Tenth anniversary of 51 Peg-b : Status of and prospects for hot Jupiter studies
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SOPHIE: the successor of the spectrograph ELODIE for extrasolar planet search and characterization

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Abstract. The SOPHIE echelle spectrograph is presently built at the Haute Provence Observatory (OHP). It will replace and upgrade the ELODIE spectrograph, well known for the discovery of the first hot Jupiter 51Peg-b ten years ago. This new spectrograph is going to be installed at the 1.93-cm telescope and be commissioned beginning of 2006. Primarily based on the experiment acquired on HARPS (3.6-m ESO), SOPHIE should be considered as its North counter part. Its main characteristics and expected performances are described. Some exoplanet programs which will be conducted these next years are presented.

1. Introduction

Radial velocity (RV) measurements have demonstrated these last ten years their efficiency and power for the detection and characterization of extrasolar planetary systems. Thanks to improvement in the Doppler techniques, radial velocity measurements continuously increased their accuracy and reached recently the level of 1 ms^{-1}. Far to be considered as an old-fashioned techniques, RV clearly offers for the next decade the possibility to complete the mass-period diagram of exoplanets, especially in the domain of Neptune-mass planets and hot big Earthes. Furthermore, RV appears to be a method fully complementary to photometry for characterizing the actual mass of transiting hot Jupiters. In this context and taking into account the limitation of the spectrograph ELODIE, it appeared that a new RV instrument had to be developed at Haute Provence Observatory.

2. ELODIE limitations

The ELODIE spectrograph (Baranne et al. 1996) is a fiber-fed cross-dispersed echelle spectrograph built on 1993 and installed on the 1.93-m telescope at Haute Provence Observatory. The 1k×1k CCD records 67 spectral orders which cover all the visible range from 391 to 681 nm with a spectral resolution of 42'000. Two optical fibers (100 μmm diameter) feed the spectrograph. The acceptance on the sky is 2 arcsec. One fiber is used for the stellar beam, the second one can be used for the sky background or the simultaneous Thorium-Argon calibration. The spectrograph is located in a thermally controlled room. ELODIE is working since 1994 and drove several discoveries and astrophysical breakthroughs. Its fame comes in a large part from the detection of the first extrasolar planet around the solar-type stars 51 Peg (Mayor & Queloz 1995). These last 11 years ELODIE led to the detection of up to 20 exoplanets. It also permitted significant progress in topics like stellar spectroscopic analysis, rotational velocity determination, discovery of very low mass stars, asteroseismology, vertical distribution of Galactic disk stars, etc. However ELODIE suffers from some limitations: 1) an overall efficiency of less than 1 %, 2) a spectral resolution of 42'000, 3) a fiber-to-fiber contamination and scattered light, and 4) a Doppler precision of 6-8 ms^{-1}. Taking into account these limitations and the performances achieved by the spectrograph HARPS installed two years ago at the 3.6-m ESO telescope (Pepe et al. 2002; Mayor et al. 2003), the development of a successor of ELODIE was decided.

3. SOPHIE project overview

Following the tradition at Haute Provence Observatory which consists in giving a woman name, the new spectrograph was called SOPHIE for Spectrograph for Observation of PHenomena in stellar Interiors and Exoplanets. The principal investigator is D. Gillet (OHP). S. Ilovaisky (OHP), M. Mayor (Genève), and J.P. Sivan (LAM) are Co-investigators. The project manager is L. Hill (OHP) and the instrument scientist is F. Bouchy (LAM/OHP). The Laboratoire d'Astrophysique de Marseille and the Observatoire de Genève are partners. One of the main science driver identified for SOPHIE is the search for extrasolar planets. The goal was to design an instrument based on the principle of HARPS but adapted for a 2-m class telescope. The requirements were to increase 3 factors compared to ELODIE: 1) the overall efficiency, 2) the spectral resolution, and 3) the Doppler accuracy.

4. Description of the instrument

Figure 1 shows the optical and mechanical design of the SOPHIE spectrograph. Table 1 gives the main characteristics of the optical components. The beam is collimated by a 200-mm spherical mirror and is folded by a pierced plane mirror. Such a configuration gives a quite compact instrument but introduces a central obstruction. Spherical aberration is corrected by a Schmidt plate used in double passage. The main dispersion is given by an R2 echelle grating and the cross dispersion is given by a prism. These two dispersive components are installed in a tank closed by the Schmidt plate. The tank is filled with N2 (dry air) and closed in order to be at constant pressure. This solution avoids the change of air optical index due to atmospheric pressure change which can typically introduce a RV instrumental drift of 90 ms^{-1} per mbar change. The CCD is installed just behind the plane mirror and is cooled at $-100°$ by liquid Nitrogen. The whole instrument is installed in a thermally controlled isolation box.

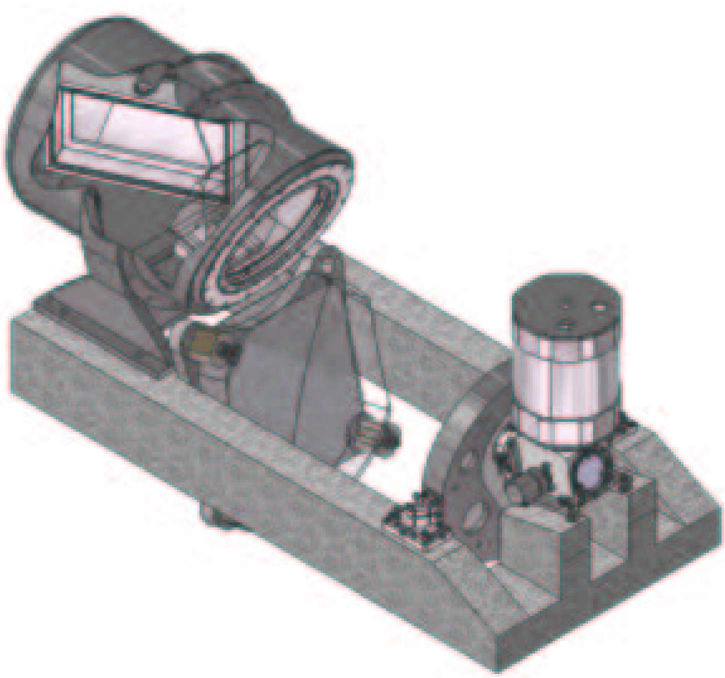

Figure 1. *Optical and mechanical design of SOPHIE spectrograph.*

In order to minimize the fiber length, the instrument is installed in the Coudé room of the 1.93-cm and is fixed in the telescope pillar. The ELODIE Cassegrain fiber adapter is used to feed the SOPHIE fibers (100 μmm diameter). The only difference is that SOPHIE fibers have an acceptance of 3 arcsec on the sky. Two set of fibers are installed for SOPHIE, the first one is called High Efficiency fibers, the second one is called High Resolution fibers. This last set of fibers includes two peculiarities : 1) a slit in front of the fiber at the spectrograph entrance in order to increase the spectral resolution and 2) a double scrambler in order to increase the homogeneity of the beam required for high RV precision. The Data reduction software is an adaptation of the HARPS one.

Table 1. *Main characteristics of SOPHIE optical components.*

Component	characteristics
Collimated beam	Ø = 200 mm
Collimator mirror	Ø = 540 mm
	f = 720 mm
	F/D = 3.6
Plane mirror	Ø = 440 mm
Schmidt plate	Ø = 320 mm
Prism cross disperser	angle = 31°
	280 × 220 mm
Echelle grating	blaze = 65°
	52.6 gr.mm^{-1}
	204 × 410 mm
Field lens	Ø = 90 mm
	R = 245 mm
CCD	EEV 44-82
	2048 × 4102 pixels
	pixel size 15 μm

The integration of the instrument will start in January 2006 with first light foreseen in March 2006. Several periods of commissioning and scientific verification will take place during spring and summer 2006. SOPHIE will be open to the community starting June 2006 on a “shared risk” basis. Documentations about SOPHIE project can be found in the OHP web page (http://www.obs-hp.fr/).

5. Expected performances

The expected performances for the two observation modes (High Efficiency and High Resolution) are given in Table 2. The overall efficiency includes CCD, spectrograph, fibers, Cassegrain adapter, telescope and atmosphere. The CCD detector records 40 spectral orders covering the spectral range from 383 nm to 693 nm. The expected S/N per pixel at 550 nm (0.025 Å) is given in Figure 2. The High Efficiency mode gives a gain of about 1 magnitude in efficiency.

Table 2. *Expected performances*

Observation Mode	Spectral Resolution	Overall efficiency at given λ [nm] 390	400	430	500	690
High Efficiency	34'000	0.046	0.059	0.082	0.104	0.083
High Resolution	68'000	0.019	0.025	0.034	0.043	0.035

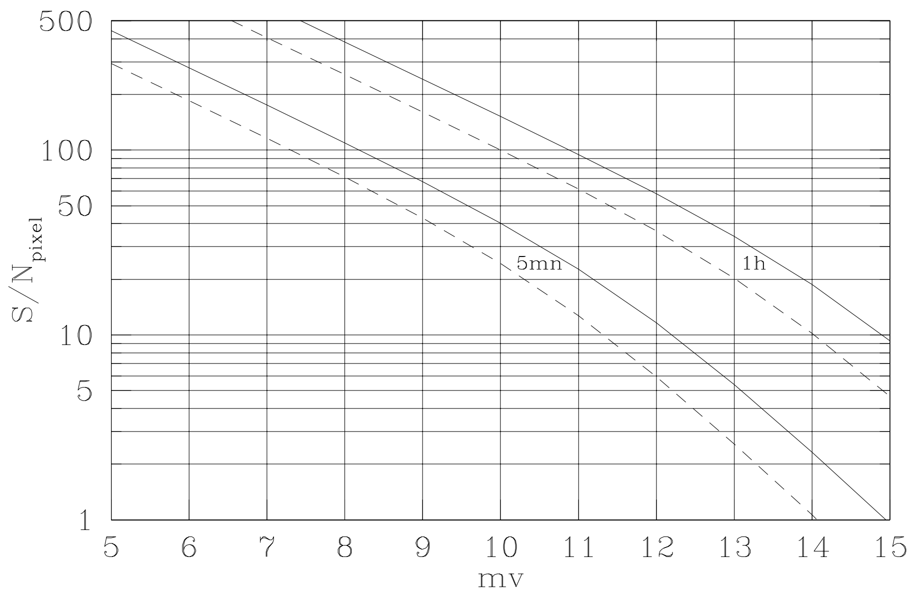

Figure 2. *Expected signal-to-noise ratio per pixel (0.025 Å) at 550 nm for a 5-mn exposure and a 1-hour exposure. The solid and dashed lines correspond respectively to High Efficiency mode and High Resolution mode.*

Radial velocity uncertainties due to photon noise were computed following Bouchy et al. (2001). RV uncertainties are given in Figure 3 versus visual magnitude in the case of a no-rotating K5V star which is the best stellar case in term of deep and numerous spectral lines. The High Efficiency mode is not optimized for high precision RV measurements and should be limited to the 5-10 ms^{-1} precision. However in case of faint stars and/or large rotating stars, this mode should be considered as more adapted than the High Resolution mode for RV measurements at the precision level of 10 ms^{-1}.

With its High Resolution mode, SOPHIE was designed to reach the same level of RV precision than HARPS (1-2 ms^{-1}). As shown in Figure 3, a photon noise uncertainty of about 1 ms^{-1} should be obtained on a 7 magnitude K5V star within a 5-mn exposure or on a 9.5 magnitude K5V star within a 1-hour exposure.

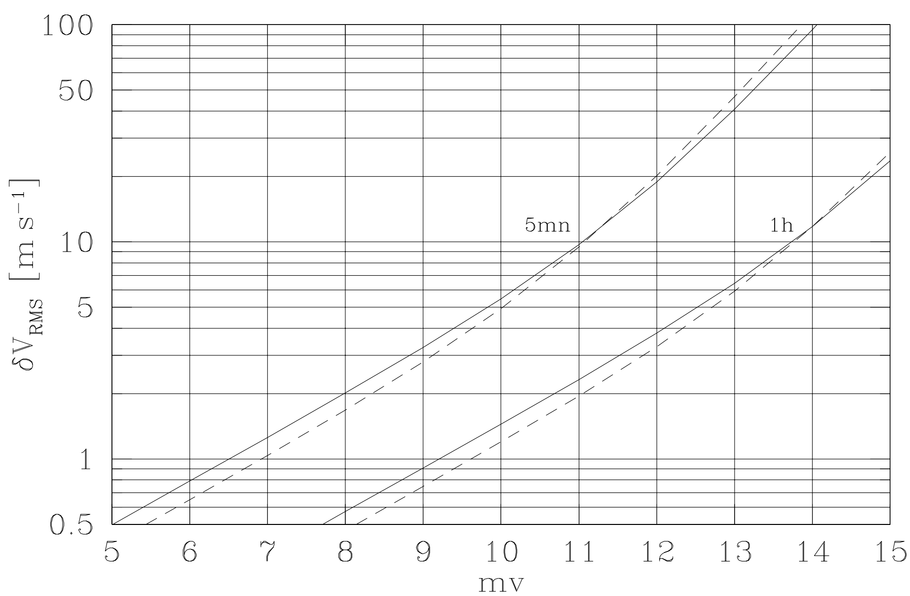

Figure 3. *Expected RV uncertainty due to photon noise for a no-rotating K5V star versus visual magnitude for a 5-mn exposure and a 1-hour exposure. The solid and dashed lines correspond respectively to High Efficiency mode and High Resolution mode. The expected systematic errors for the HE mode (solid curves) are 5-10* ms^{-1}*. The expected systematic errors for the HR mode (dashed curves) are 1-2* ms^{-1}.

6. Exoplanet programs

SOPHIE offers at least 3 main advantages for exoplanet search programs: 1) a high availability (about 180 nights per year will be dedicated for such programs), 2) a high Doppler precision (1-2 ms^{-1}) and 3) a real-time data reduction (in order to adapt the observation strategy in real-time). Exoplanet programs conducted with SOPHIE will be able to focus on :

- Searching for very low-mass planets (Neptune-mass planet and hot big Earths),
- Detection of Hot Jupiters coupled with photometric follow-up with the 1.20-m OHP telescope,
- Exploration of the HR diagram from A to M type stars,
- Follow-up of the long period ($\geq$10 years) candidates found by ELODIE,
- Follow-up of the transiting candidates of the photometric ground-based survey,
- Follow-up of the transiting candidates of the COROT space mission.

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