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SEARCH AND CHARACTERIZATION FOR EXTRASOLAR PLANETS IN THE NORTHERN HEMISPHERE WITH THE SOPHIE CONSORTIUM

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Abstract. In November 2006, our consortium started a large program of exoplanet search in the North hemisphere with the new spectrograph SOPHIE at Haute Provence Observatory (OHP). The SOPHIE spectrograph was design and optimized to provide high precision radial velocity measurements to carry out systematic searches for exoplanets. The SOPHIE consortium, which gathers 23 members from Paris, Geneva, Grenoble and Marseille exoplanet teams, takes in charge a large program to search and study exoplanets. Our objectives are to characterize the zoo of exoplanets and to bring strong constraints on their processes of formation and evolution using the radial velocity techniques. Five sub-programs are carried at once: 1) very low-mass planets; 2) hot-Jupiters; 3) planets around very low-mass stars; 4) planets around early-type stars; 5) very long-period planets. The status of these sub-programs and first results of our consortium are presented.

1 Introduction

Major breakthroughs were made these last years in exoplanetology thanks essentially to the improvement of Doppler techniques mainly illustrated by the HARPS spectrograph (3.6-m ESO). With about 250 exoplanets detected up to now (see Fig.1), several statistical properties are emerging, all of them being potential constraints for scenarios of formation and evolution of planetary systems. However there is still poorly understood relations and intriguing properties which need additional detection and characterization of planetary systems. For example only a minority of the detected planets have masses smaller than Saturn mass and the distribution of planetary masses is heavily biased. We might also mention the lack of any robust conclusions on the dependence of exoplanet parameters with the properties of host stars. Far to be considered as an old-fashioned techniques, radial velocities (RV) clearly offer for the next decade the possibility to continue and extend the exploration of exoplanet systems. In this context and tacking into account the limitation of the spectrograph ELODIE, as well as the performances of the spectrograph HARPS, the new RV instrument SOPHIE had be designed, built and installed at Haute Provence Observatory. Our consortium was created with the goal to be in charge of a significant, comprehensive and competitive program to search and study exoplanets in the Northern hemisphere.

2 The spectrograph SOPHIE

The SOPHIE echelle spectrograph was built at the Haute Provence Observatory (OHP). It replaces and upgrades the ELODIE spectrograph (Baranne et al. 1996), well known for the discovery of the first hot Jupiter 51Pegb twelve years ago (Mayor & Queloz, 1995). The goal was to design an instrument based on the principle of HARPS (3.6-m ESO; Mayor et al. 2003) but adapted for a 2-m class telescope. The requirements were to

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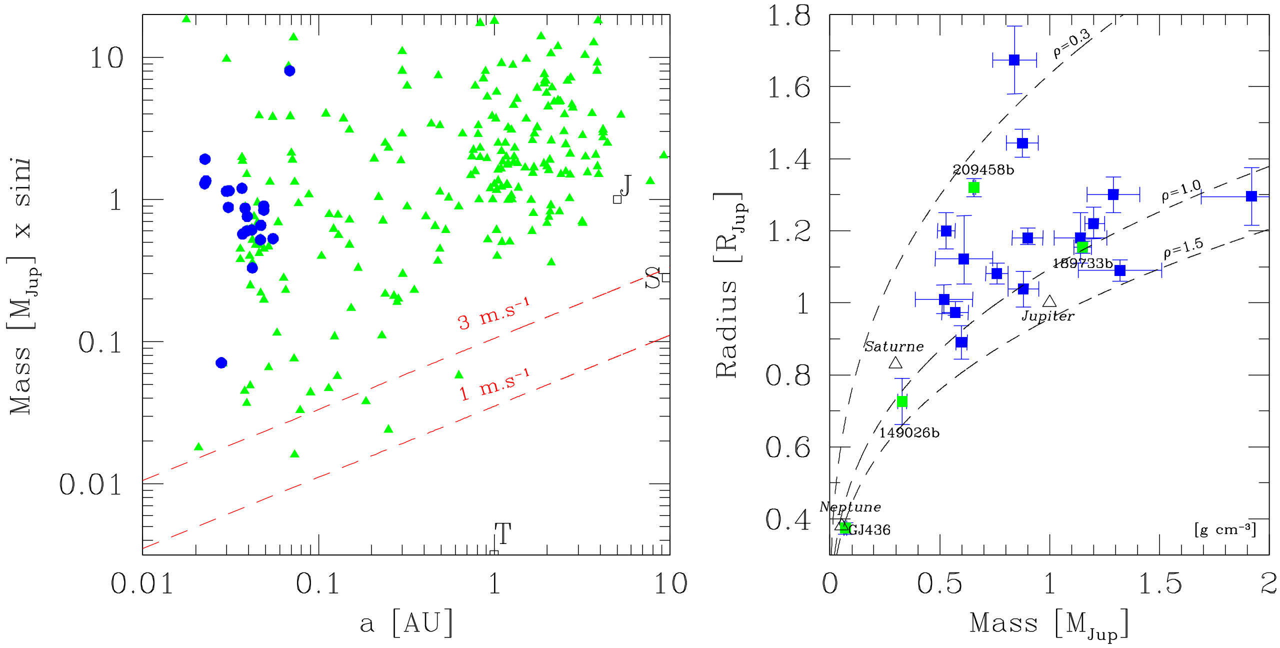

Fig. 1. (Left) Minimum mass versus orbital distance of known exoplanets detected by RV (green triangle) and photometric transit (blue circle). (Right) Mass-radius relation of known transiting exoplanets.

increase 3 factors compared to ELODIE: 1) the overall efficiency, 2) the spectral resolution, and 3) the Doppler accuracy. SOPHIE was installed at the 1.93-cm telescope on July 2006. Commissioning and science verification of SOPHIE permit to draw up its main performances. SOPHIE offers a gain in efficiency of 3 mag with its High Efficiency (H.E.) mode compared to ELODIE. A S/N of 100 per pixel (0.025 Å) is obtained with the H.E. mode on 1 hour on a 11 mag star. SOPHIE offers a gain on spectral resolution of 1.6 with its High Resolution (H.R.) mode (R=75'000) compared to ELODIE. Its radial velocity accuracy is estimated to 3 ms^{-1} on the long term (3 to 4 times better than ELODIE) but may still be improve in the next semesters (see section 5). SOPHIE is open to the community since November 2006. This instrument was briefly described by Bouchy et al (2006) and by Le Coroller et al. (these proceedings). Relevant and updated informations and documentations may be found in the OHP web page[1].

3 The EXOPLANETS SOPHIE consortium

The EXOPLANETS SOPHIE consortium was created in order to merge French and Swiss teams involved in search and study of exoplanets. This consortium gathers 23 members from 4 laboratories: Institut d'Astrophysique de Paris (IAP), Geneva observatory, Laboratoire d'Astro- physique de Marseille (LAM) and Laboratoire d'Astrophysique de l'Observatoire de Grenoble (LAOG). Three PhD students are involved in the activity of the consortium. We started in November 2006 a large program on SOPHIE which benefits of about half the available night on the 193-cm telescope (60 nights on 2006B and 90 nights on 2007A). Our objectives are to bring constraints on the processes of exoplanet formation and evolution and to characterize these objects. More precisely our goals are : 1) to determine the mass function distribution of low-mass exoplanets, 2) to increase the exoplanets sample in order to study their statistical properties; 3) to detect exoplanets around nearby stars for additional ground-based and space-based follow-up; 4) to study relation between exoplanets and host star properties; 5) to characterize mass and radius of transiting exoplanets. Our large program is fully complementary to the HARPS GTO program *"A high-precision systematic search for exoplanets in the Southern Sk"* conducted on the 3.6-m ESO telescope and led by M. Mayor.

[1] http://www.obs-hp.fr/www/guide/sophie/sophie-eng.html

4 Description, status and results of the 5 sub-programs of SOPHIE consortium

For our objectives, we decided to start simultaneously 5 complementary sub-programs using in a appropriate way the full capabilities of the spectrograph. The 5 sub-programs are listed in Table 1. The reason that we merged this 5 sub-programs comes from the goal to optimize telescope time and to share expertise and competences. The 23 Co-Is of the consortium are tacking in charge the observations as well as the analysis of results (provided on-line by the data reduction software) and the optimization of the strategy.

Table 1. The 5 sub-programs conducted with SOPHIE

Sub-Program	leader	Title	# stars	% nights[a]
SP-1	S. Udry	Search for very low-mass planets	212	33%
SP-2	C. Moutou	Search for Hot-Jupiters	2233	25%
SP-3	X. Delfosse	Search exoplanets around M-dwarfs	183	19%
SP-4	F. Galland	Search for exoplanets around early-type stars	324	19%
SP-5	D. Queloz	Search for long-period planets	41	4%

(a) dedicated fraction of nights for each sub-programs

4.1 SP1 - Search for very low-mass planets

This program is dedicated to the search for low-mass exoplanets ($m_p.v \sin i$ <0.1 M_{Jup}) around quiet solar-type stars (G and K dwarfs) with the high-precision mode of SOPHIE. With an expected precision of 1-2 ms^{-1} SOPHIE offers the unique opportunity to search for low-mass planets in the Northern sky (hence in full complement with HARPS). These low-mass planets appear to be crucial to constrain the models of formation, evolution, evaporation and migration of exoplanets. This program needs a large amount of measurements in order to average out the stellar activity and to constrain the orbital parameters of multiple systems. Furthermore each data points consist to integrate over a sufficient duration (15 mn) to reach a photon-noise uncertainty bellow 1 ms^{-1} and to average out the p-mode oscillations. In order to find a significant sample of low-mass exoplanets, we wish to follow about 200 stars over at least 5 years with in average 30 measurements per target. The stellar sample was preselected among bright stars (mv<8), non-active ($v \sin i < 3\,\mathrm{kms}^{-1}$; $\log R'_{HK} < -4.7$) and from the previous program ELODIE and the sub-program 2.

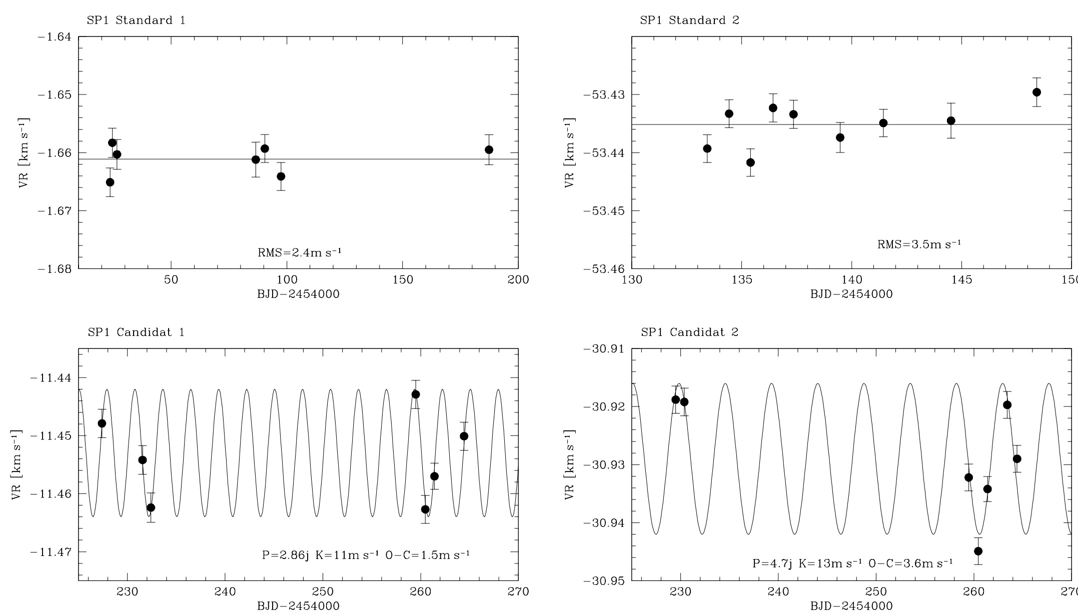

Fig. 2. Some results obtained with the sub-program 1 of SOPHIE consortium.

During the first semester 2006B (share-risked period), this high-precision program was made in a slow regime tacking into consideration that the instrument was not in its final configuration and presented some limitations. Several interventions inside the spectrograph prevented a sufficient stabilization for high-precision measurements. The optical filter in front of the Thorium-Argon lamp was not installed before April 2007 and it was not possible to use properly the simultaneous thorium calibration with a sufficient precision before this date. During the second semester 2007A, we started in its nominal regime this sub-program. About 40 stars were observed. On our more stable stars, we obtained a precision of about 3 ms^{-1}. Some stars clearly present variations which justify their follow-up. Some results are shown in Fig. 2. We have evidences that the present accuracy limitation comes from the guiding noise. Some tests demonstrated that the centering and guiding on the fiber entrance is very sensitive and may introduce radial velocity errors. The present guiding system, which is included in the old Cassegrain Fiber Adaptor (CFA) built and used for ELODIE since 1994, is clearly the main limitation in the accuracy of SOPHIE.

4.2 SP2 - Search and characterization of Hot-Jupiters

This program is dedicated to the intensive search of hot-Jupiters and the characterization of known transiting hot-Jupiters. Up to day, 20 transiting planets have been detected and characterized thank to the complementary methods of photometry and radial velocity (see Fig. 1). Among these exoplanets, 4 of them were found first from RV survey and in a second step the photometric transit was detected. These 4 exoplanets (HD209458b, HD189733b, HD149046b, GJ436b) offer the unique advantage to orbit bright and near stars and conducted to additional characterization like for example the detection of atmospheric escape and detection of IR anti-transit. The detection of transiting hot-Jupiters may then conduct more easily to bright host stars if it comes from RV survey than from photometric survey constrained to observe faint stars. This sub-program is conducted on a sample of more than 2000 solar-type stars (FGK dwarfs) up to 10th magnitude. One fraction of the time is dedicated to the spectroscopic transit (Rossiter effect) of known transiting hot-Jupiter in order to characterize the alignment spin-orbit of the systems.

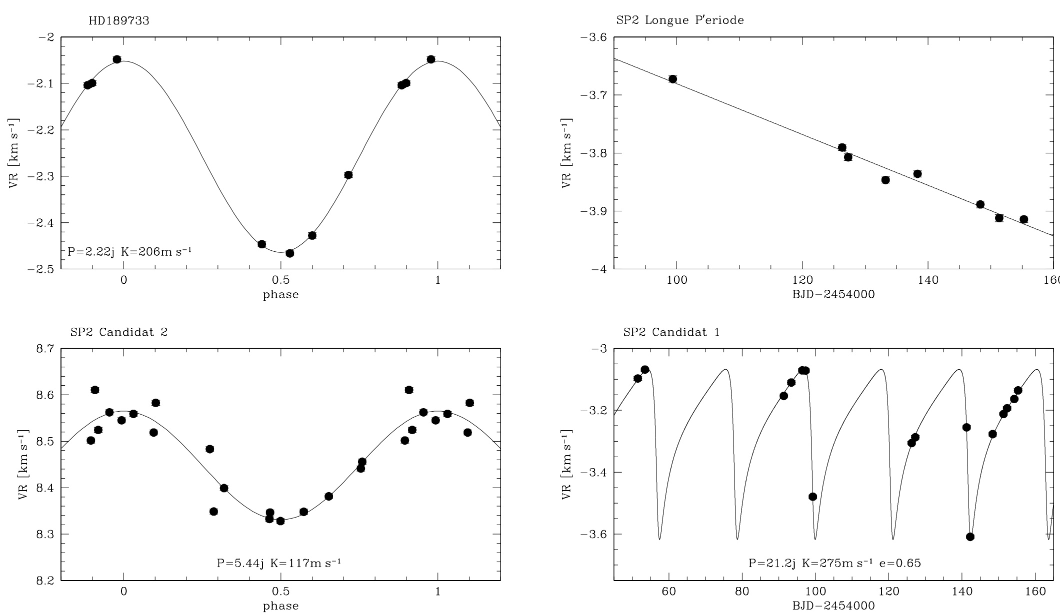

Fig. 3. Some results obtained with the sub-program 2 of SOPHIE consortium.

During the first semester we put significant effort on this sub-program which does not need the high-precision. HD189733b, discovery with ELODIE 2 years ago (Bouchy et al. 2005), is confirmed with SOPHIE and presents O-C residuals 2 times lower (see Fig. 3). Several tens of binaries were identified and about 50 stars were identified as variable. Analysis of their activity index from CaII lines demonstrated that almost majority of these stars correspond to active stars. This is the case of our candidate 2 shown in Fig. 3. One new exoplanet

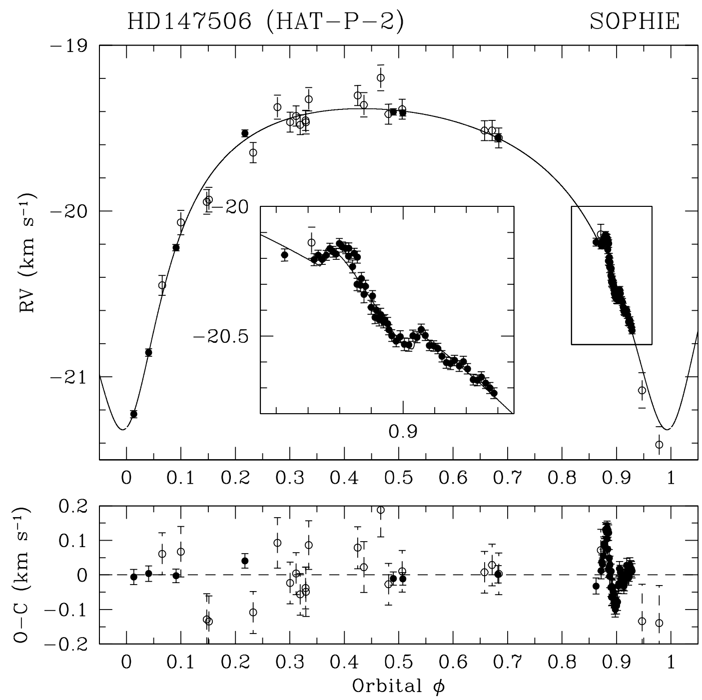

Fig. 4. Phase-folded RV measurements obtained on HD147506 (HAT-P-2) superimposed on the refined Keplerian orbital solution (from Loeillet et al. 2007). Open circles refer to the Keck and Lick measurements and filled circles refer to the SOPHIE measurements. The inset shows a zoom around the transit where RVs exhibit the Rossiter-McLaughlin effect.

was found around HD17156 but announced first by the American team (Fischer et al. 2007) with exactly the same orbital parameters (see candidate 1 in Fig. 3). Two exoplanet candidates already suspected with ELODIE around HD43691 and HD132406 were confirmed and fully characterized with SOPHIE (Da Silva et al. 2007). We refined the orbital parameters and we measured the spectroscopic transit (Rossiter-McLaughlin effect) of the super-massive planet HAT-P-2b (Loeillet et al. 2007; see Fig. 4). We developed a tool in order to have in real time an estimation of stellar metallicity index [Fe/H] and the activity index R'_{HK} in order to optimize the observational strategy (see Boisse et al., these proceedings). Few exoplanet candidates were identified but need additional measurements.

4.3 SP3 - Search for exoplanets around M-dwarfs

This program is dedicated to the search of exoplanets around low-mass stars. Such a survey will give a chance to derive the frequency and properties of planets as a function of the stellar mass. Furthermore, for these low-mass stars, short-period planets of few Earth masses might be detected. Up to day seven out of nine planets discovered around M dwarfs have mass in the range of Neptune mass or below. This is a strong constraint for planet-formation models but clearly need confirmation with a larger survey. The main objectives of this sub-programs are : 1) to detect exoplanets of few Earth masses; 2) to determine the statistical analysis of orbital and physical parameters of exoplanets around M-dwarfs; 3) to find transiting Neptune-size exoplanets (like GJ436b; Gillon et al., 2007); 4) to find exoplanets around near stars for additional ground-based and space-based follow-up. This program is conducted on two samples : 1) a volume-limited sample of slowly rotating non-binary M-dwarfs of the North sky located nearer 12 pc (V<14); 2) an extension to 25 pc for the M-dwarfs brighter than V=12. During this first year, we made two measurements on each stars of our sample (183 stars) in order to cover properly the long period and to identify the less active stars. Before April 2007, the contamination of the ThAr spectra with the Argon lines strongly affected the red spectral orders which correspond to the highest S/N orders for the M-dwarfs. The identified guiding noise, already discussed in section 4.1, is about 2-3 times greater with the High Efficiency mode (which does not include the double scrambler of fibers). It then introduce a strong limitation in our programs for our fainter stars observed with this mode.

4.4 SP4 - Search for exoplanets around early-type stars

This program is dedicated to the search of exoplanets around massive stars. Up to day almost all RV surveys are focusing on solar-type stars with spectral type later than F8. Early type stars are less appropriate for RV survey considering that they have less spectral lines often broadened by high rotational velocity. As the SP-3, such a survey will give a chance to derive the influence of the physical properties of the parent stars on the processes of formation and evolution of exoplanets. This program is conducted on a sample of 5 B dwarfs, 124 A dwarfs and 195 F dwarfs. A similar program is conducted with HARPS in the Southern sky (see Desort et al., these proceedings). After one year, 4 cases of binaries, 11 cases of active stars and 4 candidates were identified. The most promising candidate correspond to a 4 Jupiter mass planet orbiting a F4V active star ($v \sin i = 10 kms^{-1}$) with a period of ~160 days.

4.5 SP5 - Search for long period planets from ELODIE survey

This program is dedicated to the follow-up of long-period candidates from the ELODIE survey. The RV survey started with ELODIE in 1994 by M. Mayor and D. Queloz have conducted to the discovery of up to 20 exoplanets. About 320 stars were observed during 12 years. Some of them (41) clearly present slow drift which may indicate very long period exoplanets. Our objective is to follow ELODIE long-period candidates in order to identify giant exoplanets which are analog to those of our solar-system (a>5 AU) and to characterize multi-planetary systems. We decided to start this sub-program only after the last intervention made in the instrument (April 2007) in order to be sure to keep the same overlap between ELODIE and SOPHIE. We wish to conduct this program as long as possible.

5 Conclusions and perspectives

During this first year (semester 2006B and 2007A) we obtained a total of 150 nights for our large program on SOPHIE. About one third of nights were lose due to weather conditions. Only 2 nights were lose due to technical problems on the telescope and/or guiding system. During the first semester (share risked period), several interventions made on the spectrograph prevent to reach the high accuracy. Our intensive programs permit to identify some limitations and permit to strongly optimize the instrument as well as the data reduction software offered to all users. The data base of the consortium was built and installed in IAP and we can consider that our large program is now in a full operating mode. The current limitation on the RV precision mainly comes from the guiding noise and limits the sub-programs 1 and 3. A new Cassegrain Fiber Adaptor (CFA), including a Tip-Tilt correction system on the fiber entrance, is strongly mandatory to reach the 1 ms^{-1} level of precision. We also identify that photometric complementary observations are need for the two main following reasons : 1) to search for transit signature of short period exoplanets; 2) to characterize the stellar activity (rotational period). For these reasons the SOPHIE consortium strongly supports the new CFA of SOPHIE and the upgrade of the automatic telescope ROSACE in OHP.

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