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SEARCH AND CHARACTERIZATION FOR EXTRASOLAR PLANETS WITH THE SOPHIE CONSORTIUM

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Abstract. The SOPHIE Consortium started, in November 2006, several programs of exoplanet search and characterization in the Northern hemiphere with the spectrograph SOPHIE based on the 1.93m telescope at the Observatoire de Haute-Provence. We present here the latest SOPHIE results which include new exoplanets, studies of transiting planets through Rossiter-McLaughlin effect, characterizations of stellar activity of planet-host star and observation of the Earth as a transiting planet.

Keywords: planetary systems, techniques: radial velocities and spectroscopic, stars: activity, planets and satellites: atmospheres

1 Introduction

The high-precision SOPHIE spectrograph (Perruchot et al. 2008) has been opened to the community since October 2006 at the 1.93-m telescope at the Observatoire de Haute-Provence (OHP). At the same time, the SOPHIE consortium, composed of researchers from five institutes, initiated a large program to search for and characterize extrasolar planets (Bouchy et al. 2009). This large program is divided in five complementary subprograms with different objectives: a high-precision search for super-Earths, a giant planets survey on a volume-limited sample, a search for exoplanets around M-dwarfs, a search for planets around early-type main sequence stars and a long-term follow-up of ELODIE long period candidates. The consortium benefits almost half of the available night on the telescope that allows a high level of flexibility and reactivity, an involvement in the follow-up and the optimization of the instrument, and a good sharing of the telescope time as a function of weather conditions and observing strategy of the subprograms.

2 Search for planetary systems

SOPHIE has replaced the ELODIE spectrograph (Baranne et al. 1996). Then, surveys of the consortium are both continuation and extension of the planet-search programs carried out with ELODIE (Queloz et al. 1998). They also complement the HARPS programs performed in the southern hemisphere (Mayor et al. 2003). The detection of three exoplanets that were first found from the ELODIE surveys before to be monitored by SOPHIE have been published. Da Silva et al. (2006) reported two intermediate period (40 and 974 days) of, respectively, 2.5 and 5.6 M_{Jup} planets orbiting the metal-rich stars HD43691 and HD132406. Also monitored by CORALIE,

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a Jupiter-mass (0.47 M_{Jup}) planet HD45652b orbiting a metal-rich star in a 44 days was announced by Santos et al. (2008) (Fig. 1, *right*).

An early F-type star, θ Cygni was observed during five years with ELODIE and SOPHIE. A pseudo-periodic RV variations of about 150 days was detected with a variable semi-amplitude. Desort et al. (2009) showed that the available data are not well explained by a one (or two) planet system, and considered a possible stellar origin.

Three planet-host stars were discovered from SOPHIE observations that were part of the survey for giant planets around bright stars in a volume-limited sample. A massive planet (or light brown dwarf) were characterized by Bouchy et al. (2009) orbiting HD16760 with a period of 465 days. A two planets system HD9446b,c were reported by Hébrard et al. (2010a) with a hierarchical disposition. The SOPHIE RV measurements of HD9446 and the two-planets Keplerian orbits are shown in Fig. 1 (*left*). Boisse et al. (2010b) announced HD109246b, orbiting a G0V star, with a minimum mass of $0.77\,M_{Jup}$ and a orbital period of 68 days (Fig. 1, *right*). We also present a correction method for the so-called seeing effect that affects the SOPHIE RV, and a description of some calibrations that are implemented in the SOPHIE automatic reduction pipeline (derivation of the photon-noise RV uncertainty and some useful stellar properties: $v \sin i$, [Fe/H], $\log R'_{HK}$).

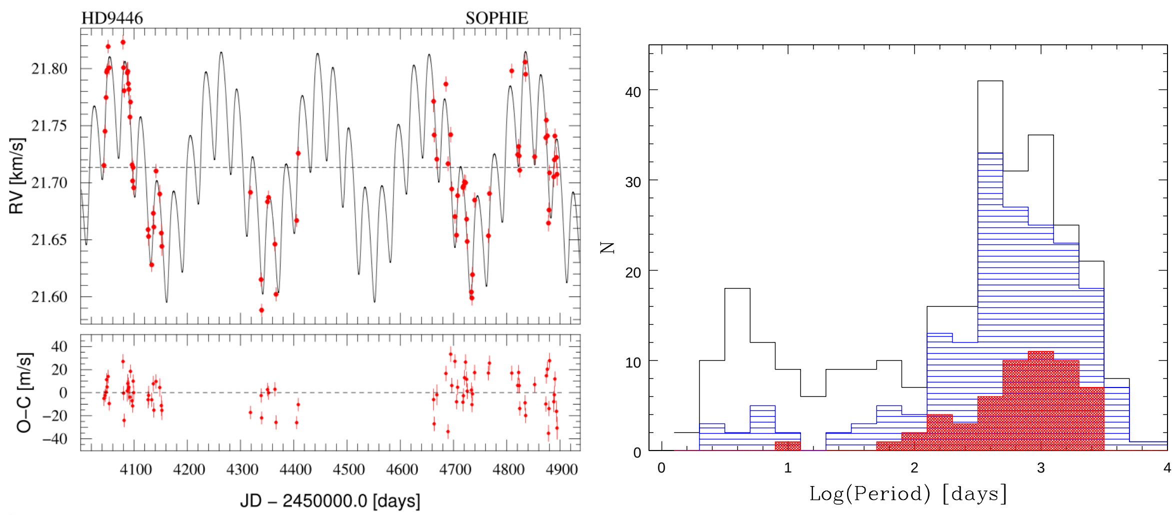

Fig. 1. *Left:* RV from SOPHIE measurements of HD9446 as a function of time and Keplerian fit revealing a two planets system. At the bottom are reported the residuals from the fit (Hébrard et al. 2010a). *Right:* Period distribution of the known extrasolar planet orbiting single dwarf stars via RV surveys. Horizontal stripped illustrates the distribution for planets more massive than $0.8\,M_{Jup}$ and the shaded one for planets more massive than $4\,M_{Jup}$ (Boisse et al. 2010b). With respective periods of 30, 44 and 68 days, HD9446b, HD45652b and HD109246b are placed in a sparsely populated region of the period distribution of extrasolar planet.

3 Characterization of planetary systems during transit observations

Spectroscopic transit of planets have also been observed by SOPHIE allowing refinement of the parameters of the system as well as measurement of the sky-projected angle between the normal of the orbital plane and the stellar spin axis. The detection of the Rossiter-McLaughlin effect of the transiting exoplanet HAT-P-2b when the planet was transiting its parent star by Loeillet et al. (2008), showed that the sky-projected spin-orbit angle is consistent with zero. The spectroscopic transit of XO-3b shown in Fig. 2 was also done with SOPHIE (Hébrard et al. 2008). This planet with a high mass and an eccentric orbit was the first detection of a misaligned spin-orbit system.

The transit of the 111-day period exoplanet was established by Moutou et al. (2009) thanks to spectroscopic observations with SOPHIE and photometric with the 120-cm telescope at OHP. We observed only the egress of the transit because ingress occurred before sunset (full duration of the transit were characterized in the following studies to be close to 12 hours). Pont et al. (2009) presented a combined analysis of photometric and spectroscopic data. With an upper limit on the transit duration, the authors reinforced the hypothesis of spin-orbit misalignment in this system. Finally, new spectroscopic observations with SOPHIE of the first half of the RM effect allowing the measurement of the second known misaligned system (Hébrard et al. 2010b). These misalignment suggest that some close-in planets might result from gravitational interaction between planets and/or stars rather than migration due to interaction with the accretion disk.

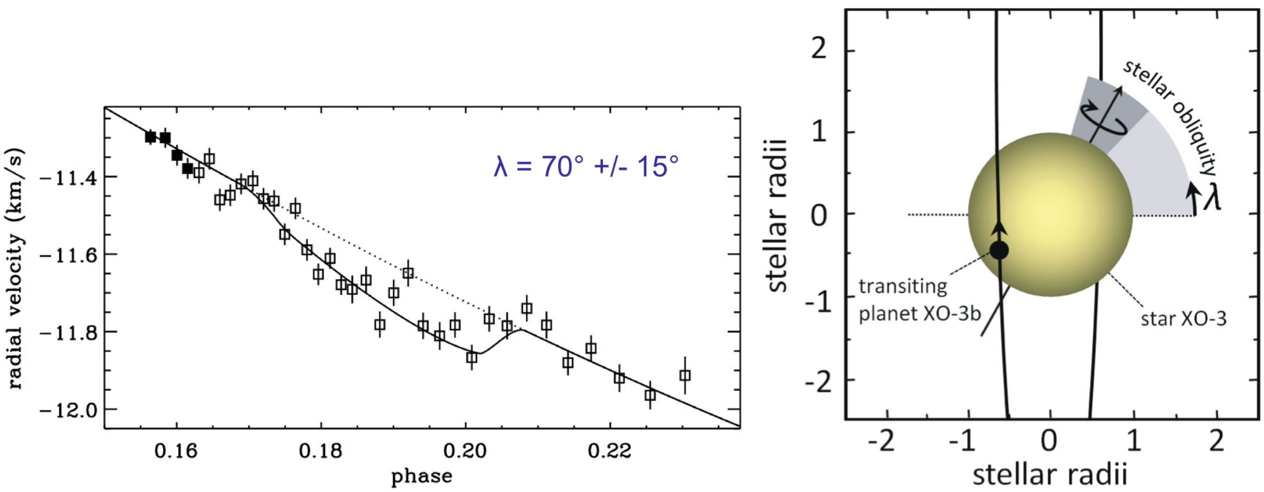

Fig. 2. *Left:* RV from SOPHIE measurements of the Rossiter-McLaughlin effect of XO-3b when the planet transits its parent star (Hébrard et al. 2008). The solid line shows the fitted model. *Right:* Schematic view of the XO-3 system with transverse transit, as seen from the Earth. The stellar spin axis is shown, as well as the planet orbit. The grey area shows the range the $\lambda = 70 \pm 15°$, which is favored by SOPHIE observations (Hébrard et al. 2008).

4 Others studies

4.1 Monitoring stellar activity

The precision of RV search for exoplanets is dependant of the noise induced by photospheric luminosity variations due to activity phenomena. Boisse et al. (2009) presented a study of the stellar activity of the transiting planet host star HD189733. We compared the variability in spectroscopic activity indices in HeI (5875.62 Å), Hα (6562.81 Å) and both of the CaII H& K lines (3968.47 Å and 3933.66 Å) with the evolution in the RV measurements and the shape of spectral lines. We used these correlations to correct from the RV jitter due to activity. This results in achieving high precision in measuring the orbital parameters of the planetary system.

4.2 The Earth as an extrasolar transiting planet

In order to identify the atmospheric gaseous bio-signatures observable in the Earth atmosphere as for an extrasolar planet, we observed the light transmitted through the Earth's atmosphere during Lunar eclipse. At optical wavelengths, we identified in the transmission spectra ozone, molecular oxygen, neutral sodium, molecular nitrogen and oxygen through the Rayleigh signature. This work is a proxy for the characterization and the search from bio-marker signatures from the ground with extremely-large telescope of future transiting Earth-like planets (Fig. 3).

5 Perspectives

Some new results are going to be published. Massive planets and brown dwarfs candidates from the giant planets survey around bright stars will be described in Díaz et al. (2010). Candidates from the follow-up of long-term trends revealed by ELODIE were fully characterized with complementary SOPHIE measurements achieving the discoveries of Jupiter-mass or massive planets on Jupiter or Saturn-like orbits.

The high-precision program permitted to identify some limitations related to the bonnette of the telescope that was designed for ELODIE some 15 years ago. Optimizations were done as the replacement of the guiding camera and its software or the installation of a new cryogenic controller system. Tests on square and octagonal

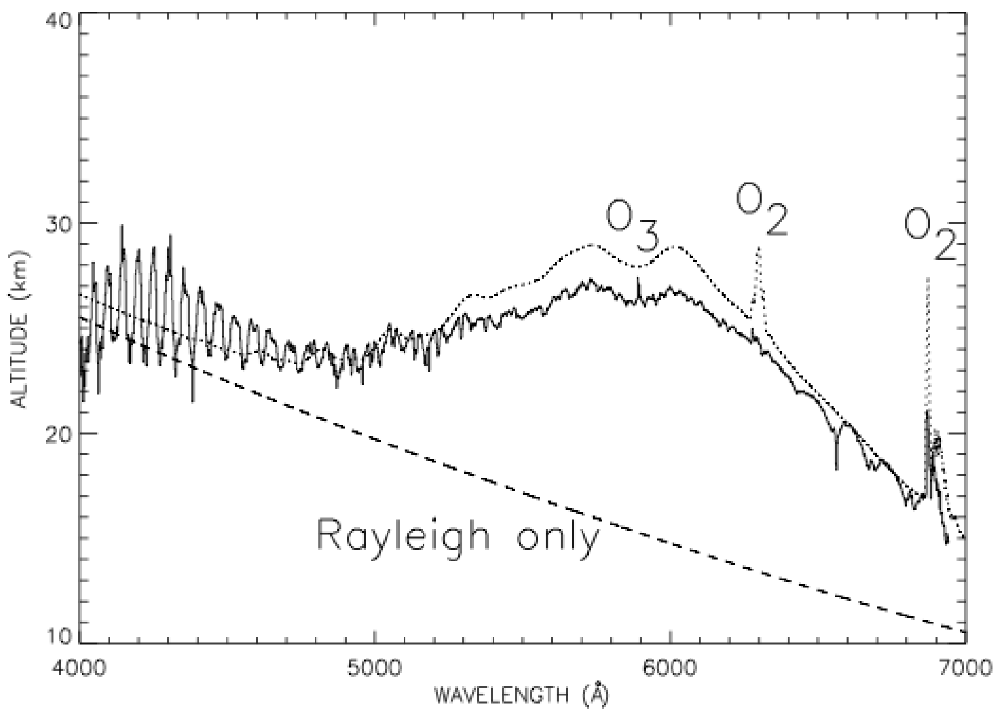

Fig. 3. Absorbing atmosphere thickness of the Earth versus wavelength as it will be observed during the transit of an extrasolar planet (observed with SOPHIE during Lunar eclipse in solid line and atmospheric model in dotted line) (Vidal-Madjar et al. 2010).

section fibers are under development in the aim to improve the stability of the spectrograph illumination (Boisse et al. 2010a). These will allow an improvement of the SOPHIE RV accuracy from now about 4-5 $\mathrm{m\,s^{-1}}$ to 2 $\mathrm{m\,s^{-1}}$. The high-precision search for super-Earths, subprogram stops since several months will then reach its objectives.

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