The SOPHIE search for northern extrasolar planets

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Received 16 April 2015 / Accepted 12 June 2015

ABSTRACT

High-precision radial velocity surveys explore the population of low-mass exoplanets orbiting bright stars. This allows accurately deriving their orbital parameters such as their occurrence rate and the statistical distribution of their properties. Based on this, models of planetary formation and evolution can be constrained. The SOPHIE spectrograph has been continuously improved in past years, and thanks to an appropriate correction of systematic instrumental drift, it is now reaching 2 m s\textsuperscript{-1} precision in radial velocity measurements on all timescales. As part of a dedicated radial velocity survey devoted to search for low-mass planets around a sample of 190 bright solar-type stars in the northern hemisphere, we report the detection of a warm Neptune with a minimum mass of 16.1 ± 2.7 M\textsubscript{Jupiter} orbiting the solar analog HD 164595 in 40 ± 0.24 days. We also revised the parameters of the multiplanetary system around HD 190360. We discuss this new detection in the context of the upcoming space mission CHEOPS, which is devoted to a transit search of bright stars harboring known exoplanets.

Key words. planetary systems – techniques: radial velocities – stars: individual: HD 164595 – stars: individual: HD 190360 – stars: individual: HD 185144

1. Introduction

Over the past 20 years, the radial velocity (RV) technique has benefited from continuous developments. Several major milestones in detection and characterization of extrasolar planets have been made possible with this technique, either in the context of large surveys or in follow-ups of transiting candidates. These developments allowed a few stabilized spectrographs like HARPS (Mayor et al. 2003) to gradually scan the area of Neptune-like objects and super-Earths and detect exoplanets with minimum masses as low as 1 M\textsubscript{Jupiter} (Dumusque et al. 2012).

Recent exoplanet RV surveys show that over 40% of non-active solar-type stars probably harbor low-mass exoplanets (Mayor et al. 2011; Howard et al. 2010) with a mass distribution that seems to increase sharply toward low masses. In addition, most of the low-mass exoplanets belong to multiple compact systems (e.g., Lovis et al. 2011b). These results overall agree with the observed properties of the transiting exoplanets detected by the Kepler mission (Borucki & Koch 2011; Howard et al. 2012; Marcy et al. 2014). Detection and characterization of new low-mass exoplanets orbiting bright stars is motivated by the need to obtain accurate measurements of the projected mass and the eccentricity and to identify all the components of multiple systems to constrain models of exoplanet evolution. Such exoplanets orbiting bright stars will also be key targets for a deeper and more extended characterization with CHEOPS (Broeg et al. 2013; Fortier et al. 2014), for instance, which searches for transits, and JWST (Beichman et al. 2014), which searches for atmospheric signatures.

The SOPHIE spectrograph (Perruchot et al. 2008) on the 1.93 m telescope of the Observatoire de Haute-Provence was improved in June 2011 with the implementation of octagonal-section fibers (Perruchot et al. 2011). This optimization led to an improvement in RV precision to nearly 2 m s\textsuperscript{-1} (Bouchy et al. 2013) on timescales of a few tens of days. This precision level is critical for detecting low-mass exoplanets around...
solar-type stars. In the context of the subprogram “High precision search for Neptunes and super-Earths” of the SOPHIE extrasolar planets research consortium (Bouchy et al. 2009), we redefined a sample of 190 bright stars on the following criteria: 1) in the northern hemisphere; 2) with spectral type G and K and 0.6 ≤ B − V ≤ 1.4; 3) on a volume limited to 35 pc; 4) non-active (e sin i ≤ 4.5 km s^{-1}, log R_{HK}′ ≤ −4.8); 5) not part of a binary system and not harboring giant planets at short orbital period; and 6) not part of RV surveys carried out with HARPS-N GTO (Cosentino et al. 2012) at the TNG. This subprogram is intensively conducted since June of 2011.

We here report on the detection of a Neptune-like exoplanet candidate orbiting the solar analog HD 164595. Section 2 describes the SOPHIE observations and the data reduction. In Sect. 2 we describe the correction of the systematic instrumental drift necessary to reach the 2 m s^{-1} precision level. This correction is then validated in Sect. 4 using the known planetary system HD 190360, for which we provide an updated orbital solution. Section 5 details our data analysis of HD 164595 and summarizes the orbital and physical properties of the planet. We finally present our conclusions in Sect. 6.

2. Observations and data reduction

Spectroscopic observations were conducted with the SOPHIE spectrograph (Perruchot et al. 2008, 2011). SOPHIE is a fiber-fed environmentally stabilized echelle spectrograph covering the visible range from 387 to 694 nm. We used the high-resolution (HR) mode (Δ/Δλ = 75 000) with thorium-argon simultaneous wavelength calibration on fiber B.

In total we gathered 75 measurements of HD 164595 with SOPHIE over 2.2 years. The exposure time was set to between 800 and 1200 s to reach a signal-to-noise ratio (S/N) of 140 at typical photon-noise RV uncertainties below 1.0 m s^{-1} while simultaneously averaging p-mode stellar oscillations. Taking into account the wavelength calibration uncertainty (close to 1.0 m s^{-1}), the average RV uncertainty is 1.43 m s^{-1}. Nine spectra were identified as low quality. One measurement has a S/N that is half of the average, indicating a strong atmospheric absorption. Three measurements are affected by moon light contamination, which cannot be corrected with the simultaneous thorium mode. Five measurements present a flux anomaly of the thorium lamp, which prevented us from computing the simultaneous drift. They were discarded for the data analysis in Sect. 4.4.

The spectra were reduced and extracted using the SOPHIE pipeline (Bouchy et al. 2009), and the resulting wavelength-calibrated 2D spectra were correlated using a numerical binary mask corresponding to spectral type G2 to obtain the radial velocity measurement (Baranne et al. 1996; Pepe et al. 2002). The full width at half maximum (FWHM), contrast, and bisector span of the cross-correlation function (CCF) are also provided by the pipeline.

The complete radial velocity dataset, after the zero-point drift correction described in the next section, is reported in the Appendix and plotted in Fig. 8.

3. Correction of the systematic instrumental drift

Despite a clear improvement in RV precision provided by the implementation of octagonal fibers on timescales of a few tens of days (Bouchy et al. 2013; Perruchot et al. 2011), we identified long-term variations of the zero point of the instrument that added up to about ±10 m s^{-1} over the last 3.5 years (cf. Fig. 1, upper panel). The first ramp seems to be correlated with the thorium-argon lamp aging. One jump of about −7 m s^{-1} is related to the implementation of additional octagonal fibers after the double scrambling in December 2012 (BJD = 55 950). A second jump of −7 m s^{-1} at BJD = 56 775 appears after the coating of the secondary mirror of the 1.93 m telescope, which introduced a significant change in the flux balance across the spectral range. Other events, with a timescale of a few weeks, are clearly correlated with strong changes of the outside temperature, which are propagated to the tripod of the spectrograph at a level of a few tenths of degrees through the telescope pillar. A thermal control loop of the spectrograph tripod is under development to avoid such thermal conduction coming from the telescope pillar.

To track this long-term zero-point drift of the instrument, we systematically monitored a set of RV constant stars each night, namely HD 185144 (Howard et al. 2010), HD 9407, HD 221354, and HD 89269A (Howard et al. 2011), which were monitored with HIRES on the 10.2 m Keck telescope with an RV dispersion of 2.0, 1.7, 1.9, and 2.0 m s^{-1}, respectively, over several years. In addition to this set of four RV constant stars, we also used 51 targets from our sample that have at least ten measurements. We recursively built an RV constant master using these two sets of stars. A first master was created using a running median on the four reliable constant stars. This master was then subtracted from the second group, and all the stars with a corrected root mean square (rms) lower than a threshold of 3 m s^{-1} were included in the first subset. The offset for each star was adjusted as well to minimize the dispersion of the residuals. A double weight was given to the four reliable constant stars. This process was repeated until convergence, that is, when no additional star was added to the first subset.

The running median was implemented with the criterium to average 15 measurements. This was preferred instead of taking a fixed time window to give the same weight to all correction points. Consequently, a period with a higher density of observations will increase the temporal resolution of the correction. On the other hand, a period with sparse measurements will lead to a lower temporal resolution instead of a poorer constraint on the correction point. In practice, with this criteria of 15 measurements averaged, the typical timescale of the correction is nine days.

The most satisfying correction uses a threshold of 3 m s^{-1} and converges after four iterations with a total of 23 constant stars in the final set. The radial velocities of these 23 constant stars as well as the derived RV constant master are1 displayed in the top panel of Fig. 1. RV variations are clearly visible on different timescales, from a few days to a global trend over the last 3.5 years. This approach allowed us to gather enough data to correctly cover the time series and to average all physical effects such as stellar activity or signals of small planets, leaving only the instrumental systematics.

To illustrate the gain provided by our correction of the systematic instrumental drift, the RV of the constant star HD 185144 is displayed in the bottom panel of Fig. 1. For this target, the RV dispersion decreases from 5.4 to 1.6 m s^{-1} when the RV constant master is subtracted. Figure 2 shows the rms distribution of the 55 stars (including the four reliable constant stars) before and after correction of the RV constant master and illustrates the fact that the SOPHIE RV precision is close to 2 m s^{-1}.

1 The RV constant master is available upon request.
4. Effect on the planetary system HD 190360

4.1. Validation of the correction

To validate the correction of the RV constant master, we analyzed the known planetary system HD 190360 that was observed with SOPHIE in the context of the science validation of the octogonal fibers (Bouchy et al. 2013). The planetary system HD 190360 is composed of a long-period Jupiter (Naef et al. 2003) and a warm Neptune (Vogt et al. 2005). A total of 41 measurements of HD 190360 were gathered with SOPHIE using the same setting as for HD 164595. The radial velocity table is reported in Tables A.1 and A.2. The RV dispersion is 9.5 m s$^{-1}$ and 9.3 m s$^{-1}$ before and after correction of the RV constant master, respectively. The span of our observations was 2.4 years, which is about one-eighth of the period of HD 190360b. This does not allow efficiently constraining the orbital parameters of this planet. We therefore focus our analysis on the warm Neptune HD 190360c.

HD 190360 is a quiet star with a log$R'_{\text{HK}}$ derived from SOPHIE spectra of −5.13. No periodic signals in either the bisector, the CCF-FWHM, or the activity index are present at the two periods found in RVs, which excludes stellar activity as the origin of the Keplerian signals.

To study the impact of our zero point drift correction, we analyzed both the HD 190360 corrected and uncorrected data set with the same methodology. We used the planet analysis and small transit investigation software (PASTIS; Díaz et al. 2014), which is a Bayesian analysis software, for fitting a two-planet model. HD 190360b orbit was not fixed but subjected to strong priors for the Bayesian analysis. Normal distributions were used, centered on the published parameters with widths equal to the published errors in Wright et al. (2009). On the other hand, the other planet parameters were let free, with a Jeffrey distribution for the period, a beta distribution for the eccentricity as defined in Kipping (2013), and uniform distributions for the other parameters. We ran 20 MCMC chains with 300 000 steps each. Only the stationary parts of each chain were kept. The distributions of parameter values of all the remaining uncorrelated chain links then correspond to the target joint posterior-probability distributions for the model parameters.

Table 1 reports our orbital parameters and their uncertainties for both cases. The results are very similar for the two data sets and agree well (within 1σ) with Wright et al. (2009). However, the errors in the uncorrected data are systematically higher (by up to 50%). The dispersion of the residuals is better in the corrected set with 2.1 m s$^{-1}$, which is consistent with the precision obtained on the constant stars, instead of 3.5 m s$^{-1}$ with the uncorrected data. Moreover, the additional jitter necessary to set the reduced $\chi^2$ to 1 is 1.9 m s$^{-1}$, instead of 2.9 m s$^{-1}$ for the uncorrected data set. This test demonstrates the relevance of the zero-point drift correction, which significantly improves the quality of the RV data.

4.2. Analysis of the joint HIRES and SOPHIE data

Finally, we combined our data set with the Keck observations used by Wright et al. (2009) to update orbital parameters for the HD 190360 system. 100 MCMC chains of 300 000 steps were run with PASTIS to conduct a global search without a priori for a two-planet fit. The RV time series with our orbital solution is plotted in Fig. 3, and the phase-folded radial velocities for both
HD 190360b and c are plotted in Fig. 4. The orbital and physical parameters of the two planets are reported in Table 2.

The updated orbital parameters all agree well (within 1σ or marginally well (within 2σ)) with the values previously published in Wright et al. (2009). The precision on all parameters is significantly improved except for the semi-amplitude and ω. Assuming a stellar mass of 0.96 ± 0.1 M⊙ as in Vogt et al. (2005), the minimum mass of HD 190360b and c is 1.50 ± 0.15 M_Jup and 20.28 ± 3.16 M_Jup, respectively.

The additional jitter (instrumental and stellar noise) necessary to set the reduced χ² to 1 is 2.9 m s⁻¹ for HIRES and 1.8 m s⁻¹ for SOPHIE. Additionally, the dispersion of the residuals is significantly higher for the HIRES data (3.3 m s⁻¹) than for SOPHIE (2.4 m s⁻¹). To take into account the much longer time span of the Keck observations (11.9 years), we computed the median dispersion of the residuals for all the 2.4 year windows in the HIRES data. Its value is 3.1 m s⁻¹, still significantly higher than for SOPHIE. This could be the result of either a higher instrumental noise or a higher stellar jitter at the time of the Keck observations. The latter case seems unlikely since the log R'HK reported in Vogt et al. (2005) is close to our value at −5.09.

5. HD 164595 data analysis

5.1. Stellar properties

HD 164595 is a G2V star with a magnitude V = 7.08. Its HIPPARCOS parallax (π = 34.57 ± 0.5 mas) implies a distance
of 28.93 ± 0.4 pc. This star is considered to be one of the closest known solar analogs. Its parameters were derived by Porto de Mello et al. (2014) in the context of their photometric and spectroscopic survey of solar twin stars within 50 parsecs of the Sun. From the SOPHIE CCFs and using the calibration given by Boisse et al. (2010), we derived a $v \sin i$ of 2.1 ± 1 km s$^{-1}$. HD 164595 is known to be a quiet star. Wright et al. (2004) reported a log $R'_{HK}$ of −5.0 from observations made between 1998 and 2003. More recently, Isaacson & Fischer (2010) reported a slight trend of log $R'_{HK}$ from −4.97 to −4.86 between 2005 and 2009. Following the method established by Boisse et al. (2010), we derived from our SOPHIE spectra an average value of −4.86 ± 0.05 for log $R'_{HK}$. Furthermore, computing the median value for each season, we find that the log $R'_{HK}$ slightly increased from −4.91 in 2012 to −4.88 in 2013 and finally −4.81 in 2014. We also note that the bisector span shows an increasing dispersion over three seasons from 1.7 m s$^{-1}$ in 2012 to 2.0 m s$^{-1}$ in 2013 and finally 3.3 m s$^{-1}$ in 2014. During the last season, the bisector span is marginally correlated with the RV. All these factors seem to indicate that the stellar activity of HD 164595 evolves along a magnetic cycle toward increased activity. Table 3 summarizes the stellar parameters of HD 164595.

### Table 3. Observed and inferred stellar parameters for HD 164595.

| Parameter | HD 164595 | Reference |
|-----------|-----------|-----------|
| Spectral type | G2V | HIPPARCOS |
| $\pi$ [mas] | 34.57 ± 0.5 | HIPPARCOS |
| Distance [pc] | 28.93 ± 0.4 | HIPPARCOS |
| $V$ | 7.1 | HIPPARCOS |
| $B-V$ | 0.635 | Porto de Mello et al. (2014) |
| $M_\star$ [$M_\odot$] | 0.99 ± 0.03 | Porto de Mello et al. (2014) |
| $T_{\text{eff}}$ [K] | 5790 ± 40 | Porto de Mello et al. (2014) |
| log $g$ | 4.44 ± 0.05 | Porto de Mello et al. (2014) |
| [Fe/H] | −0.04 ± 0.08 | Porto de Mello et al. (2014) |
| $v \sin i$ [km s$^{-1}$] | 2.1 ± 1 | This paper |
| $(\log(R'_{HK}))$ | −4.86 ± 0.05 | This paper |

5.2. Distinguishing systematic signals and aliases

The Generalized Lomb-Scargle periodogram of the uncorrected radial velocities of HD 164595 is displayed in the upper panel of Fig. 5. A number of significant features appear, the most interesting being a triplet of peaks at 40 ± 5 days. The highest one lies below the $10^{-3}$ false-alarm probability (FAP) level. The FAP was calculated with Yorbit (Ségransan et al. 2011) by scrambling the RV data many times and counting the number of randomly generated peaks in the corresponding periodograms with an amplitude higher than the peak of the original set. Here, the 40-day signal of the original data was systematically higher than the peaks of 10000 scrambled sets. Longer period signals are also found around 120, 180, and 400 days. They are similar to the aliases of the one-year observational period of the spectral window. The middle panel of Fig. 5 shows the periodogram of the RV constant master sampled at the same observing dates as HD 164595. We note that except for the 40-day triplet, other features are the same in the two periodograms. After correction of the systematic drift, that is, after subtracting the constant master RVs from the RVs of HD 164595, the only significant feature in the periodogram (Fig. 5, bottom panel) is the 40-day triplet with a FAP lower than $10^{-5}$. This signal is then clearly not introduced by our correction, while other peaks were successfully reduced or removed.

The multiplicity of the 40-day feature is due to the convolution with the one-year observational period of the spectral window. The automatic de-aliasing algorithm CLEAN (Roberts et al. 1987) implemented in Yorbit is another way to confirm the unicity of the physical signal in the feature by cleaning up the periodogram. While giving an important diagnostic, this method cannot be used to determine which frequency is the physical one. This problem is particularly essential for the 40-day and 45-day solutions, which are equally satisfying (with similar amplitudes in the GLS periodogram and a similar $\chi^2$ and residual dispersion for their respective fits).

Dawson & Fabrycky (2010) proposed a method for solving this problem. The concept is to simulate a sinusoidal signal at the period and amplitude of each observational alias and to sample it at the date of observations. By comparing their periodograms, the one that significantly better matches the data periodogram corresponds to the true physical frequency. If the test is inconclusive, it means that the noise prevents identification, and new observations are required. This was the case when we apply this method using only our 66 high-quality observations. We then used our complete data set of 75 measurements (see Fig. 6) and determined that the physical frequency is the 40-day peak.
Mamajek & Hillenbrand (2008) is 20 \pm 38, page 6 of 10

enough data points to conclude). We are therefore confident that
the 40-day signal is not induced by activity and is planetary in
origin.

5.4. Radial-velocity analysis and orbital solution

For the rest of the analysis and the fit of a Keplerian signal we
only kept the high-quality data set (66 RV measurements) after
removing the nine low-quality measurements (low S/N, moon
light contamination, anormal simultaneous thorium-argon flux,
see Sect. 2). The rms of the RV time series shown in Fig. 8 (upper
panel) is 3.73 m s\(^{-1}\). A slight long-term trend is visible. We used
PASTIS to fit a Keplerian and a linear drift to our data without
a priori. We ran 20 MCMC chains with 300,000 steps each, and
discarded the solutions that did not converge to the 40-day period
(some converged to the observational aliases, in particular the
45-day period).

Table 4 reports the orbital parameters and their uncertainties
for a Keplerian model with a linear trend, and the best fit is plot-
ted in Fig. 8. The fitted model of the planet has a 40-day period
and a semi-amplitude of 3.14 \pm 0.99 \, m\, s\(^{-1}\). With a jitter of 1.8 \, m\, s\(^{-1}\), the reduced \( r^2 \) is
equal to 1. The residuals after the fit present a dispersion of
2.3 \, m\, s\(^{-1}\), and no significant feature appears in the correspond-
ing periodogram. An interesting trend can be observed in the
last season. It might correspond to either the activity-related drift
that is correlated with the bisector span, or to a shift in the global
trend and a subsequent incomplete correction. Trying to correct
this trend on the data does not significantly change our reported
solution.

Another analysis using the genetic algorithm built into Yorbit
(Ségransan et al. 2011) yielded nearly identical parameter values
and errors (\( P = 39.99 \pm 0.19 \) days, \( K = 2.96 \pm 0.40 \, m\, s\(^{-1}\) and
\( e = 0.078 \pm 0.14 \)). We note that the analysis of the uncorrected
data does not change our results, but only increases the error
bars of our orbital solution, the scatter of the residuals (from 2.2
to 2.9 \, m\, s\(^{-1}\)), and the corresponding jitter (from 1.8 to 2.7 \, m\, s\(^{-1}\)).

6. Discussion and conclusion

We have reported the discovery of HD 164595b with the
SOPHIE spectrograph. This source is a warm Neptune-like exo-
planet with a minimum mass of 16.1 \pm 2.7 \, M\(_{\oplus}\) orbiting a bright

Table 4. Orbital and physical parameters of HD 164595b.

| Parameter | HD 164595b |
|-----------|------------|
| \( P \) [days] | 40.00 \pm 0.24 |
| \( T_0 \) [BJD] | 56280 \pm 12 |
| \( e \) | 0.088 \pm 0.066 |
| \( \omega \) [deg] | 145 \pm 10 |
| \( K \) [m s\(^{-1}\)] | 3.05 \pm 0.41 |
| \( m \sin i \) [M\(_{\oplus}\)] | 16.14 \pm 2.72 |
| \( a \) [AU] | 0.23 |
| drift [m/s/yr] | \(-2.34 \pm 0.44\) |
| \( N_{\text{meas}} \) | 66 |
| Data span [days] | 809 |
| \( \sigma \) (O–C) [m s\(^{-1}\)] | 2.3 |
| Jitter [m s\(^{-1}\)] | 1.8 |

5.3. Distinguishing stellar activity

We studied the possibility that the 40-day signal might be due to
star-induced activity and correspond to the rotational period.
While we noted a slight increase in activity level with time, HD 164595
remained a relatively quiet star even in the last ob-
serving season with a log \( R'_{\text{HK}} \) below \(-4.80\). Figure 7 shows
the periodogram of the bisector span, which can be used to re-
fect stellar activity. No signal is present at 40 days or at its
first harmonics. This also remains true with the FWHM and
the log \( R'_{\text{HK}} \). There is no correlation between RV and these activity
indicators either, except for the already mentioned marginal
 correlation between RV and the bisector, but only in the last
season. Moreover, the rotational period of HD 164595 esti-
- mated from the log \( R'_{\text{HK}} \) using the calibration published by
Mamajek & Hillenbrand (2008) is 20 \pm 5 days, which is quite
distinct from the observed 40-day signal. We note that no 20-day
signal appears in the RV periodogram, which means that the
40-day signal cannot be an observational alias. The HIPPARCOS
photometry does not show any significant variations at a level
of 13 mmag (with 147 points), and with no hint of periodic sig-
nal in the periodogram. We also checked that the 40-day signal
maintains the same phase and amplitude over the last two sea-
sons when fitted independently (the first season does not have
enough data points to conclude). We are therefore confident that

Fig. 6. GLS periodogram of the complete HD 164595 RV data (with all
the 75 measurements; solid black curve), the 40-day sinusoid (dashed
blue curve) and the 45-day sinusoid (dotted and dashed red curve). The
40-day sinusoid clearly is the best match to the RV data.

Fig. 7. HD 164595 bisector Generalized Lomb-Scargle periodogram
with 0.1 FAP level (dashed line). Long-period signals above this
level are caused by a trend in the last season that is marginally correlated with
the radial velocities.

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Fig. 8. Upper panel: radial velocities of HD 164595 with the best-fit orbital solution (solid line). Error bars include the photon and instrumental noise and the stellar jitter. Bottom panel: phase-folded radial velocities of HD 164595 with the best-fit orbital solution (solid line). Error bars include the photon and instrumental noise and the stellar jitter.

Fig. 9. Mass – orbital period of known planets with $m \sin i < 40$ $M_\oplus$, $\Delta m \sin i / m \sin i < 0.3$. Another three planets with $P > 300$ days are not represented because of visibility problems. Transiting planets are shown in red, while the others are black. Triangles correspond to planets in multiplanetary systems. HD 164595b and HD 190360c are the blue circle and triangle. The green curves refer to the 3 m s$^{-1}$ (dashed) and 1 m s$^{-1}$ (solid) iso RV semi-amplitudes for a solar-type star. This diagram is based on data from the exoplanet.org database.

A solar-analog star with a period of 40.00 ± 0.24 days with no significant eccentricity. An additional long-term RV drift is seen on our data. At this stage, we cannot conclude on its origin. It might be due to a long-period additional companion in the system, but it might likewise be the signature of a stellar magnetic cycle since we observe an slight increase of the activity index over our observing span of 2.2 years. According to Lovis et al. (2011a), a change of 0.1 dex in the log $R'_{\text{HK}}$ may introduce a change of up to 10 m s$^{-1}$ in radial velocity. At this stage, we cannot completely exclude an under-correction of the zero-point drift either. Additional SOPHIE measurements will help to conclude on the long-term drift.

To validate and illustrate the capacity of SOPHIE to reach the 2 m s$^{-1}$ precision thanks to an appropriate correction of systematic instrumental effect, we refined the orbital parameters of the known planetary system HD 190360 based on SOPHIE and HIRES radial velocity measurements. With this precision on all timescales, SOPHIE can detect exoplanets with an RV semi-amplitude as low as 3 m s$^{-1}$. Nevertheless, pushing the RV precision down to 1 m s$^{-1}$ will be crucial to efficiently cover the parameter space of low-mass exoplanets. Additional improvements are ongoing on SOPHIE, such as the thermal control of the spectrograph tripod and the implementation of a Fabry-Perot etalon within the calibration unit to improve the determination of the simultaneous drift.

About 70 exoplanets with $m \sin i$ smaller than 40 $M_\oplus$ and an uncertainty on $m \sin i$ smaller than 30% are known. They are displayed in the mass – orbital period diagram in Fig. 9. In that sample, no transiting low-mass planets with period greater than ten days are known except for Kepler-20c (Gautier et al. 2012), which has a period of 10.9 days. Two-thirds of the 18 exoplanets with orbital periods longer than ten days are part of a multiperplanetary system. Only three transiting planets with masses in the range 10–20 $M_\oplus$ are known (Kepler-20c, GJ3470b, and HAT-P-26b). Their radii range from 3.1 to 6.3 $R_\oplus$, illustrating the diversity in density of this type of objects. This also underlines the current lack of constraints on these objects. The transition between super-Earths and Neptune-like planets and its dependence on the orbital period is poorly understood. The actual number of planets with precise density measurements is indeed far too low to cover the parameter space and constrain interior, formation, or evolution models for the low-mass planet population. The future transit search missions around bright stars TESS (Ricker et al. 2014) and CHEOPS (Broeg et al. 2013; Fortier et al. 2014) will address this issue from two complementary perspectives. While TESS will substantially increase the number of transiting exoplanets suitable for high-precision RV measurement, CHEOPS will measure precise radii of known exoplanets that have been discovered with radial velocities to derive precise densities. However, the low overall transit probability of the nontransiting planets of this sample (~300%) implies that CHEOPS will need a significant number of targets at various periods, requiring continuous efforts on low-mass RV surveys.

In this context, HD 164595b is an interesting and potential target for the follow-up transit mission CHEOPS, although its transit probability is only 2%. HD 164595 matches all CHEOPS requirements in terms of coordinates, magnitude, and spectral type. The uncertainty of the transit window extrapolated to 2018...
is about six days at this stage, but long-term monitoring of this target with SOPHIE is planned to reduce this uncertainty. Following the mass-radius relation given by Marcy et al. (2014) and assuming that \( \sin i = 1 \), the expected size of HD 164595b is around 4.7 \( R_\oplus \). Hence the expected transit probably has a depth close to 1.9 mmag with a duration of 6.1 h. We note, however, that the three transiting planets with similar masses as HD 164595b that were previously mentioned have a radius between 3.1 and 6.3 \( R_\oplus \). In case of transit, CHEOPS will be fully appropriate to derive the radius with a precision better than 10%. Finally, CHEOPS could also be used to detect transits of additional short-period low-mass companions that are unseen in radial velocities in the HD 164595 system.

Acknowledgements. We gratefully acknowledge the Programme National de Planétologie (telescope time attribution and financial support) of CNRS/INSU, the Swiss National Science Foundation, and the Agence Nationale de la Recherche (grant ANR-08-JCJC-0102-01) for their support. We warmly thank the OHP staff for their great care in optimizing the observations. N.C.S. acknowledges support by Fundação para a Ciência e a Tecnologia (FCT) through Investigator FCT contract of reference IF/00169/2011 and POPH/FSE (EC) by FEDER funding through the program “Programa Operacional de Factores de Competitividade – COMPETE”. We further acknowledge FCT through FEDER funds in program COMPETE, as well as through national funds, in the form of the grants with reference UID/FIS-04434/2013. A.S. is supported by the European Union under a Marie Curie Intra-European Fellowship for Career Development with reference FP7-PEOPLE-2013-IEF, number 627202. P.A.W. acknowledges the support of the French Agence Nationale de la Recherche (ANR), under program ANR-12-BS05-0012 “Exo-Atmos”.

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### Table A.1. Radial-velocity measurements, error bars, and bissector for HD 164595.

| BJD     | RV [km s^−1] | Uncertainty [km s^−1] | Biss [km s^−1] |
|---------|--------------|-----------------------|----------------|
| 56 051.596 | 2.1088       | 0.0013                | −0.0248        |
| 56 058.576 | 2.1094       | 0.0013                | −0.0240        |
| 56 059.487 | 2.1056       | 0.0014                | −0.0282        |
| 56 061.524 | 2.1112       | 0.0018                | −0.0260        |
| 56 062.557 | 2.1057       | 0.0015                | −0.0285        |
| 56 072.524 | 2.1118       | 0.0013                | −0.0262        |
| 56 074.524 | 2.1118       | 0.0014                | −0.0283        |
| 56 076.503 | 2.1117       | 0.0013                | −0.0295        |
| 56 432.514 | 2.1091       | 0.0017                | −0.0270        |
| 56 434.581* | 2.1123       | 0.0014                | −0.0270        |
| 56 436.544 | 2.1077       | 0.0018                | −0.0240        |
| 56 438.527 | 2.1145       | 0.0018                | −0.0238        |
| 56 443.518 | 2.1100       | 0.0016                | −0.0288        |
| 56 447.595 | 2.1026       | 0.0014                | −0.0253        |
| 56 449.414 | 2.1022       | 0.0014                | −0.0265        |
| 56 451.437 | 2.1048       | 0.0017                | −0.0273        |
| 56 454.408 | 2.1032       | 0.0015                | −0.0262        |
| 56 456.381 | 2.1039       | 0.0013                | −0.0290        |
| 56 458.520 | 2.1048       | 0.0016                | −0.0262        |
| 56 465.499 | 2.1049       | 0.0015                | −0.0277        |
| 56 468.582* | 2.1067       | 0.0017                | −0.0280        |
| 56 469.377 | 2.1085       | 0.0019                | −0.0290        |
| 56 470.421 | 2.1093       | 0.0015                | −0.0247        |
| 56 471.402 | 2.1095       | 0.0018                | −0.0238        |
| 56 486.475 | 2.1099       | 0.0015                | −0.0290        |
| 56 487.540 | 2.1099       | 0.0016                | −0.0278        |
| 56 489.510 | 2.1075       | 0.0014                | −0.0258        |
| 56 495.437 | 2.1032       | 0.0013                | −0.0280        |
| 56 497.549 | 2.1034       | 0.0014                | −0.0303        |
| 56 499.486 | 2.1042       | 0.0014                | −0.0267        |
| 56 501.441 | 2.1059       | 0.0013                | −0.0262        |
| 56 502.480 | 2.1041       | 0.0020                | −0.0327        |
| 56 517.400 | 2.1114       | 0.0014                | −0.0252        |
| 56 520.402* | 2.1097       | 0.0013                | −0.0283        |
| 56 521.390 | 2.1045       | 0.0014                | −0.0270        |
| 56 524.431 | 2.1102       | 0.0019                | −0.0288        |
| 56 730.676* | 2.1143       | 0.0013                | −0.0347        |
| 56 733.663* | 2.1124       | 0.0017                | −0.0248        |
| 56 734.647 | 2.1037       | 0.0014                | −0.0280        |
| 56 753.586 | 2.1137       | 0.0014                | −0.0258        |
| 56 755.611 | 2.1098       | 0.0013                | −0.0222        |
| 56 756.578* | 2.1169       | 0.0023                | −0.0287        |
| 56 758.605 | 2.1112       | 0.0013                | −0.0273        |
| 56 761.624 | 2.1082       | 0.0013                | −0.0240        |
| 56 777.522 | 2.1037       | 0.0015                | −0.0283        |
| 56 778.570 | 2.1034       | 0.0016                | −0.0200        |
| 56 782.561 | 2.1047       | 0.0012                | −0.0298        |
| 56 783.568 | 2.1039       | 0.0012                | −0.0313        |
| 56 786.585 | 2.1081       | 0.0014                | −0.0287        |
| 56 788.581 | 2.1076       | 0.0014                | −0.0267        |
| 56 792.607 | 2.1072       | 0.0014                | −0.0288        |
| 56 793.555 | 2.1065       | 0.0013                | −0.0295        |
| 56 794.603 | 2.1078       | 0.0012                | −0.0313        |
| 56 795.529 | 2.1070       | 0.0013                | −0.0342        |
| 56 815.447 | 2.1043       | 0.0011                | −0.0312        |
| 56 815.483 | 2.1046       | 0.0011                | −0.0323        |
| 56 816.560 | 2.1007       | 0.0012                | −0.0323        |
| 56 816.592 | 2.1031       | 0.0012                | −0.0327        |
| 56 817.421 | 2.1020       | 0.0011                | −0.0323        |
| 56 817.593 | 2.1062       | 0.0011                | −0.0295        |
| 56 819.464 | 2.1047       | 0.0013                | −0.0322        |
| 56 819.564 | 2.0997       | 0.0012                | −0.0332        |
| 56 820.440 | 2.0995       | 0.0011                | −0.0310        |

**Notes.** The dates with an asterix correspond to low quality data discarded for the analysis.
Table A.1. continued.

| BJD    | RV [km s\(^{-1}\)] | Uncertainty [km s\(^{-1}\)] | Biss [km s\(^{-1}\)] |
|--------|---------------------|-------------------------------|-----------------------|
| 56 820.514 | 2.1013              | 0.0011                        | −0.0335               |
| 56 834.466 | 2.1039              | 0.0013                        | −0.0295               |
| 56 838.411 | 2.1085              | 0.0015                        | −0.0278               |
| 56 841.415 | 2.1080              | 0.0013                        | −0.0322               |
| 56 844.519 | 2.1062              | 0.0012                        | −0.0313               |
| 56 847.487 | 2.1010              | 0.0014                        | −0.0320               |
| 56 850.546*| 2.0970              | 0.0016                        | −0.0363               |
| 56 854.401 | 2.1044              | 0.0012                        | −0.0315               |
| 56 860.493 | 2.0982              | 0.0021                        | −0.0422               |
| 56 900.431*| 2.0949              | 0.0012                        | −0.0310               |
| 56 901.312*| 2.1002              | 0.0013                        | −0.0317               |
| 56 902.312*| 2.0951              | 0.0015                        | −0.0360               |

Table A.2. Radial-velocity measurements and error bars for HD 190360 (after correction).

| BJD    | RV [km s\(^{-1}\)] | Uncertainty [km s\(^{-1}\)] |
|--------|---------------------|-------------------------------|
| 55 756.500 | −45.2113            | 0.0013                        |
| 55 757.487 | −45.2097            | 0.0012                        |
| 55 758.507 | −45.2077            | 0.0011                        |
| 55 759.532 | −45.2057            | 0.0012                        |
| 55 760.522 | −45.2055            | 0.0011                        |
| 55 761.349 | −45.2096            | 0.0012                        |
| 55 762.493 | −45.2104            | 0.0011                        |
| 55 763.380 | −45.2151            | 0.0012                        |
| 55 765.622 | −45.2167            | 0.0011                        |
| 55 767.627 | −45.2197            | 0.0014                        |
| 55 769.479 | −45.2178            | 0.0011                        |
| 55 772.359 | −45.2144            | 0.0011                        |
| 55 785.487 | −45.2181            | 0.0011                        |
| 55 793.383 | −45.2056            | 0.0011                        |
| 55 796.467 | −45.2088            | 0.0011                        |
| 55 797.380 | −45.2107            | 0.0012                        |
| 55 813.428 | −45.2038            | 0.0011                        |
| 55 818.330 | −45.2123            | 0.0010                        |
| 55 835.417 | −45.2154            | 0.0010                        |
| 55 848.299 | −45.2048            | 0.0010                        |
| 55 908.236 | −45.2075            | 0.0014                        |
| 56 175.409 | −45.1906            | 0.0012                        |
| 56 200.333 | −45.1865            | 0.0012                        |
| 56 220.319 | −45.1856            | 0.0011                        |
| 56 517.451 | −45.1907            | 0.0011                        |
| 56 519.428 | −45.1901            | 0.0011                        |
| 56 521.443 | −45.1921            | 0.0012                        |
| 56 554.416 | −45.1969            | 0.0011                        |
| 56 557.378 | −45.1977            | 0.0011                        |
| 56 583.355 | −45.1921            | 0.0012                        |
| 56 613.268 | −45.1914            | 0.0011                        |
| 56 624.292 | −45.2050            | 0.0011                        |
| 56 625.297 | −45.2042            | 0.0010                        |
| 56 626.280 | −45.2035            | 0.0011                        |
| 56 628.290 | −45.1997            | 0.0011                        |
| 56 629.263 | −45.2015            | 0.0011                        |
| 56 630.238 | −45.1979            | 0.0010                        |
| 56 631.246 | −45.1935            | 0.0010                        |
| 56 638.266 | −45.2044            | 0.0011                        |
| 56 643.254 | −45.2092            | 0.0010                        |
| 56 644.242 | −45.2058            | 0.0011                        |