.77$ mas (71 pc distant from the Sun). These parameters set a value of $M_V = 4.19$ for the absolute magnitude. The bolometric correction is BC = −0.062.

The metallicity and the projected rotation velocity of this star are [Fe/H] = 0.18 ± 0.05 and $v \sin i = 1.7$ km s^{-1} respectively, estimated from the calibrations of the ELODIE cross-correlation functions. The effective temperature derived is $T_{\rm eff} = 5885 \pm 50$ K and comes from the calibrations of $T_{\rm eff}$ as a function of $B - V$ and [Fe/H] from Santos et al. (2004). The derived mass and age are $M_\star = 1.09 \pm 0.05$ $M_\odot$ and 6.4 ± 0.8 Gyr, from the Geneva models of stellar evolution. These parameters are listed in Table 3.

Table 4. Orbital elements for the best Keplerian solution of HD 43691 and HD 132406, as well as the inferred planetary parameters.

	HD 43691	HD 132406	
P	36.96 ± 0.02	974 ± 39	[days]
T	54046.6 ± 0.5	53474 ± 44	[JD – 2 400 000]
e	0.14 ± 0.02	0.34 ± 0.09	
V	−29.000 ± 0.003	−37.840 ± 0.008	[km s^{-1}]
ω	290 ± 5	214 ± 19	[deg]
K	124 ± 2	115 ± 26	[m s^{-1}]
$N_{\rm meas}$	22 (E) + 14 (S)	17 (E) + 4 (S)	
$\Delta_{\rm S-E}$	23 ± 4	93 ± 17	[m s^{-1}]
σ_E	17.5	12.1	[m s^{-1}]
σ_S	9.0	4.1	[m s^{-1}]
σ_{ES}	10.0	7.5	[m s^{-1}]
$a_1 \sin i$	4.17	9.73	[10^{-4} AU]
$f(m)$	7.06	1.30	[10^{-9} $M_\odot$]
$m_2 \sin i$	2.49	5.61	[$M_{\rm Jup}$]
a	0.24	1.98	[AU]

4.2. Orbital solution for HD 132406 b

A Keplerian solution fitted to the radial velocity measurements of HD 132406, from both ELODIE and SOPHIE observations, results in an orbit with period $P = 974 \pm 39$ days and eccentricity $e = 0.34 \pm 0.09$. The velocity zero-point of the two datasets is a free parameter, and the difference between them is $\Delta_{\rm S-E} = 93 \pm 17$ m s^{-1}.

The top panel of Fig. 3 shows the radial velocities of this star together with the best Keplerian solution. The bottom panel of the same figure shows the residuals around the adopted solution, for which the weighted rms is $\sigma_E = 12.1$ m s^{-1} for ELODIE, $\sigma_S = 4.1$ m s^{-1} for SOPHIE, and $\sigma_{ES} = 7.5$ m s^{-1} for the combined set of measurements. HD 132406 is slightly fainter than HD 43691, but has smaller photon-noise errors, which is probably due to broader line profiles of HD 43691. Table 4 lists the orbital elements and the planetary parameters of the HD 132406 system, which was obtained with the best Keplerian fit.

As in the case of the star HD 43691, no correlation between the BIS values and the observed radial velocities is found for HD 132406 (Fig. 4). In addition, no chromospheric reemission is observed in the core of the Ca II absorption line at λ3968.5 Å.

5. Discussion and conclusions

In this paper we have announced the discovery of two new planet candidates resulting from our ELODIE search programme biased towards metal-rich stars. In this programme, a total of six planets have been discovered thus far, out of which four are Hot Jupiters ($P < 10$ days) and two are the intermediate-period planets presented here. Five of the host stars have metallicity greater than 0.1 dex, while the one with a transiting very Hot Jupiter (HD 189733) is a solar-metallicity star.

So far, we have observed almost 82% of the 1061 sample stars at least once, and for each one we estimated a value for metallicity. We have verified that about 26% of the observed stars have [Fe/H] ≥ 0.1 dex (about 15% for 0.1 ≤ [Fe/H] < 0.2, 8% for 0.2 ≤ [Fe/H] < 0.3, and 3% for 0.3 ≤ [Fe/H] < 0.4). Furthermore, according to the percentage of stars with planets per metallicity bin determined by Santos et al. (2004), 10−30% of the stars with [Fe/H] ≥ 0.1 dex are likely to host a giant planet (about 9, 24 and 28% respectively for the same three ranges of metallicity mentioned above). Applying these percentages to the

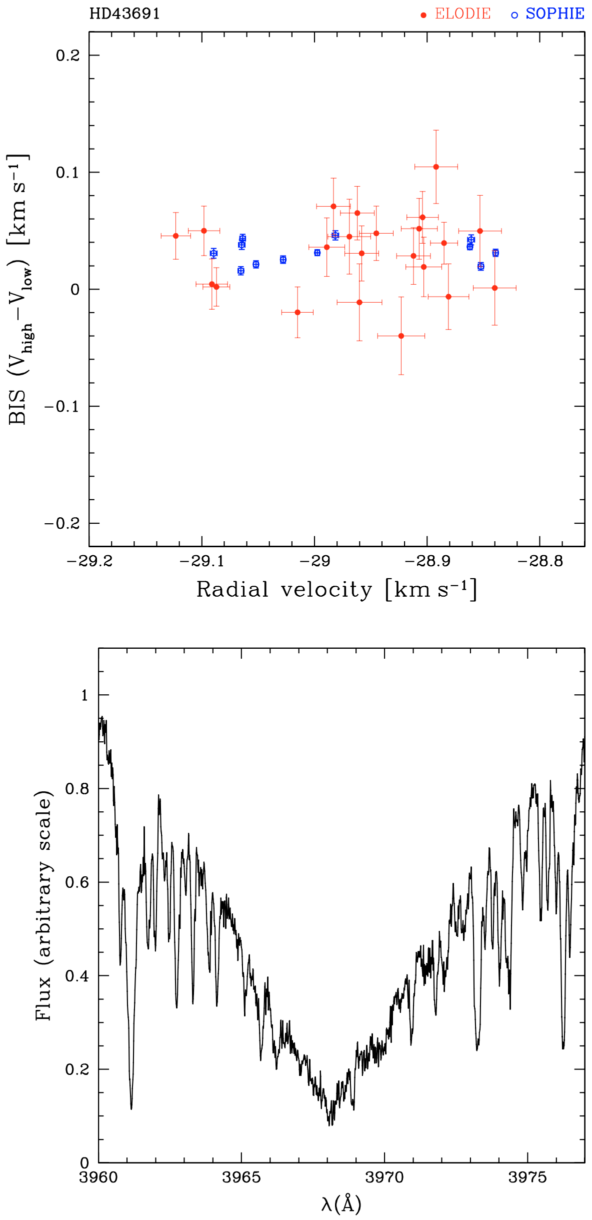

Fig. 2. *Top*: Comparison between bisector inverse slope (BIS) and radial velocities of HD 43691 showing no correlation between them for both ELODIE and SOPHIE measurements. *Bottom*: λ3968.5 Å Ca II absorption line region of the high S/N spectrum obtained for HD 43691. No clear emission feature is observed in the centre of this line, indicating a low activity level.

867 observed stars, we conclude that the number of giant planets we expect to discover in each of those metallicity ranges is 12, 17 and 7 respectively, a total of 36 planets, from which roughly 25% (9 planets) are predicted to be Hot Jupiters.

Although most of our target stars were already observed, only 75% of the metal-rich stars have a minimum of three measurements. Stars with one or two spectra need more observations before being rejected or classified as possible planet hosts. On the other hand, long-period planets are more difficult to detect, and stars showing long-term radial-velocity trends also need more observations. In any case, we have already found almost a half of the expected number of Hot Jupiters among the metallic portion of our sample.

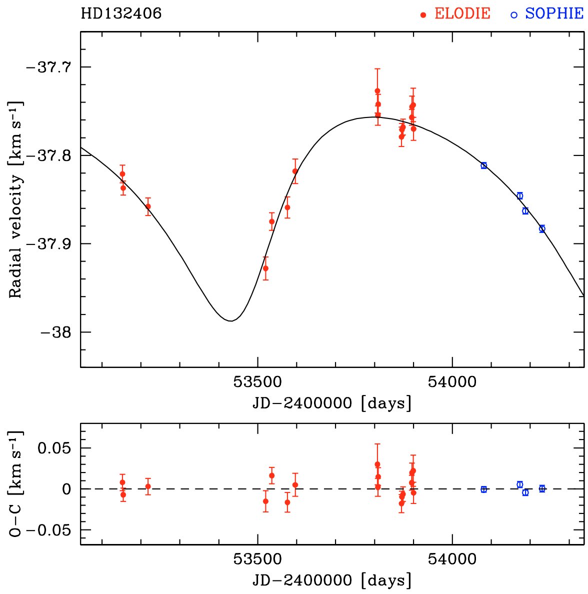

Fig. 3. *Top*: ELODIE and SOPHIE radial velocities of HD 132406 plotted together with the adopted Keplerian solution that better fits the combined measurements. *Bottom*: Residuals around the solution, with σ_E = 12.1 m s^{-1} for ELODIE, σ_S = 4.1 m s^{-1} for SOPHIE, and σ_{ES} = 7.5 m s^{-1} for the combined data points. Error bars represent the photon-noise errors.

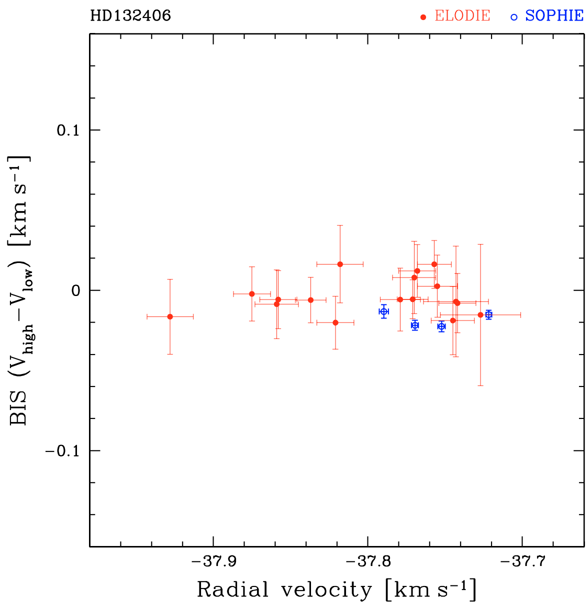

Fig. 4. Comparison BIS and radial velocities of HD 132406 showing no correlation between them. Both ELODIE and SOPHIE measurements are plotted.

The stars presented in this paper were also observed using the new SOPHIE spectrograph. The proposed orbital solutions, first found with ELODIE, were improved with the new observations. With ELODIE decommissioned, this new instrument will also continue monitoring other high-metallicity stars, especially the most promising cases.

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