LETTER TO THE EDITOR

The SOPHIE search for northern extrasolar planets

XVI. HD 158259: A compact planetary system in a near-3:2 mean motion resonance chain


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ABSTRACT

Aims. Since 2011, the SOPHIE spectrograph has been used to search for Neptunes and super-Earths in the northern hemisphere. As part of this observational program, 290 radial velocity measurements of the 6.4 V magnitude star HD 158259 were obtained. Additionally, TESS photometric measurements of this target are available. We present an analysis of the SOPHIE data and compare our results with the output of the TESS pipeline.

Methods. The radial velocity data, ancillary spectroscopic indices, and ground-based photometric measurements were analyzed with classical and \( \ell_i \) periodograms. The stellar activity was modeled as a correlated Gaussian noise and its impact on the planet detection was measured with a new technique.

Results. The SOPHIE data support the detection of five planets, each with \( m \sin i \approx 6 \, M_\oplus \), orbiting HD 158259 in 3.4, 5.2, 7.9, 12, and 17.4 days. Though a planetary origin is strongly favored, the 17.4 d signal is classified as a planet candidate due to a slightly lower statistical significance and to its proximity to the expected stellar rotation period. The data also present low frequency variations, most likely originating from a magnetic cycle and instrument systematics. Furthermore, the TESS pipeline reports a significant signal at 2.17 days corresponding to a planet of radius \( \approx 1.2 \, R_\oplus \). A compatible signal is seen in the radial velocities, which confirms the detection of an additional planet and yields a \( \approx 2 \, M_\oplus \) mass estimate.

Conclusions. We find a system of five planets and a strong candidate near a 3:2 mean motion resonance chain orbiting HD 158259. The planets are found to be outside of the two and three body resonances.

Key words. planets and satellites: detection – planets and satellites: dynamical evolution and stability – planets and satellites: fundamental parameters – planets and satellites: formation – methods: statistical – techniques: radial velocities

⋆ CHEOPS fellow.
1. Introduction

Transit surveys have unveiled several multiplanetary systems where the planets are tightly spaced and close to low order mean motion resonances (MMRs). For instance, Kepler-80 (Xie 2013; Lissauer et al. 2014; Shallue & Vanderburg 2018), Kepler-223 (Borucki et al. 2011; Mills et al. 2016), and TRAPPIST-1 (Gillon et al. 2016; Luger et al. 2017) present 5, 4, and 7 planets, respectively, in such configurations. These systems are often qualified as compact, in the sense that any two subsequent planets have a period ratio below 2. Compact, near resonant configurations could be the result of a formation scenario where the planets encounter dissipation in the gas disk, are locked in resonance, and then migrate inwards before potentially leaving the resonance (e.g., Terquem & Papaloizou 2007; MacDonald et al. 2016; Izidoro et al. 2017).

Near resonant, compact systems are detectable by radial velocity (RV), as demonstrated by follow up observations of transits (Lopez et al. 2019). However, such detections with only RV are rare: HD 40307 (Mayor et al. 2009) and HD 215152 (Delisle et al. 2018) both have three planets near 2:1 – 2:1 and 5:3 – 3:2 configurations, respectively.

In the present work, we analyze the 290 SOPHIE radial velocity measurements of HD 158259. We detect several signals, which are compatible with a chain of near resonant planets. The signals have an amplitude in the 1–3 m s\(^{-1}\) range. At this level, in order to confirm their planetary origin, it is critical to consider whether these signals could be due to the star or to instrument systematics. To this end, we include the following data sets in our analysis as well as ground-based photometric data. The periodicity search is performed with a \(f_1\) periodogram (Hara et al. 2017) including a correlated noise model, selected with new techniques. The results are compared to those of a classical periodogram (Balunev 2008).

Furthermore, HD 158259 has been observed in sector 17 of the TESS mission (Ricker et al. 2014). The results of the TESS reduction pipeline (Jenkins et al. 2010, 2016) are included in our analysis.

The data support the detection of six planets close to a 3:2 MMR chain, with a lower detection confidence for the outermost one. The orbital stability of the resulting system is checked with numerical simulations, and we discuss whether the system is in or out of the two and three-body resonances.

The Letter is structured as follows. The data and its analysis are presented in Sects. 2 and 3, respectively. The study of the system dynamics is presented in Sect. 4, and we conclude in Sect. 5.

2. Data

2.1. HD 158259

HD 158259 is a G0 type star in the northern hemisphere with a \(V\) magnitude of 6.4. The known stellar parameters are reported in Table 1. The stellar rotation period is not known precisely, but it can be estimated. The median \(\log R'_{\text{HK}}\), which was obtained from SOPHIE measurements, is \(-4.8 \pm 0.1\). With the empirical relationship of Mamajek & Hillenbrand (2008), this translates to an estimated rotation period of 18 ± 5 days. Additionally, the SOPHIE RV data give \(v\sin i = 2.9 \pm 1\) km s\(^{-1}\) (see Boisse et al. 2010). Assuming \(i = 90^\circ\) and taking the \(\text{Gaia}\) radius estimate of 1.21 \(R_\odot\), the \(v\sin i\) estimation yields a rotation period of \(\approx 20 \pm 7\) days.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ascension (J2000)</td>
<td>17 h 25 min 24\hspace{1em}05</td>
</tr>
<tr>
<td>Declination (J2000)</td>
<td>+52.7906°</td>
</tr>
<tr>
<td>Proper motion (mas y(^{-1}))</td>
<td>(-91.047 \pm 0.055, -49.639 \pm 0.059)</td>
</tr>
<tr>
<td>Parallax</td>
<td>36.93 ± 0.029 mas</td>
</tr>
<tr>
<td>Spectral type</td>
<td>G0</td>
</tr>
<tr>
<td>(V) magnitude</td>
<td>6.46</td>
</tr>
<tr>
<td>Radius</td>
<td>1.21^{+0.03}<em>{-0.08} (R</em>\odot)</td>
</tr>
<tr>
<td>Mass</td>
<td>1.08 ± 0.1 (M_\odot)</td>
</tr>
<tr>
<td>(v\sin i)</td>
<td>2.9 km s(^{-1})</td>
</tr>
<tr>
<td>(\log R'_{\text{HK}})</td>
<td>(-4.8)</td>
</tr>
</tbody>
</table>

Notes. Parallax, coordinates, proper motion, and radius are taken from \(\text{Gaia}\) Collaboration et al. (2018), spectral type is from Cannon & Pickering (1993), and \(V\) magnitude is from Høg et al. (2000). Mass is from Chandler et al. (2016).

2.2. SOPHIE radial velocities

SOPHIE is an échelle spectrograph mounted on the 193cm telescope of the Haute-Provence Observatory (Bouchy et al. 2011). Several surveys have been conducted with SOPHIE, including a moderate precision survey (3.5–7 m s\(^{-1}\)), aimed at detecting Jupiter-mass companions (e.g., Bouchy et al. 2009; Moutou et al. 2014; Hébrard et al. 2016), as well as a search of smaller planets around M-dwarfs (e.g., Hobson et al. 2018, 2019; Diaz et al. 2019).

Since 2011, SOPHIE has been used for a survey of bright solar-type stars, with the aim of detecting Neptunes and super-Earths (Bouchy et al. 2011). For all the observations performed in this survey, the instrumental drift was measured and corrected for by recording on the detector, close to the stellar spectrum, the spectrum of a reference lamp. This one is a thorium-argon lamp before barycentric Julian date (BJD) 2458181 and a Fabry-Perot interferometer after this date. The observations of HD 158259 were part of this program. Over the course of seven years, 290 measurements were obtained with an average error of 1.2 m s\(^{-1}\). The data, which were corrected from instrumental drift and outliers (see Appendix A.1 and A.2), are shown in Fig. 1.

Fig. 1. SOPHIE radial velocity measurements of HD 158259 after outliers at BJD 2457941.5059, 2457944.4063, and 2457945.4585 have been removed.

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