Template-matching for the SOPHIE SP3 M-dwarf Exoplanet Survey: Two Neptune-mass Exoplanets

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Abstract: Since 2006, the SP3 subprogram of the RPE consortium on SOPHIE has been carrying out a systematic planet-hunting survey around the nearest M-dwarf stars. The 2011 upgrade of SOPHIE with an octogonal fiber link provided a significant improvement. In this contribution, we present an analysis of SP3 observations since 2011 using a template-matching algorithm, with specific focus on the detection of two Neptune-sized exoplanets around two M-dwarf stars. Both planets are potentially within the habitable zone of their host stars.

1. Introduction

M-dwarf stars are both interesting and promising targets for exoplanet hunts. They are the most common stars in the Galaxy, and studies suggest their planet occurrence rates are high. Moreover, they are interesting candidates for habitable planet searches, as low-mass short-period habitable planets are easier to detect for M-dwarfs than for sun-like stars.

SOPHIE is a fibre-fed, environmentally stabilised, cross-dispersed echelle spectrograph mounted on the 193 cm telescope at OHP (Perruchot et al. 2008). SOPHIE was upgraded in 2011 by inserting an octagonal-section fibre in the fibre link (Perruchot et al.2011; Bouchy et al. 2013). Since 2006, the SOPHIE exoplanet consortium has been carrying out several planet-hunting programmes using SOPHIE (Bouchy et al. 2009). **Sub-programme 3, or SP3**, consists of a **systematic survey of nearby M-dwarfs which aims at detecting habitable SuperEarths and Neptunes, constraining the statistics of planets around M-dwarfs, and finding potentially transiting companions.**

We report the results of the SP3 study of two M-dwarfs, Gl96 and Gl617A.

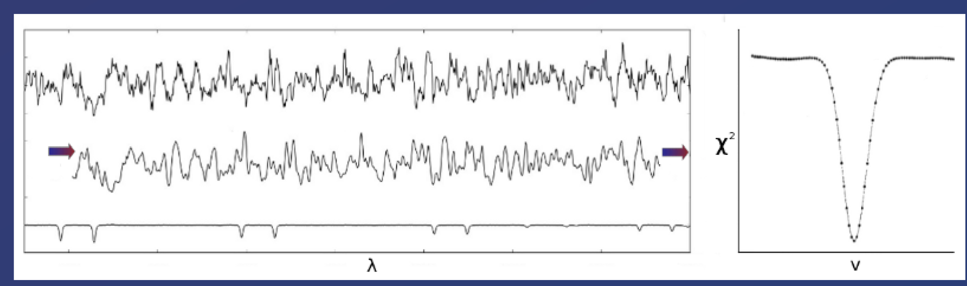

Fig 1. χ^2 -minimisation process. Left: an observed spectrum (top), the stellar template (middle) and the telluric template (bottom). The stellar template is shifted at different velocities and the χ^2 calculated. Right: the resulting χ^2

2. Data Analysis

Radial velocities have usually been obtained by the CCF method. For M-dwarfs, where numerous overlapping molecular bands complicate the continuum determination, binary masks which target only clearly defined lines underutilise the Doppler information present in the spectrum. Therefore, other methods have been developed to better exploit this information, such as template-matching using a true stellar template. **We applied a template-matching algorithm developed by N. Astudillo-Defru** (Astudillo-Defru et al. 2015, Astudillo-Defru et al. 2017) **to all the SOPHIE+spectra**. Figure 1 illustrates the process.

Corrections were applied for the charge transfer inefficiency (CTI) effect, the instrumental drift, and the long-term variations of the zero-point.

In order to study the stellar activity of our targets, we calculated several indicators: Hα index, log(R'HK) index, NaI index, and CCF bisector.

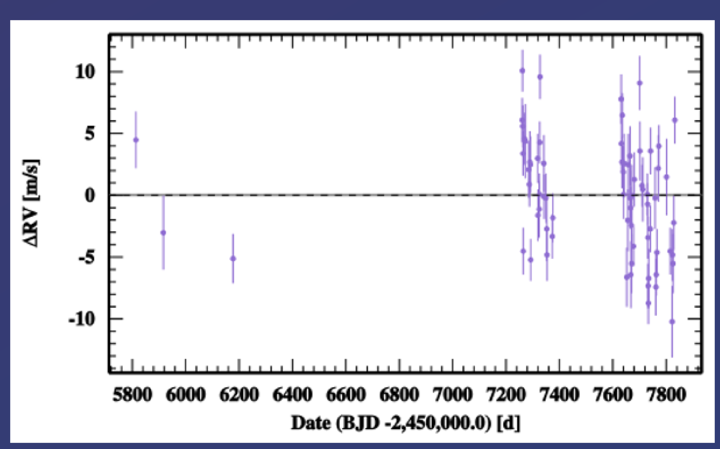

Fig. 2. Time series of the radial velocities calculated with template-matching for Gl96 from the SOPHIE+ measurements.

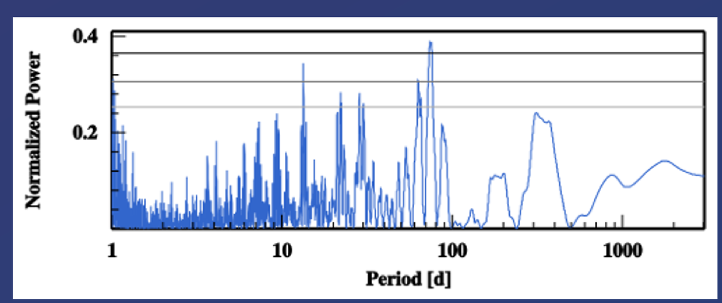

Fig. 3. Periodogram of the radial velocities calculated with template-matching for Gl96 from the SOPHIE+ measurements, corrected from the zero-point drift.

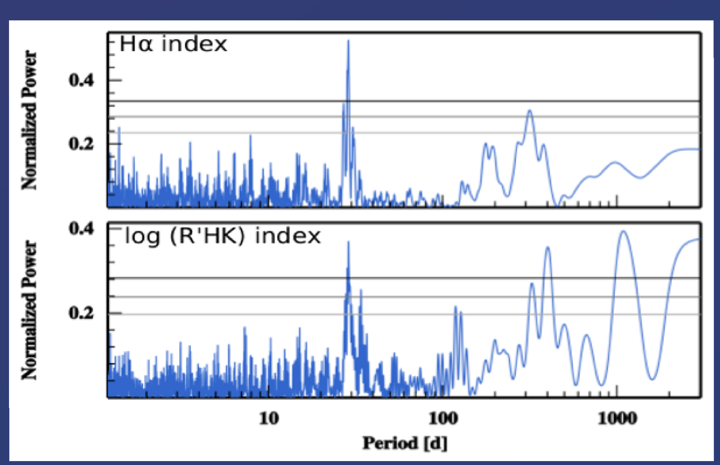

Fig. 4. Periodograms of activity indicators for Gl96: Hα index and log(R'_{HK}) index. The horizontal lines correspond to 50%, 10%, and 1% FAP respectively.

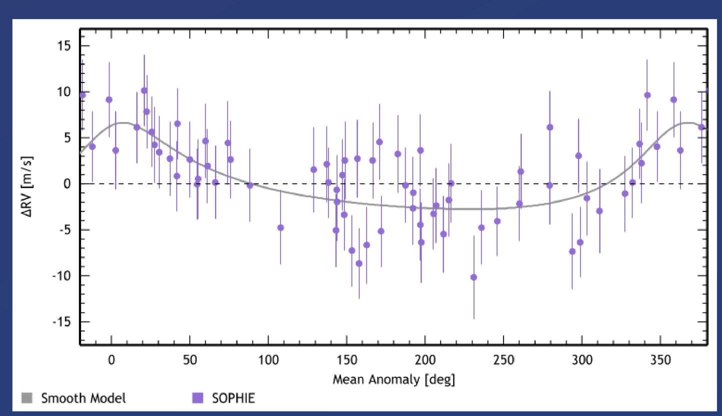

Fig. 5. Phase-folded radial velocities of Gl96 for a one-planet model with P=74.7d.

3. Results: Gl96

The RVs calculated with template-matching from the SOPHIE+ observations of Gl96 were analysed using DACE (Data and Analysis Center for Exoplanets, https://dace.unige.ch). The time series and periodogram are shown in Figures 2 and 3. In Figure 4 we show periodograms of the activity indicators Hα and log(R 'HK).

The RV periodogram shows a **peak at 75d below 1% FAP**, which bootstrap resampling places below 0.05% FAP. We fit this signal by a keplerian model. The highest peak in the residuals, at 29d, is only below 50% FAP, and is close to the peaks seen at 28-29d below 1% FAP in the Hα and log(R'HK) indices' periodograms. Therefore, it is probably linked to stellar activity. We carried out an MCMC analysis of the single-planet model for Gl96, summarized in Table 1. Figure 5 shows the phase-folded data points.

To quantify the **habitability** of this eccentric planet, we calculated the mean incident flux over an orbit, and compared it with the limits given by Kopparapu et al. (2013). For Gl96 b, the mean incident flux is<F> /F⊕=1.168, placing it **between the Recent Venus and Runaway Greenhouse limits.**

4. Results: Gl617A

A planet at 86.54 d around this star was recently announced by the CARMENES team (Reiners et al. 2017). We present an independent detection of this planet from our SOPHIE data. We analysed the RVs calculated by template-matching from the SOPHIE+ observations of Gl617A. The time series and periodogram of the Gl617A RVs are shown in Figures 6 and 7 respectively. In Figure 8 we show the periodogram of the activity indicator Hα, with a strong signal at 21d. The RV periodogram shows a **very strong signal at 86d well below 1% FAP**, which bootstrap resampling places below 0.01% FAP, and which is not present in any of the activity indicators. We employed an MCMC sampler to fit a keplerian model, summarised in Table 1. Figure 9 shows the phase-folded RVs for Gl617A b.

The highest signal in the residuals, at 21d below 10%FAP, coincides with the signal in Hα below 1%FAP, so it is probably due to stellar activity.

As Gl617A b is moderately eccentric, we calculate the mean incident flux in order to better quantify its **habitability**. The mean incident flux is<F> /F⊕=1.053, placing it **between the Recent Venus and Runaway Greenhouse limits** as defined by Kopparapu et al. (2013).

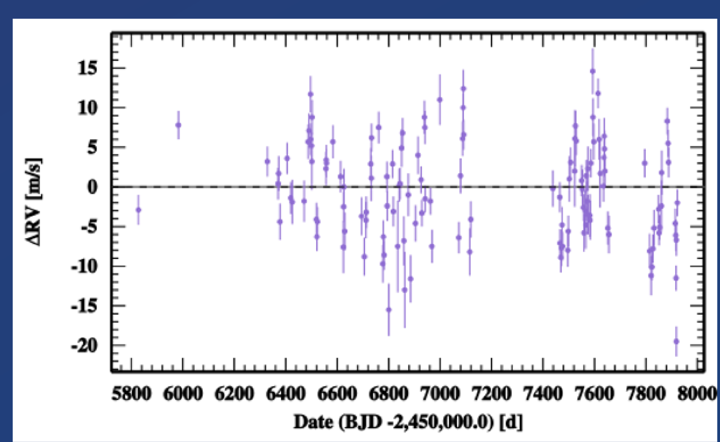

Fig. 6. Time series of the radial velocities calculated with template-matching for Gl617A from the SOPHIE+ measurements.

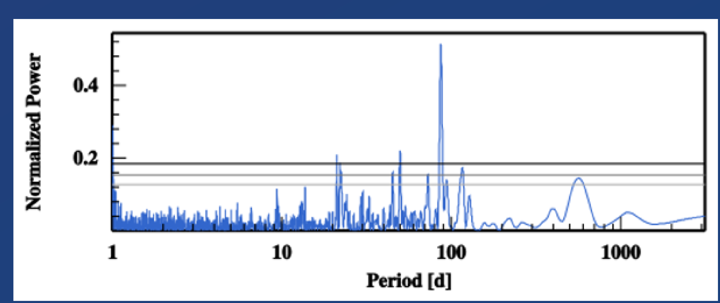

Fig. 7. Periodogram of the radial velocities calculated with template-matching for Gl617A from the SOPHIE+ measurements, corrected from the zero-point drift.

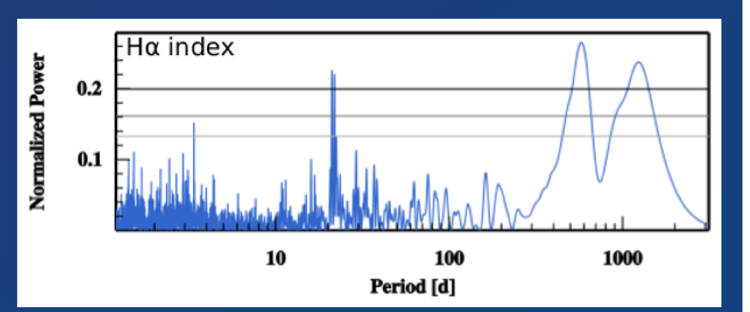

Fig. 8. Periodogram of the Hα index activity indicator for Gl617A. The horizontal lines correspond to 50%, 10%, and 1% FAP.

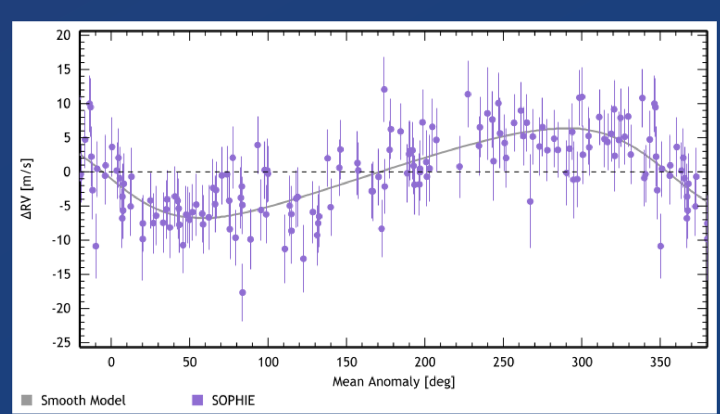

Fig. 9. Phase-folded radial velocities of Gl617A for a P=86d planet..

Table 1: planetary parameters.

Parameter	Gl96b	Gl617Ab
Stellar spectral type	M2	M1
P [d]	$73.94^{+0.33}_{-0.38}$	$86.72^{+0.20}_{-0.18}$
K [m/s]	$4.69^{+0.72}_{-0.62}$	$6.57^{+0.36}_{-0.38}$
e	$0.44^{+0.09}_{-0.11}$	$0.23^{+0.07}_{-0.08}$
ω	$339.58^{+12.45}_{-14.52}$	$97.25^{+13.55}_{-13.46}$
T_P [d]	$55556.39^{+10.57}_{-8.98}$	$55470.17^{+4.97}_{-4.85}$
a [AU]	$0.291^{+0.005}_{-0.005}$	$0.323^{+0.006}_{-0.005}$
M.sin(i) [M_{Earth}]	$19.66^{+2.42}_{-2.30}$	$31.29^{+2.20}_{-2.15}$

5. Conclusions

We have presented the **detection of a new Neptune-like exoplanet orbiting the M dwarf Gl96** and the **independent detection of a second Neptune-like exoplanet orbiting the M dwarf Gl617A** for which we refine the planetary parameters, using the SOPHIE+ spectrograph at OHP and a template-matching algorithm. **The planets have minimum masses of 29 and 31 Earth masses and orbital periods of 74 and 87 days respectively, and are close to the inner limit of the HZ.** Both host stars are metal-rich, consistent with trends found for M-dwarfs hosting planets. Additionally, the masses determined for the planets are compatible with the upper mass boundary determined for Neptune-like planets around M-dwarfs by Courcol et al. (2016). Low-mass planets orbiting M-dwarfs are mainly found in multiplanet systems. Follow-up observations with SPIRou in spectropolarimetry will permit us to disentangle the stellar activity and planetary signals, refine the mass and identify possible additional rocky planets.

Some 146 exoplanets around M-dwarf stars are presently known. The two planets presented here fall in the **mid-to-long period and mid-to-high mass ranges of this sample**, as shown in Figure 9 (median period=13.5 d,median mass=14.3 MEarth). **Gl96 b is among the most eccentric known planets around M-dwarf stars** (mean e=0.12).

The results presented here are from Hobson et al (2018). Other publications on SP3 targets are upcoming. **The template-matching method presented here provides significant improvement** by avoiding some instabilities of the wavelength solution, dealing better with tellurics, etc. **SOPHIE remains competitive with other instruments** (e.g. CARMENES) for M-dwarf RV surveys, especially with the planned spectrograph upgrade to SOPHIE-RED. We also anticipate synergy between SOPHIE and SPIRou.

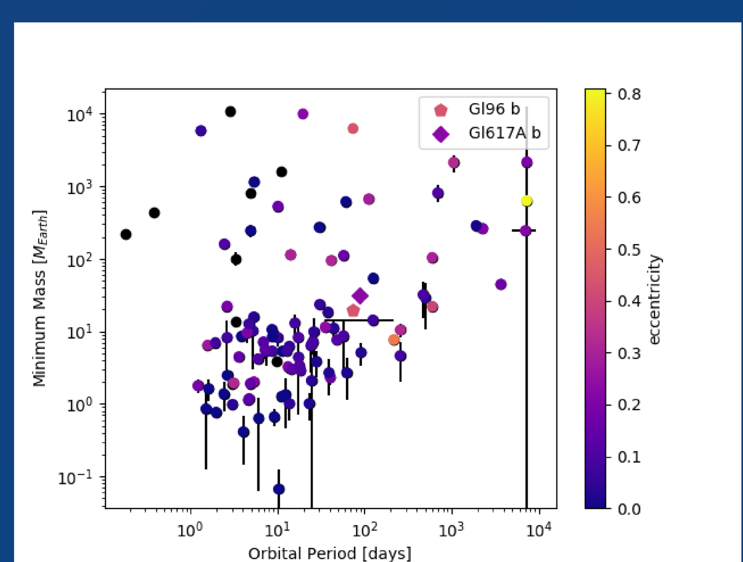

Fig. 9. Orbital period versus minimum mass for planets around M-dwarfs detected by radial velocities or transits. Each point represents a planet, with Gl96 b indicated by a pentagon and Gl617A b by a diamond. The colours indicate the orbital eccentricity.

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