ELODIE & SOPHIE spectrographs: 20 years of continuous improvements in radial velocities

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Abstract

From the first light of ELODIE spectrograph in 1993 up to the recent upgrade of SOPHIE, the radial-velocity precision was improved by an order of magnitude. The different steps of instrumental refinement are described and their impact on the detection and characterization of giant exoplanets are highlighted. Synergies of these two instruments with other detection techniques like photometric transit and astrometry are presented with a special focus on the incoming space missions GAIA, CHEOPS, TESS and PLATO.

1 ELODIE & SOPHIE spectrographs

The ELODIE spectrograph (Baranne et al. 1996), also known as super CORAVEL, was developed in the early 90s and was in operation on the 1.93-m telescope of Observatoire de Haute Provence (OHP) from June 1993 till August 2006. It was the first fiber-link echelle spectrograph using the simultaneous Thorium-Argon technique for radial velocity measurements. Made famous by the discovery of 51 Pegb (Mayor & Queloz 1995), ELODIE was intensively used for exoplanets search (e.g., Perrier et al. 2003, da Silva et al. 2006) but also for asteroseismology (Martic et al. 1999), rotation and activity of low-mass stars (Delbosse et al. 1998), and galactic kinematics (Soubiran et al. 2003).

SOPHIE spectrograph (Perruchot et al. 2008) has replaced ELODIE during summer 2006. This double-passed Schmidt echelle spectrograph associated with a high efficiency coupling fiber offers a gain in efficiency, in spectral resolution and in stability with respect to ELODIE. The adopted concept to improve the stability is that all the dispersive components are encapsulated inside a constant-pressure vessel in order to avoid spectral drift due to atmospheric pressure change. Two observing modes are offered on SOPHIE: High Resolution (HR) and High

Figure 1: ELODIE spectrograph design
Figure 2: SOPHIE spectrograph design

Efficiency (HE). Both instrument designs are shown on Figures 1 and 2. Main characteristics of both instruments are listed on Table 1.

## 2 Continuous improvements of SOPHIE spectrograph

During the first years of operation, SOPHIE has showed a clear limitation in radial velocity (RV) precision with a level in the range 5-7 m/s (Bouchy et al. 2009a, 2013). Several instrumental limitations were identified. The CCD Charge Transfer Inefficiency (CTI) effect introduces a spectral shift as function of the flux level for the low S/N exposures. This effect was described by Bouchy et al. (2009b) and a software correction is applied in order to minimize its impact. An empirical correction directly applied on the radial velocities was also proposed by Santerne et al. (2012). The atmospheric-dispersion corrector (ADC) was suffering a spurious displacement and was introducing both a decentering and a chromatic effect at the fiber entrance. This effect was identified and repaired.

<table>
<thead>
<tr>
<th>ELODIE</th>
<th>SOPHIE</th>
</tr>
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<tbody>
<tr>
<td>spectral range</td>
<td>390-681 nm (67 orders)</td>
</tr>
<tr>
<td>spectral resolution</td>
<td>42 000</td>
</tr>
<tr>
<td>Pupil diameter / aperture</td>
<td>100 mm</td>
</tr>
<tr>
<td>Cross disperser</td>
<td>Grism</td>
</tr>
<tr>
<td>Environment</td>
<td>thermal controlled</td>
</tr>
<tr>
<td>CCD detector</td>
<td>1k×1k – 24 μm</td>
</tr>
<tr>
<td>échelle grating</td>
<td>R4 – 31 gr.mm⁻¹</td>
</tr>
<tr>
<td>fiber size &amp; acceptance</td>
<td>100 μm – 2 arcsec</td>
</tr>
<tr>
<td>S/N¹ in 20 mm</td>
<td>150 for V=7.5</td>
</tr>
<tr>
<td>( \sigma_{RV_{phot}} )</td>
<td>3 m s⁻¹</td>
</tr>
<tr>
<td>RV precision</td>
<td>8 m s⁻¹</td>
</tr>
</tbody>
</table>

¹ Signal-to-noise ratio per bin of 3 km s⁻¹ at 550 nm
on 2008. A new guiding camera for centering and guiding on the fiber entrance was installed in 2009 with an accuracy better than 0.3 arcsec.

A continuous N2 filling was implemented in 2010 to avoid thermo-mechanical shocks on the dewar of the detector. Octagonal-section fibers were implemented in 2011 and 2012 to remove guiding and seeing effects due to insufficient scrambling of standard fibers (Bouchy et al. 2013). This upgrade permitted a significant improvement of the radial velocity precision down to the level of 2 m s\(^{-1}\). A calibration unit was developed on 2014 to remove all the lamps from the Cassegrain fiber adapter and to install them on a thermal-controlled room. This calibration unit includes a laser-driven light source (LDLS) for spectral flat field, two Thorium-Argon Hallow-Cathode lamps and a visitor slot. In 2015 a complete upgrade of electronic and control-command of Cassegrain Fiber Adapter was realized. Several improvements are foreseen for 2016 including the installation of Fabry-Pérot etalon in the calibration unit for drift measurement, a new thermal control to remove thermal bridge with the telescope pillar, and the adaptation of the last version of the HARPS data-reduction software.

3  Exoplanets search surveys

The ELODIE Planet Search Survey, was an extensive radial-velocity survey of dwarf stars in the northern hemisphere. It was initiated in 1994 by M. Mayor and D. Queloz with the aim to detect very low-mass stellar companions. ELODIE survey, which allowed the discovery of the first extra-solar planet 51Pegb orbiting a solar-type star (Mayor & Queloz 1995), is described by Perrier et al. (2003)

The SOPHIE search for northern extrasolar planets program (Bouchy et al. 2009a) started in October 2006 with the aim of covering a large part of the exoplanetary science. The observing strategies and target samples were optimized to achieve a variety of science goals and to solve several issues like: 1) planetary statistical properties to constrain the formation and evolution models; 2) relationships between planets and the physical and chemical properties of their stars; 3) detection of exoplanets around nearby stars, allowing space and ground-based follow-up. All these aspects are treated through the five following complementary subprograms:

SP1 : High-precision search for Neptunes and Super-Earths
SP2 : Giant planets survey on a volume-limited sample
SP3 : Search for exoplanets around M dwarfs
SP4 : Search for exoplanets around early-type main sequence stars
SP5 : Extension of ELODIE survey to search for Jupiter analogs

This large program totalizes about 150 nights per year and includes in total more than 2500 stars.

Figure 3 displays the minimum mass and orbital semi-major axis of giant planets known so far. Among the detections made with ELODIE and SOPHIE (red dots), one can emphasize particular objects like 51Pegb (Mayor & Queloz 1995), HD189733b (Bouchy et al. 2005), HD80606b (Naef et al. 2001; Moutou et al. 2009), some massive objects at the transition with brown-dwarf like HD16760b (Bouchy et al. 2009a) and HD22781b (Diaz et al. 2012); some Jupiter analogs like HD24040b and HD222155b (Boisse et al. 2012); and several giant planets in multiple systems like HD74156bc (Naef et al. 2004), HD94466bc (Hebrard et al. 2010), HD13908bc (Moutou et al. 2014).

4  Follow-up of transiting planets

SOPHIE is a key instrument for the follow-up and characterization of transiting planets. WASP-1b and WASP-2b (Collier Cameron et al. 2007) were established and their masses measured with SOPHIE during the science-verification phase in august and september 2006. SOPHIE is routinely used for the follow-up of transiting candidates from SWAPs, HAT, CoRoT, Kepler, and K2 surveys. SOPHIE helps to the identification of false positives, the mass and orbital eccentricity measurements, the host star spectroscopic classification, the spin-orbit obliquity (through the Rossiter-McLaughlin effect), and the long term follow-up to search for additional distant exoplanets. The SOPHIE transit consortium led by G. Hebrard uses about 70 nights per year for the follow-up of transiting planets.

Figure 4 displays the mass and radius of transiting giant planets detected so far. Among the highlights made with SOPHIE, one can emphasize inflated hot Jupiters WASP-12b (Hebb et al. 2009) and Kepler-435 (Almenara et al. 2015); massive giants at the transition with brown-dwarfs like CoRoT-3b (Deleuil et al. 2009) and Kepler-39b (Bouchy et al. 2011), the first misaligned spin-orbit system XO-3b (Hebrard et al. 2009); the Saturn-like giant WASP-21b (Bouchy et al. 2010) and Kepler-425b (Hebrard et al. 2010).
Figure 3: $M_{\sin i}$ - semi-major axis diagram of giant planets detected by radial velocity. Red points correspond to planets detected with ELODIE and/or SOPHIE.

Figure 4: Mass - radius diagram of transiting giant planets. Red points correspond to planets measured with SOPHIE.
5  Synergies with incoming space missions

SOPHIE will continue to play an important contribution for exoplanet programs in the coming years. SOPHIE is benefiting of several strengths and advantages:
- The 1.93-m OHP telescope is almost entirely dedicated to exoplanet science.
- A significant large number of allocated nights can be devoted to the exoplanet studies.
- The regroupement of sub-programs with a common pool of observers permit a very high flexibility and reactivity.
- The radial velocity precision, now close to 2 m s\(^{-1}\), permits to explore the domain of low-mass exoplanets.
- The maintenance and the on-going improvement of the instrument secures the long term exploitation.
- Real time data reduction at the telescope allows a very fast reactivity and an optimization of the observing strategy.

Several synergies with incoming space missions are foreseen. CHEOPS (Fortier et al. 2014) is an ESA small-class mission dedicated to search for exoplanetary transits by performing ultra-high precision photometry on bright stars already known to host planets. The CHEOPS science goals are to measure the bulk density of super-Earths and Neptunes and to provide suitable targets for future in-depth characterization. SOPHIE is identified as a provider of RV planets for CHEOPS and is also used to refine the ephemeris of low-mass RV planets in order to minimize the observational window around the expected transit.

The space mission GAIA will soon provide astrometric measurements with a precision allowing the detection of giant planetary companions with orbital periods of few years (Sozzetti et al. 2015). The combination of radial velocity measurements and GAIA astrometric measurements will permit to increase the number of detection as well as to refine orbital parameters of giant exoplanets (Neveu et al. 2012).

The Transiting Exoplanet Survey Satellite (TESS) (Ricker et al. 2015) will employ 4 x 10-cm telescopes to observe all the sky with 26 sectors covering 24 x 96 degrees in a two-year survey. TESS will monitor more than 200000 stars and is expected to discover thousands of exoplanets ranging from Earth size to gas giants. Thanks to overlaps, ecliptic poles will benefit of continuous observation up to almost one year. From TESS simulations (Sullivan et al. 2015), about 1700 exoplanets are expected to be discovered. PLATO (Rauer et al. 2014), recently selected for ESA M3 mission, will consist of 34 small aperture telescopes providing a wide FoV and large photometric dynamic range. PLATO will focus on bright stars to detect and characterize planets down to Earth size. Asteroseismology will allow to derive accurate stellar parameters. The combination of high precision, seismology and ground-based follow-up will result in high accuracy on the bulk planet parameters. For these two space missions devoted to search for transiting exoplanets, SOPHIE will play a crucial role for the screening of candidates as well as for the mass determination of giant and Neptune-like planets.

6  ELODIE and SOPHIE spectroscopic archives

ELODIE has produced over 35500 spectra on about 8000 distinct identifiers. 26300 spectra have measured radial velocities. Data are available on the archive web site http://atlas.obs-hp.fr/elodie/. Publications making use of the ELODIE Archive should refer to Moultaka et al. (2004). Publications making use of the ELODIE Library should refer to Prugniel & Souffrin (2001).

SOPHIE has produced so far over 81500 spectra on more than 6100 distinct objects. 56000 spectra are now fully public and available on the archive web site http://atlas.obs-hp.fr/sophie/. In addition, 20000 spectra are available with the time information masked (5-year protection), and 5500 spectra are still under the normal 1-year embargo. Cross-correlation information now exists for 80000 spectra, corresponding to 5700 distinct object names, only available for data having cleared the 1-year embargo.

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References


