

# ELODIE metallicity-biased search for transiting Hot Jupiters<sup>★</sup>

## V. An intermediate-period Jovian planet orbiting HD 45652

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Received 15 January 2008 / Accepted 30 April 2008

### ABSTRACT

We present the detection of a  $0.47 M_{\text{Jup}}$  planet in a 44-day period eccentric trajectory ( $e = 0.39$ ) orbiting the metal-rich star HD 45652. This planet, the seventh giant planet discovered in the context of the ELODIE metallicity-biased planet search program, is also confirmed using higher precision radial-velocities obtained with the CORALIE and SOPHIE spectrographs. The orbital period of HD 45652b places it in the middle of the “gap” in the period distribution of extra-solar planets.

**Key words.** stars: individual: HD 45652 – stars: planetary systems – planetary systems: formation – techniques: radial velocities – stars: fundamental parameters

## 1. Introduction

More than 280 exoplanets have been found orbiting solar-type stars, most of them discovered using radial-velocity techniques (for a review see Udry & Santos 2007)<sup>1</sup>. In about 40 cases, the discovered planets are known to transit their host stars. The detection of a photometric signature of a transiting planet, when complemented with its dynamical detection by means of the radial-velocity technique, provides the possibility of deriving its mass, radius, and mean density (e.g. Charbonneau et al. 2000; Pont et al. 2005). These data provide invaluable information about the physical properties of the planet (e.g. its composition – Valencia et al. 2006; Fortney et al. 2007), as well as about its formation and evolution.

It is well known that the probability of finding a giant planet is a strongly rising function of stellar metallicity (Gonzalez 1998; Santos et al. 2004; Fischer & Valenti 2005). This correlation is generally accepted to reflect the higher probability of forming planets around stars with a higher dust content in the proto-planetary disk, and supports the core-accretion model for

giant planet formation (e.g. Ida & Lin 2004b; Benz et al. 2006; Matsuo et al. 2007)<sup>2</sup>.

Using the metallicity-giant planet relation, several programs are now searching for planets around high metal-content stars (e.g. Tinney et al. 2002; Fischer et al. 2005; Da Silva et al. 2006; Melo et al. 2007). These programs mostly unveiled short-period planets (as expected due to their observing strategy), and increased the number of detected transiting planets orbiting bright stars (e.g. Sato et al. 2005; Bouchy et al. 2005).

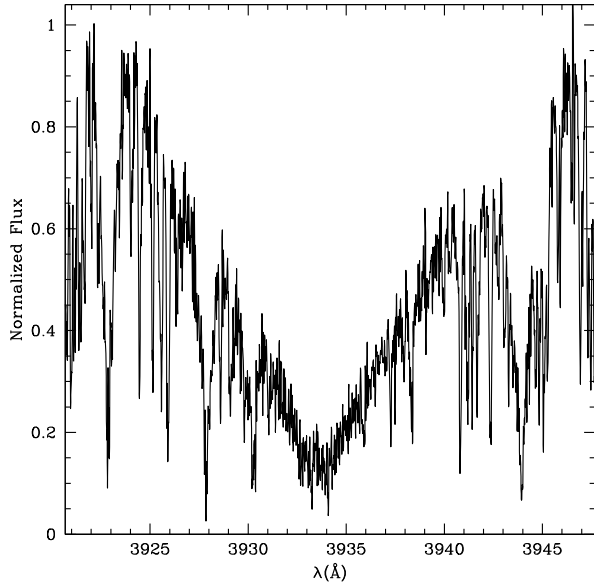
One of these programs was based on the former ELODIE spectrograph (Baranne et al. 1996), mounted on the 1.93-m telescope at the OHP observatory (for details of the program see Da Silva et al. 2006). The results of this survey were presented in a series of four papers (Da Silva et al. 2006; Bouchy et al. 2005; Moutou et al. 2006; Da Silva et al. 2007), announcing the discovery of 6 giant planets, one of which transits its star (HD 189733b).

In this paper, we announce the discovery of a  $\sim 0.5$  Jupiter-mass companion orbiting HD 45652, one star from the ELODIE metallicity-biased survey. In Sect. 2, we describe the stellar characteristics of HD 45652. In Sect. 3, we present the radial-velocity measurements used to detect HD 45652b, as well as the derived orbital solution and planetary characteristics. We present our conclusions in Sect. 4, discussing how this new

<sup>★</sup> Based on observations collected at the La Silla-Paranal Observatory, ESO (Chile) with the CORALIE spectrograph at the Euler 1.2-m Swiss Telescope, and with the ELODIE and SOPHIE spectrographs at the 1.93-m telescope of the Observatoire de Haute Provence (OHP), France.

<sup>1</sup> See updated tables at <http://www.exoplanets.eu> and <http://www.exoplanet.eu>

<sup>2</sup> See however recent discussion in Pasquini et al. (2007) and Hekker & Meléndez (2007).



**Fig. 1.** Spectral region of HD 45652 centered at the Ca II K line (CORALIE spectrum).

intermediate-period planet is placed in the general picture of giant-planet formation models.

## 2. Stellar properties of HD 45652

According to the SIMBAD database, HD 45652 (HIP 30905, BD +11 1197) is a high proper-motion  $V = 8.1$ , K5 star ( $B - V = 0.85$ ). In the Hipparcos catalogue (ESA 1997), the star is listed as having a parallax of  $\pi = 27.67 \pm 1.29$  mas, a value that implies a distance of  $36 \pm 2$  pc. No reference for a close companion to HD 45652 is mentioned in this catalogue, and no significant photometric variability was detected.

We used a high-resolution ( $R = 50\,000$ ) CORALIE spectrum with a signal-to-noise-ratio (S/N)  $\sim 100$  to derive the stellar parameters and metallicity of HD 45652, using the methodology described in Santos et al. (2004). The resulting effective temperature, surface gravity, and [Fe/H] are 5312 K, 4.32 dex, and +0.29 dex, respectively (see Table 1). These parameters are typical of a metal-rich main-sequence late-G or early-K dwarf, and slightly disagree with the spectral type of K5 listed in the Hipparcos catalogue (ESA 1997) and in SIMBAD. The above-mentioned temperature is also in good agreement with the value expected on the basis of its  $B - V$  colour and metallicity (5315 K, using the calibration presented in Santos et al. 2004), as well as with other temperature estimates in the literature, namely by Strassmeier et al. (2000,  $T_{\text{eff}} = 5150$  K), Allende Prieto & Lambert (1999,  $T_{\text{eff}} = 5370$  K), and Robinson et al. (2007,  $T_{\text{eff}} = 5349$  K).

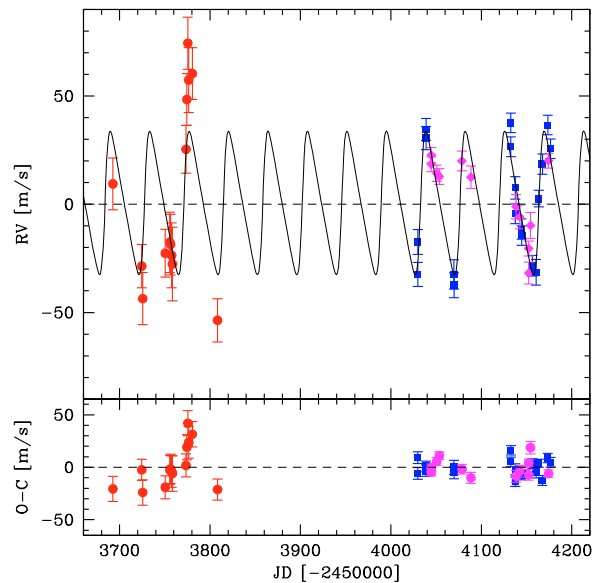
Using stellar evolution tracks from Schaerer et al. (1993), we derived a stellar mass of  $0.83 \pm 0.05 M_{\odot}$ , and an age above 12 Gyr for HD 45652. Strassmeier et al. (2000) classified this star as chromospherically non-active, in agreement with its derived age. From SOPHIE spectra, we also derived a value of  $\log R'_{\text{HK}} = -4.90 \pm 0.10$ . The low activity level is confirmed by an inspection of the center of the Ca II H and K line regions (see Fig. 1). Such a low level of activity is also compatible with the low value of projected rotational velocity ( $v \sin i < 2 \text{ km s}^{-1}$ ) as derived from the Cross-Correlation Function (CCF) of the ELODIE spectra (Table 1).

**Table 1.** Stellar parameters for HD 45652.

Parameter	Value	Reference
Spectral type	K5/G8-K0	Hipparcos/This Paper
$m_v$	8.1	Hipparcos
$B - V$	0.85	Hipparcos
Distance [pc]	$36 \pm 2$	Hipparcos
$v \sin i$ [ $\text{km s}^{-1}$ ]	$< 2^{\dagger}$	This paper
$\log R'_{\text{HK}}$	$-4.90 \pm 0.10^{\dagger\dagger}$	This paper
$T_{\text{eff}}$ [K]	$5312 \pm 68$	This paper
$\log g$ [cgs]	$4.32 \pm 0.21$	This paper
$\xi_t$	$0.89 \pm 0.09$	This paper
[Fe/H]	$+0.29 \pm 0.07$	This paper
Mass [ $M_{\odot}$ ]	$0.83 \pm 0.05$	This paper

$^{\dagger}$  From ELODIE spectra using a calibration similar to that presented by Santos et al. (2002).

$^{\dagger\dagger}$  From SOPHIE spectra using a calibration similar to that presented by Santos et al. (2000).

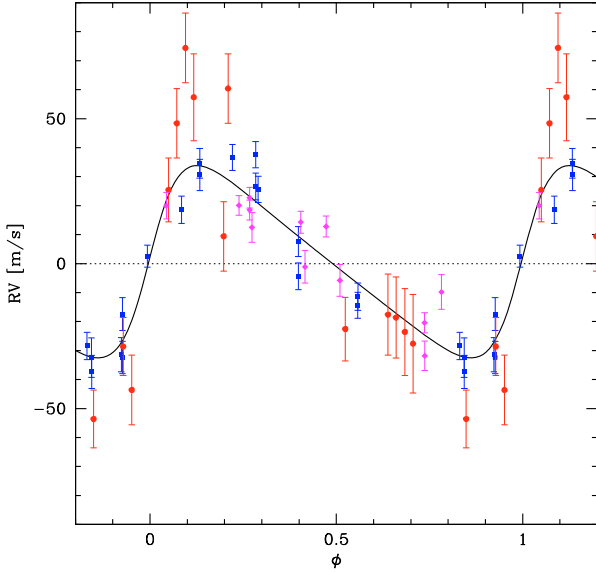


**Fig. 2.** Top: ELODIE (red circles), CORALIE (blue squares), and SOPHIE (magenta diamonds) radial-velocities for HD 45652 as a function of time, and the best-fit Keplerian function to the data. Bottom: residuals of the fit.

## 3. A giant planet orbiting HD 45652

HD 45652 was part of the ELODIE metallicity-biased planet search sample (Da Silva et al. 2006). A series of 14 radial velocities were obtained with this instrument between October 2005 and March 2006 (Table 3), using the 1.93-m telescope at the Observatoire de Haute Provence (France). The data showed the presence of a clear radial-velocity variation, although the time coverage of the data did not allow us to confirm the nature of the observed signal. The average photon-noise error of the measurements is  $12.6 \text{ m s}^{-1}$ .

HD 45652 was then monitored using the CORALIE spectrograph, at the Euler 1.2-m Swiss telescope (La Silla observatory, ESO, Chile – between October 2006 and March 2007), and with the SOPHIE spectrograph, at the 1.93-m OHP telescope (France – between November 2006 and March 2007). The average photon-noise error of the 18 CORALIE and 12 SOPHIE radial-velocities is  $5.5 \text{ m s}^{-1}$  and  $4.4 \text{ m s}^{-1}$ , respectively. Both sets of higher quality radial-velocities obtained (Table 3) confirm our earlier results, showing a clear radial-velocity signal (Fig. 2).



**Fig. 3.** Phase-folded ELODIE, CORALIE, and SOPHIE radial velocities for HD 45652 at a period of 43.6 days. Symbols are as in Fig. 2.

**Table 2.** Elements of the fitted orbit for HD 45652b, derived using the ELODIE, CORALIE, and SOPHIE data.

$P$	$43.6 \pm 0.2$	[d]
$T$	$2\,454\,120.3 \pm 1.2$	[d]
$a$	0.23	[AU]
$e$	$0.38 \pm 0.06$	
$V_r$ (ELODIE)	$-5.117 \pm 0.006$	[km s <sup>-1</sup> ]
$V_r$ (CORALIE)	$-5.044 \pm 0.002$	[km s <sup>-1</sup> ]
$V_r$ (SOPHIE)	$-4.999 \pm 0.002$	[km s <sup>-1</sup> ]
$\omega$	$273 \pm 12$	[degr]
$K_1$	$33.1 \pm 2.5$	[m s <sup>-1</sup> ]
$\sigma(\text{O-C})$	8.9	[m s <sup>-1</sup> ]
$N$	44	
$m_2 \sin i$	0.47	[ $M_{\text{Jup}}$ ]

The combined ELODIE, CORALIE, and SOPHIE radial-velocity measurements are best fitted using a Keplerian function with a semi-amplitude  $K = 33 \text{ m s}^{-1}$ , an eccentricity  $e = 0.38$ , and a period  $P = 43.6$  days (see Figs. 2 and 3, and Table 2). The residuals around the fit ( $8.9 \text{ m s}^{-1}$ ) are within the expected value given the photon-noise errors of the data. Monte Carlo simulation results shows that the false-alarm probability is only 0.1%. The observed Keplerian fit corresponds to the expected radial-velocity variation induced by the presence of a giant planet with a minimum mass of  $0.47 M_{\text{Jup}}$ , orbiting HD 45652 in an eccentric orbit with a semi-major axis of 0.23 AU.

A similar orbital solution is obtained if we use only the CORALIE and SOPHIE data to derive the best-fit Keplerian function (similar orbital parameters are obtained, within the errors). The observed residuals are smaller in this case ( $7.4 \text{ m s}^{-1}$ ).

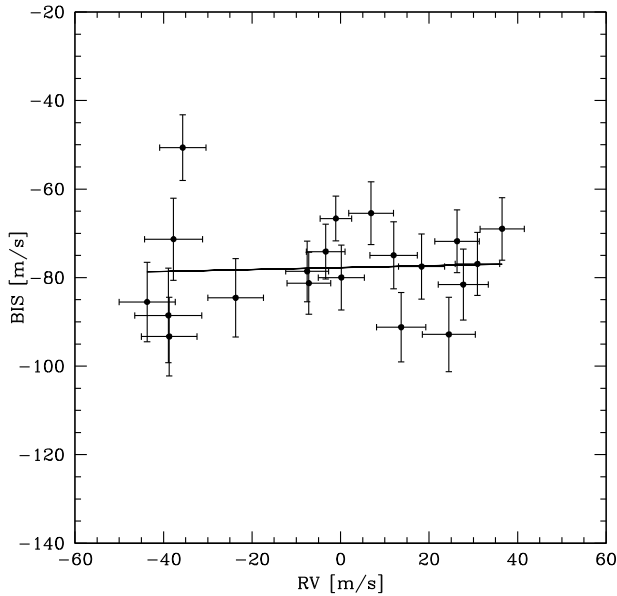
A look at the residuals of the Keplerian function fitting (Fig. 2) suggests that the adopted orbital solution does not well describe the ELODIE data. The observed residuals are probably due to the higher quality CORALIE and SOPHIE measurements which are then weighted more significantly than the ELODIE measurements when fitting the data. Since we do not have any overlap between the ELODIE and CORALIE datasets, it may be that the zero point of radial-velocity measurements for the different instruments is not well constrained. Alternatively, a second signal could be present in the data. A scrutiny of old CORAVEL

**Table 3.** ELODIE and CORALIE radial-velocity measurements of HD 45652.

JD	$V_r$ [km s <sup>-1</sup> ]	$\sigma(V_r)$ [km s <sup>-1</sup> ]
ELODIE		
2 453 692.65990	-5.108	0.012
2 453 724.51830	-5.146	0.010
2 453 725.52840	-5.161	0.012
2 453 750.52140	-5.140	0.011
2 453 755.52560	-5.135	0.014
2 453 756.46230	-5.136	0.014
2 453 757.49900	-5.141	0.015
2 453 758.44960	-5.145	0.017
2 453 773.45970	-5.092	0.011
2 453 774.42840	-5.069	0.012
2 453 775.42810	-5.043	0.012
2 453 776.41300	-5.060	0.015
2 453 780.42370	-5.057	0.012
2 453 808.29880	-5.171	0.010
CORALIE		
2 454 029.79264	-5.0607	0.0063
2 454 029.80422	-5.0757	0.0063
2 454 038.83579	-5.0093	0.0057
2 454 038.84718	-5.0125	0.0060
2 454 069.78922	-5.0759	0.0076
2 454 069.81454	-5.0807	0.0063
2 454 132.62897	-5.0005	0.0050
2 454 132.64037	-5.0107	0.0050
2 454 137.62078	-5.0233	0.0056
2 454 137.63218	-5.0301	0.0050
2 454 144.58745	-5.0442	0.0049
2 454 144.59885	-5.0368	0.0052
2 454 151.59608	-5.0445	0.0048
2 454 156.52101	-5.0726	0.0052
2 454 160.52499	-5.0747	0.0066
2 454 163.57158	-5.0404	0.0044
2 454 167.58467	-5.0250	0.0053
2 454 173.53990	-5.0061	0.0050
2 454 176.55337	-5.0187	0.0052
SOPHIE		
2 454 044.67360	-4.9763	0.0035
2 454 044.68380	-4.9805	0.0034
2 454 050.66630	-4.9847	0.0038
2 454 053.63090	-4.9862	0.0036
2 454 078.56860	-4.9790	0.0045
2 454 088.56780	-4.9865	0.0051
2 454 138.40400	-5.0001	0.0056
2 454 142.48580	-5.0048	0.0055
2 454 152.40650	-5.0194	0.0034
2 454 152.41540	-5.0308	0.0051
2 454 154.37280	-5.0088	0.0059
2 454 174.29350	-4.9789	0.0033

data, which has a precision of  $\sim 300 \text{ m s}^{-1}$ , does not uncover the existence of any long-term radial-velocity trend. We also studied the residuals of the Keplerian fit for the presence of a second significant low-amplitude signal in the data, without success. We thus do not endorse the idea that a second signal is present.

Given the low projected rotational velocity and activity level of the star, we do not expect that activity-related phenomena could induce the observed periodic radial-velocity signal. Although not a fully effective diagnostic for stars rotating very slowly (Santos et al. 2003; Desort et al. 2007), an analysis of the CCF bisectors also lends support to this idea (Fig. 4). No significant correlation is found between the observed radial-velocity and the shape of the CCF denoted by a measurement of the Bisector Inverse Slope, BIS (defined as in Queloz et al. 2001).



**Fig. 4.** BIS versus radial-velocity for the CORALIE data of HD 45652. To demonstrate the nonexistence of a correlation, the vertical and horizontal scales were set to be identical. The best linear fit to the data is also shown. The slope of the fit has a non significant value of  $0.02 \pm 0.09$ .

The observed radial-velocity variation of HD 45652 is therefore best explained by the presence of a planetary-mass companion in a  $\sim 44$ -day period orbit.

#### 4. Discussion and concluding remarks

Statistical studies of the properties of observed extra-solar planets have shown that the orbital period distribution is characterized by a well-defined peak for  $P < 10$ -days, followed by some sort of period valley for values of  $P$  up to  $\sim 100$  days. Above this latter value, the distribution is again an increasing function of orbital period (Cumming et al. 1999; Udry et al. 2003; Udry & Santos 2007). The observed shape of the period distribution is predicted by some models of planet formation and evolution (Ida & Lin 2004a; Mordasini et al. 2007).

With an orbital period of  $\sim 44$ -days, HD 45652b is placed in the middle of the so-called period valley.

Interestingly, Burkert & Ida (2007) pointed out that the observed period valley is more pronounced for planets orbiting more massive stars (F-dwarfs with mass above  $\sim 1.2 M_{\odot}$ ). Furthermore, the period gap appears to be more significant for the higher mass planets ( $> 0.8 M_{\text{Jup}}$ ). Burkert & Ida (2007) attributed this observation to shorter timescales of disk depletion for higher-mass stars.

HD 45652b, a  $0.47 M_{\text{Jup}}$  planet with an orbital period of  $\sim 44$  days orbiting a  $0.83 M_{\odot}$  star perfectly fits this scenario.

*Acknowledgements.* We thank the Swiss National Research Foundation (FNRS) and the Geneva University for their continuous support to our planet search programmes. N.C.S. would like to thank the support from Fundação para a Ciência e a Tecnologia, Portugal, in the form of a grant (references POCI/CTE-AST/56453/2004 and PPCDT/CTE-AST/56453/2004), and through programme Ciência 2007 (C2007-CAUP-FCT/136/2006). The support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES – Brazil) to R.D.S. in the form of a scholarship is gratefully acknowledged as well. We acknowledge support from the French National Research Agency (ANR) through project grant NT05-4\_44463.

#### References

- Allende Prieto, C., & Lambert, D. L. 1999, *A&A*, 352, 555  
 Baranne, A., Queloz, D., Mayor, M., et al. 1996, *A&AS*, 119, 373  
 Benz, W., Mordasini, C., Alibert, Y., & Naef, D. 2006, in *Tenth Anniversary of 51 Peg-b: Status of and prospects for hot Jupiter studies*, ed. L. Arnold, F. Bouchy, & C. Moutou, 24  
 Bouchy, F., Udry, S., Mayor, M., et al. 2005, *A&A*, 444, L15  
 Burkert, A., & Ida, S. 2007, *ApJ*, 660, 845  
 Charbonneau, D., Brown, T., Latham, D., & Mayor, M. 2000, *ApJ*, 529, L45  
 Cumming, A., Marcy, G. W., & Butler, R. P. 1999, *ApJ*, 526, 890  
 Da Silva, R., Udry, S., Bouchy, F., et al. 2006, *A&A*, 446, 717  
 Da Silva, R., Udry, S., Bouchy, F., et al. 2007, *A&A*, 473, 323  
 Desort, M., Lagrange, A.-M., Galland, F., Udry, S., & Mayor, M. 2007, *A&A*, 473, 983  
 ESA 1997, *The Hipparcos and Tycho Catalogues*  
 Fischer, D. A., & Valenti, J. 2005, *ApJ*, 622, 1102  
 Fischer, D. A., Laughlin, G., Butler, P., et al. 2005, *ApJ*, 620, 481  
 Fortney, J. J., Marley, M. S., & Barnes, J. W. 2007, *ApJ*, 659, 1661  
 Gonzalez, G. 1998, *A&A*, 334, 221  
 Hekker, S., & Meléndez, J. 2007, *A&A*, 475, 1003  
 Ida, S., & Lin, D. N. C. 2004a, *ApJ*, 604, 388  
 Ida, S., & Lin, D. N. C. 2004b, *ApJ*, 616, 567  
 Matsuo, T., Shibai, H., Ootsubo, T., & Tamura, M. 2007, *ApJ*, 662, 1282  
 Melo, C., Santos, N. C., Gieren, W., et al. 2007, *A&A*, 467, 721  
 Mordasini, C., Alibert, Y., Benz, W., & Naef, D. 2007, *ArXiv e-prints*, 710  
 Moutou, C., Loeillet, B., Bouchy, F., et al. 2006, *A&A*, 458, 327  
 Pasquini, L., Döllinger, M. P., Weiss, A., et al. 2007, *A&A*, 473, 979  
 Pont, F., Bouchy, F., Melo, C., et al. 2005, *A&A*, 438, 1123  
 Queloz, D., Henry, G. W., Sivan, J. P., et al. 2001, *A&A*, 379, 279  
 Robinson, S. E., Ammons, S. M., Kretke, K. A., et al. 2007, *ApJS*, 169, 430  
 Santos, N. C., Mayor, M., Naef, D., et al. 2000, *A&A*, 361, 265  
 Santos, N. C., Mayor, M., Naef, D., et al. 2002, *A&A*, 392, 215  
 Santos, N. C., Udry, S., Mayor, M., et al. 2003, *A&A*, 406, 373  
 Santos, N. C., Israelian, G., & Mayor, M. 2004, *A&A*, 415, 1153  
 Sato, B., Fischer, D. A., Henry, G. W., et al. 2005, *ApJ*, 633, 465  
 Schaefer, D., Charbonnel, C., Meynet, G., Maeder, A., & Schaller, G. 1993, *A&AS*, 102, 339  
 Strassmeier, K., Washuettl, A., Granzer, T., Scheck, M., & Weber, M. 2000, *A&AS*, 142, 275  
 Tinney, C. G., Butler, R. P., Marcy, G. W., et al. 2002, *ApJ*, 571, 528  
 Udry, S., & Santos, N. 2007, *ARA&A*, 45, 397  
 Udry, S., Mayor, M., & Santos, N. 2003, *A&A*, 407, 369  
 Valencia, D., O’Connell, R. J., & Sasselov, D. 2006, *Icarus*, 181, 545