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Letter to the Editor

Photometric and spectroscopic detection of the primary transit of the 111-day-period planet HD 80 606 b⋆,⋆⋆

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ABSTRACT

We report the detection of the primary transit of the extra-solar planet HD 80 606 b, thanks to photometric and spectroscopic observations performed at the Observatoire de Haute-Provence, simultaneously with the CCD camera at the 120-cm telescope and the *SOPHIE* spectrograph on the 193-cm telescope. We observed the whole egress of the transit and partially its central part, in both datasets with the same timings. The ingress occurred before sunset so was not observed. The full duration of the transit was between 9.5 and 17.2 h. The data allows the planetary radius to be measured ($R_{\rm p} = 0.9 \pm 0.10\,R_{\rm Jup}$) 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 of a spin-orbit misalignment. If confirmed, this misalignment would corroborate the hypothesis that HD 80 606 b owes its unusual orbital configuration to Kozai migration. HD 80 606 b is by far the transiting planet on the longest period detected today. Its unusually small radius reinforces the observed relationship between the planet radius and the incident flux received from the star and opens new questions for theory. Orbiting a bright star ($V = 9$), it opens opportunities for numerous follow-up studies.

Key words. stars: planetary systems – techniques: photometric – techniques: radial velocities – stars: individual: HD 80 606

1. Introduction

The extra-solar planet HD 80 606 b was discovered with the ELODIE spectrograph by Naef et al. (2001). This is a giant planet ($4\,M_{\rm Jup}$) with a 111-day orbital period on an extremely eccentric orbit ($e = 0.93$). HD 80 606 is a member of a binary system (with HD 80 607) with a separation of ~1200 AU (~20″ on the sky). Wu & Murray (2003) suggest that the present orbit of HD 80 606 b results from the combination of the Kozai cycles (induced by the distant stellar companion) and tidal friction. Recently, Laughlin et al. (2009) report detecting a secondary transit for HD 80 606 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 for detecting them are rare because the orbital period of the planet is almost four months. We managed an observational campaign to attempt detection of the transit of HD 80 606 b scheduled to happen on Valentine's Day (14 February 2009). We simultaneously used instruments of two telescopes of the 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 80 606 b, in photometry as well as in spectroscopy through the Rossiter-McLaughlin effect.

We recall the stellar characteristics of the primary star, which we used in our analysis of the transit data presented hereafter: HD 80 606 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 0.33 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, relating radius with luminosity and temperature, we derive a radius of $0.98 \pm 0.07\,R_{\odot}$. These mean values were obtained after several iterations over mass and radius determination. Chromospheric activity gives an age interval of 1.7 to 7.6 Gyr (Saffe et al. 2005).

2. The photometric transit of HD 80 606 b

Predicted epochs for the primary transit of HD 80 606 b were given by Laughlin et al. (2009). We carried observations around

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

⋆⋆ Radial velocity and photometry tables are available 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/498/L5

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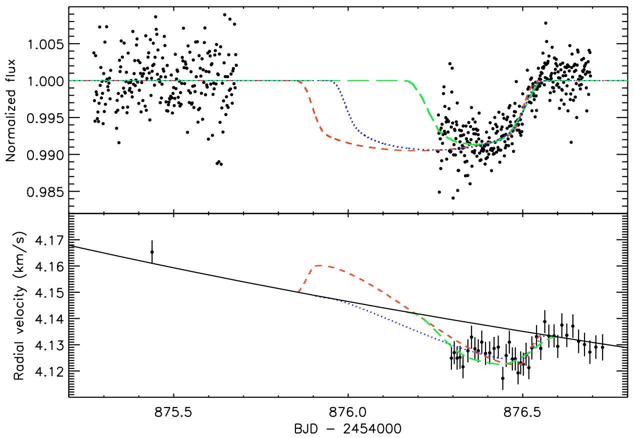

Fig. 1. Photometry (*top*) and radial velocities (*bottom*) of HD 80 606 from 12 to 14 February, 2009, obtained at OHP with the 120-cm and 193-cm telescopes, respectively. The planetary transit is detected in both datasets at the same timing. *Top*: superimposed are the two extreme ($b = 0$ in red-dashed, 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 ($b = 0.91$, $\lambda = 80°$).

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 between 60 sec on the first night and 20–30 s 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 nights, respectively. The secondary companion HD 80 607 is taken as a reference for HD 80 606. 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 radii. The resulting lightcurve is shown in 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 0.0023 and 0.0030, respectively.

An egress is clearly detected in the data sequence obtained during 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 strongly affect the transit shape. It is checked on the 12–13 February sequence that long-term fluctuations are low (not corrected for in 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 indicates 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 observed in total 7 h during transit on the second night, and 3.4 h after the transit. In addition, we gathered 9.8 h out of transit on the first night.

Modelling the primary transit lightcurve of HD 80 606 b is done in the first place using models of circular orbits, to constrain the inclination and the radius ratio. The Universal Transit

Table 1. Fitted orbit and planetary parameters for HD 80 606 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}
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	h
t_{23}	8.7−15.7	h
$M_\star$	0.98 ± 0.10	$M_\odot$
$R_\star$	0.98 ± 0.07	$R_\odot$
R_p/R_*	0.094 ± 0.009	
R_p	0.9 ± 0.10	R_{Jup}
b	0.75 (−0.75, +0.16)	
i	89.6(−0.4, +0.4)	°

†: using $M_\star = 0.98 \pm 0.10\, M_\odot$; ‡: from Laughlin et al. (2009)

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

i (deg)	Transit duration (h)	Ttransit BJD -2 454 000	Spin-orbit λ (deg)	χ^2
90.0	17.2	876.20	0	33.0
89.6	15.5	876.24	63	25.3
89.2	9.4	876.32	86	33.4

Modeler (Deeg 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. Figures 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 h, with $b = 0.75$ and rms of 0.0023. The transit depth imposes a radius ratio R_p/R_* of 0.094 ± 0.009. The planet radius is then estimated to be 0.9 ± 0.10 R_{Jup}. 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 the relative projection of the transit angle and the line of sight into account. In a further study, we plan to investigate the modelling of the asymmetric 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.

3. The spectroscopic transit of HD 80 606 b

We observed HD 80 606 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 centred on the

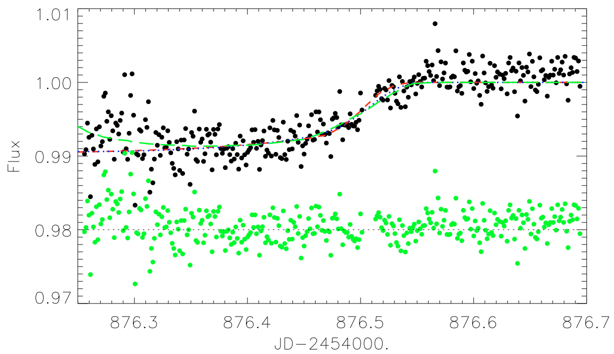

Fig. 2. Zoom-in plot on the photometric transit and the three models with the impact parameter ranging from 0 to 0.91. The residuals are shown below, with an offset of 0.02 on the Y-axis for clarity, and they correspond to the mean model with b = 0.75.

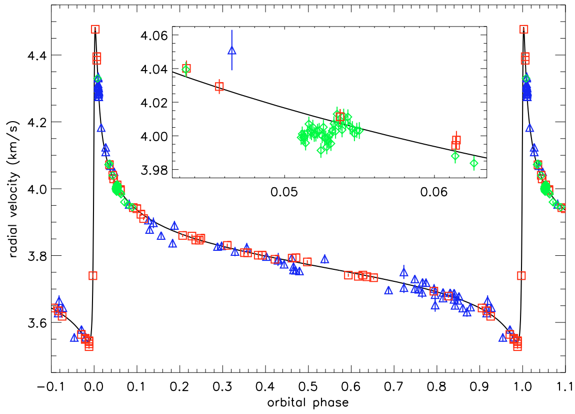

Fig. 3. Phase-folded radial velocity measurements of HD 80 606 as a function of the orbital phase, and Keplerian fit to the data. ELODIE data in blue, Keck data in red, *SOPHIE* data in green. Orbital parameters corresponding to this fit are reported in Table 1. The inset shows a zoom around the transit phase. One Keck spectrum was obtained 1hr after transit.

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 48 radial velocity measurements from 8 to 17 February 2009, including a full sequence during the night 13 February (BJD = 54 876), when the possible transit was expected to occur according to the ephemeris. The exposure times range from 600 to 1500 s, 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 ~10 m s^{-1} from the Keplerian curve in the 1st half of the night, then match the Keplerian curve in the 2nd half of the night. This is the feature expected for a planet transiting 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 (Ohta et al. 2005; Giménez et al. 2006b; Gaudi & Winn 2007).

On the RM feature of HD 80 606 b (Fig. 1), the third and fourth contacts occurred at BJD ≃ 54 876.45 and BJD ≃ 54 876.55, 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) and 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 80 606 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 (55 published by Naef et al. (2001) and 19 additional measurements obtained from BJD = 52 075 to 52 961). We allowed free radial-velocity shifts between the three datasets. We used the constraint of the secondary transit given by Laughlin et al. (2009) (T_e = 2 454 424.736 ± 0.003 HJD). We also used our constraint on the primary transit considering that the end of transit is T_{egress} = 2 454 876.55 ± 0.03 BJD. From these contraints, 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 adjusted 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 Fig. 3. We note that no anterior data was obtained during the transit by any instrument, as shown in the inset of Fig. 3.

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 values 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 slightly overestimated here due to the high metallicity of HD 80 606. 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.

4. Discussion and conclusion

Despite the low probability of a 111-day period system being seen edge-on at both at the primary and the secondary transit phases (about 1% in the case of HD 80 606 b), the data acquired

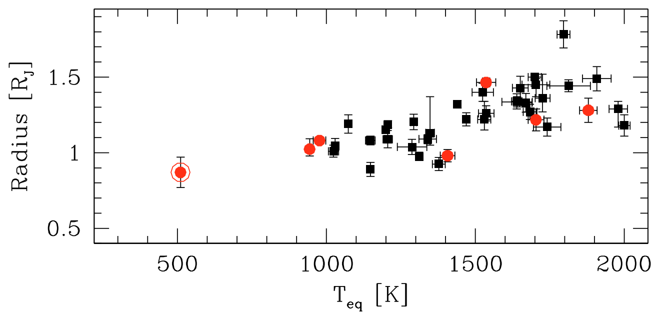

Fig. 4. Radius of transiting gas giant planets as a function of the equilibrium temperature ($T_{eq} \sim T_*(R_*/a)^{1/2}(1-e^2)^{-1/8}$). HD 80 606 is circled. Its position reinforces the correlation between incident flux and radius. All transiting gas giants are included above 0.4 M_{Jup}. The red circles show the planets with mass higher than 2 M_{Jup}. They follow the same tendency as Jupiter-like planets (black squares).

at the Observatoire de Haute-Provence and presented here show this alignment unambiguously. 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, and the system's parameters slightly revised when more complete data is obtained, since systematic noise is more difficult to correct with incomplete transits.

The planet has a low radius (0.9 R_{Jup}) considering its mass (4 M_{Jup}). Since it is also by far the 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 caused primarily to stellar irradiation, as proposed for instance by Guillot & Showman (2002). Figure 4 shows the increasingly clear correlation between equilibrium temperature and size for transiting gas giants. The relation holds for both massive planets (>2 M_{Jup}) and Jupiter-like planets. Tidal effects (Jackson et al. 2007) may play a role in the observed radius of HD 80 606 b. The high metallicity of the parent star also helps provide refractory material for a massive core, although the required enrichment would be beyond actual expectations. More theoretical development is needed to reproduce the system's parameters, taking the whole history of orbital evolution and variations in the irradiation conditions into account.

Most of the ~60 known transiting planets are orbiting close to their hosting stars. Only 5 of them have periods longer than 5 days, the most distant from its star being HD 17 156 b, on a 21.2-day period. HD 80 606 b has by far the longest period (111.4 days). It may be compared to other planetary systems with a massive planet in an eccentric orbit: HD 17 156, HAT-P-2, and XO-3. HD 80 606 b has a smaller radius than those planets, which can be related to the migration history or to the changes in stellar irradiation along the orbit (Laughlin et al. 2009). The shape of the Rossiter-McLaughlin anomaly shows that the orbit of HD 80 606 b is prograde, and suggests that it could be significantly inclined relative to the stellar equator. Since a high initial relative inclination is a key requirement for Kozai migration to work (Wu & Murray 2003), this observation is not surprising. Tighter constraints on the spin-orbit misalignment in HD 80 606 may support the Wu & Murray formation scenario and may provide compelling evidence that the orbital evolution of HD 80 606 b was once dominated by the binary companion. Among the 11 other transiting planets with Rossiter-McLaughlin measurements, the only system to show 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).

HD 80 606 b is thus a new Rosetta stone in the field of planetary transits. By orbiting a bright star ($V = 9$), it opens opportunities for numerous follow-up studies, including: observation of a full photometric transit from space or multi-site campaigns to measure a complete spectroscopic transit sequence.

After submission, we learned that other observations of this system had been obtained on the same day. Fossey et al. (2009) and Garcia-Melendo & McCullough (2009) independently confirm the detection of the photometric transit. In addition, MEarth observations (Charbonneau, priv. comm. and oklo.org) held in Arizona show a flat lightcurve of HD 80 606, which limits the transit duration to less than 12 h, hence reinforcing evidence of a spin-orbit misalignment (solutions of red and blue models in Fig. 1 are rejected). The grazing eclipse configuration would also result in a slightly larger planetary radius. Further analyses will follow in a forthcoming paper.

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