Radial velocity search for long-period exoplanets and brown dwarfs with ELODIE and SOPHIE

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1 Introduction

As radial velocity (RV) surveys extend their time baseline, more planets beyond 4 AU start to emerge. But even though the number of confirmed planets has reached two thousand, we have only just surpassed 40 systems with giant planets at orbital distances greater than 4 AU. This relatively low number is clearly due to an observational bias. Only a decade ago, the long-term accuracy of several spectrographs began to be high enough to allow the detection of long-period Jupiter-like planets.

It is important to take advantage of long-term surveys to detect this particular kind of planets for several reasons. First, it allows us to put the solar system into perspective. Second, to constrain planet formation and evolution models, it is important to probe systems with bodies beyond the ice line. Finally, giant planetary companions can play an important role in the dynamical evolution of the system. This is of special interest to understand the orbital parameters of hot Jupiters.

In our search for long-period exoplanets, it is inevitable to encounter another population of substellar objects: brown dwarfs. Brown dwarfs have masses in the range of 13 to 80 Jupiter masses, enough to ignite the deuterium burning in their inner cores (Burrows et al. 1997, Chabrier & Baraffe 2000, Spiegel et al. 2011). The separation between the planetary and brown dwarf population may be given not only by their mass range, but also different formation mechanisms. Brown-dwarf companions with periods of up to about ten years orbiting around solar-like stars are far less common than stellar and planetary companions (e.g., Grether & Lineweaver 2006, Sahlmann et al.
As of today, we only know a few of them with orbital periods longer than ten years (e.g., Sahlmann et al. 2011). This means we need to do a special effort to improve the statistics of the orbital parameters of this type of objects, in order to distinguish between the different formation and evolution scenarios.

In this range of masses and orbital distances, a synergy exists between radial velocities and other detection techniques as direct imaging and astrometry. This can be particularly useful to rule out low-mass stellar companions in the case of incomplete orbits and drifts, and to constrain the orbital parameters of sub-stellar companions.

In the search for long-period exoplanets we encounter two main difficulties that can introduce spurious signals: first, important offsets are caused by the replacement and modification of instruments, and second, we find ourselves in the typical timescale of stellar activity cycles. This is why it is important to well constrain the offsets between instruments and also be able to disentangle stellar activity and a possible sub-stellar companion.

# 2 Long-period exoplanet search programs

## 2.1 Follow-up of ELODIE long periods

This subprogram is part of the large program to search for exoplanets (RPE), conducted by the SOPHIE consortium (Bouchy et al. 2009). All targets were part of the historical program started by M. Mayor and D. Queloz in 1994 (Mayor & Queloz 1995) and were observed using ELODIE ([Baranne et al. 1996]) a cross-dispersed echelle spectrograph mounted at the 1.93-m telescope at the Haute-Provence Observatory, between late 1996 and mid-2006. ELODIE could yield radial velocities with a precision down to 10 ms\(^{-1}\). From that sample, we selected around 60 G and K stars showing long-term trends. This selection of targets has been monitored from 2007 to present day, with the SOPHIE spectrograph ([Perruchot et al. 2008]) installed at the 1.93-m telescope after the decommission of ELODIE. SOPHIE had a typical precision limited to 5-6 ms\(^{-1}\) until its upgrade in 2011. After a piece of octagonal-section fiber was implemented in the fiber link ([Bouchy et al. 2013]) the new instrument SOPHIE+ now reaches radial velocity precision in the range of 1-2 ms\(^{-1}\). This also gives SOPHIE+ the efficiency to detect low-mass exoplanets down to 5-10 M\(_{\odot}\). This unique database extends our time baseline over more than 20 years and allows us to look for giant planets and brown dwarfs beyond 4 AU.

For both instruments, the observations were made simultaneously with a thorium-argon calibration. SOPHIE spectra were taken using the high-resolution mode (R = 75000). To derive the radial velocities, we used the SOPHIE automatic data reduction software, that does a cross-correlation with a G2 or K5-spectral type numerical mask. This program has 5 nights of allocated time each semester.

## 2.2 Long-term follow-up of known transiting hot Jupiters

Unlike results from RV surveys, only a few transiting hot Jupiters are known to be part of multiplanetary systems that include long-period giant planets. This is mostly due to an observational bias, as the radial velocity confirmation of transiting hot Jupiters normally consists of just a few measurements over a short timespan, and hence longer-term trends are missed. Radial velocities are, however, an excellent option to look for these outer companions, since by extending the observing baseline it is relatively easy to detect trends evidencing the presence of additional bodies in the system.

In terms of formation, it is commonly accepted that hot Jupiters form beyond the ice line and then migrate inwards (e.g., Lin et al. 1996), but the migration mechanism is still a subject of debate. Another aspect that remains unexplained, is the considerable number of hot Jupiters that present misaligned and/or eccentric orbits.

One possible explanation for inward migration might be the interaction with these massive companions. Increase the number of identified multiplanetary systems is the best way to understand the different orbital parameters and distinguish between migration models.

This subprogram is part of the TRANSIT follow-up large program. It started in 2014A with a set of 35 known hot Jupiters from photometric surveys as CoRoT, Kepler, HAT and WASP and now has approximately 5-6 nights of allocated time each semester. We recovered previous measurements done with SOPHIE as part of the Transit follow-up program, to extend our time baseline. The faintest targets are done in high efficiency mode (R = 40000), while the brightest ones in high resolution mode.

Both of these programs are complementary to similar ones conducted in the southern hemisphere with HARPS and CORALIE.
3 Instrumental offset and drifts

While observing a star with more than one instrument, the RV offsets between datasets can be fitted as a free parameter when adjusting a Keplerian, or they can be fixed. For most cases we use the color-dependent solution to fix the ELODIE-SOPHIE offset (see Fig.A.1 from Boisse et al. 2012). For some preliminary results done with Yorbit (like the ones shown here) and cases with large uncertainty in the RV offset relation (brown dwarfs from Bouchy et al. 2016), we left the offset as a free parameter.

To sample the long-term variations in radial velocities due to instrumental effects, a set of stable stars has been followed-up since the beginning of SOPHIE. This is used as a correction for all data taken from June 2011, as described in Courcol et al. (2015).

4 Magnetic cycles

We know that magnetic cycles can induce radial velocity variations that could mimic the signature of a planet (e.g., Lovis et al. 2011, Díaz et al. 2016). In the Sun, the number of spots and plages on the stellar photosphere changes with a period of 11 years. Therefore, stars with similar activity cycles could show radial velocity variations with periods of the order of a Jupiter-like orbit. We aim to disentangle stellar activity from any possible planetary signal in our data to avoid any false detections.

For SOPHIE data we can see hints of activity in different ways, e.g. correlations between the RVs and bisector or FWHM. We can also use the log $R^\prime_{HK}$ index (Noyes et al. 1984) which is computed from the Ca II H&K lines and it is sensitive to the presence of plages in the stellar chromosphere. Unfortunately, the blue part of the spectrum is not well covered with ELODIE, so we can only trace the activity back to 2007 using this method.

On the other hand, for both ELODIE and SOPHIE spectra we have the Hα line, which is formed at lower altitude in the atmosphere than the H & K lines. Nevertheless, the Hα line has shown to be a good chromospheric activity indicator. We compute this activity index as the ratio between the flux in the line, centered at 6562.808Å and a reference flux on both sides of the line, near the continuum level.

Our main interest is to study the long term evolution of the Hα index of each star, and not to compare the activity levels between stars. This is why we did not apply any spectral-type correction to the index. One example of this long term evolution is shown in Fig. 1. The offset has been fixed for both RVs and Hα, the latter computed using approximately 20 non-active stars.

![Figure 1](image)

Figure 1: Radial velocities and Hα index of HD210460, with ELODIE points in green and SOPHIE in red. Left panel: Variation of radial velocities as a function of time. Central panel: Evolution of the activity cycle using the Hα index as a function of time. Right panel: correlation between radial velocities and the Hα activity index.

5 Results

5.1 Brown dwarfs

Most of the brown-dwarf companions have been discovered by radial velocity surveys of nearby solar-type stars (Nidever et al. 2002, Sahlmann et al. 2011, Díaz et al. 2012). Results of these surveys show a clear lack of brown-dwarf companions within 5 AU compared to planetary systems and stellar binaries (Grether & Lineweaver 2006).
Sahlmann et al. 2011; Ma & Ge 2014). To understand the formation and evolution processes that could explain this deficit, there must be an increase in the number of such objects. There have been numerous efforts to achieve this task, one of them being conducted with the SOPHIE spectrograph (Wilson et al. submitted).

Beyond 5 AU, only a few objects have been discovered so far, clearly due to the relatively low amount of long-term surveys. Nevertheless, it is expected that the number of brown-dwarf companions increases with orbital separation. This conclusion is reinforced by the results Bouchy et al. (2016), where new brown-dwarf companions to solar-type stars are presented. The five new objects, orbiting around HD10844, HD14348, HD18757, HD72946 and HD209262, double the number of known brown-dwarf companions with orbital periods longer than 10 years. The orbital parameters and radial velocities are presented in Fig. 2.

Figure 2: Radial velocity curves of three brown dwarfs around HD209262A (left), HD14348 (center) and HD72946 (right). ELODIE points are shown in blue and SOPHIE in red.

5.2 Updated orbits and new candidates

New data allows us to better constrain the orbital parameters of previously identified companions, which is the case of all five targets in Boisse et al. (2012). In the case of HD150706, there is an important change in eccentricity now that the orbit is better covered. The updated orbits for HD150706 and HD222155 are presented in Fig. 3.

Figure 3: Updated radial velocity curves for HD222155 (left) and HD150706 (center) without the partial correction of the effect of the stellar spot on the SOPHIE radial-velocities, done in Boisse et al. (2012). Incomplete curve of one of our planetary candidates (right). ELODIE data are plotted in blue, SOPHIE in red and Keck (Moro-Martín et al. 2007) in orange.

5.3 Long-period candidates in systems with a transiting hot Jupiter

After 2 years of observations, we present one preliminary result. More data and further analysis are needed to discard other possible sources of variation in our radial velocities and complete the orbit of our candidates. In terms of number of expected long-period companions, we can mention similar surveys conducted in the south with the CORALIE spectrograph (Neveu-VanMalle et al. 2015) and the north with HIRES at Keck (Knutson et al. 2014) and HARPS-N at TNG. From their sample of 51 hot Jupiters, Knutson et al. (2014) estimated an occurrence rate of
55\(^\pm\)10\% for companions with masses between 1-13 \(M_{\text{Jup}}\) and orbital semi major axes between 1-20 AU. According to this work, we should expect between 16-23 companions of similar characteristics. On the other hand, the sample of Neveu-VanMalle et al. (2015) consisted in more than 100 WASP host stars followed for durations of two to eight years, including about 90 targets followed for more than three years. Their results include at least two stars with a second planet, besides the hot Jupiter, that has completed at least one orbit (Neveu-VanMalle et al., in prep.). This leaves them with a lack of multiple systems within 2 AU compared to the number of multiple systems with hot Jupiters discovered by radial velocity surveys. One of our preliminary results is presented in Fig. 4.

Figure 4: Radial velocity curve for one of the hot Jupiters in our sample presenting a massive long-period companion. FIES data in blue, HARPS in orange and SOPHIE in red.

### 6 Conclusion

Even though the relatively low number of long-term surveys has biased the detection of sub-stellar companions beyond 4-5 AU, the amount of long-period planets and brown dwarfs is starting to grow. In this context, our subprograms contribute with two Jupiter analogs [Boisse et al. 2012] and five brown-dwarf companions to solar-like stars [Bouchy et al. 2016]. These discoveries help to set up a better observational base with which to compare models of formation and migration of giant planets and brown dwarfs. These bodies are also excellent candidates for observations with complementary techniques such as astrometry and direct imaging, not only to better constrain the orbital parameters, but also to determine the inclination of the system and the true mass of the companion. These is also helpful to discard possible stellar companions which are compatible with radial velocity drifts found in our survey. We started a collaboration with J. Hagelberg to image possible low-mass stellar companions compatible with some of our drifts, using the instrument SCExAO installed at the Subaru telescope.

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### References