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MISALIGNED SPIN-ORBIT IN THE XO-3 PLANETARY SYSTEM?

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Abstract. The SOPHIE Consortium started a large program of exoplanets search and characterization in the Northern hemisphere with the new spectrograph SOPHIE at the 1.93-m telescope of Haute-Provence Observatory, France. The objectives of this program are to characterize the zoo of exoplanets and to bring strong constraints on their processes of formation and evolution using the radial velocity technique. We present here new SOPHIE measurements of the transiting planet host star XO-3. This allowed us to observe the Rossiter-McLaughlin effect and to refine the parameters of the planet. The unusual shape of the radial velocity anomaly during the transit provides a hint for a nearly transverse Rossiter-McLaughlin effect. The sky-projected angle between the planetary orbital axis and the stellar rotation axis should be $\lambda = 70^\circ \pm 15^\circ$ to be compatible with our observations. This suggests that some close-in planets might result from gravitational interaction between planets and/or stars rather than migration. This result requires confirmation by additional observations.

1 Presentation

Accurate radial velocity measurements are an efficient and powerful technique for research and characterization of exoplanetary systems. They allow the statistic of known systems to be extended by completing the mass-period diagram of exoplanets, in particular toward lower masses and longer periods, as the measurements accuracy is improving. In addition, parameters of the transiting planets could be measured thanks to spectroscopic transit observations (the Rossiter-McLaughlin effect), and Doppler follow-up are mandatory to establish the planetary nature and characterize the parameters of the transiting candidates obtained from photometric surveys.

The SOPHIE instrument replaces the ELODIE spectrograph at the 1.93-m telescope of Haute-Provence Observatory. SOPHIE is a fiber-fed, cross-dispersed, environmentally stabilized echelle spectrograph dedicated to high-precision radial velocity measurements (Bouchy et al. 2006). Since its first light on the sky in summer 2006, SOPHIE was used in particular for Doppler follow-up of photometric surveys for planetary transits search. SOPHIE allowed the discovery of transiting planets found by SuperWASP (Collier Cameron et al. 2007, Pollacco et al. 2008), CoRoT (Barge et al. 2008, Alonso et al. 2008, Bouchy et al. 2008) and HAT (Bakos et al. 2007) surveys, as well as the parameters of these new planets to be characterized.

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2 The SOPHIE Consortium

Together with the advent of this new instrument, the SOPHIE Consortium has been established to carry out a program of detection and characterization of extrasolar planets (Bouchy 2008). Using 120 to 160 nights per year, this large program aims at covering several aspects of exoplanetary science. In particular, we perform a moderate-precision survey ($7-10\,\mathrm{m/s}$) of FGK stars, with the aim of monitoring and characterizing known transiting hot Jupiters, as well as detecting new transiting planets. For this latter goal, the main interest of radial velocity surveys, by comparison with photometric surveys, is to detect planets transiting in front of stars brighter than $m_V \simeq 9$. The few known planets transiting in front of bright stars are the ones that allow the most accurate parameters determination and the studies of the planetary atmospheres.

As part of the SOPHIE Consortium program, the detection of three exoplanets have been published up to now: HD 43691b and HD 132406b (Da Silva et al. 2008), and HD 45652b (Santos et al. 2008). These planets are respectively 2.5, 5.6 and 0.5 $\mathrm{M_{Jup}}$ for $M_\mathrm{p} \sin i$, and 37, 975 and 44 days for the orbital periods. There were first found from the ELODIE survey and then monitored by SOPHIE (and by CORALIE at the Euler 1.2-m Swiss Telescope in the case of HD 45652b). SOPHIE data show 9.0, 4.1, and 7.3 m/s dispersion around the fitted orbits for these three targets respectively. Spectroscopic transits of the massive planet HD 147506b were also observed by the SOPHIE Consortium, allowing a refinement of the parameters of this system (Loeillet et al. 2008). Moreover, a study of the stellar activity of the transiting planet host star HD 189733 from SOPHIE Consortium data is presented by Boisse et al. (2008).

3 XO-3b with SOPHIE

3.1 Observations and data reduction

Johns-Krull et al. (2008) announced the detection of XO-3b, which is an extra-solar planet transiting its F5V parent star with a 3.2-day orbital period. There was a quite large uncertainty on the parameters of this system. Johns-Krull et al. (2008) presented a spectroscopic analysis favoring large masses and radii, whereas their light curve analysis suggests lower values. Winn et al. (2008) solved the issue from accurate photometric transit observations, and favored lower values ($R_\mathrm{p} = 1.22 \pm 0.07\ \mathrm{R_{Jup}}$).

We acquired 36 spectra of XO-3 ($m_V = 9.91$) with SOPHIE during the night of January 28th, 2008, where a full coverage of the planetary transit was observed. The airmass ranged from 1.2 to 3.1 during this ~6-hour observation sequence. Another 19 spectra were acquired at other orbital phases during the following two months.

Through the SOPHIE pipeline, the spectra are extracted and cross-correlated with numerical masks, then the resulting cross-correlation functions are fitted by Gaussians to get the radial velocities. We eliminated the first eight spectral orders of the 39 available ones from the cross-correlation; these blue orders are particularly noisy, especially for the spectra obtained at the end of the transit, when the airmass was high. We corrected the Moon contamination thanks to the second aperture, targeted on the sky.

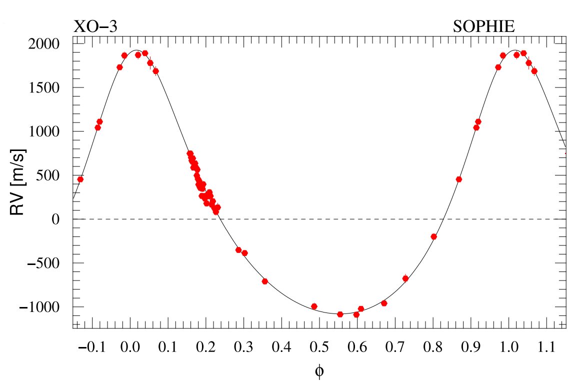

Fig. 1. Phase-folded radial velocity SOPHIE measurements of XO-3 (corrected from the velocity $V_r = -12.045\,\mathrm{km\,s^{-1}}$) as a function of the orbital phase and Keplerian fit to the data. Fig. 2 (top panel) displays a magnification on the transit night measurements (around $\Phi = 0.2$).

3.2 Refined orbit

We made a Keplerian fit of the SOPHIE measurements performed outside the transit (Fig. 1). The dispersion of the data around the fit is 29 $\mathrm{m\,s^{-1}}$, in agreement with the estimated errors on the individual radial velocities. The derived orbital parameters are reported by Hébrard et al. (2008); they agree with the Johns-Krull et al. (2008) parameters but the error bars are reduced by factors of three to six. They agree also with updated parameters from Winn et al. (2008). The residuals show no trend that might suggest the presence of another companion in the system over two months.

3.3 Transverse Rossiter-McLaughlin effect?

The radial velocities of XO-3 measured with SOPHIE during the transit are plotted on the top panel of Fig. 2. Surprisingly, they do not show the ordinary anomaly seen in case of prograde transits, but the typical shape for a transverse Rossiter-McLaughlin effect. The sky-projected angle between the planetary orbital axis and the stellar rotation axis should be $\lambda = 70° \pm 15°$ to be compatible with our observations.

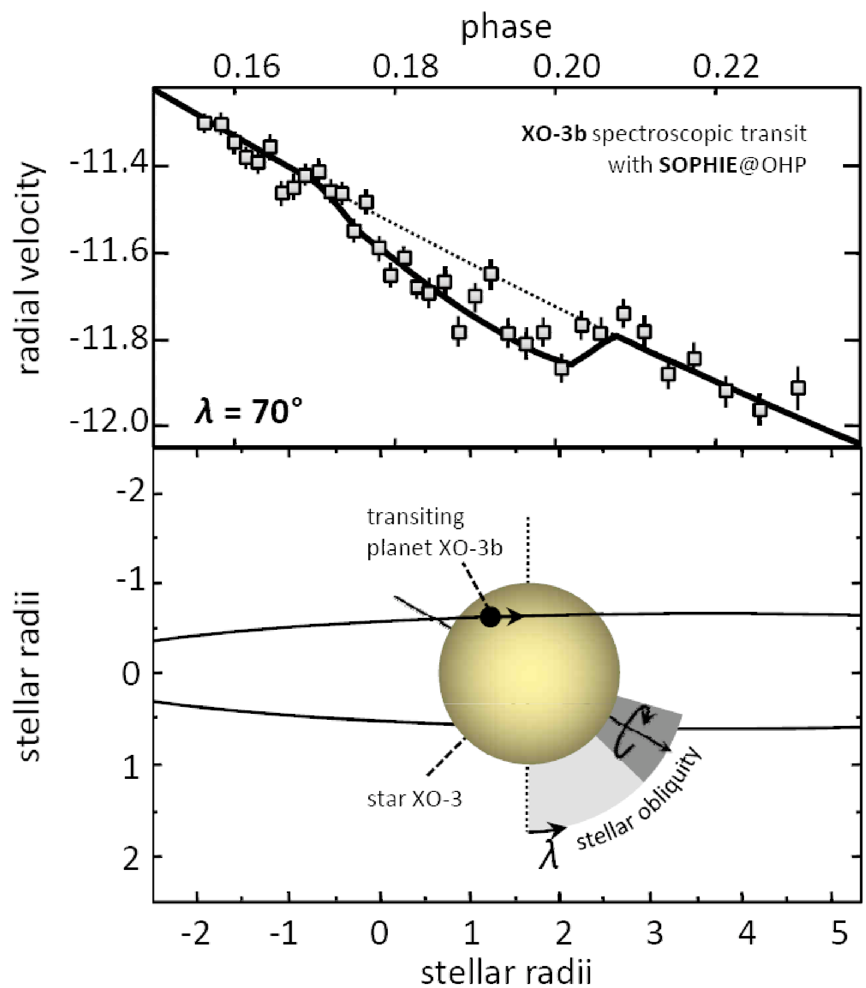

Fig. 2. *Top:* Rossiter-McLaughlin effect models with $\lambda = 70°$. The squares are the SOPHIE radial-velocity measurements of XO-3 with 1-σ error bars as a function of the orbital phase. The solid and dotted lines are the Keplerian fits with and without Rossiter-McLaughlin effect. *Bottom:* Schematic view of the XO-3 system with nearly transverse transit, as seen from the Earth. The stellar spin axis is shown, as well as the planet orbit and the λ misalignment angle (or stellar obliquity). The range $\lambda = 70° \pm 15°$ which is favored by our observations is shown.

The model of the Rossiter-McLaughlin anomaly is over-plotted on the top panel of Fig. 2; it produces a good fit of the data, centered on the expected mid-transit and with the adequate duration and depth (see also Hébrard et al. 2008). The SOPHIE measurements performed just before and after the transit are well described by the Keplerian orbit model. The 43 $\mathrm{m\,s^{-1}}$ dispersion of the data from these transverse models remains slightly above the computed uncertainties on radial velocity measurements.

4 Discussion

A schematic view of the XO-3 system in this nearly transverse configuration is shown in Fig. 2, bottom panel. The SOPHIE observation remains noisy, and we consider this result as a tentative detection of a spin-orbit misalignment rather than a firm detection. Indeed, the end of the transit was observed at large airmasses, which could possibly bias the radial velocity measurements in a way that is difficult to quantify. Other spectroscopic transits of XO-3b should thus be observed.

Narita et al. (2008) also found a possible spin-orbit misalignment, in the case of the eccentric planet HD 17156b; however Barbieri et al. (2008) and Cochran et al. (2008) found $\lambda \simeq 0°$ for this system from extra observations. The timescale for spin-orbit alignment through tidal dissipation is much longer than the timescale for orbital circularization. There are thus no obvious reasons to exclude an eccentric, transverse system. A strong spin-orbit misalignment would favor formation that invokes planet-planet or planet-star scattering rather than inward migration due to interaction with the accretion disk. This suggests in turn that some close-in planets might result from gravitational interactions in multi-body systems (Takeda 2008; see also Papaloizou & Terquem 2001).

Tidal frictions might be high enough to tune the stellar rotation velocity close to the velocity of its companion on its orbit at the periastron. The expected pseudo-synchronized stellar rotation is $V_{\mathrm{rot}} \simeq 30\frac{R_\star}{\mathrm{R}_\odot}\,\mathrm{km\,s^{-1}}$. The XO-3 rotation velocity, $V \sin I = 18.5\,\mathrm{km\,s^{-1}}$, is clearly smaller than the pseudo-synchronized velocity. However, we note that a spin-orbit misalignment would tend to reduce the pseudo-synchronized rotation velocity of the star. Pseudo-synchronization might thus be possible if actually there is a spin-orbit misalignment in the XO-3 system.

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