

The Neptunian ridge planet WASP-156 b does not have a polar orbit

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ABSTRACT

The population of short-period exo-Neptunes is thought to be shaped by an interplay between different dynamical mechanisms, such as orbital migration and tidal effects, and photoevaporation. We can gain insight into these processes by studying observables such as the stellar obliquity. Here, we study the Rossiter–McLaughlin (RM) effect and measure the projected obliquity, λ , of the Neptunian ridge planet WASP-156 b. We analyse new ESPRESSO and MAROON-X spectroscopic transit observations, and new Next-Generation Transit Survey (NGTS) photometry simultaneous to the ESPRESSO data. Our analyses show an aligned orbit ($\lambda = -8 \pm 16^\circ$, based on the ESPRESSO observations), in contrast to a previous report of a highly misaligned orbit. We also find the star’s projected rotational velocity to be $v \sin i_\star \leq 2 \text{ km s}^{-1}$ from spectral line modelling and $v \sin i_\star = 0.40 \pm 0.11 \text{ km s}^{-1}$ from the RM modelling. This is lower than the previously reported value of $\sim 4 \text{ km s}^{-1}$, which could partly explain the previously derived polar orbit. We also update the system’s orbital parameters and rule out Jupiter-mass companions within 5 au using long-term radial velocity data. The planet’s aligned and circular orbit ($e < 0.16$ at 3σ), and lack of nearby massive companions, are consistent with *in situ* formation or early disc-driven migration. Our findings move WASP-156 b from a tentative cluster of close-in Neptunes in polar orbits to the group of aligned Neptunes.

Key words: instrumentation: spectrographs – methods: observational – techniques: spectroscopic – exoplanets – planets and satellites: fundamental parameters – planets and satellites: individual: WASP-156 b.

1 INTRODUCTION

With over 6000 exoplanets discovered to date,¹ studies of planetary demographics are increasingly powerful. Short-period Neptunes (orbital period $P \lesssim 30 \text{ d}$, planetary radius $2 \lesssim R_p \lesssim 8 R_\oplus$) are an interesting population showing a diverse landscape that traces a variety of formation and evolution processes. A combination of orbital migration, tidal decay, and photoevaporation (e.g. T. A. Davis & P. J. Wheatley 2009; J. E. Owen & Y. Wu 2013; T. Matsakos & A. Königl 2016; D. E. Ionov, Y. N. Pavlyuchenkov & V. I. Shematovich 2018; J. E. Owen & D. Lai 2018) is thought to be responsible for the observed scarcity of very close-in ($P \lesssim 3 \text{ d}$) Neptunes, the so-called hot Neptunian ‘desert’ (e.g. A. Lecavelier des Etangs 2007; Gy. M. Szabó & L. L. Kiss 2011; M. S. Lundkvist et al. 2016; T. Mazeh, T. Holczer & S. Faigler 2016; A. Castro-González et al. 2024a; K. Cui et al. 2026; see Fig. 1).

The occurrence of Neptunes mildly increases at longer periods ($P \gtrsim 5 \text{ d}$) in a Neptunian ‘savanna’, implying different formation and evolution mechanisms for the two regions (V. Bourrier et al. 2023). A Neptunian ‘ridge’ between the desert and the savanna has recently been proposed from an observed overabundance of the *Kepler* sample with periods between around 3 and 6 d (A. Castro-González et al. 2024a).

The host star’s obliquity, ψ , the angle between its spin axis and a planet’s orbital axis (or λ , its sky-projection), is a useful observable that provides information on the planet’s formation and evolution. The most simplistic picture assumes that protoplanetary discs are aligned with the stellar spin, since both originate from the same rotating molecular cloud core, resulting in stars with primordial low obliquities. Aligned close-in planets are then thought to have migrated inwards early-on via disc driven migration (e.g. P. Goldreich & S. Tremaine 1979; D. N. C. Lin, P. Bodenheimer & D. C. Richardson 1996), while misaligned close-in planets should have experienced high-eccentricity tidal migration due to gravitational interactions with another body capable of altering the primordial aligned obliquity, such as planet–planet scattering (e.g. S. Chatterjee et al. 2008; E. B. Ford & F. A. Rasio

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¹NASA Exoplanet Archive <https://exoplanetarchive.ipac.caltech.edu/>

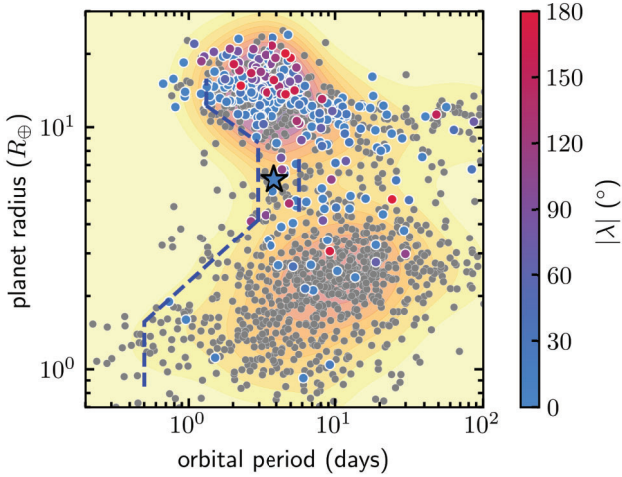


Figure 1. Orbital period versus planet radius diagram. Grey points are transiting exoplanets from the TEPcat catalogue (J. Southworth 2011, 2026, accessed on 2026 May 11). Systems with a measured projected obliquity are coloured according to that value. WASP-156 b is highlighted as a star following the same colour code. The dashed blue lines indicate the boundaries of the Neptune desert, savanna, and ridge from A. Castro-González et al. (2024a). Contours show the density of points.

2008; M. Nagasawa & S. Ida 2011; C. Beaugé & D. Nesvorný 2012), secular cyclic interactions (e.g. H. Zeipel 1910; Y. Kozai 1962; M. L. Lidov 1962; Y. Wu & N. Murray 2003; S. Naoz et al. 2011; J. Teyssandier, C. Terquem & J. C. B. Papaloizou 2013; S. Naoz 2016), or secular chaos (e.g. Y. Wu & Y. Lithwick 2011; A. S. Hamers et al. 2017). However, reality might be more complex. Primordial misalignments are also possible (e.g. K. Batygin 2012; M. R. Bate 2018; L. I. Biddle et al. 2025), and interactions with the disc and tidal dissipation can result in misaligned obliquities being damped into aligned orbits (e.g. D. Fabrycky & S. Tremaine 2007; M. Nagasawa, S. Ida & T. Bessho 2008; J. N. Winn et al. 2010a; A. C. M. Correia et al. 2011; S. Albrecht et al. 2012; J. Teyssandier, D. Lai & M. Vick 2019).

A wide range of obliquities have been observed, including well-aligned planets, planets in polar orbits, and retrograde planets (see e.g. S. H. Albrecht, R. I. Dawson & J. N. Winn 2022; L. Mancini et al. 2022). Observational data seem to show a tentative dichotomy in the obliquities of giant planets and Neptunes, with clusters at 0° and 90° (e.g. S. H. Albrecht et al. 2021; V. Bourrier et al. 2023). Tentative empirical evidence of a significant preponderance of polar orbits among Neptunes has been found using statistical analyses (J. I. Espinoza-Retamal et al. 2024; E. Knudstrup et al. 2024; A. M. Rossi et al. 2026). However, the number of Neptunes with measured obliquities is still small, and a larger sample of planets is needed to reach a robust conclusion.

One of the most direct and accurate ways to estimate obliquities is through the well-known Rossiter–McLaughlin effect (RM; D. B. McLaughlin 1924; R. A. Rossiter 1924; S. H. Albrecht et al. 2022). As a planet transits its host star, it blocks different parts of the rotating stellar disc, which results in a distortion of the observed stellar spectral lines. This affects the disc-integrated radial velocities (RVs) measured from the stellar spectra in a manner that depends on the sky-projected obliquity λ and the projected rotational velocity of the star $v \sin i_*$ (see e.g. A. H. M. J. Triaud 2018). The amplitude of the RM distortion depends on the area of the stellar disc occulted by the planet and the rotation of the

star. Hence, the method is more sensitive to large, close-in planets and stars that are fast rotators, which yield RM signals with larger amplitudes, easier to detect.

In this work, we study the obliquity of the Neptunian-ridge planet WASP-156 b. WASP-156 b is a hot super-Neptune ($R_p \simeq 6.1 R_\oplus$, $M_p \simeq 42 M_\oplus$, and $P \simeq 3.84$ d; see Fig. 1) orbiting a relatively bright ($V = 11.6$ mag) K3 V star (O. D. S. Demangeon et al. 2018, also see Table 3 for the system parameters used in this work).

Here, we report on two new spectroscopic transit observations obtained with the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO; F. Pepe et al. 2021) and one new transit observed with the M-dwarf Advanced Radial velocity Observer Of Neighboring eXoplanets (MAROON-X; A. Seifahrt et al. 2016, 2018), and use them to measure the obliquity of the system. Previously, V. Bourrier et al. (2023) had reported an RM measurement of the star’s projected obliquity that indicated a nearly polar orbit, based on observations of one transit with the visible arm of the Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES; mounted at the 3.5 m telescope in Calar Alto, Spain, with wavelength range 5200–9600 Å and resolving power $R = 94\,600$; A. Quirrenbach et al. 2014, 2018). Recently, Z. Jiang et al. (2026) used the first night of ESPRESSO observations and derived an obliquity compatible with an aligned orbit, contradicting the CARMENES results. Compared to CARMENES, both ESPRESSO and MAROON-X are mounted at larger telescopes, the European Southern Observatory’s (ESO) 8.2 m Very Large Telescope (VLT) in Paranal, Chile, and the 8.1 m Gemini North telescope in Mauna Kea, Hawai’i, USA, respectively. These telescopes have a larger collecting area than the 3.5 m Calar Alto telescope, allowing for a higher signal-to-noise ratio (S/N), shorter exposure times, and better time sampling of the transit.

In Section 2, we present the observations used in this work. We derive updated spectroscopic stellar parameters of the host star in Section 3 and, in Section 4, we perform a re-characterization of the star–planet system to obtain updated parameters. In Section 5, we present our spectroscopic transit analyses exploiting the RM effect. We discuss the previous and new obliquity measurements of WASP-156 b, explore its possible formation mechanisms, and put the system in context in Section 6. Finally, we conclude our work in Section 7.

2 OBSERVATIONS

2.1 Spectroscopic data

We observed two transits of WASP-156 b with ESPRESSO and one with MAROON-X. We show a summary of the observations in Table 1 and Fig. A1, and detail them in the following sections.

2.1.1 ESPRESSO transits

We observed two transits of WASP-156 b with the high-resolution, optical spectrograph ESPRESSO (wavelength range 3782–7887 Å; F. Pepe et al. 2021) installed on the VLT at ESO’s Paranal Observatory, in Chile (ESO programme ID: 109.23FU, PI: Lafarga). The observations were performed in 1-UT configuration (on UT 2, Kueyen) and high-resolution mode HR21 (i.e. with 2×1 read-out binning, median resolving power of $R = 138\,000$, and spectral sampling of 4.5 pixels per spectral element). The target star

Table 1. Spectroscopic observations and average S/N.

Instrument	Night	# Observations	Median S/N per pixel
ESPRESSO	2022-09-02	21 (11/10)	85
	2022-09-29	21 (10/11)	70
MAROON-X	2021-11-04	38 (17/21)	71

Note. # observations shows the total number of observations, and inside the brackets is the number of in-transit/out-of-transit observations. The per pixel median S/N is that of order 87 (central wavelength ~ 703 nm), one of the orders with the highest S/N for both spectrographs for WASP-156. Note that the S/N that we quote here corresponds to the values of the individual slices into which order 87 is divided added in quadrature (two slices for ESPRESSO and three slices for MAROON-X).

was observed with fibre A. Fibre B was used to simultaneously monitor the sky. We obtained the raw data from the ESO archive and reduced them with the ESPRESSO Data Reduction Software² (DRS) version 3.0.0, which performs standard reduction steps for échelle spectra (for details, see F. Pepe et al. 2021). In the following analysis, we used the blaze-corrected and sky-subtracted (i.e. corrected for telluric sky emission) two-dimensional spectra.

During the first transit (2022 September 2), because the measured flux in the first exposure was lower than expected, we decided to increase the exposure time from 600 to 700 s for subsequent exposures. During the second transit (2022 September 29), we kept the exposure time at 600 s since the flux difference between 600 and 700 s did not seem to affect our preliminary results (i.e. the RV uncertainty difference between the two different exposure times was small). Close to the end of the second transit, observations had to be aborted because of pointing restrictions due to wind. Observations restarted after the end of the transit, missing the transit egress. The observations of the first night covered airmasses from ~ 1.5 to 1 and a line of sight seeing below 1 arcsec for most of the observations, while the second night covered airmasses from ~ 2 to 1, with the seeing close to 1 arcsec. For both nights, most in-transit observations occurred at airmasses below 1.5. As a result of the slightly longer exposure times, observations of the first night reached per pixel S/Ns close to 85 at 703 nm (order 87, where the spectrograph achieves a high S/N for this target), while for the second night, the S/N at that same wavelength was close to 70. Note that this is the S/N that results from adding in quadrature the S/N of the two slices into which order 87 is divided for ESPRESSO.

2.1.2 MAROON-X transit

We also observed one transit of WASP-156 b with MAROON-X (A. Seifahrt et al. 2016, 2018, 2020) at the 8.1 m Gemini North telescope in Hawai'i on 2021 November 4 (programme ID: GN-2021B-Q-218, PI: Stefánsson). MAROON-X is a high-resolution ($R = 85\,000$, spectral sampling of 3.5 pixels per spectral element), optical-red spectrograph with a blue and a red channel, covering the wavelength ranges 5000–6700 Å and 6500–9200 Å. The data were reduced with a custom PYTHON pipeline that produces extracted two-dimensional spectra.

The MAROON-X observations were performed with an exposure time of 400 s and cover airmasses from ~ 3 before the start of the transit down to ~ 1 towards the end of the transit and later out-of-transit observations. The in-transit observations in particular

cover airmasses from ~ 2 to ~ 1 . The seeing during the pre-out-of-transit observations was of ~ 1.5 arcsec, and it decreased down to ~ 0.75 arcsec close to the end of the transit. The post-out-of-transit observations (close to phase 0.15) reached a seeing of ~ 0.5 – 0.6 arcsec. The S/N per pixel is close to 60 at ~ 703 nm at the start of the observations and increases to 80–100 towards the end of the transit, likely reflecting the decrease in airmass and seeing. Again, note that the S/N values quoted here are those corresponding to the three slices that order 87 is divided into for MAROON-X.

2.1.3 Archival out-of-transit data

WASP-156 has previously been observed with the spectrographs CORALIE (D. Queloz et al. 2001), Spectrographe pour l'Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes (SOPHIE; S. Perruchot et al. 2008), High Resolution Echelle Spectrometer (HIRES; S. S. Vogt et al. 1994), and High Accuracy Radial velocity Planet Searcher (HARPS; M. Mayor et al. 2003) in out-of-transit phases. The CORALIE and SOPHIE data were used to initially confirm the nature of the planet and measure its mass (O. D. S. Demangeon et al. 2018). HIRES data were used by A. S. Polanski et al. (2024) to refine the parameters of the planet and perform a uniform analysis together with other targets of the TESS–Keck survey. The HARPS data have never been published in the past and are publicly available in the ESO Archive.³ These archival observations of WASP-156, along with the best-fitting model, are shown in Fig. 2.

We note that there exist CARMENES (see V. Bourrier et al. 2023) and HARPS spectra obtained in transit for RM measurements. We decided not to include these data here because they have significantly lower S/N than the new ESPRESSO and MAROON-X data we obtained. This is mainly due to the larger collecting power of the VLT and Gemini North telescopes. We do not expect the derived parameters to improve by adding lower S/N CARMENES and HARPS data; therefore, we restrict our spectroscopic transit analysis to the ESPRESSO and MAROON-X data.

2.2 Photometric data

2.2.1 TESS

To better constrain the parameters of the planet and its orbit, in this work, we also made use of TESS (*Transiting Exoplanet Survey Satellite*; G. R. Ricker et al. 2015) photometric data. For the past 8 yr, TESS has been observing nearly the whole sky in

²<https://www.eso.org/sci/software/pipelines/espresso/espresso-pipeline-recipes.html>

³https://archive.eso.org/eso/eso_archive_main.html, Programme 0102.C-0618(A).

Programme

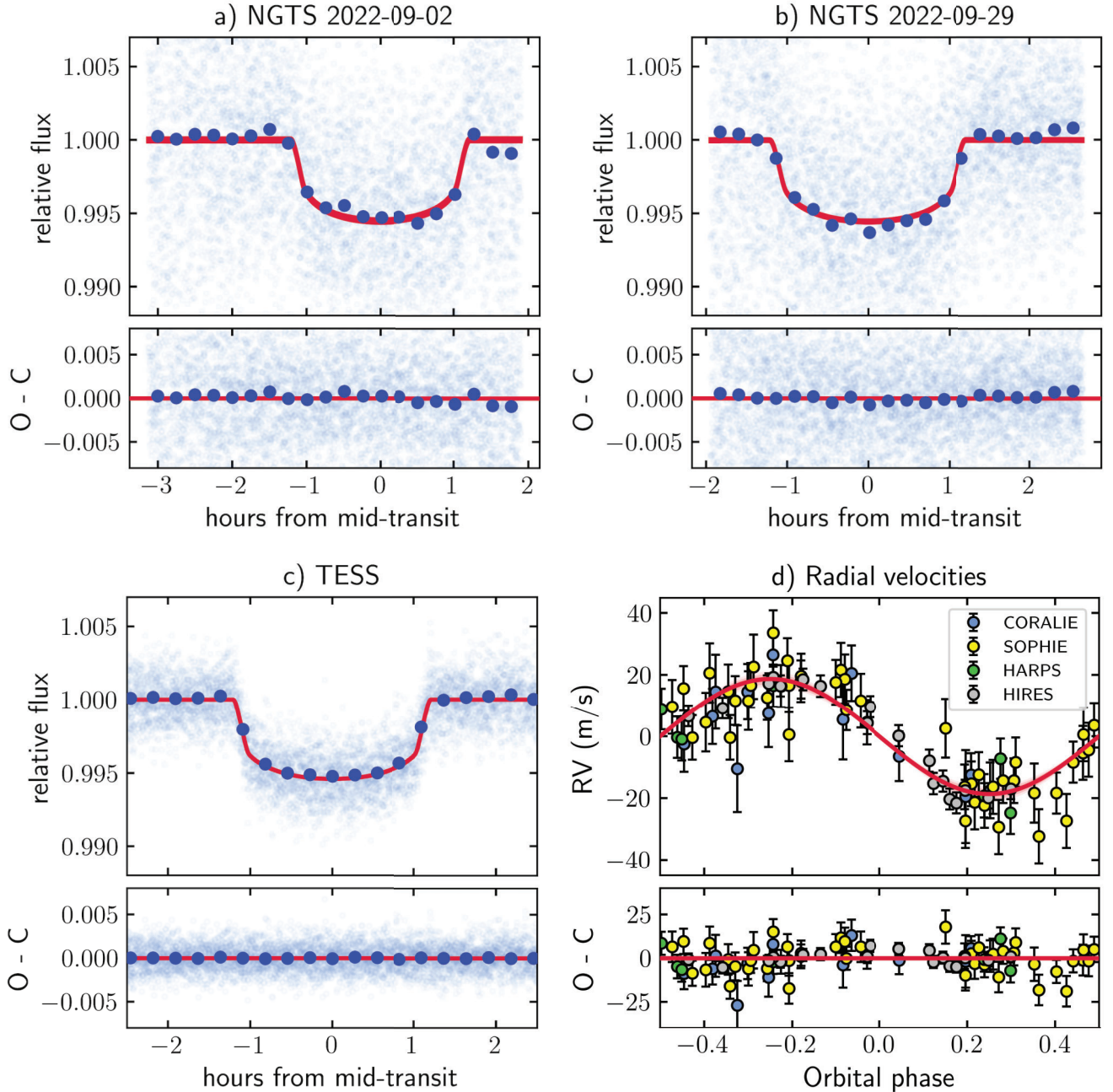


Figure 2. *TESS*, NGTS, and archival RV observations of WASP-156 along with the best-fitting model from JULIET. (a) and (b) airmass-detrended NGTS transits from 2022 September 2 and 2022 September 29, respectively, where large filled circles show the binned data of all cameras on a time-scale of about 15 min. (c) Phase-folded and GP-detrended *TESS* light curve. (d) Phase-folded out-of-transit RVs taken with different instruments. Shaded red areas represent 1σ , 2σ , and 3σ models (the confidence intervals are too small to be seen clearly).

the form of 27-d sectors. WASP-156 has been observed by *TESS* in sectors 4, 31, 42, 43, 70, and 71. None of the sectors coincides with our ESPRESSO or MAROON-X spectroscopic transit observations. In particular, we worked with the combined 2-min light curves from these sectors. These light curves were processed using the Science Processing Operations Center (SPOC) pipeline (J. M. Jenkins et al. 2016), and are corrected for pointing- or focus-related instrumental signatures, discontinuities resulting from radiation events in the CCD detectors, outliers, and flux contamination from nearby sources. We searched for, downloaded, and combined all the light curves using the LIGHTKURVE package

(Lightcurve Collaboration 2018). The phase-folded *TESS* light curve, along with the best-fitting model (see Section 4), is shown in Fig. 2.

2.2.2 NGTS

We used the Next-Generation Transit Survey (NGTS; P. J. Wheatley et al. 2018) to observe the transits of WASP-156 b simultaneously with the ESPRESSO observations (i.e. on 2022 September 2 and 2022 September 29). The NGTS facility consists of 12

Table 2. Spectroscopic stellar parameters derived with PAWS.

Observation set	T_{eff} (K)	$\log g$	[Fe/H]	$v \sin i_*$ (km s ⁻¹)
(1) 2022-09-02	5022±105	4.47±0.10	0.31±0.15	≤2.0
(2) 2022-09-29 1	5022±105	4.47±0.10	0.31±0.15	≤2.0
(3) 2022-09-29 2	5022±105	4.47±0.10	0.31±0.15	≤2.0
(4) All	5036±104	4.46±0.08	0.32±0.15	≤2.0

telescopes with 20 cm diameter and is located in ESO's Paranal Observatory, Chile. The NGTS cameras are independent, have a custom optical-red filter covering the wavelength range 520–890 nm, a wide field of view of $2.8 \times 2.8^\circ$ each, and a pixel scale of 5 arcsec. By observing the same star simultaneously with several cameras, NGTS achieves high-precision photometry of exoplanet transits (E. M. Bryant et al. 2020; A. M. S. Smith et al. 2020).

WASP-156 was observed in 10 s exposure times with four cameras on the first night of ESPRESSO observations (2022 September 2), and with five cameras on the second night (2022 September 29). The observations were reduced with a custom aperture photometry pipeline that utilizes the SEP library (E. Bertin & S. Arnouts 1996; K. Barbary 2016) for source extraction and photometry. We used an aperture radius of 3 pix for all cameras and nights. A time series of differential flux is produced using a set of unblended comparison stars similar in apparent magnitude, colour, and nearby position in the CCD to WASP-156, selected using *Gaia* information (Gaia Collaboration 2018, 2023).

3 STELLAR PARAMETERS

3.1 Stellar parameters from spectroscopy

We derived stellar parameters (effective temperature T_{eff} , surface gravity $\log g$, metallicity [Fe/H], and projected equatorial rotational velocity $v \sin i_*$) from the ESPRESSO observations using the PAWS⁴ pipeline (A. V. Freckelton et al. 2024). The curve-of-growth equivalent widths method was used to generate initial estimates of the stellar parameters. We employed the WIDTH (L. Sbordone et al. 2004) radiative transfer code and solar input parameters. Spectral synthesis, using the SPECTRUM (R. O. Gray & C. J. Corbally 1994) radiative transfer code, was then used to refine these estimates, in addition to determining the macroturbulence velocity and projected rotational velocity. As is standard in PAWS, both the SPECTRUM line list (R. O. Gray & C. J. Corbally 1994) and ATLAS model atmospheres (R. L. Kurucz 2005) were used by both methods.

We ran PAWS on four different sets of one-dimensional co-added rest-frame-shifted spectra: (1) all the observations of the first night, (2) the first 15 observations of the second night, (3) the last 6 observations of the second night, and (4) all observations co-added. Sets 1 to 3 were obtained directly from the ESPRESSO DRS pipeline, and we used PAWS to co-add all the observations for set 4. The ESPRESSO DRS provided two co-added spectra for the second night instead of one because the observations were aborted (due to pointing restrictions) and restarted towards the end of the transit, resulting in two different observing blocks.

Table 2 shows the stellar parameters obtained by PAWS on the ESPRESSO data, for the four different sets of co-added spectra considered. All sets show extremely similar results, showcasing

the quality of the ESPRESSO data. The T_{eff} , $\log g$, and [Fe/H] are in agreement (within 1σ) with previous literature results obtained in O. D. S. Demangeon et al. (2018; $T_{\text{eff}} = 4910 \pm 61$ K, $\log g = 4.60^{+0.04}_{-0.07}$, [Fe/H] = 0.24 ± 0.12) from 40 co-added SOPHIE spectra ($R = 40\,000$; F. Bouchy et al. 2009) using methods from A. P. Doyle et al. (2013), and from *Gaia* photometry (Gaia Collaboration 2018; $T_{\text{eff}} = 4970^{+49}_{-118}$ K).

Regarding the $v \sin i_*$, PAWS converged on a value close to ~ 0.9 km s⁻¹. However, below 2 km s⁻¹, it is challenging to accurately distinguish between different broadening mechanisms (e.g. instrumental, rotational, macroturbulence). Therefore, we constrain the $v \sin i_*$ to an upper limit of 2 km s⁻¹. This value is lower than the literature value of 3.8 ± 0.91 km s⁻¹ from O. D. S. Demangeon et al. (2018), obtained from the SOPHIE spectra by fitting the profiles of several unblended lines, which, as reported, also agrees with a method that uses the cross-correlation function (CCF) profiles following I. Boisse et al. (2010). Note that both methods are based on empirically calibrated relations. The line-fitting method used a macroturbulence value based on the calibration of A. P. Doyle et al. (2014), valid for T_{eff} between 5200 and 6400 K, which had to be extrapolated for WASP-156. The method using CCFs is based on an empirically calibrated relation obtained for SOPHIE, based on a relation between the SOPHIE CCF widths and the star's $v \sin i_*$ computed for a range of stars with known $v \sin i_*$. Hence, these methods are sensitive to the stars used in the calibration. As explained above, PAWS uses a different methodology based on spectral synthesis, which could explain the difference in $v \sin i_*$. An in-depth analysis on this $v \sin i_*$ discrepancy is out of the scope of this work, however, for the remainder of this article, we consider the upper limit of 2 km s⁻¹ obtained with PAWS from ESPRESSO, and not the previous SOPHIE-based value, due to the higher resolution of ESPRESSO and the PAWS methodology, which does not rely on calibrations.

3.2 Stellar rotation period

The stellar rotation period of the star is currently unknown. Unless the star has a low stellar inclination (i.e. it is seen close to pole-on), the low value of $v \sin i_*$ would suggest a long stellar rotation period. The stellar rotation period can be used to disentangle the stellar inclination from $v \sin i_*$, which allows us to measure the true three-dimensional obliquity instead of the projected one.

We performed an archival search of long-term photometry to try to estimate the stellar rotation period of WASP-156. We looked for periodicities in the All-Sky Automated Survey for Supernovae (ASAS-SN; B. J. Shappee et al. 2014; C. S. Kochanek et al. 2017)⁵ and the Hungarian-made Automated Telescope PI Steradians (HATPI) data.⁶ Our analysis did not result in a clear signal that

⁴<https://github.com/alixviolet/PAWS>

⁵<https://asas-sn.osu.edu/>

⁶<https://hatpi.org>

Table 3. Summary statistics of posterior distributions of the main orbital parameters of the JULIET fit. The posterior summary statistics for the rest of parameters are shown in Table C1.

Sampled parameter	Posterior
P (d)	3.8361629 ± 0.0000006
t_0 (BJD – 2450 000)	9058.6113 ± 0.0001
R_p/R_*	0.0682 ± 0.0007
b	0.40 ± 0.05
ρ_* (g cm^{-3})	2.25 ± 0.14
e	0 (fixed, < 0.16 at 3σ)
K (m s^{-1})	18.6 ± 0.8
q_1^{TESS}	$0.32^{+0.13}_{-0.10}$
q_2^{TESS}	$0.43^{+0.22}_{-0.17}$
q_1^{NGTS}	$0.53^{+0.21}_{-0.17}$
q_2^{NGTS}	$0.31^{+0.25}_{-0.18}$
Derived parameters	
a/R_*	12.04 ± 0.26
i ($^\circ$)	88.1 ± 0.3
a (au)	0.046 ± 0.001
M_p ($M_\oplus$)	42 ± 2
R_p ($R_\oplus$)	6.15 ± 0.12
ρ_p (g cm^{-3})	0.990 ± 0.070

we can confidently assign to the stellar rotation, see details in Appendix B. We also checked the *TESS* All-Sky Rotation Survey (TARS) catalogue (A. W. Boyle, L. G. Bouma & A. W. Mann 2026), a recent rotation survey based on *TESS* data, but WASP-156 does not appear in it, implying that a rotation-related signal has not been detected for this star in *TESS*.

4 RE-CHARACTERIZATION OF THE SYSTEM

To refine the parameters of WASP-156 b, we performed a joint analysis of all the available *TESS* and NGTS photometry and out-of-transit CORALIE, SOPHIE, HARPS, and HIRES RVs using the JULIET (N. Espinoza, D. Kossakowski & R. Brahm 2019) code. JULIET uses BATMAN (L. Kreidberg 2015) for the photometric transit model, RADVEL (B. J. Fulton et al. 2018) for the Keplerian orbit model, and the DYNESTY dynamic nested sampler (J. S. Speagle 2020) to obtain posterior probability distributions. For the fit, we adopted 4500 live points, and the default configurations of the sampler for the bounding and sampling methods (i.e. multi-ellipsoidal bounding and random-walk sampling). The runs were stopped when the change in the logarithm of the Bayesian evidence ($\log Z$) was less than 0.01, which is the default convergence criterion. We placed uninformative priors on the parameters, with an informative Gaussian prior on the stellar density of $\rho_* = 2.154 \pm 150 \text{ g cm}^{-3}$ based on the value reported by M. G. MacDougall et al. (2023). Limb-darkening parameters were sampled using the quadratic q_1 and q_2 parametrization from D. M. Kipping (2013b) with uniform priors. To model the RVs, we placed an uninformative prior on the RV semi-amplitude K . We included independent RV offsets (γ_{inst}) and log-uniform jitter terms (σ_{inst}) for each instrument to account for possible systematics. For the NGTS transits, we treated each camera separately with shared limb-darkening coefficients, and detrended the light curves with airmass during the fit. Finally, to account for variability and systematic noise in the *TESS* light curve, we included a Matern-3/2 Gaussian Process as implemented in CELERITE (D. Foreman-Mackey et al. 2017) and available in JULIET.

The final parameters derived from this analysis are shown in Tables 3 (main orbital parameters) and C1 (additional instrumental parameters), and the photometric and RV data, along with the best-fitting model, are shown in Fig. 2. Our newly derived parameters generally agree with literature values within 1σ and have comparable or in some cases smaller uncertainties, probably due to the large amount of data used in our fit. In particular, we obtained improved uncertainties on the orbital period P compared with A. Kokori et al. (2023; 6×10^{-7} versus 9.7×10^{-7} d, about 1.6 times more precise), better planetary-to-stellar radius ratio R_p/R_* uncertainties compared with J. A. Patel & N. Espinoza (2022; 7×10^{-4} versus 8.7×10^{-4} , 1.2 times more precise), and better RV semi-amplitude K uncertainties compared with O. D. S. Demangeon et al. (2018; 0.8 versus 1 m s^{-1} , 1.25 times more precise). Regarding derived parameters, we improved on the planetary mass M_p and density ρ_p compared with A. S. Polanski et al. (2024, 2 versus $2.9 M_\oplus$, 1.5 times more precise, and 0.07 versus 0.18 g cm^{-3} , 2.6 times more precise; note that for that work we also improved on the reported K , 1.1 m s^{-1} , which drives the improvement in mass). Note that here we are directly comparing the uncertainties, since the parameter values are similar. We consider the literature parameters with smaller uncertainties. These come from different works, therefore, the different values that we are using to compare our own values to are not necessarily self-consistent with each other.

5 SPECTROSCOPIC TRANSIT ANALYSIS

To analyse the RM effect in the ESPRESSO and MAROON-X observations, we first computed the standard disc-integrated RVs with two different methods: the CCF and the template matching approaches. We then used two different techniques that exploit the RM effect to measure the stellar obliquity of the system: the classical RM and the reloaded RM. We describe in detail our methodology in the following sections.

5.1 Disc-integrated RV computation

For the ESPRESSO observations, we used the CCFs and disc-integrated RVs computed by the ESPRESSO DRS pipeline. The CCFs of the reduced spectra (corrected by the barycentric Earth RV, BERV, of each observation) are computed by cross-correlating them with a weighted binary mask. We used the default ESPRESSO mask of spectral type K2, the closest to the spectral type of WASP-156. The star's systemic velocity is about 9.3 km s^{-1} (Gaia Collaboration 2018), therefore, the RV grid of the CCF was defined to be centred at that value and computed over an RV span of $\pm 60 \text{ km s}^{-1}$ from the centre in steps of 0.5 km s^{-1} (which is the average ESPRESSO pixel size in velocity units). The cross-correlation is performed on an order-by-order basis, resulting in a disc-integrated CCF per order. A final CCF per observation is obtained by co-adding the CCFs of all orders. Finally, a Gaussian function is fitted to the co-added CCF. The final disc-integrated RVs are the centroids of the best-fitting Gaussians to the co-added CCFs.

MAROON-X covers a redder wavelength range than ESPRESSO (up to $9200 \text{ \AA}$, while ESPRESSO goes up to $7887 \text{ \AA}$), hence, using one of the default ESPRESSO masks (which only go up to $7887 \text{ \AA}$) results in the loss of information from several red orders. To include information from the whole spectral range, we needed a different CCF mask to include all the

RV information of the reddest orders. We used the RACCOON⁷ pipeline (M. Lafarga et al. 2020) to build a mask using a high-S/N, observation-co-added template built from the MAROON-X observations themselves with SERVAL (see next paragraph for more information on SERVAL; M. Zechmeister et al. 2018). We selected lines with full width at half-maximum (FWHM) between 2 and 20 km s⁻¹, minimum contrast of 6 per cent, and relative depth below 80 per cent. We removed lines in strongly contaminated telluric regions using a custom telluric mask from the MAROON-X site. We then used this custom mask to compute the CCFs of all orders using a custom PYTHON CCF code for MAROON-X.

In addition to the standard CCF-based RVs, we also computed disc-integrated RVs using the template matching approach implemented in SERVAL (M. Zechmeister et al. 2018). SERVAL performs an iterative process consisting of first computing an initial set of RVs by performing a least-squares fit between all the observations and the observation with the highest S/N, then building a high-S/N template by co-adding the Doppler-shifted observations, and finally improving on the Doppler shift solution by recomputing the RVs with the high-S/N co-added template. We applied SERVAL to both the ESPRESSO and MAROON-X reduced observations.

We note that we had to perform a relatively strong masking of telluric lines when computing the SERVAL RVs for both instruments, as well as when creating the mask and CCFs for the MAROON-X data. Not removing enough telluric-affected regions of the spectrum resulted in an extra slope in the computed RVs, as reported by, e.g. A. M. Silva et al. (2025). A. M. Silva et al. (2025) found extra slopes in template matching RVs compared to CCF-derived RVs, especially for time series observations taken over a short time span, as is our case. The authors argue that the cause of these extra slopes in template-matching-based RVs stems from contamination from micro-tellurics and other sources of correlated noise, which could explain the slopes we initially obtained here with SERVAL. The MAROON-X CCF RVs, which initially also showed a similar slope, are computed using a mask that has been derived from a template built with SERVAL. Therefore, we can expect that these RVs will also suffer from similar effects. In our case, an aggressive removal of the telluric lines removed the slope, however, this was at the expense of losing some of the contaminated stellar lines. Other possible avenues to solve this bias, currently not available to us, would be obtaining further observations at different BERV, so that the impact of tellurics is spread over different spectral regions, or using another template of a similar star built from enough observations spread over time.

5.2 Classical Rossiter–McLaughlin

The classical Rossiter–McLaughlin method consists of fitting the time series of the disc-integrated RVs. During the transit occultation, these ‘disc-integrated’ RVs only account for the unocculted part of the stellar disc, which result in the RM anomaly.

5.2.1 IRONMAN

For this analysis, we only worked with the ESPRESSO SERVAL RVs. For the current data set, they are more precise than the CCF-derived RVs, likely because the template matching of the

full spectra ends up extracting more RV information than the pre-selected lines of the CCF mask. Moreover, the classical RM effect is not detected in the MAROON-X data. Given the small RM amplitude that we measure from the ESPRESSO data and the scatter of the MAROON-X data, we do not expect to be able to measure the RM effect in the MAROON-X data alone (see Figs D1 and D2).

To model the in-transit data sets, we used the IRONMAN⁸ code (J. I. Espinoza-Retamal et al. 2024), which relies on different publicly available codes to derive stellar obliquities. Namely, RMFIT (G. Stefansson et al. 2022) to model the in-transit RVs, RADVEL (B. J. Fulton et al. 2018) to model the Keplerian signal, and the DYNesty dynamic nested sampler (J. S. Speagle 2020) to get the posteriors.

We placed informative Gaussian priors for almost all the parameters of the planet and its orbit, based on the values shown in Table 3. The exceptions were the sky-projected obliquity λ and the projected rotational velocity $v \sin i_*$, where we placed uninformative priors between -180 and 180° , and 0 and 2 km s⁻¹, respectively. We also placed an informative prior for β , the intrinsic linewidth accounting for instrumental and macroturbulence broadening (see T. Hirano et al. 2010). We considered an instrumental broadening of 2.15 km s⁻¹ because of the ESPRESSO resolution and a macroturbulence broadening of 2.8 km s⁻¹ derived from the macroturbulence law of J. A. Valenti & D. A. Fischer (2005) using the effective temperature reported in Table 2. We added the instrumental and macroturbulence broadening in quadrature to set our prior, with an uncertainty of 2 km s⁻¹. We performed the analysis for each ESPRESSO data set independently and for both data sets together. For the joint analysis, we considered both data sets as taken with the same instrument, but allowed a different jitter term to take into account the differences in the observing conditions each night. Shared parameters between data sets are the limb-darkening coefficients and the RV offset. We tested fitting different RV offsets, but found a negligible difference between the two nights.

5.2.2 Results

Our fit for the first night resulted in $\lambda = -28^{+17}_{-15}^\circ$, while for the the second night we obtained $\lambda = 6^{+41}_{-49}^\circ$, with the relatively large uncertainty mostly coming from the lack of transit egress observations. As the projected obliquity was consistent between data sets, we decided to formally adopt the results of the joint fit, which gave $\lambda = -15^{+17}_{-16}^\circ$.

We derive a $v \sin i_* = 0.44 \pm 0.08$ km s⁻¹ from the joint fit of the two nights (and $v \sin i_* = 0.52^{+0.12}_{-0.11}$ and $0.25^{+0.17}_{-0.16}$ km s⁻¹ for the first and second night separately, which agree within 1σ). This is significantly smaller than the reported SOPHIE-based value of ~ 4 km s⁻¹ (note again that the SOPHIE value is based on a calibration), but consistent with the upper limit of 2 km s⁻¹ we obtained from our PAWS analysis of the ESPRESSO data.

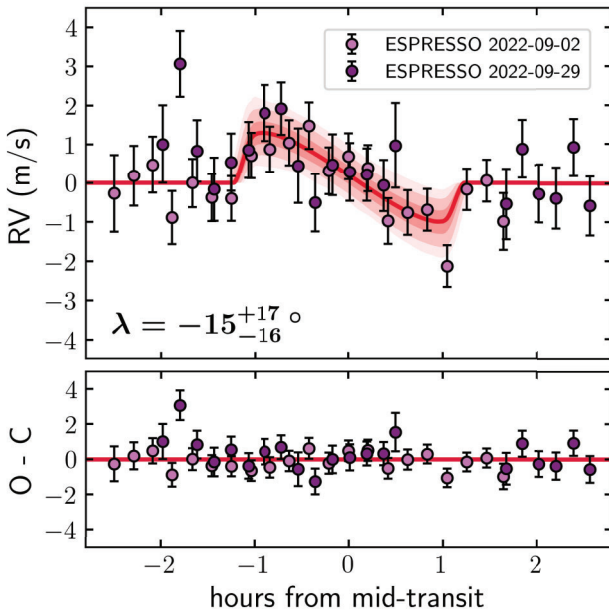
The posteriors for the remaining parameters of our joint fit are presented in Table 4; the data and best-fitting model are illustrated in Fig. 3. We show corner plots with the posterior distributions of λ and $v \sin i_*$ for the different fits to data in Fig. D2. This analysis of the classical RM effect suggests that the planetary orbit is well aligned with the equator of the host star.

⁷<https://github.com/mlafarga/raccoon>

⁸<https://github.com/jiespinozar/ironman>

Table 4. Summary of posteriors of the IRONMAN fit to the *classical* Rossiter–McLaughlin effect for the ESPRESSO transits.

Parameter	Posterior
λ ($^\circ$)	-15^{+17}_{-16}
$v \sin i_*$ (km s^{-1})	0.44 ± 0.08
P (d)	3.8361627 ± 0.0000006
t_0 (BJD – 2450 000)	9058.6112 ± 0.0001
R_p/R_*	0.0680 ± 0.0007
b	0.40 ± 0.05
ρ_* (kg m^{-3})	2130 ± 140
e	0 (fixed)
K (m s^{-1})	19.4 ± 0.9
β (km s^{-1})	3.6 ± 1.9
q_1^{ESPRESSO}	$0.35^{+0.37}_{-0.25}$
q_2^{ESPRESSO}	$0.41^{+0.37}_{-0.29}$
γ^{ESPRESSO} (m s^{-1})	-0.15 ± 0.16
$\sigma^{\text{ESPRESSO1}}$ (m s^{-1})	$0.02^{+0.12}_{-0.02}$
$\sigma^{\text{ESPRESSO2}}$ (m s^{-1})	$0.04^{+0.34}_{-0.04}$

**Figure 3.** Disc-integrated radial velocities taken with ESPRESSO during the transit of WASP-156 b, after subtracting the Keplerian motion induced by the planet. We show in light pink and dark purple the measurements taken on two different nights. The best-fitting model is shown as a red line, with 1σ , 2σ , and 3σ models as the shaded regions. The best fit reveals a sky-projected obliquity $\lambda = -15^{+17}_{-16}^\circ$, suggesting that the planetary orbit is well aligned with the stellar spin.

5.3 Reloaded Rossiter–McLaughlin

We also applied the *reloaded* Rossiter–McLaughlin technique (H. M. Cegla et al. 2016) to the new spectroscopic transit data. Rather than modelling the time series of apparent RVs, this method isolates the stellar light behind the planetary transit chord, thus mapping the path of the planet on the surface of the star. We modelled the disc-integrated co-added CCFs, which ensure a higher S/N than directly using the observed spectra. We treated each transit (two from ESPRESSO and one from MAROON-X) independently; therefore, we repeated this process for each of the three nights. In this section, we provide a brief overview of the

steps followed, and refer the reader to H. M. Cegla et al. (2016) for more details.

5.3.1 Local CCFs

We started by Doppler-shifting the CCFs to remove the Keplerian reflex motion of the star caused by the planet using orbital parameters from Table 3. Correcting the CCFs by the planetary RVs results into CCFs sampled at slightly different RV points. To co-add and subtract the CCFs in the next steps, we interpolated them into a common RV grid using a cubic spline.

We then co-added all the CCFs of out-of-transit observations into a master-out CCF (as mentioned above, we work with the three sets of observations independently, so we obtained one master-out CCF per transit). In the case of the MAROON-X data, we discarded the first four out-of-transit observations, which were taken at relatively high airmass (> 2.3) and have low S/N. The ESPRESSO observations were all taken at airmasses below 2.3 and hence we use all of them. Preliminary tests using only pre-transit or post-transit observations to build the master-out ESPRESSO CCF did not result in a clear improvement of our results. We measure the systemic velocity of the star by fitting a Gaussian to the master-out CCF. For the first and second ESPRESSO nights, we obtained a systemic velocity of 9.670 ± 0.036 and $9.6689 \pm 0.036 \text{ km s}^{-1}$, consistent with literature values ($9.30 \pm 0.61 \text{ km s}^{-1}$ from *Gaia* DR2, *Gaia* Collaboration 2018). Note that this assumes that the CCF mask used by the DRS has been calibrated to be at 0 velocity. The RACCOON mask used for the MAROON-X data has not been set to 0 km s^{-1} , hence, we do not derive a systemic velocity from that data set.

We normalized the master-out CCF and the CCFs of individual observations by dividing them by the mean of their continuum (i.e. the region of ‘flat’ flux outside the CCF minimum, which we define as the region outside 3.5 times the width of the CCF on either side of the CCF minimum, to make sure we are not including part of the CCF profile). To account for the decreasing amount of light coming from the star as the planet occults it during the transit, we further normalized the CCFs by the transit light curve. We used a transit light curve model generated with BATMAN (L. Kreidberg 2015) and parameters from Table 3.

After normalization, we subtracted the CCF of each individual observation from the corresponding master-out, resulting in a residual CCF (see Fig. 4). For the in-transit observations, the residual CCFs only contain light coming from the stellar disc region occulted by the planet. For the out-of-transit observations, the residual CCFs only contain noise. Note that we are assuming that the stellar disc does not change significantly during the time span of each transit. We refer to these residual CCFs as local CCFs because they contain stellar light from a localized area on the stellar disc. We propagated flux uncertainties from the original disc-integrated CCFs to the local CCFs. Finally, we fit the in-transit local CCFs with a Gaussian function to derive the local RVs, that is, the RV of the stellar disc regions occulted by the planet during its transit.

5.3.2 Stellar surface model

Next, we modelled the Doppler shifts of the local RVs following the models presented in H. M. Cegla et al. (2016), which account for stellar rotation. The stellar rotation along the transit chord is

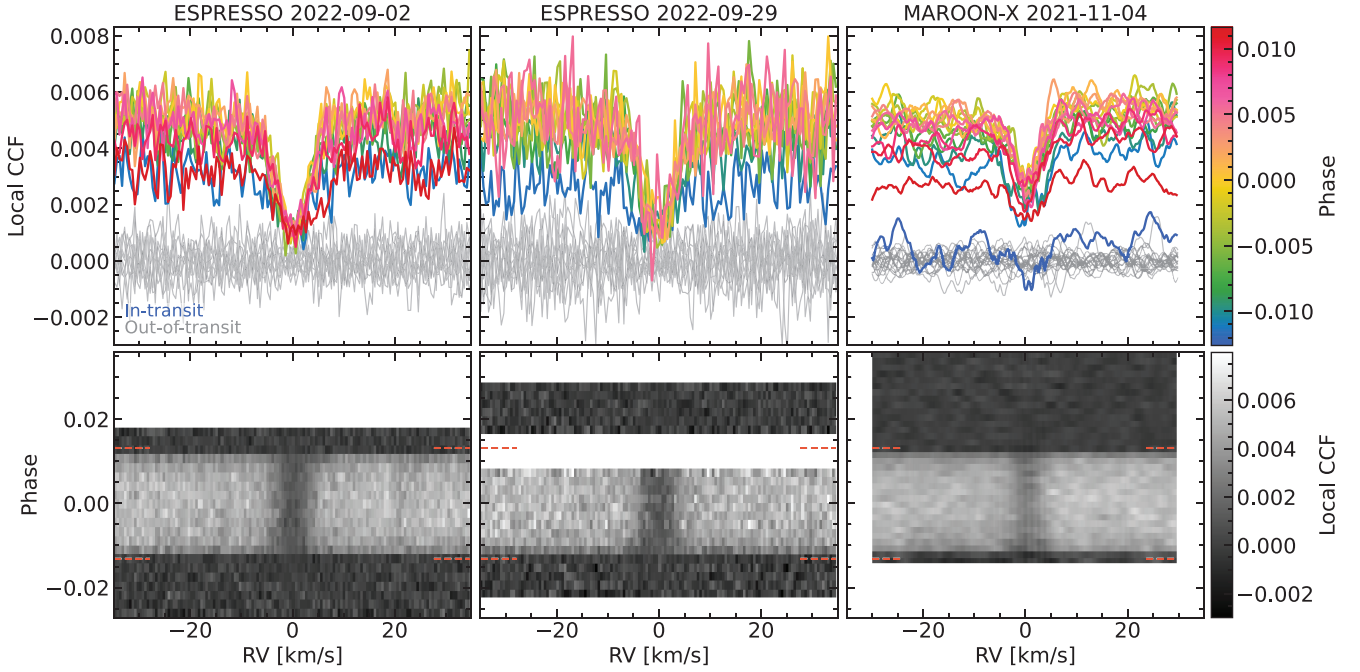


Figure 4. Local CCFs, that is, profiles after subtracting each of the disc-integrated CCF from their corresponding master-out CCF (one per transit). The RV is in stellar rest frame. Left to right correspond to the first and second ESPRESSO transits, and to the MAROON-X one. The top panels show the CCF profiles (i.e. CCF flux as function of RV). The in-transit CCFs are colour-coded as a function of the orbital phase of the planet (with start-of-transit phases in blue and end-of-transit phases in red), and out-of-transit CCFs are in grey. The bottom panel shows the same data but in a map format, with each of the CCF points colour-coded by their flux and shown as a function of the orbital phase in the y-axis. The red dashed lines indicate the start (T_1) and end (T_4) of the transits.

modelled by computing the brightness-weighted average stellar rotational velocity of the stellar disc area occulted by the planet at each observation, which depends on the projected obliquity λ and the projected rotational equatorial velocity of the star $v \sin i_*$. The model we used assumes that the star is a solid body (SB, i.e. rigid rotation).

We fitted our models with the affine-invariant ensemble sampler for Markov chain Monte Carlo (MCMC) implemented in the package EMCEE (D. Foreman-Mackey et al. 2013). We used uniform priors on λ ($\mathcal{U}(-180, -180^\circ)$) and $v \sin i_*$ ($\mathcal{U}(0, 100 \text{ km s}^{-1})$). We used 40 walkers, 4000 total iterations, and discarded a burn-in of 300 iterations. We initialized our walkers around a multivariate Gaussian distribution with small (10^{-7}) width centred on initial values of $\lambda = 0^\circ$ and $v \sin i_* = 2 \text{ km s}^{-1}$. Setting the starting points at different values did not affect final posterior distributions obtained. We modelled each of the three transits separately, the two ESPRESSO transits together, and all three transits together.

Our main data set considered all in-transit observations. Additionally, we also fitted the models to a reduced data set where we discarded data points close to the stellar limb, with $\langle \mu \rangle < 0.3$.⁹ This cut in $\langle \mu \rangle$ discards the first in-transit observation of the second ESPRESSO night, and the first and last MAROON-X in-transit observations. Our motivation to consider this slightly reduced data set is that at the limb, the local CCFs have significantly less flux than closer to the disc centre (see first and last

in-transit local CCFs in Fig. 4), and hence the derived local RVs are less precise (see e.g. H. M. Cegla et al. 2016). All of the derived parameters of this reduced data set agree well within 1σ with those derived from the data set that considered all observations. Therefore, in the following, we only report our results for the data set that considered all observations.

Note that we also considered models which, in addition to SB rotation, also include centre-to-limb convective variations. However, we found that those models overfit the data and do not necessarily improve the fit, despite being more complex. We provide details about these models in Appendix E but do not consider them further here.

5.3.3 Results

The best-fitting SB models for the different data sets considered are shown in Fig. 5, Table 5 shows a summary of the posteriors for the ESPRESSO data, and we show the corner plots and posterior distributions in Fig. E1.

The first night of ESPRESSO observations results in an aligned projected obliquity of $\lambda = 7_{-17}^{+17}^\circ$. The second night of ESPRESSO observations yields a projected obliquity of $\lambda = -75_{-45}^{+34}^\circ$, with larger uncertainties than the first night, similarly to what happens in the classical RM analysis. This value could indicate a slight misalignment, however, the uncertainties are large enough that an aligned orbit cannot be ruled out. The value derived from the second night agrees within 2σ with the one from the first night, but again, note the larger uncertainties of the second night. Each night agrees within 1σ with the individual night values derived from the classical RM.

⁹Where $\langle \mu \rangle$ is the brightness-weighted stellar disc position, with 0 being at the limb and 1 at disc centre, and $\mu = \cos \theta$, where θ is the centre-to-limb angle.

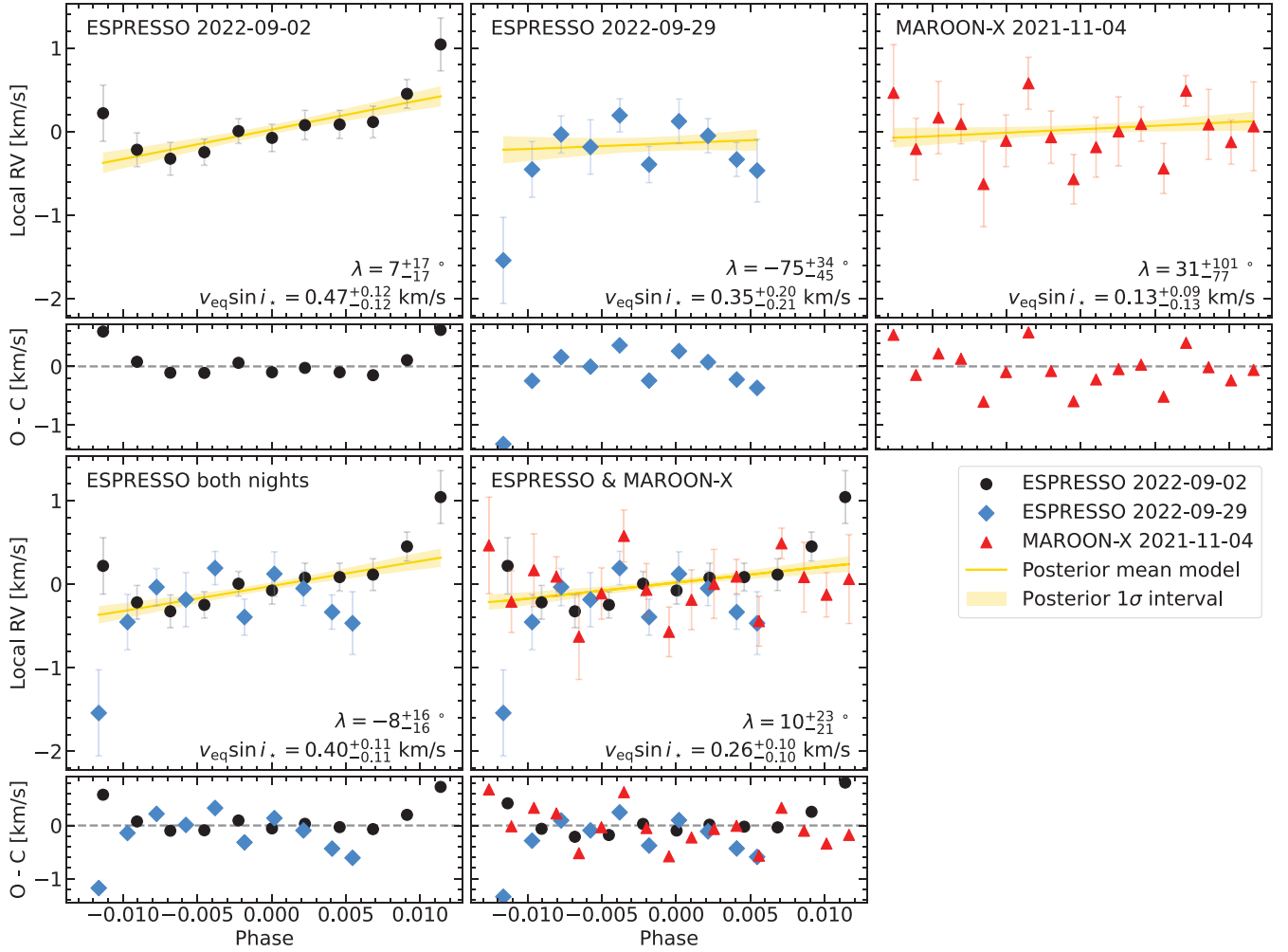


Figure 5. Local RVs and preferred solid body models for the ESPRESSO (first night in black circles, second night in blue diamonds) and MAROON-X (red triangles) transits. Top panels show the fits to individual transits, and bottom panels show the fit to the two ESPRESSO transits together (left) and to all ESPRESSO and MAROON-X transits together (right). The solid yellow line represents the posterior mean model of the fit to each set of data, and the yellow shaded area the 1σ credibility interval around the model. The text in each panel shows the mean posterior parameters and their 1σ uncertainties.

Table 5. Summary statistics of posterior distributions of the SB model fit of the *reloaded* RM analysis for the ESPRESSO observations.

Parameter	Night 1	Night 2	Both nights
λ ($^\circ$)	7^{+17}_{-17}	-75^{+34}_{-45}	-8^{+16}_{-16}
$v \sin i_*$ (km s^{-1})	$0.47^{+0.12}_{-0.12}$	$0.35^{+0.20}_{-0.21}$	$0.40^{+0.11}_{-0.11}$

The observing conditions of the second night were slightly worse, with a higher airmass at the start of the night, higher water vapour and ambient humidity during the transit and during the post-transit observations, and higher seeing during the post-transit observations. As a result, the S/N was also lower than that of the first night, although note that the observations of the second night were 100 s shorter than those of the first night (600 s versus 700 s), which also contributes to the S/N decrease. These factors result in local CCFs with lower S/N, and hence local RVs with larger uncertainties. More importantly, the transit egress of the second night, which significantly helps constrain the obliquity, was not observed due to pointing restrictions.

Despite these differences, the average local RVs show a strong overlap during most of the transit (except at very low μ angles and right before the second night observations had to be aborted, where we expect a low local RV precision), and the systemic velocities that we derive from the master out CCFs of each night agree well with each other, showing that there is not a large disagreement between the two data sets.

When modelling both nights together, we obtained a projected obliquity of $\lambda = -8^{+16}_{-16}^\circ$. The higher quality observations of the first night dominate the fit, and the measured λ agrees within 1σ with the value derived from the first night alone, and within 2σ with the value from the second night. Comparing with the results

from the classical RM, again the λ values derived from the two nights together agree within 1σ .

The local RVs extracted from the MAROON-X data are significantly noisier than the ESPRESSO RVs. We obtained a projected obliquity of $\lambda = 31^{+101}_{-77}^\circ$ considering the MAROON-X data alone. The value has large uncertainties, making it unconstrained, as within 1σ , the orbit is consistent with being aligned, polar, and retrograde. Using the two ESPRESSO nights and the MAROON-X night together, we obtained $\lambda = 10^{+23}_{-21}^\circ$. Again, the first ESPRESSO night dominates the fit, and the measured λ agrees well within 1σ with the value derived from the first ESPRESSO night alone, both ESPRESSO nights, and the classical RM analysis.

As in the case of the classical RM analysis, we decided to adopt the value derived from the fit to both ESPRESSO nights, that is, $\lambda = -8^{+16}_{-16}^\circ$. Note again that this value is consistent within 1σ with the results derived for the first ESPRESSO night, all ESPRESSO and MAROON-X nights together, and with the classical RM analysis (for all ESPRESSO individual nights and both nights considered together).

Regarding the measured $v \sin i_*$, we obtained values below $\simeq 1 \text{ km s}^{-1}$ for almost all data sets and models considered, in agreement with the value measured with PAWS in Section 3.1. In particular, for the ESPRESSO data we obtained $v \sin i_* = 0.47^{+0.12}_{-0.12} \text{ km s}^{-1}$, $0.35^{+0.20}_{-0.21} \text{ km s}^{-1}$, and $0.40^{+0.11}_{-0.11} \text{ km s}^{-1}$ for the first, second, and both nights, respectively. All these values agree within 1σ with the $v \sin i_*$ measured in the classical RM analysis. The MAROON-X data alone yielded a lower $v \sin i_*$ of $0.13^{+0.09}_{-0.13} \text{ km s}^{-1}$, with a posterior distribution peaking at 0 km s^{-1} (see Fig. E1), which we consider a non-detection. The MAROON-X data also seem to affect the fit when considering all nights together, with $v \sin i_* = 0.26^{+0.10}_{-0.10} \text{ km s}^{-1}$. For the $v \sin i_*$ we also adopt the value derived from the fit to the two ESPRESSO nights together, $0.40^{+0.11}_{-0.11} \text{ km s}^{-1}$.

6 DISCUSSION

6.1 Obliquity and rotational velocity values

V. Bourrier et al. (2023) estimated the projected stellar obliquity of the system to be $\lambda = 105.7^{+14.0}_{-14.4}^\circ$ using one transit obtained with the visible arm of CARMENES. In comparison, here, our analyses of the new ESPRESSO transits suggest that the obliquity is instead consistent with an aligned orbit ($\lambda = -15^{+17}_{-16}^\circ$ from the classical RM and $\lambda = -8^{+16}_{-16}^\circ$ from the reloaded RM), and is not compatible with a polar orbit.

The RM analysis of the CARMENES data presented in V. Bourrier et al. (2023) clearly detects the planet-occulted CCFs (i.e. equivalent to the local CCFs). As explained in V. Bourrier et al. (2023), a preliminary fit to the CARMENES local CCFs performed with broad uninformative priors results in a broad posterior for the $v \sin i_*$, peaking at 0 km s^{-1} and $< 6 \text{ km s}^{-1}$ at 3σ , and a posterior for λ peaking at $\sim 100^\circ$ with shallow wings spanning the whole parameter space. A subsequent fit constraining the $v \sin i_*$ prior to a normal distribution following the value of $3.8 \pm 0.9 \text{ km s}^{-1}$ from O. D. S. Demangeon et al. (2018) removes the broad wings on the λ posterior, yielding a well-defined value of $105.7^{+14.0}_{-14.4}^\circ$. In general, RM measurements can suffer from degeneracies between λ and $v \sin i_*$, especially if the impact parameter b is close to 0, and/or if the amplitude of the RM signal is small compared to the RV uncertainties (e.g. S. Albrecht et al. 2011; D. J. A. Brown et al. 2012, 2017). WASP-156 b does not transit

the centre of the stellar disc ($b \sim 0.4$), however the RM signal is relatively small, making a precise measurement of λ challenging, especially with the low S/N data obtained with CARMENES.

Our re-analysis of the stellar parameters of WASP-156 using the ESPRESSO data and the PAWS pipeline (see Section 3.1) shows that the $v \sin i_*$ is likely $\leq 2 \text{ km s}^{-1}$. Hence, the polar obliquity derived from the CARMENES data relied on an inaccurate prior for the $v \sin i_*$. This low $v \sin i_*$ value also agrees with the $v \sin i_*$ estimated from both the classical ($v \sin i_* = 0.44 \pm 0.08 \text{ km s}^{-1}$) and reloaded RM ($v \sin i_* = 0.40 \pm 0.11 \text{ km s}^{-1}$) analyses presented here using the new data. Note that due to the spatial information of the stellar disc that we extract from the RM effect, our analyses can measure extremely low $v \sin i_*$ values (lower than the intrinsic line profile of the spectrograph; A. Collier Cameron et al. 2010), but we still would advise caution with the specific $v \sin i_*$ values derived from RM analyses.

Although it seems like the restrictive prior on the (inaccurate) $v \sin i_*$ helped constrain the polar orbit in V. Bourrier et al. (2023), their initial fit with uninformative priors still resulted in a polar orbit, albeit with looser constraints. Therefore, there could be other factors in play that led to that result. According to V. Bourrier et al. (2023), the WASP-156 CARMENES data suffer from strong telluric contamination. Out of three transits taken on different nights, two were discarded due to clear telluric contamination or spurious signals in the CCFs, and the night used in the RM analysis still showed residuals correlated with airmass, also probably due to tellurics. The wide posterior distribution obtained with the initial unconstrained fit to the CARMENES data means that there is a non-negligible probability that the orientation of the transit chord (constrained through λ and $v \sin i_*$, that is, the RM signature itself), was not constrained with those data. This would imply then that the signal at $\lambda \sim 100^\circ$, which the subsequent fit with the restrictive prior on $v \sin i_*$ makes more likely, could be a spurious signal from systematics in the data. The telescopes used here and in V. Bourrier et al. (2023) also have different collecting power, with CARMENES mounted on a 3.5 m telescope and ESPRESSO and MAROON-X in 8 m class telescopes. This led to observations with higher S/N and better time sampling for the new data presented here, which could also have an effect in explaining the different constraints in the derived orbit.

Recently, Z. Jiang et al. (2026) used the ESPRESSO data obtained on 2022 September 2 to measure the obliquity of the system using the classical RM method, obtaining $\lambda = -5^{+33}_{-35}^\circ$ and $v \sin i_* = 0.64^{+0.16}_{-0.33} \text{ km s}^{-1}$, which agree within 1σ with our results but are significantly less precise. Note that Z. Jiang et al. (2026) used CCF-derived RVs from the data reduced with DRS version 2.5.0 and adopted literature system parameters (from O. D. S. Demangeon et al. 2018), in particular, a smaller impact parameter b than the one we derived here, which can introduce a degeneracy between $v \sin i_*$ and λ , increasing uncertainties. To understand this difference, we repeated our RM analyses of the first ESPRESSO night using the same impact parameter as in Z. Jiang et al. (2026) and also using CCF-derived RVs. In particular, we applied the classical RM to (i) CCF-derived RVs using the same orbital parameters as in Z. Jiang et al. (2026), (ii) CCF-derived RVs using our newly derived parameters, and (iii) template-matching derived RVs with the Z. Jiang et al. (2026) parameters. For all cases we obtained an aligned orbit with λ uncertainties of $\pm 30^\circ$ for case (i), and $\pm 25^\circ$ for cases (ii) and (iii). Case (i) is the most similar to the analysis presented in Z. Jiang et al. (2026) and we obtained similar uncertainties. For the other

two cases, the uncertainty decrease is likely driven by the larger impact parameter of our new orbit (ii) and the better precision of the RVs derived with template-matching compared to those from the CCFs (iii). As a reminder, our original classical RM fit with the template-matching RVs and new orbital parameters yields an aligned orbit with $\pm 16^\circ$ uncertainties. For completeness, the reloaded RM analysis using the Z. Jiang et al. (2026) parameters also results in an uncertainty increase, $\pm 30^\circ$. We conclude that our results improved on the uncertainties due to the new orbital parameters (increased impact factor) and the better precision of the SERVAL RVs compared to the CCF ones.

Our analyses indicate that the projected obliquity of the planet is aligned rather than polar. However, the true three-dimensional obliquity ψ of the system could still be polar if the star has an inclination close to pole on. Currently, the stellar inclination of WASP-156 is unknown and challenging to constrain. The star has a non-detected rotation period and a relatively old age (e.g. ~ 5.6 Gyr; M. G. MacDougall et al. 2023), which could be consistent with a low equatorial rotational velocity, implying a stellar inclination close to edge on. However, the measured $v \sin i_*$ is so low, that even inclinations moderately close to pole on would still result in relatively low equatorial rotational velocities. Since the stellar inclination is unknown, to estimate the possible ψ of the system we simulated 10 000 random system configurations by sampling an isotropic distribution of stellar inclinations i_* (uniform $\cos i_*$ between 0 and 1), and Gaussian distributions based on our values of λ ($-15^{+17}_{-16}^\circ$ from the classical and $-8^{+16}_{-16}^\circ$ from the reloaded RM) and orbital inclination ($i_p = 88.1 \pm 0.3^\circ$), and compute ψ as $\cos \psi = \sin i_* \cos \lambda \sin i_p + \cos i_* \cos i_p$ (e.g. D. C. Fabrycky & J. N. Winn 2009). This results in a ψ distribution with median and 1σ uncertainties of $37^{+22}_{-18}^\circ$ and $34^{+23}_{-18}^\circ$ for the classical and reloaded RM λ values, respectively (see Fig. F1). Therefore, given a randomly distributed stellar inclination, it is unlikely that the true obliquity is polar.

6.2 Search for companions

In this section, we explore the potential presence of companions in the system, which is key information to understand the system's formation and evolution. High-resolution imaging observations of WASP-156 rule out stellar companions within ~ 25 to 500 au, down to companions ~ 3 –5 to 7 mag fainter than WASP-156. In particular, WASP-156 was observed with the Zorro speckle imaging instrument on Gemini South on 2020 November 28 (N. J. Scott et al. 2021), which performs simultaneous speckle imaging in two bands (centred at 562 and 832 nm) and provides contrast curves out to ~ 1 arcsec (S. B. Howell et al. 2011). Results for WASP-156 (as available on ExoFOP, PI: Howell, see Fig. G1) show that it does not have companions brighter than ~ 5 to 7 mag below that of WASP-156 from 0.2 arcsec (the diffraction limit) out to 1.2 arcsec (corresponding to a projected physical separation of ~ 25 and ~ 150 au at the distance¹⁰ of WASP-156). C. Dressing et al. (subm.) observed WASP-156 on 2019 July 21 using the ShARCS camera on the Shane 3-m telescope at Lick Observatory (R. Kupke et al. 2012; D. Gavel et al. 2014; R. McGurk et al. 2014), using the Shane adaptive optics system in natural guide star mode and a K_s filter ($\lambda_0 = 2.150 \mu\text{m}$, $\Delta\lambda = 0.320 \mu\text{m}$), and reduced the data using the publicly available SIMMER pipeline (A. B. Savel

et al. 2020).¹¹ The observations achieved a magnitude contrast of 3.2 at 0.5 arcsec, 5.0 at 1.0 arcsec, down to below 7 at 4 arcsec (corresponding to a projected physical separation between ~ 60 and ~ 500 au at the distance of WASP-156), finding no nearby stellar companions within their detection limits. On wider scales, WASP-156 is not listed in the wide binary catalogue of K. El-Badry, H.-W. Rix & T. M. Heintz (2021), which is based on *Gaia* Early DR3 proper motions and parallaxes (Gaia Collaboration 2021), indicating the absence of co-moving stellar companions out to separations of ~ 1 pc. The *Gaia* DR3 Renormalised Unit Weight Error (RUWE; Gaia Collaboration 2023) value of ~ 1.1 indicates a well-behaved single-star astrometric solution, with no evidence for significant perturbations from an unresolved companion. Altogether, all these constraints strongly support a single-star configuration for WASP-156.

In addition to stellar companions, we also searched for additional planetary companions in the system. The residuals of the fit presented in Section 4 do not show any significant periodic signals or long-term RV trends (Fig. 6), suggesting the absence of massive close-in or intermediate-separation planets. Following the approach of J. I. Espinoza-Retamal et al. (2024), we performed a population synthesis analysis to quantify the types of planetary companions that can be ruled out by our data. In brief, we generated a synthetic population of companions with masses between 0.01 and 50 M_J and semimajor axes between 0.01 and 100 au, assuming isotropic inclinations and eccentricities drawn from the distribution of D. M. Kipping (2013a), with random arguments of periastron. The RV signals induced by these synthetic companions were then compared to the observed RV residuals. By fitting the unknown instrumental offsets in Section 4, we could have potentially removed long-term trends due to companions from the data. Hence, here we only use the SOPHIE and CORALIE data, which span the longest baseline and overlap. Fig. 6 shows the regions of the mass versus semimajor axis plane that can be excluded at different confidence levels. With a baseline of 2.4 yr, our RV data rule out the presence of Jupiter-mass companions within ~ 5 au at the 5σ confidence level.

6.3 Possible formation mechanisms

The close-in, aligned, and nearly circular orbit of WASP-156 b ($e < 0.16$ at 3σ) can be naturally explained if the planet formed and evolved within a protoplanetary gas disc that was aligned with the stellar equator. In this scenario, both *in situ* formation (e.g. K. Batygin, P. H. Bodenheimer & G. P. Laughlin 2016; A. C. Boley, A. P. Granados Contreras & B. Gladman 2016) and inward migration driven by nebular tides (e.g. P. Goldreich & S. Tremaine 1980; D. N. C. Lin & J. Papaloizou 1986) provide viable pathways to produce a short-period, well-aligned Neptune.

However, protoplanetary discs aligned with the stellar spin are not necessarily expected, and several studies based on simulations and observational data show that primordial disc misalignments can be common (e.g. M. R. Bate, G. Lodato & J. E. Pringle 2010; D. Lai, F. Foucart & D. N. C. Lin 2011; I. Thies et al. 2011; D. B. Fielding et al. 2015; M. R. Bate 2018; S. A. Hurt & M. A. MacGregor 2023; L. I. Biddle et al. 2025). On the other hand, young exoplanets have been found to be mostly aligned (e.g. T. Hirano et al. 2020, 2024; E. Martioli et al. 2020; B. T. Montet et al. 2020; E. Palle et al. 2020; A. Heitzmann et al. 2021; C. P. Wirth

¹⁰ ~ 122 pc from *Gaia* DR3.

¹¹ <https://github.com/arjunsavel/SIMMER>

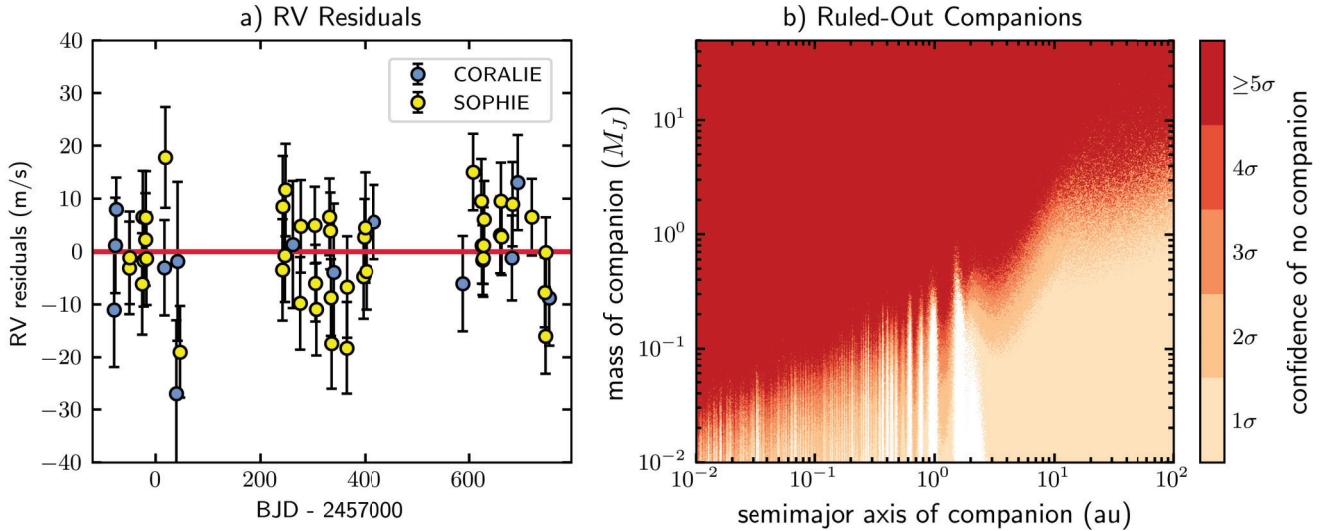


Figure 6. (a) RV residuals from the JULIET fit as a function of time. Different colours represent different instruments used to observe the star. No signals of additional companions are identified. (b) Mass versus semimajor axis diagram of companions that can be ruled out thanks to the lack of additional signals in the RV residuals. Different colours represent different confidence levels. Based on the 2.4 yr of RV observations, we can rule out Jupiter-mass companions to WASP-156 within 5 au at a 5σ confidence.

et al. 2021; M. C. Johnson et al. 2022; K. Franson et al. 2023; T. Gan et al. 2024), and most compact multiplanet systems, thought to preserve primordial alignments and migrate inwards via disc migration, have also been found in aligned configurations (e.g. D. R. Anderson et al. 2015; R. Sanchis-Ojeda et al. 2015; X.-Y. Wang et al. 2022; E. Knudstrup et al. 2024; J. Zak et al. 2024; B. T. Radzom et al. 2025). Despite that, the sample of known young exoplanets and compact systems is still small and exceptions to the commonly observed alignment exist (e.g. D. Huber et al. 2013; S. Dalal et al. 2019; H. Yu et al. 2025).

The apparent contradiction between these two results regarding formation can be resolved if primordial misalignments between the star and disc mainly impact the outer disc regions, while the inner parts of the disc, where planets form, remain aligned (e.g. S. Marino, S. Perez & S. Casassus 2015; M. Ansdell et al. 2016; S. Casassus et al. 2018; L. Francis & N. van der Marel 2020). If WASP-156 b formed in an inner disc region that remained aligned with the stellar spin, its current aligned and circular orbit follows naturally from disc-driven evolution.

High-eccentricity tidal migration offers, in principle, an alternative route to produce a short-period, circular orbit. In this framework, the planet is initially placed on a highly eccentric orbit by dynamical interactions (e.g. D. Fabrycky & S. Tremaine 2007; S. Naoz et al. 2011; C. Beaugé & D. Nesvorný 2012; C. Petrovich 2015), and subsequently circularizes through tidal dissipation. Following P. Goldreich & S. Soter (1966) and P. Hut (1981), we estimate an orbital circularization time-scale of ~ 0.1 – 10 Gyr, assuming a modified planetary tidal quality factor (e.g. G. I. Ogilvie & D. N. C. Lin 2007) of $Q'_p = 10^4$ – 10^6 . Given the estimated system age of ~ 5.6 Gyr (M. G. MacDougall et al. 2023), this implies that tidal circularization from a highly eccentric orbit is, in principle, feasible and depends on the exact value of the tidal quality factor.

However, the absence of detected long-period companions capable of exciting such extreme eccentricities makes this sce-

nario dynamically unlikely. Moreover, high-eccentricity migration pathways are generally associated with the production of misaligned orbits, in contrast with the observed alignment of WASP-156 b. Following S. Albrecht et al. (2012), we estimate a tidal realignment time-scale of $\sim 3 \times 10^4$ Gyr, far exceeding the age of the Universe. This is expected for a relatively low-mass planet that does not raise significant tides on its host star, and strongly suggests that the system did not undergo a phase of large spin-orbit misalignment. Typical high-eccentricity migration mechanisms are therefore disfavoured. The system could, however, remain consistent with coplanar high-eccentricity migration (C. Petrovich 2015), which preserves spin-orbit alignment throughout the dynamical evolution. This mechanism will require the existence of a massive Jupiter companion on an eccentric and aligned orbit at more than ~ 5 au to be consistent with the constraints from long-term RV observations we derived here.

Another potential indicator of high-eccentricity migration is a large difference between a star's isochronal and gyrochronological ages. For WASP-156, O. D. S. Demangeon et al. (2018) derived an isochronal age of 6.50 ± 4.03 Gyr and a much younger gyrochronological age of $0.58^{+0.51}_{-0.31}$ Gyr using the relation from S. A. Barnes (2007). As mentioned above, recent work by M. G. MacDougall et al. (2023) also obtained a relatively old isochronal age of $5.6^{+3.9}_{-3.2}$ Gyr. The gyrochronological age was derived by assuming a stellar rotation period of $\simeq 12.6$ d, computed from the reported $v \sin i_*$ $\simeq 3.8$ km s $^{-1}$ (using the stellar radius and assuming edge-on stellar inclination). A gyrochronological age shorter than an isochronal age can be explained by transfer of angular momentum from the planet to the star during tidal circularisation occurring due to high-eccentricity migration. Hence, O. D. S. Demangeon et al. (2018) proposed that a gyrochronological age younger than an isochronal age is a potential signature of high-eccentricity migration. This age discrepancy would also support the existence of a polar orbit induced by high-eccentricity migration (V. Bourrier et al. 2023). Here, however, we estimated

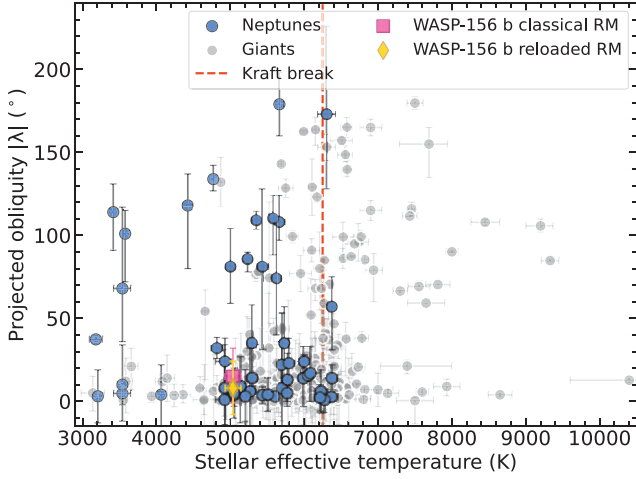


Figure 7. Neptune and giant planets with known projected obliquity λ with and uncertainty better than 50° from the TEPcat catalogue (note that we have removed the previously measured polar obliquity for WASP-156 b) as a function of stellar effective temperature. Blue circles correspond to Neptunes ($2 \leq R_p \leq 8 R_\oplus$ and/or $10 \leq M_p \leq 50 M_\oplus$), grey circles show giant planets ($R_p > 8 R_\oplus$ and/or $M_p > 50 M_\oplus$), and the pink square and yellow diamond show the new obliquity measured for WASP-156 b, from the classical and reloaded RM analyses, respectively. The red vertical dashed line shows the Kraft break at ~ 6250 K (R. P. Kraft 1967).

the $v \sin i_*$ of the star to be much lower, $\leq 2 \text{ km s}^{-1}$ from our stellar characterization with PAWS, and $\simeq 0.4 \text{ km s}^{-1}$ from our RM analyses. These lower $v \sin i_*$ values result in slower rotation periods of $\gtrsim 24$ and $\simeq 120$ d, which, also following S. A. Barnes (2007), correspond to a gyrochronological age of approximately 2 Gyr and an age longer than that of the Universe, respectively. These values are now more in line with the isochronal age, and there is no need for a transfer of angular momentum to increase the stellar rotation. This picture is now compatible with disc migration or in situ formation, and also aligns well with our new obliquity measurement.

6.4 WASP-156 in context

6.4.1 Obliquity bi-modality?

S. H. Albrecht et al. (2021) suggested the existence of a bimodality in the three-dimensional obliquity distribution (ψ) in a sample of 57 systems, including some Neptunes, with a preference for aligned and polar orbits (see e.g. Fig. 7, although note that we show the distribution of projected obliquities λ rather than the three-dimensional obliquity ψ). However, there is still a debate on whether this dichotomy is real or not. For example, V. Bourrier et al. (2023) also found a large fraction of polar planets, while J. Dong & D. Foreman-Mackey (2023), J. Siegel, J. Winn & S. Albrecht (2023), and A. M. Rossi et al. (2026) did not find strong evidence for a general clustering at $\sim 90^\circ$. High obliquities, especially for giant planets, have also been linked to stellar hosts with effective temperatures above the Kraft break ($T_{\text{eff}} \sim 6250$ K; R. P. Kraft 1967), see Fig. 7, with thin or negligible outer convective zones unable to realign misaligned planets (e.g. J. N. Winn et al. 2010a; S. Albrecht et al. 2012; A. H. M. J. Triaud 2018; L. Mancini et al. 2022; A. M. Rossi et al. 2026). Note that the exact value of the Kraft break has a dependency on metallicity (e.g. L. Amard & S. P.

Matt 2020; L. Amard, J. Roquette & S. P. Matt 2020; C. Spalding & J. N. Winn 2022).

Recently, J. I. Espinoza-Retamal et al. (2024), E. Knudstrup et al. (2024), and A. M. Rossi et al. (2026) showed that the preference for polar orbits is particularly strong among Neptunes, although, given the limited number of measurements, these results are only tentative. Note that J. I. Espinoza-Retamal et al. (2024) and E. Knudstrup et al. (2024) included WASP-156 b among the polar Neptunes. When considering a larger sample of Neptunes and using our updated stellar obliquity measurement for WASP-156, J. I. Espinoza-Retamal et al. (2026) found no significant evidence for a preference for polar orbits, although still with large uncertainties due to the small sample size. More stellar obliquity measurements would be necessary to continue testing the preference for polar orbits. Also, compared to giant planets, there is not a large number of Neptunes with a measured obliquity around hot ($T_{\text{eff}} \gtrsim 6250$ K) stars (see e.g. Fig. 7). A larger sample of Neptunes around hot stars can be proven with studies that estimate the obliquity distribution of transiting planets from $v \sin i_*$ measurements. Such studies suggest that small planets around cool stars tend to have higher obliquities than small planets around cooler stars, similar to the trend initially observed for giant planets (T. Mazeh et al. 2015; J. N. Winn et al. 2017; E. M. Louden et al. 2021, 2024). However, E. M. Louden et al. (2024) show a potential dependency of this result on orbital period, with planets with $P < 10$ d being in general more aligned, and planets with $P > 10$ d showing more differences between planets around hot and cool stars, resulting in a wider obliquity distribution.

Our new obliquity measurement of WASP-156 b moves the planet from the tentative cluster of polar obliquities to the more abundant group of planets with aligned orbits (see Fig. 7). The host WASP-156 is a relatively cool star ($T_{\text{eff}} = 5036 \pm 104$), and the aligned obliquity we measure here for WASP-156 b seems to follow the tentative trend that planets tend to be more aligned for cool stars, potentially for orbital periods < 10 d (E. M. Louden et al. 2024). However, the sample of Neptunes with measured obliquities in this regime of the parameter space ($P < 10$ d and $T_{\text{eff}} < 6250$ K) only reaches 24 to date (16 with obliquity uncertainties better than 20°), which is not large enough to draw population-level conclusions, and more results are needed to confirm any trends.

6.4.2 Short-period Neptunian landscape

Recently, A. Castro-González et al. (2024b) highlighted that the Neptunian savanna tends to have low-density planets ($\rho \sim 0.5 \text{ g cm}^{-3}$) while ridge planets tend to be high-density ($\rho \sim 1.5\text{--}2.0 \text{ g cm}^{-3}$), suggesting different evolutionary processes for the planets in the two regimes, divided by a density of $\rho \sim 1.0 \text{ g cm}^{-3}$ (note that this trend holds for planets with radii $R_p \sim 4.5\text{--}8.0 R_\oplus$, but not for smaller Neptunes). Expanding on this idea, V. Bourrier et al. (2025) proposed a unified view to explain the close-in Neptunian landscape integrating migration mechanisms, photoevaporation, and planetary densities. The authors propose that disc-driven migration primarily affects low-density Neptunes, which migrate inwards early-on, preserving their primordial obliquities and circular orbits. Those low-density Neptunes in the desert and ridge would be fully eroded due to the high irradiation from their stellar hosts, and only those in the savanna, further away from the star, would survive. This should result in an observable

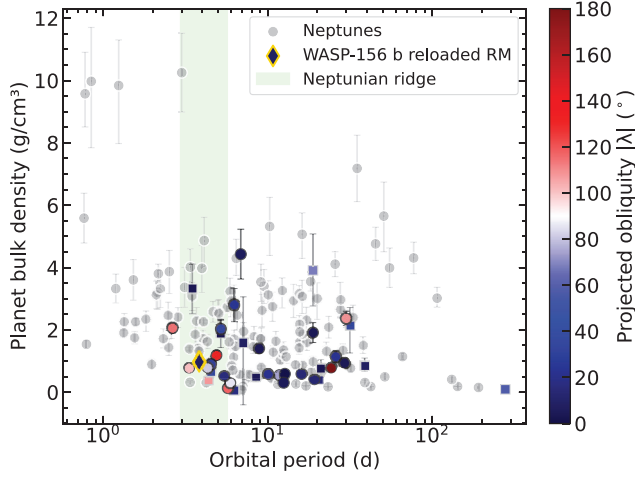


Figure 8. Planet bulk density as a function of orbital period for Neptunes ($2 \leq R_p \leq 8 R_\oplus$ and/or $10 \leq M_p \leq 50 M_\oplus$) from the TEPcat catalogue. Grey circles show planets without known projected obliquity and relative uncertainty in mass, radius, and density ≤ 20 per cent. Planets with known projected obliquity λ with uncertainty better than 50° are colour-coded as a function of λ , with circles representing planets with relative uncertainty in mass, radius, and density ≤ 20 per cent, and squares, the rest of planets in the catalogue. WASP-156 b is represented as a diamond with yellow outline colour-coded with the reloaded RM λ value we measure here. We also show the approximate region of the Neptunian ridge as a shaded green region (from 2.95 to 5.7 d, following A. Castro-González et al. 2024a, noting that the ridge is a feature specific to the Neptunian population with radii $R_p \sim 4.5 - 8.0 R_\oplus$, while this plot additionally shows smaller Neptunes).

density ‘brink’ along the ridge, with densities decreasing with increasing period (see e.g. the lower envelope in Fig. 8). On the other hand, high eccentricity migration, acting during a wide range of ages, would mainly affect high-density planets, bringing them preferentially to the desert or ridge, potentially in eccentric and misaligned orbits. Hence, only high-density planets and/or late migrators would survive within the desert.

The sample of Neptunes with obliquities is still small but, as can be seen in Fig. 9, most Neptunes in the savanna tend to have aligned orbits (with few exceptions), while planets in the ridge seem to show a wider diversity of obliquities, including several polar cases. There is not a large number of desert planets with measured obliquities.

WASP-156 b is a ridge planet that has a density of $\rho \simeq 1 \text{ g cm}^{-3}$, which places it at the boundary between low- and high-density planets in the picture proposed by V. Bourrier et al. (2025). It sits close to the proposed density brink (Fig. 8), suggesting that it is sufficiently dense to have survived photoevaporation if it migrated early-on via disc-driven migration. This picture is also consistent with the low eccentricity and obliquity we measure here.

Photoevaporation is thought to play a key role in shaping the close-in Neptunian planet population (e.g. T. A. Davis & P. J. Wheatley 2009; J. E. Owen & Y. Wu 2013; J. E. Owen & D. Lai 2018). X-ray and UV radiation from the host star can result in an expansion of the planetary atmospheres and a subsequent atmospheric escape, with the effect being strongest during the star’s early, more active phase. The number of atmospheric escape studies on Neptunes is still limited; hence, it is still unclear when photoevaporation occurs and if it affects Neptunes with

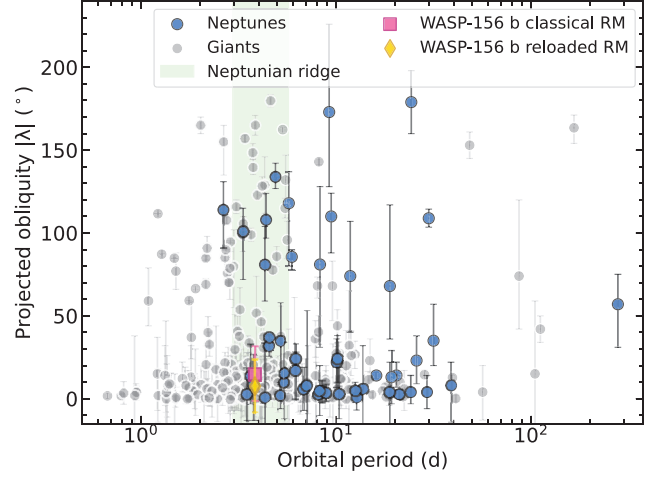


Figure 9. Neptune and giant planets with known projected obliquity λ with and uncertainty better than 50° from the TEPcat catalogue (note that we have removed the previously measured polar obliquity for WASP-156 b) as a function of orbital period. Blue circles correspond to Neptunes ($2 \leq R_p \leq 8 R_\oplus$ and/or $10 \leq M_p \leq 50 M_\oplus$), grey circles show giant planets ($R_p > 8 R_\oplus$ and/or $M_p > 50 M_\oplus$), and the pink square and yellow diamond show the new obliquity measured for WASP-156 b, from the classical and reloaded RM analyses, respectively. We also show the approximate region of the Neptunian ridge as a shaded green region (from 2.95 to 5.7 d, following A. Castro-González et al. 2024a, noting that the ridge is a feature specific to the Neptunian population with radii $R_p \sim 4.5 - 8.0 R_\oplus$, while this plot contains smaller Neptunes and giant planets).

specific orbital distances, densities, and/or obliquities. So far, only Neptunes within or very close to the ridge have shown clear signs of photoevaporation (escaping neutral H detected in the Lyman- α line or neutral He detected in the metastable 1083 nm triplet)¹² and all are in polar orbits: GJ 436 b (D. Ehrenreich et al. 2015; V. Bourrier et al. 2022), GJ 3470 b (V. Bourrier et al. 2018; G. Stefansson et al. 2022), and HAT-P-11 b (J. N. Winn et al. 2010b; R. Sanchis-Ojeda & J. N. Winn 2011; R. Allart et al. 2018; V. Bourrier et al. 2023). For the Neptune HAT-P-26 b, also within the ridge and in a polar orbit (X. Luo et al. 2026), current data suggest contradictory results regarding its atmospheric mass-loss (S. Vissapragada et al. 2022; J. Orell-Miquel et al. 2026), and TOI-942 c, an aligned Neptune in the savanna, shows tentative signs of photoevaporation (H.-Y. Teng et al. 2024).

For WASP-156 b, C. Jiang et al. (2023) report a lack of atmospheric features from one transit observed in the optical, long-slit spectroscopic mode of the Optical System for Imaging and low Resolution Integrated Spectroscopy on the 10 m Gran Telescopio Canarias (GTC OSIRIS, $R \sim 1000$; J. Cepa et al. 2000). The observations are reported to be affected by strong instrument systematics, which reduce the S/N of the transmission spectra, leading to a non-detection. J. Orell-Miquel et al. (2026) do not detect escaping He in two transits observed in the near-infrared with the Habitable-zone Planet Finder (HPF, $R = 55000$; S. Mahadevan et al. 2012, 2014) on the 10 m Hobby–Eberly Telescope (L. W. Ramsey et al. 1998; M. Shetrone et al. 2007). They place a 3σ upper limit to the expected absorption of 0.9 per cent. Z. Jiang et al. (2026) looked for absorption signals of several species on the ESPRESSO data obtained on 2022 September 2 using both the

¹²<https://research.iac.es/proyecto/exoatmospheres/table.php>

transmission spectrum directly and the cross-correlation function. The authors also find a featureless transmission spectrum. Future observations of the atmosphere of WASP-156 b could help determine whether or not the planet is affected by photoevaporation.

7 CONCLUSION

We analysed new spectroscopic transit observations of the Neptunian ridge planet WASP-156 b obtained with ESPRESSO and MAROON-X to measure its projected stellar obliquity λ using the RM effect. Contrary to a previous estimate that suggested a polar orbit from CARMENES data, we found that the planet has a λ consistent with being aligned. Our best λ estimates are obtained using the two ESPRESSO transits with a classical and a reloaded RM analyses, for which we measure $\lambda = -15^{+17}_{-16}^\circ$ and $\lambda = -8^{+16}_{-16}^\circ$, respectively. Both results are consistent with each other within 1σ and are not consistent with a polar orbit.

The CARMENES observations that led to the polar orbit estimate were modelled with an informative prior on an inaccurate $v \sin i_*$ estimate of $3.8 \pm 0.9 \text{ km s}^{-1}$ (O. D. S. Demangeon et al. 2018). Here, we derived new stellar parameters from our ESPRESSO observations, showing that the star appears as a very slow rotator with $v \sin i_* \leq 2 \text{ km s}^{-1}$. Our modelling of the RM effect, both using the classical and the reloaded methods, also suggests a low $v \sin i_*$ value, of $v \sin i_* = 0.44 \pm 0.08 \text{ km s}^{-1}$ from the classical RM analysis and $v \sin i_* = 0.40 \pm 0.11 \text{ km s}^{-1}$ from the reloaded RM one. Together with telluric contamination and low-S/N in the CARMENES data, the inaccurate $v \sin i_*$ could be partly responsible for the polar obliquity measurement, since the RM effect can show degeneracies between λ and $v \sin i_*$. It is also possible that the CARMENES data did not have enough information to constrain the true RM signal, and that the polar orbit was due to systematics in the data. Our work highlights the importance of well-constrained stellar parameters in RM analyses.

We also re-analysed all *TESS* transits, two new NGTS transits, and archival out-of-transit RVs to derive updated orbital parameters for the WASP-156 system. To explore potential formation scenarios, we performed a population synthesis analysis to study the presence of planetary and brown dwarf companions in the residual RVs. We find that this allows us to rule out Jupiter-mass companions within $\sim 5 \text{ au}$ in this system. High-resolution imaging observations also rule out the presence of stellar companions within $\sim 500 \text{ au}$.

The observed close-in, nearly circular, and aligned orbit of WASP-156 b is consistent with early-on disc-driven migration. High-eccentricity migration mechanisms require a companion capable of exciting a strong eccentricity and might lead to a misaligned obliquity. The tidal realignment timescale necessary to re-align the planet into its present-day aligned orbit exceeds the age of the Universe. Therefore, the lack of nearby companions and the observed aligned orbit make high-eccentricity migration unlikely. Co-planar high-eccentricity migration, which preserves the obliquity, could still be possible if an eccentric, aligned massive Jupiter companion exists at more than $\sim 10 \text{ au}$.

Several works have suggested a tentative bi-modality in the obliquity distribution consistent in planets aligned or in polar orbits. With our new results, WASP-156 b moves from the tentative cluster of polar obliquities to the abundant group of planets with aligned orbits. Regarding the short-period Neptunian landscape, recent works propose three different regimes:

a desert of short period planets, a higher density of planets in a savanna at longer periods, and an overabundance of planets in a ridge in between. This variety in the population suggests different formation and evolution mechanisms, with potential observables in the density and obliquity distribution of the planets. WASP-156 b sits in the middle of the ridge, which shows a large diversity of obliquities and a tentative trend of decreasing density with increasing period, a potential sign of photoevaporation. Our work suggests that WASP-156 b arrived at its current position via disc-driven migration and survived photoevaporation. The number of Neptunian planets with known obliquities is still small, however, programmes such as Ancestry, Traits, and Relations of Exoplanets Inhabiting the Desert Edges and Savanna (ATREIDES; V. Bourrier et al. 2025) or POSEIDON (J. I. Espinoza-Retamal et al. 2026) are currently working towards increasing the sample and understanding the formation and migration pathways of the population of short-period Neptunes.

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DATA AVAILABILITY

The HARPS and ESPRESSO data used in this work are publicly available in the ESO archive under programmes 0102.C-0618(A) and 109.23FU. The MAROON-X data used in this work are publicly available in the Gemini archive under programme GN-2021B-Q-218. The reduced NGTS data used here are provided as online material. Raw NGTS data are available upon request to the authors and will be made available on the ESO archive on a future general release by NGTS. The *TESS* data used in this work are

publicly available in MAST. The Zorro data used in this work are available in ExoFOP. The ASAS-SN data used here are available online in the ASAS-SN archive. The HATPI data used here are available online in the HATPI archive.

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SUPPORTING INFORMATION

Supplementary data are available at [MNRAS](#) online.

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APPENDIX A: OBSERVATIONAL PARAMETERS

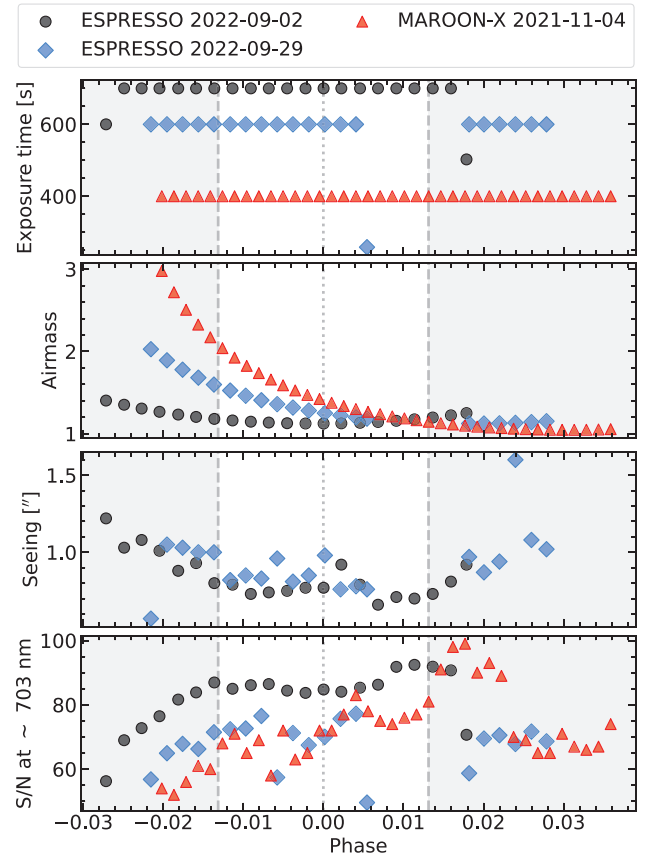


Figure A1. From top to bottom: exposure time, airmass, seeing, and S/N for the ESPRESSO (first night in black circles, second night in blue diamonds) and MAROON-X (red triangles) observations as a function of the planet orbital phase. The seeing corresponds to the delivered seeing corrected by airmass. We show the median S/N of order 87 (central wavelength ~ 703 nm), which is one of the orders with highest S/N for both spectrographs for WASP-156. Note that the S/N values shown are the sum in quadrature of the individual S/N values of each of the different slices (fibres) of order 87 (two for ESPRESSO and three for MAROON-X). Grey areas indicate out-of-transit phases, dashed lines indicate the transit start (T_1) and end (T_4), and dotted lines indicate mid-transit time (T_0).

APPENDIX B: STELLAR ROTATION PERIOD ANALYSIS

We used archival WASP-156 data from ASAS-SN and HATPI to look for signals related to the stellar rotation. We used the Sky Patrol portal to recompute ASAS-SN light curves. The data consist of 1035 observations in the *V* band taken between 2012 January 15 and 2018 November 28, and 3604 observations in the *g'* band taken between 2017 September 17 and 2026 March 2. We used the aperture photometry flux. We discarded observations with large uncertainties in the flux (> 2 mJy, note that most of the observations had flux uncertainties well below 1 mJy, with a median of ~ 0.4 mJy) and afterwards performed an iterative 3σ clipping two times. This process decreased the number of observations to 981 and 3336 for the *V* and *g'* band data sets, respectively. Finally, we detrended the light curves with a two-degree polynomial fit. We then computed the generalized Lomb–Scargle (LS) periodogram (M. Zechmeister & M. Kürster 2009) of the data of each band both

before and after detrending. Our frequency grid spanned from 1.01 d (to avoid strong 1 d signals) up to 1500 d (about half the span of the *g'* band data set). The cleaned data and corresponding periodograms can be seen in Fig. B1.

Similarly, we also looked for periodicities in HATPI data. WASP-156 was observed by HATPI in two different seasons, between 2023 June 12 and 2024 February 3 (14711 observations), and between 2024 June 12 and 2025 February 3 (23 995 observations). We used the aperture photometry flux, extracted using 1.95 pixels (index 0), following the recommendation of the HATPI data base given the brightness of our target. The HATPI data are detrended via external parameter decorrelation (EPD, using e.g. airmass or image position), and further using a trend-filtering algorithm (TFA, which removes common systematics, applied after EPD). We looked for periodicities in both detrended data sets, using a frequency grid from 1.01 to 300 d (again about half the time span of the data set). The EPD and TFA data, and their corresponding periodograms, can be seen in Fig. B2.

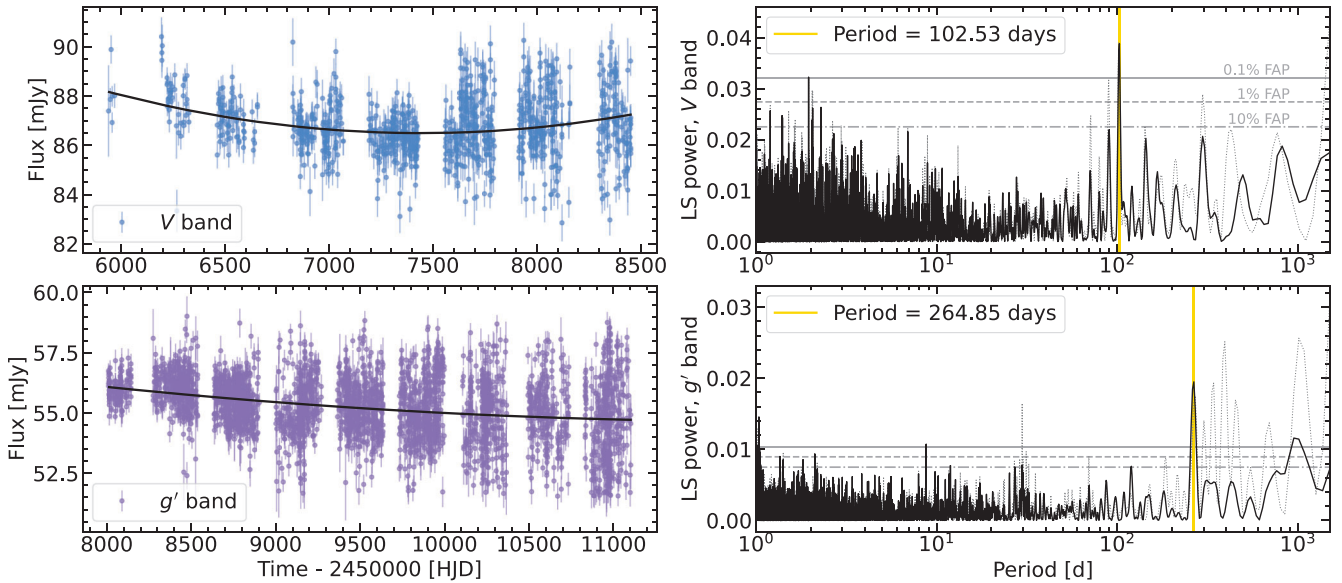


Figure B1. ASAS-SN WASP-156 data. Left: Observations in the *V* (top) and *g'* (bottom) bands (circles), with the two-degree polynomial fit as the solid black line. Right: Generalized LS of the *V* (top) and *g'* (bottom) band data sets, where the solid black line corresponds to the LS computed after detrending the data by the polynomial, the dotted grey line shows the LS before detrending, and the solid, dashed, and dash-dotted horizontal grey lines show the false alarm probability (FAP) levels for 0.1, 1, and 10 per cent FAP. The solid yellow vertical lines show the highest peak of the detrended periodogram.

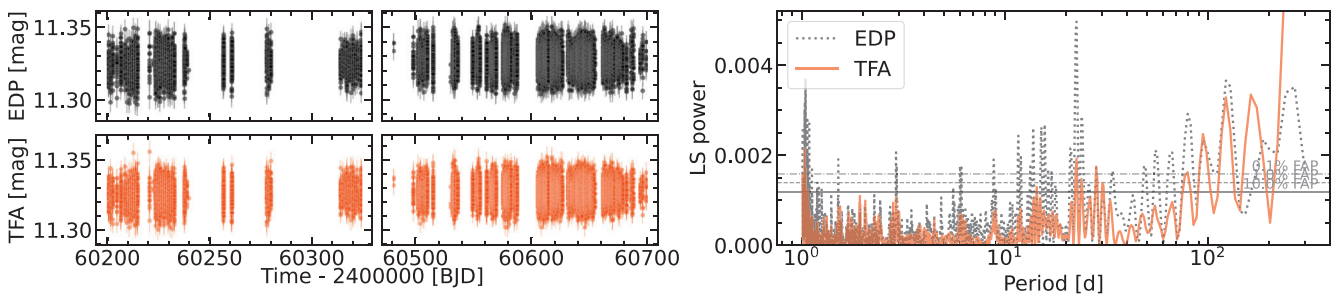


Figure B2. HATPI WASP-156 data. Left: The two epochs of data, EPD-detrended (top, black circles) and TFA-detrended (bottom, orange circles). Right: Generalized LS of the EPD and TFA data (dotted black line and solid orange line, respectively). The solid, dashed, and dash-dotted horizontal grey lines show the power corresponding to 0.1, 1, and 10 per cent FAP.

Table C1. Summary statistics of the additional posteriors of the JULIET fit, in addition to those presented in Table 3.

Sampled parameter	Posterior
γ_{CORALIE} (m s ⁻¹)	9630.5 ± 2.5
σ_{CORALIE} (m s ⁻¹)	0.1 ^{+1.6} _{-0.1}
γ_{SOPHIE} (m s ⁻¹)	9589 ± 1
σ_{SOPHIE} (m s ⁻¹)	5.2 ± 1.4
γ_{HARPS} (m s ⁻¹)	9650 ± 2
σ_{HARPS} (m s ⁻¹)	6.4 ^{+2.3} _{-1.5}
γ_{HIRES} (m s ⁻¹)	0.8 ± 0.8
σ_{HIRES} (m s ⁻¹)	3.0 ^{+0.8} _{-0.6}
σ_{TESS} (ppm)	1.4 ^{+8.5} _{-1.2}
$m_{\text{flux,TESS}}$	0.002 ± 0.004
$\text{GP}_{\sigma,\text{TESS}}$ (ppm)	0.0105 ^{+0.0008} _{-0.0004}
$\text{GP}_{\rho,\text{TESS}}$ (d)	14.4 ^{+1.2} _{-1.0}
σ_{NGTS11} (ppm)	0.02 ^{+17.15} _{-0.02}
$m_{\text{flux,NGTS11}}$	0.007 ± 0.002
$\theta_{0,\text{NGTS11}}$	0.0071 ± 0.0015
σ_{NGTS12} (ppm)	0.02 ^{+19.84} _{-0.02}
$m_{\text{flux,NGTS12}}$	0.006 ± 0.002
$\theta_{0,\text{NGTS12}}$	0.007 ± 0.0015
σ_{NGTS13} (ppm)	0.03 ^{+20.77} _{-0.03}
$m_{\text{flux,NGTS13}}$	-0.0003 ± 0.0018
$\theta_{0,\text{NGTS13}}$	0.001 ± 0.001
σ_{NGTS14} (ppm)	0.02 ^{+18.14} _{-0.02}
$m_{\text{flux,NGTS14}}$	-0.002 ± 0.002
$\theta_{0,\text{NGTS14}}$	0.0003 ± 0.0015
σ_{NGTS21} (ppm)	0.01 ^{+11.44} _{-0.01}
$m_{\text{flux,NGTS21}}$	-0.001 ± 0.001
$\theta_{0,\text{NGTS21}}$	0.001 ± 0.001
σ_{NGTS22} (ppm)	0.03 ^{+18.61} _{-0.03}
$m_{\text{flux,NGTS22}}$	-0.001 ± 0.001
$\theta_{0,\text{NGTS22}}$	0.001 ± 0.001
σ_{NGTS23} (ppm)	0.02 ^{+14.85} _{-0.02}
$m_{\text{flux,NGTS23}}$	0.003 ± 0.001
$\theta_{0,\text{NGTS23}}$	0.004 ± 0.001
σ_{NGTS24} (ppm)	0.02 ^{+14.24} _{-0.02}
$m_{\text{flux,NGTS24}}$	0.004 ± 0.001
$\theta_{0,\text{NGTS24}}$	0.005 ± 0.001
σ_{NGTS25} (ppm)	0.02 ^{+14.06} _{-0.02}
$m_{\text{flux,NGTS25}}$	0.003 ± 0.001
$\theta_{0,\text{NGTS25}}$	0.004 ± 0.001

Note. For the RV instruments, γ_{inst} is an independent RV offset, and σ_{inst} is the jitter term. For *TESS*, σ_{TESS} is a jitter term added in quadrature to the nominal flux uncertainties, $m_{\text{flux,TESS}}$ is the mean instrumental offset of the out-of-transit flux, $\text{GP}_{\sigma,\text{TESS}}$ is the amplitude of the GP, and $\text{GP}_{\rho,\text{TESS}}$ is the length-scale of the GP. For the NGTS parameters, the first number in the subscript represents the night of observations (1 for 2022 September 2 and 2 for 2022 September 29), and the second number is an arbitrary number for each of the different cameras. Similarly to the *TESS* parameters, σ_{NGTSij} is a jitter term, $m_{\text{flux,NGTSij}}$ is the out-of-transit flux offset, and $\theta_{0,\text{NGTSij}}$ is the linear coefficient for the airmass detrending.

The ASAS-SN data (both before and after detrending) show several significant peaks at long periods. However, there is no common periodicity between the *V* and the *g* band data. The HATPI data (both with the EDP and with the TFA detrending) also show significant peaks close to ~ 20 d and at longer periods, but none coincide with the peaks observed in the ASAS-SN periodograms. We conclude that we cannot derive a clear estimate for the stellar rotation period from these data.

APPENDIX C: ADDITIONAL PARAMETERS FROM THE JULIET FIT

APPENDIX D: CLASSICAL RM ADDITIONAL FIGURES

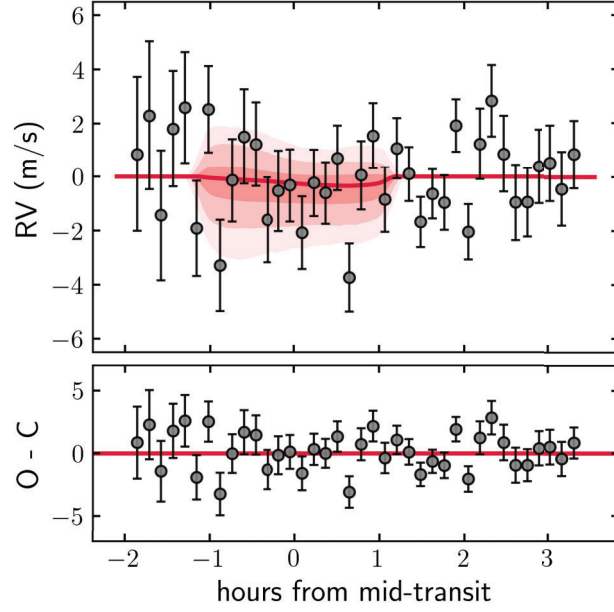


Figure D1. MAROON-X SERVAL disc-integrated RVs (grey circles, after subtracting the Keplerian motion induced by the planet) and best-fitting classical RM model (red line, with 1σ , 2σ , and 3σ intervals shown as the shaded regions).

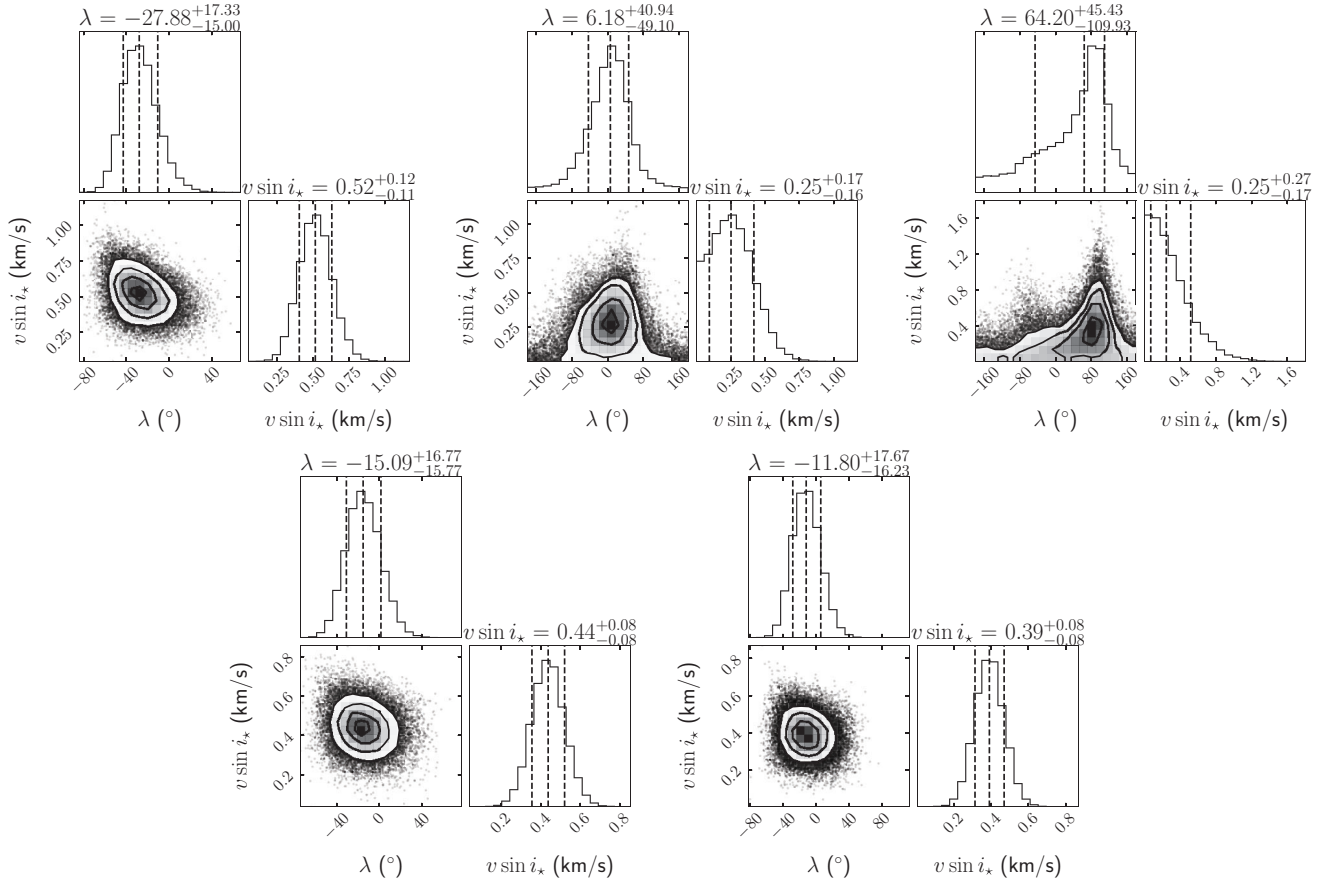


Figure D2. Corner plot with the posteriors for the obliquity λ and rotational velocity $v \sin i_*$ from the classical RM analysis of the first ESPRESSO night (top left), the second ESPRESSO night (top centre), the MAROON-X night (top right), both ESPRESSO transits (bottom left), and all three transits together (bottom right). We adopt the values from the fit to both ESPRESSO transits (bottom left).

APPENDIX E: RELOADED RM ADDITIONAL TABLE AND FIGURES

In addition to the SB models presented in Section 5.3.2, we also considered more complex models that include, together with the SB rotation, centre-to-limb convective variations (CLV). The CLVs are modelled with a first or second order polynomial radially symmetric from the stellar disc centre, where c_1 and c_2 are the first and second order coefficients, respectively. Again, for more details about the models, we refer the reader to H. M. Cegla et al. (2016).

For these SB + CLV models we used the same MCMC method to fit the data as described in Section 5.3.2. We used uninformative priors (i.e. unconstrained) for c_1 and c_2 with initial values for our walkers of c_1 and $c_2 = 0 \text{ km s}^{-1}$. Different initial values for these parameters do not affect the final results of the fit.

For each set of observations (individual transits, both ESPRESSO transits, and all three transits together) we fit an SB rotation in conjunction with a linear CLV, and SB rotation with quadratic CLV. Note that we also preliminarily considered

more complex models that account for differential rotation, but discarded them due to our data not being sufficiently precise to see such effects. As done for the SB model, we also considered a reduced set of observations with $\langle \mu \rangle < 0.3$. We also found that the results obtained from this reduced data set agree well within 1σ with those using the full data set, and hence do not consider them further.

We assessed the goodness of fit with the reduced chi-squared statistic (χ^2_{red}) and the Bayesian information criterion (BIC). We note that the BIC values can only be compared for models fitted to the same data set. Our full results for the SB and CLV models are shown in Table E1.

The SB + CLV models, which are more complex than the SB model, tend to overfit the data ($\chi^2_{\text{red}} < 1$) and/or do not show a significant enough difference compared to the simpler SB models (the difference in BIC is less than $\simeq 6$, which is the minimum difference for a model to be considered a better fit; A. E. Raftery 1995; J. Lorah & A. Womack 2019).

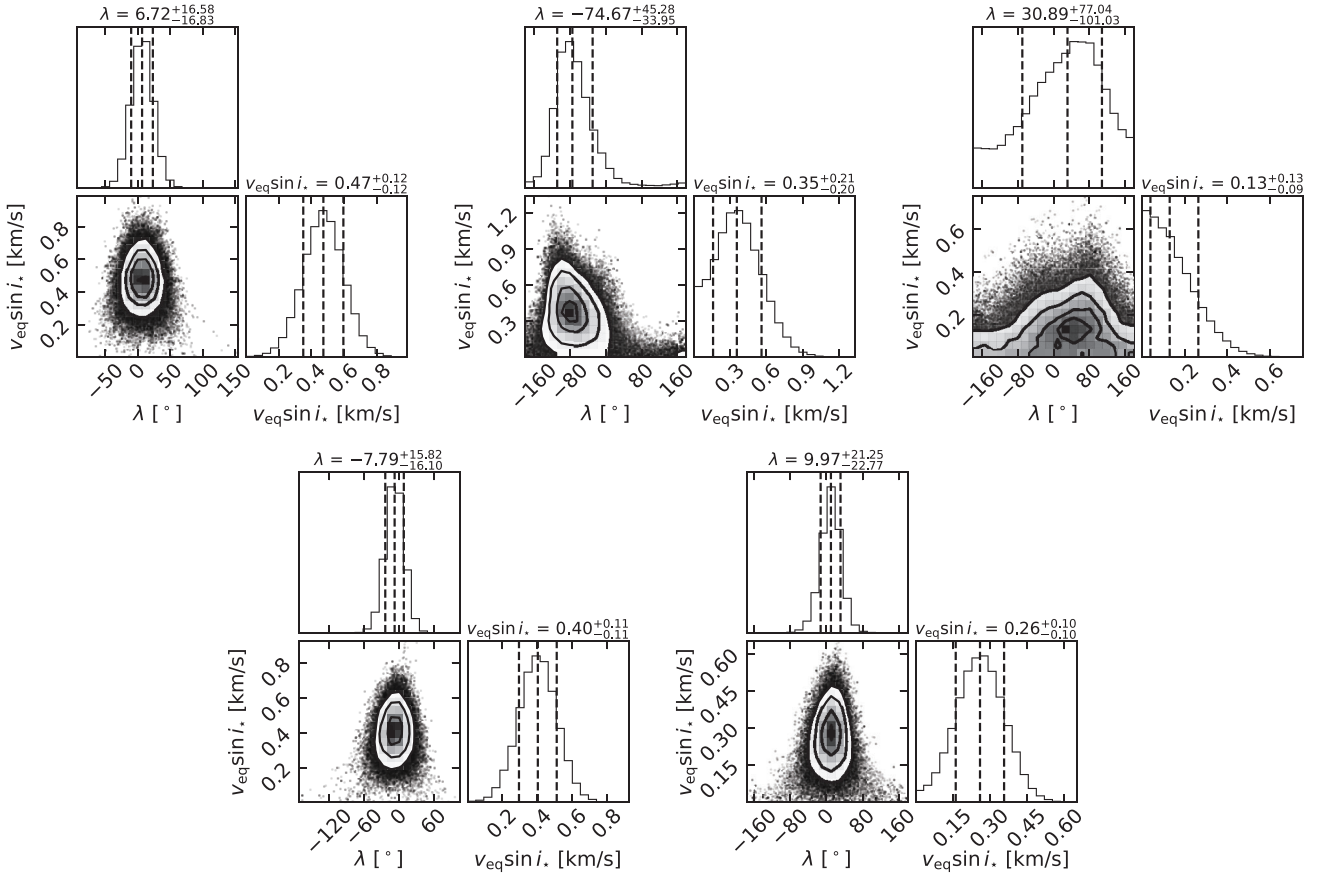


Figure E1. Corner plot with the posteriors of the SB model fit from the reloaded RM analysis of the first ESPRESSO transit (top left), the second ESPRESSO transit (top centre), MAROON-X (top right), both ESPRESSO transits (bottom left), and all three transits (bottom right). We adopt the values from the fit to both ESPRESSO transits (bottom left).

Table E1. RRM fit results for the different sets of observations considered and different models tested.

Model	λ ($^{\circ}$)	$v \sin i_*$ (km s^{-1})	c_1 (km s^{-1})	c_2 (km s^{-1})	# In-transit obs.	# Model param.	χ_{red}^2	BIC
ESPRESSO 2022-09-02								
SB, $\langle \mu \rangle \geq 0.0$	7^{+17}_{-17}	$0.47^{+0.12}_{-0.12}$	—	—	11	2	1.10	14.65
SB CLV1, $\langle \mu \rangle \geq 0.0$	25^{+18}_{-17}	$0.49^{+0.13}_{-0.12}$	$-0.85^{+0.36}_{-0.36}$	—	11	3	0.50	11.11
SB CLV2, $\langle \mu \rangle \geq 0.0$	34^{+17}_{-15}	$0.55^{+0.13}_{-0.13}$	$-4.9^{+2.6}_{-2.6}$	$3.0^{+1.9}_{-2.0}$	11	4	0.17	10.78
ESPRESSO 2022-09-29								
SB, $\langle \mu \rangle \geq 0.0$	-74^{+34}_{-45}	$0.35^{+0.20}_{-0.20}$	—	—	10	2	1.93	20.01
SB CLV1, $\langle \mu \rangle \geq 0.0$	-112^{+8}_{-12}	$1.32^{+0.48}_{-0.47}$	$2.35^{+0.96}_{-0.93}$	—	10	3	0.99	13.80
SB CLV2, $\langle \mu \rangle \geq 0.0$	-108^{+9}_{-13}	$1.33^{+0.45}_{-0.46}$	$7.7^{+4.4}_{-4.3}$	$-4.1^{+3.3}_{-3.2}$	10	4	0.89	14.57
ESPRESSO 2022-09-02 & 2022-09-29								
SB, $\langle \mu \rangle \geq 0.0$	-8^{+16}_{-16}	$0.40^{+0.11}_{-0.11}$	—	—	21	2	1.57	35.97
SB CLV1, $\langle \mu \rangle \geq 0.0$	9^{+18}_{-17}	$0.42^{+0.11}_{-0.11}$	$-0.56^{+0.31}_{-0.31}$	—	21	3	1.47	35.54
SB CLV2, $\langle \mu \rangle \geq 0.0$	11^{+19}_{-17}	$0.43^{+0.11}_{-0.11}$	$-1.5^{+2.2}_{-2.2}$	$0.7^{+1.7}_{-1.7}$	21	4	1.54	38.39
MAROON-X 2021-11-04								
SB, $\langle \mu \rangle \geq 0.0$	31^{+101}_{-77}	$0.13^{+0.09}_{-0.13}$	—	—	17	2	1.31	25.33
SB CLV1, $\langle \mu \rangle \geq 0.0$	31^{+102}_{-73}	$0.13^{+0.09}_{-0.14}$	$-0.19^{+0.43}_{-0.42}$	—	17	3	1.39	27.90
SB CLV2, $\langle \mu \rangle \geq 0.0$	22^{+113}_{-86}	$0.12^{+0.09}_{-0.14}$	$1.8^{+2.6}_{-2.5}$	$-1.6^{+2.0}_{-2.0}$	17	4	1.46	30.36
ESPRESSO 2022-09-02 and 2022-09-29, and MAROON-X 2021-11-04								
SB, $\langle \mu \rangle \geq 0.0$	10^{+23}_{-21}	$0.260^{+0.098}_{-0.097}$	—	—	38	2	1.62	65.80
SB CLV1, $\langle \mu \rangle \geq 0.0$	8^{+20}_{-19}	$0.310^{+0.090}_{-0.089}$	$-0.46^{+0.24}_{-0.25}$	—	38	3	1.41	60.42
SB CLV2, $\langle \mu \rangle \geq 0.0$	7^{+20}_{-20}	$0.309^{+0.089}_{-0.087}$	$-0.4^{+1.7}_{-1.7}$	$0.0^{+1.3}_{-1.3}$	38	4	1.46	64.07

Note. We show the preferred models fitted to each transit individually, to both ESPRESSO transits together, and to all three transits together. Models: SB means solid body model, CLV1 means centre-to-limb linear model (polynomial of order 1, for which we fit c_1), and CLV2 means centre-to-limb quadratic model (polynomial of order 2, for which we fit c_1 and c_2).

APPENDIX F: THREE-DIMENSIONAL OBLIQUITY DISTRIBUTION

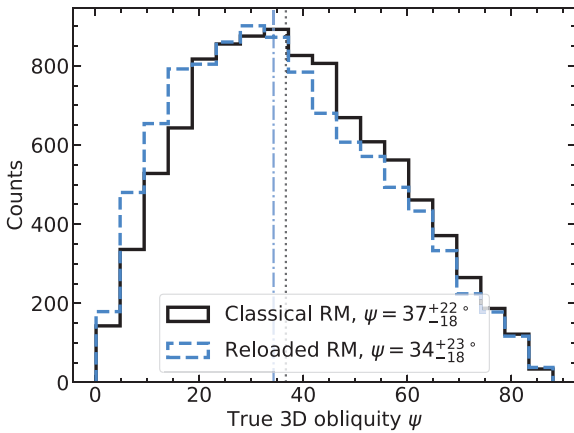


Figure F1. Three-dimensional obliquity distribution ψ obtained after simulating random system configurations (see Section 6.1). The black solid-line histogram shows the distribution obtained using the λ value from the classical RM, and the blue dashed-line histogram shows the same but for the reloaded RM λ . The vertical black dotted line and the blue dash-dotted line show the median values of each distribution, also shown in the legend.

APPENDIX G: EXOFOP FOLLOW-UP FIGURES

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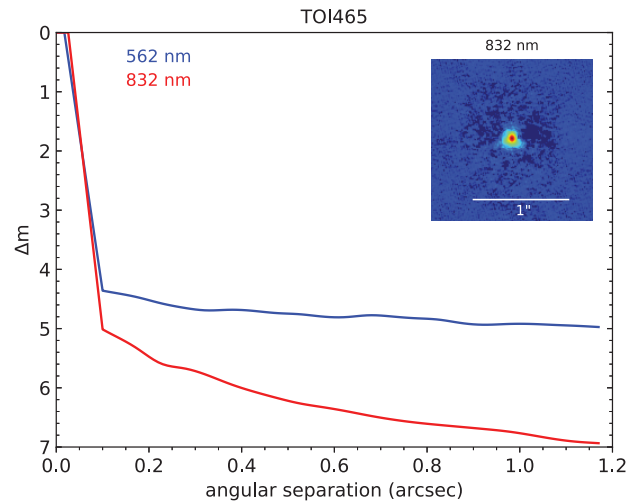


Figure G1. Speckle imaging contrast curves of WASP-156 from the 562 and 832 nm bandpasses of the Zorro speckle imager at Gemini South Observatory, from the ExoFOP archive (PI: Howell). The inset shows the reconstructed image from the 832 nm filter.

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