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The ELODIE survey for northern extra-solar planets

II. A Jovian planet on a long-period orbit around GJ 777 A[⋆,⋆⋆]

D. Naef[1], M. Mayor[1], S. G. Korzennik[2], D. Queloz[1], S. Udry[1], P. Nisenson[2], R. W. Noyes[2], T. M. Brown[3], J. L. Beuzit[4], C. Perrier[4], and J. P. Sivan[5]

[1] Observatoire de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA-02138, USA
[3] High Altitude Observatory/National Center for Atmospheric Research, 3450 Mitchell Lane, Boulder, 80307, USA
[4] Laboratoire d'Astrophysique, Observatoire de Grenoble, Université J. Fourier, BP 53, 38041 Grenoble, France
[5] Observatoire de Haute-Provence, 04870 St-Michel L'Observatoire, France

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Abstract. We present radial-velocity measurements obtained with the ELODIE and AFOE spectrographs for GJ 777 A (HD 190360), a metal-rich ([Fe/H] = 0.25) nearby ($d = 15.9$ pc) star in a stellar binary system. A long-period low radial-velocity amplitude variation is detected revealing the presence of a Jovian planetary companion. Some of the orbital elements remain weakly constrained because of the smallness of the signal compared to our instrumental precision. The detailed orbital shape is therefore not well established. We present our best fitted orbital solution: an eccentric ($e = 0.48$) 10.7–year orbit. The minimum mass of the companion is 1.33 $M_{\rm Jup}$.

Key words. techniques: radial velocities – stars: individual: GJ 777 A – stars: individual: HD 190360 – stars: planetary systems

1. Introduction

The *ELODIE Planet Search Survey* is a programme aiming at detecting planetary companions around Solar-type stars with the ELODIE echelle spectrograph (Baranne et al. 1996) mounted on the 193–cm Telescope of the Observatoire de Haute-Provence. Details about the programme and the surveyed sample have already been presented (Mayor & Queloz 1996; Perrier et al. 2003). Several planets have been detected by this survey (see Perrier et al. 2003, and references therein).

Four extra-solar planets have been discovered or codiscovered by the the Advanced Fiber-Optic Echelle spectrometer (AFOE, Brown et al. 1994) planet search team (Korzennik et al. 1998): ρ CrB b (Noyes et al. 1997); Ups And c and d (Butler et al. 1999) and HD 89744 b (Korzennik et al. 2000).

In 1997, our two teams decided to start a collaboration on a sample of about 20 stars present in both observing lists and having a similar radial-velocity precision of the order of 10 m s^{-1}. The detection of the low-amplitude radial-velocity variability of GJ 777 A and the characterisation of the planetary companion responsible for these variations are the first results of our common effort.

A preliminary ELODIE orbital solution was presented in Udry et al. (2003b). In Sect. 3, we present our combined radial-velocity data and the updated orbital solution. We also examine and rule out alternative explanations for the origin of the observed radial-velocity variation.

2. Stellar properties

The main stellar properties of GJ 777 A are listed in Table 1. Spectral Type, m_V, $B-V$, π, $\mu_\alpha\cos(\delta)$ and μ_δ are from the HIPPARCOS Catalogue (ESA 1997). The effective temperature $T_{\rm eff}$, the surface gravity $\log g$, the metallicity [Fe/H] and the microturbulence velocity $\xi_{\rm t}$ are taken from Santos et al. (2003). M_* is the stellar mass derived from these atmospheric parameters using the Geneva evolutionary models (Schaerer et al. 1993). The bolometric correction *B.C.* is computed from the effective temperature with the calibration in Flower (1996).

The star does not appear to be active. We do not see any trace of emission in the core of the λ 3968.5 Å Ca II H line

Send offprint requests to: D. Naef,
e-mail: dominique.naef@obs.unige.ch

⋆ Based on observations made with the ELODIE echelle spectrograph mounted on the 1.93-m Telescope at the Observatoire de Haute-Provence (CNRS) and with the AFOE spectrograph mounted on the 1.5-m Telescope at the Fred Lawrence Whipple Observatory (SAO).

⋆⋆ The ELODIE and AFOE measurements discussed in this paper are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/410/1051

Table 1. Observed and inferred stellar parameters for GJ 777 A.

HD		190 360
HIP		98 767
Sp. Type		G6IV
m_V		5.73
$B-V$		0.749 ± 0.001
π	(mas)	69.92 ± 0.62
Distance	(pc)	15.89 ± 0.16
$\mu_\alpha \cos(\delta)$	(mas yr^{-1})	683.32 ± 0.42
μ_δ	(mas yr^{-1})	−524.06 ± 0.51
M_V		4.72
$B.C.$		−0.1175
L	($L_\odot$)	1.13
$T_{\rm eff}$	(K)	5590 ± 50
[Fe/H]		0.25 ± 0.05
$\log g$	(cgs)	4.48 ± 0.15
$\xi_{\rm t}$	(km s^{-1})	1.06 ± 0.10
$\log R'_{\rm HK}$		−5.05
$P_{\rm rot}$	(d)	38
age(HK)	(Gyr)	6.7
$v \sin i$	(km s^{-1})	<1
R_*	($R_\odot$)	1.13
M_*	($M_\odot$)	0.96

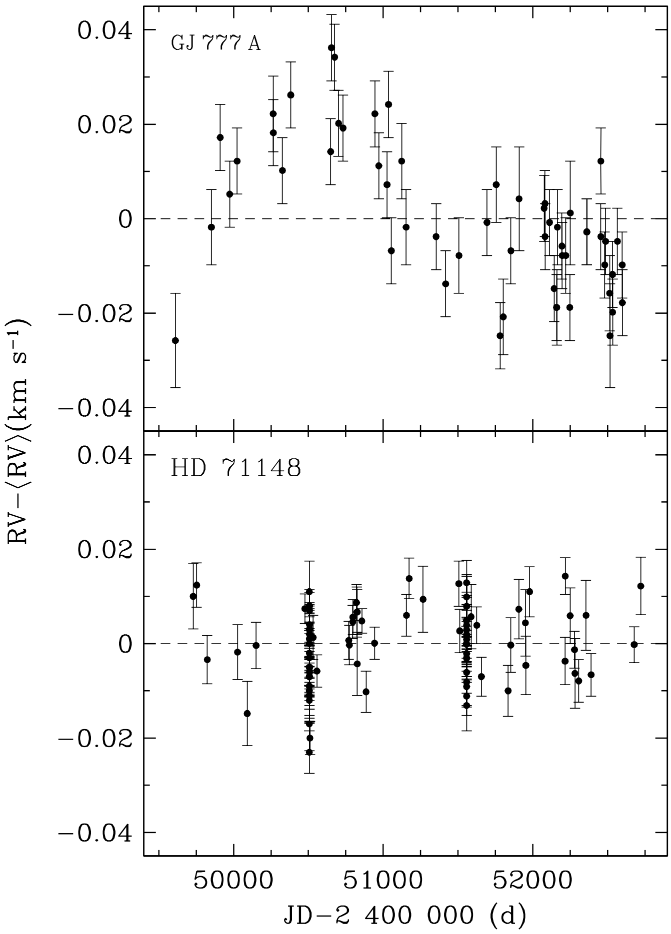

Fig. 1. ELODIE data. *Top*: $RV - \langle RV \rangle$ for GJ 777 A. *Bottom*: residuals of HD 71148, a radial-velocity constant G5V star. The residuals slope is compatible with zero whereas a clear trend is seen for GJ 777 A. This demonstrates that the GJ 777 A radial-velocity signal does not result from some undesirable instrumental effect.

on our ELODIE coadded spectra. A $\log R'_{\rm HK} = -5.05$ chromospheric activity indicator is computed from the S chromospheric flux indexes in Duncan et al. (1991). The rotation period $P_{\rm rot}$ and age(HK) are derived from the activity indicator using the calibrations in Noyes et al. (1984) and Donahue (1993)[1], respectively. The rotational broadening measured for GJ 777 A from ELODIE cross-correlation function widths is very small. It only allows us to derive an upper limit for the projected rotational velocity: $v \sin i < 1$ km s^{-1}. The radius R_* is computed from L and $T_{\rm eff}$. With a measured HIPPARCOS photometric scatter of 7 mmag, GJ 777 A is flagged as a constant star.

GJ 777 B, a 14.4-mag M4.5 companion about 3′ away, is mentioned in the *Catalogue of Nearby Stars* (Gliese 1969). Recent proper motions determinations by Bakos et al. (2002) give $\mu_\alpha \cos(\delta) = 737$ mas yr^{-1} and $\mu_\delta = -551$ mas yr^{-1} for this object. These values are close to the proper motions quoted in Table 1 for GJ 777 A, thus these two stars probably form a physical pair. The separation between A and B computed from the revised coordinates in Bakos et al. (2002) is $\rho = 177''$. The minimum semi-major axis, $a_{\rm min} = 0.5\rho/\pi$, is 1266 AU for the GJ 777 AB binary. This leads to a minimum period of the order of 40 000 yr (assuming $M_{\rm A} = 0.96\,M_\odot$ and $M_{\rm B} = 0.3\,M_\odot$).

3. Radial-velocity data and orbital solution

Between JD = 2 449 611 (September 1994) and JD = 2 452 598 (November 2002), 56 ELODIE and 13 AFOE radial-velocity measurements have been gathered. The method used for extracting precise velocities from the observed spectra is described in Baranne et al. (1996) and Perrier et al. (2003) for ELODIE and in Noyes et al. (1997) for AFOE. The mean radial-velocity uncertainty achieved for GJ 777 A is $\langle \epsilon_{\rm RV} \rangle = 7.5$ m s^{-1} with ELODIE and $\langle \epsilon_{\rm RV} \rangle = 9.7$ m s^{-1} with AFOE. The rms of the radial velocities is 15.2 m s^{-1} (18.2 m s^{-1}) for ELODIE (AFOE). The χ^2 probability for hypothesis of constant velocities is less than 5×10^{-4} for both instruments so GJ 777 A is clearly a radial-velocity variable.

GJ 777 A is a slowly rotating, chromospherically quiescent star. The expected stellar-activity induced radial-velocity signal is therefore very low. Even so, we checked the stability of the line bisectors using the method presented in Queloz et al. (2001). Our ELODIE bisectors were found to be constant without any trace of correlation with the radial velocities. The effect of long-period magnetic activity cycles on radial-velocity measurements is still not well known. The possibility that this kind of phenomenon is responsible for the observed long-period signal cannot be rejected for the moment. Accurate studies of this problem will be soon performed with the new HARPS spectrograph on the 3.6-m Telescope at ESO–La Silla Observatory, especially designed for high-precision radial-velocity measurements (Pepe et al. 2002).

We also checked the radial-velocity signal against instrumental effects. Figure 1 shows a comparison between the observed GJ 777 A signal and the residuals for HD 71148, a G5V

[1] Also quoted in Henry et al. (1996).

Table 2. Combined ELODIE (E) + AFOE (A) orbital solution for Gl 777 A. $\sigma_{\rm O-C}$ is the weighted rms of the residuals. $\chi^2_{\rm red}$ is the reduced χ^2 value (χ^2/ν where ν is the number of degrees of freedom).

P	(days)	3902 ± 1758
T	(JD[†])	50 557 ± 89
e		0.48 ± 0.20
γ	(km s^{-1})	−45.350 ± 0.004
w	(°)	361 ± 13
K_1	(km s^{-1})	0.020 ± 0.003
$\Delta RV_{\rm E-A}$	(km s^{-1})	−45.143 ± 0.003
$a_1 \sin i$	(10^{-3} AU)	6.3 ± 2.7
$f_1(m)$	(10^{-9} $M_\odot$)	2.22 ± 0.94
$m_2 \sin i$	($M_{\rm Jup}$)	1.33 ± 0.19
a	(AU)	4.8
$d_{\rm min}$[‡]	(AU)	2.5
$d_{\rm max}$[♮]	(AU)	7.1
N		69
$N_{\rm E}$		56
$N_{\rm A}$		13
$\sigma_{\rm O-C}$	(m s^{-1})	9.3
$\sigma_{\rm O-C,E}$	(m s^{-1})	9.1
$\sigma_{\rm O-C,A}$	(m s^{-1})	10.4
$\chi^2_{\rm red}$		1.69

[†] = JD−2 400 000 [‡] at periastron [♮] at apastron.

non-variable star. The rms of the 98 HD 71148 residuals is 7.8 m s^{-1} and their fitted slope is compatible with zero. The detected signal for GJ 777 A is not seen for this comparison star.

The fitted orbital elements to the combined ELODIE and AFOE radial velocities are presented in Table 2. The AFOE velocity zero-point is arbitrary so we also adjust the radial-velocity offset between the two instruments: $\Delta RV = RV_{\rm ELODIE} - RV_{\rm AFOE}$. Some of the parameters are weakly constrained. This is specially the case for the period and the eccentricity. The time span of the ELODIE measurements is 2987 d, a value smaller than the derived period. This causes a significant uncertainty in P. We can see in Fig. 2 that the radial-velocity maximum is not perfectly covered. This probably increases the derived eccentricity. With these orbital elements and assuming 0.96 $M_\odot$ for the primary star mass, we compute a minimum mass of 1.33 $M_{\rm Jup}$ for GJ 777 Ab and an orbital semi-major axis of 4.8 AU. As GJ 777 A is close to the Sun ($d = 15.9$ pc), its projected orbital semi-major axis is relatively large: $a_1 \sin i \simeq 0.4$ mas on the sky. This system is thus an easy target for the future interferometric astrometric facilities (VLTI, SIM).

We also computed the orbital solution using the ORBIT software described in Forveille et al. (1999). The resulting orbital elements were in full agreement with the values in Table 2. This software also allowed us to check the fit errors by performing Monte Carlo simulations. The output of these simulations are 68% confidence level (i.e. 1 σ) intervals for each parameter. As expected, the error in P is largely asymmetric: +4700/−965 d. This is also the case for the error in e: +0.23/−0.14. The Monte Carlo errors in the other parameters are rather symmetric but sometimes slightly larger than the errors obtained from the fit. This is particularly the case for T where the Monte Carlo error is ±118 d.

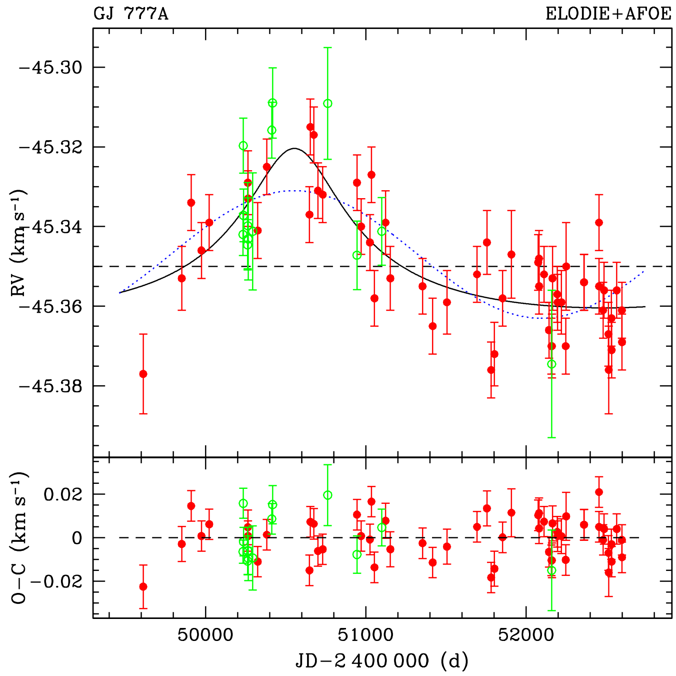

Fig. 2. *Top*: ELODIE (filled circles) and AFOE (open circles) temporal velocities. The fitted eccentric orbit is shown (solid line). The radial-velocity maximum is not well covered. This probably tends to artificially increase the fitted eccentricity. The fitted circular orbit (dotted line) is also plotted for comparison. *Bottom*: residuals to the fitted eccentric orbit.

We see from the Monte Carlo simulations that a zero eccentricity is more than 3 σ away from the fitted value. We nevertheless tried to fit a circular orbital solution to the data. The residuals value obtained for this latter solution is 10.2 m s^{-1} a value that is not much larger than the eccentric orbit value. From these facts, we conclude that a circular orbit cannot be excluded with the available data but it is rather unlikely.

4. Concluding remarks

The number of detected extra-solar planets resembling Jupiter is slowly increasing with the duration of the different radial-velocity planet searches. What would be in our sense a real Jupiter analog? It would be a planet with a period not too different from $P_{\rm Jup}$ (say for example: $P_{\rm Jup} \pm 25\%$), a moderate eccentricity ($e < 0.2$), a mass close to one Jupiter mass (±50% for example). Moreover, this planet would have to be the innermost gas giant in the system. Table 3 lists the characteristics of the 4 best Jupiter-analog candidates (planets with $P > 2500$ d and $m_2 \sin i < 5\,M_{\rm Jup}$): ϵ Eri b (Hatzes et al. 2000); 47 UMa c (Fischer et al. 2002); GJ 777 Ab (this paper) and 55 Cnc d (Marcy et al. 2002). None of them matches all the criteria mentioned above.

The distributions of the orbital elements as well as the planet-mass distribution seem to be continuous so we do not see any reason why real Jupiter analogs would not eventually be detected.

Table 3. Comparison between Jupiter and the extra-solar planets having $P > 2500$ d and $m_2 \sin i < 5\,M_{\rm Jup}$. IGG is the Innermost Gas Giant flag (yes or no).

Name	P (yr)	e	m or $m \sin i$ ($M_{\rm Jup}$)	a (AU)	IGG
ϵ Eri b	7	0.43	0.92	3.40	y
47 UMa c	7.1	0.1	0.76	3.73	n
GJ 777 Ab	10.7	0.48	1.33	4.8	y
Jupiter	11.86	0.05	1	5.2	y
55 Cnc d	14.7	0.16	4.05	5.9	n

GJ 777 Ab is a planet in a stellar binary system. The number of extra-solar planets detected in multiple systems now approaches 20 (Eggenberger et al., in prep.). Although the sample of such planets is not large, some properties are now emerging. Significant differences between planets in multiple systems and planets orbiting single stars are found (Zucker & Mazeh 2002; Udry et al. 2003a). The study of planets in multiple systems is potentially very rich in information on formation scenarios and migration processes (Eggenberger et al., in prep.).

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