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LETTER TO THE EDITOR

Photometric and spectroscopic detection of the primary transit of the 111-day-period planet HD 80606 b⋆

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ABSTRACT

We report the detection of the primary transit of the extra-solar planet HD 80606 b, thanks to photometric and spectroscopic observations performed at Observatoire de Haute-Provence, simultaneously with the CCD camera at the 120-cm telescope and the *SOPHIE* spectrograph at the 193-cm telescope. We observed in both datasets the whole egress of the transit and partially its central part, with the same timings. The ingress occurred before sunset and was not observed. The full duration of the transit is between 9.5 and 17.2 hours. The data allows the planetary radius to be measured ($R_p = 0.86 \pm 0.10\,R_{Jup}$) and other parameters of the system to be refined. Radial velocity measurements show the detection of a prograde Rossiter-McLaughlin effect, and provide a hint for a spin-orbit misalignment. If confirmed, this misalignment would corroborate the hypothesis that HD 80606 b owes its unusual orbital configuration to Kozai migration. HD 80606 b is by far the transiting planet on the longest period detected today. Its radius reinforces the observed relationship between the planet radius and the incident flux received from the star. Orbiting a quite bright star ($V = 9$), it opens opportunities to numerous follow-up studies.

Key words. Planetary systems – Techniques: radial velocities – Techniques: photometry – Stars: individual: HD 80606

1. Introduction

The extra-solar planet HD 80606 b was discovered with the ELODIE spectrograph by Naef et al. (2001). This is a giant, massive planet ($4\,M_{Jup}$) with a 111-day orbital period, on an extremely eccentric orbit ($e = 0.93$). HD 80606 is a member of a common proper motion binary (HD 80606 - HD 80607) with a separation of ∼ 1200 AU (∼ 20″ on the sky). Wu & Murray (2003) suggested that the present orbit of HD 80606 b results from the combination of the Kozai mechanism (induced by the distant stellar companion) and tidal dissipation. Recently, Laughlin et al. (2009) report the detection of a secondary transit for HD 80606 b using 8 μm Spitzer observations around the periastron passage. This implies an inclination of the system near $i = 90°$, and a ∼ 15 % probability that the planet also shows primary transits.

If transits occur, opportunities to detect them are rare as the orbital period of the planet is almost four months. We managed an observational campaign to attempt the detection of the transit of HD 80606 b scheduled to happen on Valentine's day (Feb. 14th, 2009). We simultaneously used instruments of two telescopes of Observatoire de Haute-Provence (OHP), France: the CCD camera at the 120-cm telescope, and the *SOPHIE* spectrograph at the 1.93-m telescope. This allows us to report the detection of the primary transit of HD 80606 b, in photometry as well as in spectroscopy through the Rossiter-McLaughlin effect.

We recall the stellar characteristics of the primary star, that we used in our analysis of the transit data presented hereafter: HD 80606 is a G5-type star with a parallax measured by Hipparcos of 17±5 mas. A compilation of spectroscopic data from the literature gives an effective temperature of 5574 ± 50 K, $\log g$ of 4.45 ± 0.05 and a high metallicity of 0.43 dex (Santos et al. 2004, Valenti &Fischer 2005). The stellar mass can be estimated using isochrones and we get $0.98 \pm 0.10\,M_\odot$. Using the relationship between luminosity, temperature, gravity and mass, the stellar luminosity is estimated $0.84 \pm 0.13\,L_\odot$. Finally, with the relation between radius and luminosity and temperature, we derive a radius of $0.98 \pm 0.07\,R_\odot$. These mean values are obtained after several iterations over mass and radius determination. The projected rotational velocity is $v \sin I = 1.8$ km/s (Valenti & Fischer 2005), hence the rotation period of the star is slow.

In the following, we discuss the full set of data that we have gathered on HD 80606: new photometric data, new radial-velocity measurements, as well as a combination of all available velocity data to further consolidate the orbital solution.

⋆ Based on observations made with the 1.20-m and 1.93-m telescopes at Observatoire de Haute-Provence (CNRS), France, by the *SOPHIE* consortium (program 07A.PNP.CONS).

2. The photometric transit of HD 80606b

Predicted epochs for the primary transit of HD 80606b were given by Laughlin et al. (2009). We carried observations around the expected transit epoch JD=2,454,876.5 with the 120-cm telescope at OHP, equipped with a 12 arcmin × 12 arcmin CCD camera. The Bessel R filter and a neutral density were inserted, to insure unsaturated focused images of the $V = 9$ target. We obtained 326 frames on 13 Feburary 2009 and 238 frames on the preceeding night, for comparison. Typical exposure times range are 60 sec on the first night and 20-30 sec on the second. Aperture photometry was then performed on both data sequences. Apertures of 8 and 6 pixels were used, for the first and second observing night, respectively. The secondary companion HD 80607 is taken as a reference for HD 80606. Both stars are separated by 24 pixels, which prevents contamination even using simple aperture photometry. The sky background is evaluated in rings of about 12-15 pixel radius. The resulting lightcurve is shown on Fig. 1 (upper panel), with all data included. The data quality is significantly better during the transit night, because of different seeing conditions. The *rms* is about 0.0025 to 0.0030 over the full time series.

An egress is clearly detected in the data sequence obtained on the night 13-14 February. A shift of almost one half transit is observed, in comparison to expected ephemeris. Long-term systematics are observed in the lightcurve, and removed by a polynomial function of the airmass, with the criterion of getting a flat section of the out-of-transit flux. This correction does not affect the transit shape. It is checked on the 12-13 February sequence that long-term fluctuations are low (not corrected for on Fig. 1). The beginning of the transit sequence unambiguously shows that we do not detect the ingress of the transit. The first hour of the sequence shows indications of a slight decrease but the data are quite noisy due to the low object's elevation and this may be introduced by the correction for airmass variations. We observe in total 7 hours during transit on the second night, and 3.4 hours after the transit. In addition, we gathered 9.8 hours out of transit on the first night.

Modelling the primary transit lightcurve of HD 80606 b is done in the first place using models of circular orbits, to constrain the inclination and the radius ratio. The Universal Transit Modeler 2008 is used, including the limb-darkening coefficients of Claret (2000) for the r' filter, and parameters of the orbits given in the next section. Fig. 1 and 2 show three transit models superimposed to the data, corresponding to impact parameter b ranging from 0 to 0.91 or inclinations ranging from 89.2 to 90.0 deg. The $O - C$ residuals depicted in Fig.2 correspond to an average transit duration of 13.5 hours, with $b = 0.75$ and *rms* of 0.0025. The transit depth imposes a radius ratio R_p/R_* of 0.090 ± 0.009. The planet radius is then estimated to be $0.86 \pm 0.10\,R_{Jup}$. In order to match the full transit lightcurve, a model including eccentricity would be required. The asymmetry of the ingress and egress should be detected and properly fitted, for instance. Since we have a partial transit, the approximation of the circular modelling is acceptable here, if one takes into account the relative projection of the transit angle and the line of sight. In a further study, we plan to investigate the modelling of the asymetric transit by including the eccentric orbit. We do not expect major differences compared to the simple fit performed here, before new, more complete photometric data are obtained.

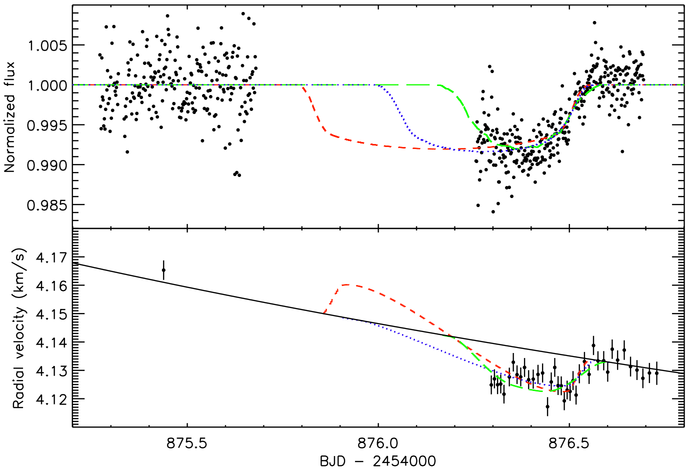

Fig. 1. Photometry (top) and radial velocities (bottom) of HD 80606 from 12th to 14th February, 2009, obtained at OHP with the 120-cm and 193-cm telescopes, respectively. The planetary transit is detected in both datasets at the same timing. *Top:* Superimposed are the two extreme ($b = 0$ in red-dashed, and $b = 0.91$ in green-long-dashed) and the mean (in blue-dotted, $b = 0.75$) models that correspond to our data set. *Bottom:* The orbital solution is overplotted (solid line, Table 1), together with Rossiter-McLaughlin effect models presented in Table 2, in red-dashed ($b = 0$, $\lambda = 0°$), blue-dotted ($b = 0.75$, $\lambda = 63°$), and green-long-dashed lines ($b = 0.91$, $\lambda = 80°$).

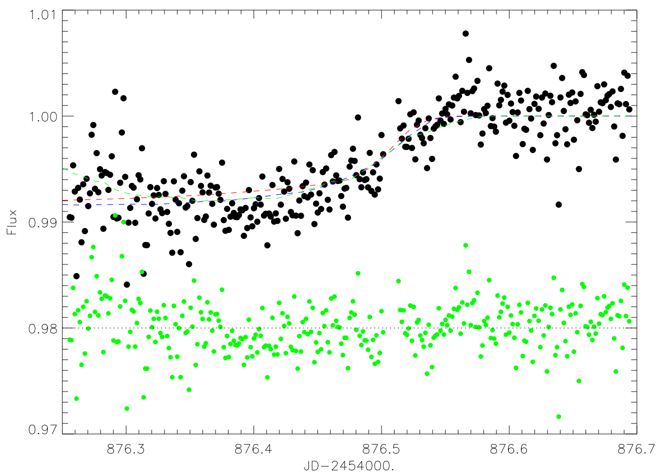

Fig. 2. Zoom-in plot on the photometric transit and the three models with the impact parameter ranging from 0 to 0.91. The residuals are shown below, with an offset of 0.02 on the Y-axis for clarity; they correspond to the mean model with $b = 0.75$.

3. The spectroscopic transit of HD 80606b

We observed HD 80606 with the *SOPHIE* instrument at the 1.93-m telescope of OHP. *SOPHIE* is a cross-dispersed, environmentally stabilized echelle spectrograph dedicated to high-precision radial velocity measurements (Bouchy et al. 2006; Perruchot et al. 2008). We used the high-resolution mode (resolution power $R = 75,000$) of the spectrograph and the fast-readout mode of the CCD detector. The two 3"-wide circular apertures (optical fibers) were used, the first one centered on the target and the second one on the sky to simultaneously measure its background.

This second aperture, 2' away from the first one, allows us to check that there is no significant pollution due to moonlight on the spectra of the target. We obtained 45 radial velocity measurements from 8th to 17th February, 2009, including a full sequence during the night 13th February (BJD = 54876), when the possible transit was expected to occur according to the ephemeris. The exposure times range from 600 to 1500 sec, insuring a constant signal-to-noise ratio. This observation was performed in parallel to the photometric ones.

The sequence of the transit night is plotted in Fig. 1, lower panel, together with the measurement secured the previous night. The Keplerian curve expected from the orbital parameters is overplotted. The radial velocities of the 13 February night are clearly blue-shifted by $\sim$ 10 m s^{-1} from the Keplerian curve in the first half of the night, then match the Keplerian curve in the second half of the night. This is the feature expected in case of transit of a planet on a prograde orbit, according to the Rossiter-McLaughlin (RM) effect. This effect occurs when an object transits in front of a rotating star, causing a spectral distortion of the stellar lines profile, and thus resulting in a Doppler-shift anomaly (see Ohta et al. 2005; Giménez et al. 2006b; Gaudi & Winn 2007).

On the RM feature of HD 80606 b (Fig. 1), the third and fourth contacts occurred at BJD $\simeq$ 54876.45 and BJD $\simeq$ 54876.55 respectively, whereas the first contact occurred before sunset, and was not observed. These timings agree with those of the photometry (Sect. 2 and Fig. 2); the detection of the Rossiter-McLaughlin anomaly is unambiguous.

The Keplerian curve in Fig. 1 corresponds to the orbital parameters that we refined for HD 80606 b. We used the *SOPHIE* measurements performed out of the transit, as well as 45 Keck measurements (Butler et al. 2006) and 74 ELODIE measurements (44 published by Naef et al. (2001) and 30 additional measurements obtained from BJD = 51977 to 52961). We allow free radial velocity shifts between the three datasets. We use the constraint of the secondary transit given by Laughlin et al. (2009) (T_e = 2 454 424.736 ± 0.003 HJD). We also use our constraint on the primary transit considering that the end of transit is T_{egress} = 2 454 876.55 ± 0.03 BJD. From these constraints, we estimated that the inclination of the system is from 90° (T_t = 2 454 876.20 BJD with 17.2 h duration) to 89.2° (T_t = 2 454 876.32 BJD with 9.4 h duration).

Assuming those constraints, we adjust the Keplerian orbit. The dispersion of the radial velocities around this fit is 8.6 m s^{-1}, and the reduced χ^2 is 1.4. The obtained parameters are reported in Table 1. They agree with those of Laughlin et al. (2009), except for the period, where there is a 3-σ disagreement. The full data set and orbital solution are plotted in Figs. 3 and 4.

To model the RM effect, we used the analytical approach developed by Ohta et al. (2005). The complete model has 12 parameters: the six standard orbital parameters, the radius ratio r_p/R_*, the orbital semi-major axis to stellar radius a/R_* (constrained by the transit duration), the sky-projected angle between the stellar spin axis and the planetary orbital axis λ, the sky-projected stellar rotational velocity $v \sin I$, the orbital inclination i, and the stellar limb-darkening coefficient ϵ. For our purpose, we used the orbital parameters and photometric transit parameters as derived previously. We fixed the linear limb-darkening coefficient ϵ = 0.78, based on Claret (2000) tables for filter g' and for the stellar parameters derived in Sect. 1. Our free parameters are then λ, $v \sin I$ and i. As we observed a partial transit, there is no way to put a strong constraint on the inclination i. We then decided to adjust λ for different value of i in the range 89.2 - 90 °. The results of our fits (Table 2 and Fig. 1, lower panel) first show that the stellar rotation is prograde relative to the planet orbit. Assuming i = 90° and λ = 0°, the projected rotation velocity of the star $v \sin I$ determined by our RM fit is 2.2 km s^{-1}. This agrees with the value 1.8 km s^{-1} obtained by Valenti & Fisher (2005) as well as our spectroscopic determination (2-3 km s^{-1}) from SOPHIE spectra. This latest one could be here slightly overestimated due to the high metallicity of HD 80606. We decided to fix this value and to explore the different values of inclination angle i to estimate the spin-orbit λ angle. We see in Table 2 that if the transit is not central, then the RM fit suggests that the spin-orbit angle is not aligned.

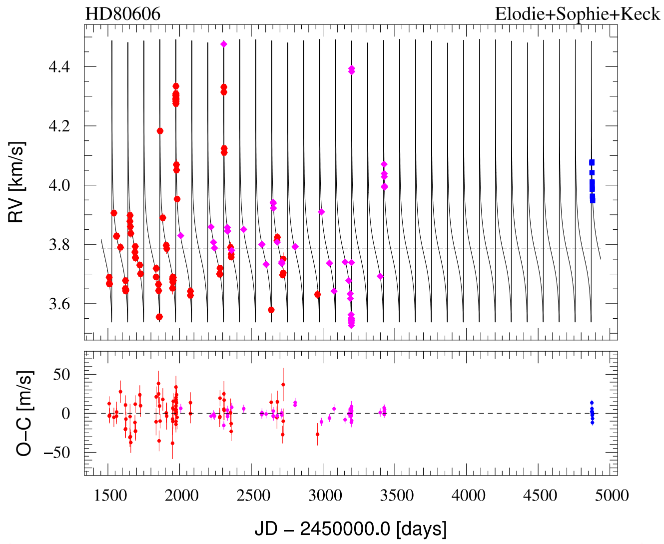

Fig. 3. *Top:* Radial velocity measurements of HD 80606 as a function of time, and Keplerian fit to the data. ELODIE data in red, Keck data in pink, *SOPHIE* data in blue. The orbital parameters corresponding to this fit are reported in Table 1. *Bottom:* Residuals of the fit with 1-σ error bars.

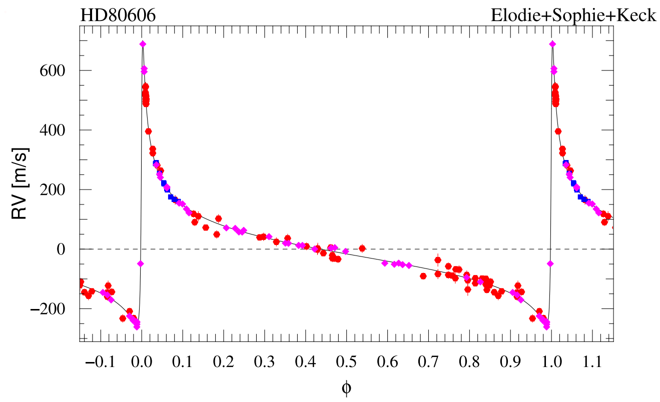

Fig. 4. Phase-folded radial velocity measurements of HD 80606 as a function of the orbital phase, and Keplerian fit to the data. ELODIE data in red, Keck data in pink, *SOPHIE* data in blue. Orbital parameters corresponding to this fit are reported in Table 1.

Table 1. Fitted orbit and planetary parameters for HD 80606 b.

Parameters	Values and 1-σ error bars	Unit
V_r (Elodie)	3.788 ± 0.002	km s^{-1}
V_r (*SOPHIE*)	3.911 ± 0.002	km s^{-1}
V_r (Keck)	–	–
P	111.436 ± 0.003	days
e	0.934 ± 0.003	
ω	300.6 ± 0.4	°
K	472 ± 5	m s^{-1}
T_0 (periastron)	2 454 424.857 ± 0.05	BJD
$M_p \sin i$	4.0 ± 0.3†	M$_{Jup}$
a	0.453 ± 0.015†	AU
T_t (primary transit)	2 454 876.27 ± 0.08	BJD
T_e (secondary transit)	2 454 424.736 ± 0.003‡	BJD
t_{14}	9.5 – 17.2	hours
t_{23}	8.7 – 15.7	hours
$M_\star$	0.98 ± 0.10	M$_\odot$
$R_\star$	0.98 ± 0.07	R$_\odot$
R_p/R_*	0.090 ± 0.009	
R_p	0.86 ± 0.10	R$_{Jup}$
b	0.75 (-0.75, +0.16)	
i	89.6(−0.4, +0.4)	°

†: using $M_\star$ = 0.98 ± 0.10 M$_\odot$
‡: from Laughlin et al. (2009)

Table 2. Parameter sets for the Rossiter-McLaughlin effect models.

i (deg)	transit duration (hours)	Ttransit BJD -2454000	spin-orbit λ (deg)	χ^2
90.0	17.2	876.20	0	56.3
89.6	15.5	876.24	63	42.4
89.2	9.4	876.32	86	52.0

4. Discussion and Conclusion

Despite the low probability for a 111-day period system to be seen edge-on at both at the primary and the secondary transit phases (about 1 % in the case of HD 80606 b), the data acquired at Observatoire de Haute-Provence and presented here unambiguously show this alignment. With a partial transit observed, we were able to constrain the orbital parameters, including the inclination with a precision of $\simeq 0.4°$, and to measure the planetary radius. The error bars of our measurements should be taken with caution, however, since systematic noise is more difficult to correct with incomplete transits. The planet has a relatively low radius (0.86 R$_{Jup}$) considering its mass (4 M$_{Jup}$).

Since it is also by far the known transiting gas giant receiving the lower irradiation from its parent star, it is tempting to see its small radius as reinforcing the explanation of anomalously large hot Jupiters as due primarily to stellar irradiation, as proposed for instance by Guillot & Showman (2002). Figure 5 shows the increasingly clear correlation between equilibrium temperature and size for transiting gas giants. Explanations in terms of increased opacities (Burrows et al., 2009) or tidal effects (Jackson et al., 2007) could also play a role. Also, the high metallicity of the parent star could influence the small radius of HD 80606 b, since it helps provide refractory material for a big core, as in HD 149026.

HD 80606 may be compared to other planetary systems with a massive planet in an eccentric orbit: HD 17156, HAT-P-2, and XO-3. HD 80606 b has a smaller radius than those planets, which can be related to the migration history or to the changes of stellar irradiation along the orbit (Laughlin et al, 2009). The shape of the Rossiter-McLaughlin anomaly shows that the orbit of HD 80606 b is prograde, and suggests that it could be significantly inclined relative to the stellar equator. A spin-orbit misalignment is expected if HD 80606 b owes its current orbital configuration to Kozai migration (Wu & Murray 2003). Kozai migration can explain the formation of the planet only if the initial relative inclination of the system is large. Among the 11 other transiting planets with Rossiter-McLaughlin measurements, the only system which shows a significant spin-orbit misalignment is XO-3, another massive and eccentric planet (Hébrard et al. 2008; Winn et al. 2009). HAT-P-2b is aligned (Winn et al. 2007; Loeillet et al. 2008). Tighter constraints on spin-orbit misalignments in HD 80606 will be crucial and may provide compelling evidence that the orbital evolution was once dominated by the binary companion (Fabrycky & Winn 2009).

Most of the ∼ 60 known transiting planets are orbiting at close distances from their hosting stars. Only five of them have a period longer than five days, the most distant from its star being HD 17516b, on a 21.2-day period. HD 80606 b is the sixth detected transiting planet above 5-day period, with by far the longest period (111.4 days).

HD 80606 b is thus a new Rosetta stone in the field of planetary transits. Orbiting a quite bright star (V = 9), it opens opportunities for numerous follow-up studies. This includes the observation of a full photometric transit, which can be performed from space observatories only. Also, multi-site campaigns to measure a full spectroscopic transit sequence could be scheduled.

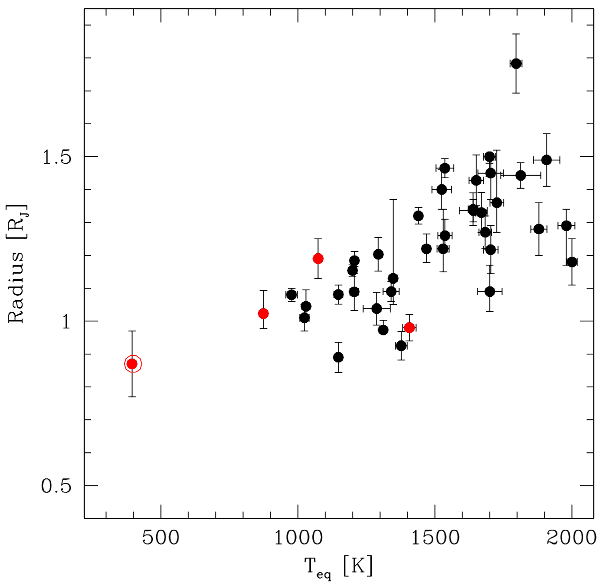

Fig. 5. Radius of transiting gas giant planets as a function of the equilibrium temperature ($T_{eq} \sim T_*(R_*/a)^{1/2}$). HD80606 is circled. Its position reinforces the correlation between incident flux and radius. All transiting gas giants are included, above 0.4 M$_{Jup}$. The red points show the planets with period longer than 5 days.

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