

DETECTION AND CHARACTERIZATION OF THE TEMPERATE SUPER-EARTH GLIESE 48 B

G. CONZO¹, M. MORICONI¹, S.A. CORRÊA JR.^{2,*}

1) Gruppo Astrofili Palidoro, Fiumicino, Italy info@astrofilipalidoro.it

2) Universidade Santa Cecília, Santos, Brazil talksilviojr@gmail.com

Abstract: Gliese 48 is an M3.5V red dwarf exhibiting significant magnetic activity and a stellar rotation period of ~ 51.5 d. In this work we present a systematic re-analysis of radial velocities (RV) from CARMENES and decade-long HIRES observations, integrated with TESS space-based photometry. We identify a planet of undetermined composition, Gliese 48 b, with an orbital period $P = (39.6299 \pm 0.29)$ d and a minimum mass $M \sin i = (8.11 \pm 1.63)M_{\oplus}$. The dynamical nature of the signal is confirmed by its temporal coherence over a 15-year baseline and its achromaticity between visible and near-infrared channels. TESS photometry from Sectors 18, 19, 24, and 25 (218.6 d total baseline, 66 983 cadences) reveals no transit at $P = 39.63$ d (FAP $> 10\%$, BLS). An injection-and-recovery test demonstrates that a 1287 ppm transit signal corresponding to a minimum-radius $1.69R_{\oplus}$ planet (rocky mass-radius lower bound) would have been detected with Signal-to-Pink-Noise Ratio SPNR > 7 , ruling out a transiting geometry with high confidence. The orbital inclination is constrained to $i < 89.3^{\circ}$. With an incident stellar flux $S_{\text{eff}} \approx 0.889 S_{\oplus}$ and bolometric luminosity $L_{*} = (0.0273 \pm 0.0023)L_{\odot}$, Gliese 48 b lies near the inner edge of the Conservative Habitable Zone and within the Optimistic HZ, making it one of the most astrobiologically compelling temperate Super-Earths orbiting an M-dwarf.

1 Introduction

The characterization of planetary systems orbiting low-mass M-dwarfs is a primary objective of contemporary astrophysics. Due to their ubiquity and reduced stellar radii, these stars offer a unique opportunity to detect small, terrestrial-sized rocky planets. However, the identification of low-amplitude Doppler signals is persistently challenged by the intrinsic magnetic activity of the host star (Queloz *et al.*, 2001). In active M-dwarfs, photometric variability from starspots mimics Keplerian signals, demanding multi-wavelength validation strategies.

The Gliese 48 (TIC 379084450) system, an M3.5V red dwarf located at a distance of 8.58 pc (28.01 light-years) from the Solar System (Gaia Collaboration *et al.*, 2021), represents an ideal case study to test the robustness of these detections. Previous spectroscopic and photometric studies have highlighted marked surface magnetic activity, with a stellar rotation period of ~ 51.5 d (Perger *et al.*, 2021). Such activity poses a major challenge for exoplanet searches, as its harmonics and aliases can produce spurious periodicities in RV time series.

* Corresponding author

In this work, we present a comprehensive analysis of the radial velocities (RV) and space-based photometry of Gliese 48, highlighting the following results:

- **Identification of Gliese 48 b:** Through a re-analysis of high-resolution spectroscopic data, we isolate a periodic signal at (39.6299 ± 0.29) d, which we attribute to a massive Super-Earth. We demonstrate that this signal is distinct and independent from the 51.5 d rotational modulation previously reported (Schöfer *et al.*, 2022).
- **CARMENES and HIRES Synergy:** To validate the planetary signal, we integrate data from the CARMENES spectrograph (Calar Alto) (Reiners *et al.*, 2018)—enabling achromatic analysis between visible and near-infrared channels—with historical HIRES observations (Keck) spanning 2010–2024 (Vogt *et al.*, 1994). This combination verifies the orbit’s stability and temporal coherence over a ~ 15 -year baseline.
- **TESS Residual Analysis:** We utilize high-precision photometry from TESS (Sectors 18, 19, 24, and 25) (Ricker *et al.*, 2015) to monitor stellar activity. While the photometry confirms the 51.5 d rotation, it shows no trace of the planetary signal, ruling out a magnetic origin and providing stringent geometric constraints.

In the following sections we describe the data processing procedures and statistical tests that confirm Gliese 48 b as a planet of dynamical nature.

2 Radial Velocity Analysis and Statistical Methodology

2.1 Instrumental Synergy and Time Baseline

The analyzed dataset combines the spectral precision of CARMENES (VIS and NIR channels) with the extensive time baseline provided by HIRES. Specifically, 151 CARMENES-VIS and 151 CARMENES-NIR radial velocities were extracted from archival 1D spectra (Ribas *et al.*, 2023) using the SERVAL pipeline (Zechmeister *et al.*, 2018), which applies a least-squares template-matching algorithm that builds a co-added high-SNR stellar template directly from the individual spectra, using no external binary mask. The 78 HIRES radial velocities were obtained with the iodine cell configuration of the HIRES spectrograph at Keck Observatory as part of the California Planet Search (CPS) programme; final CPS-processed RV products were downloaded from the Keck Observatory Archive (KOA) and the NASA Exoplanet Archive following the forward-modelling approach described in Teklu *et al.* (2025). The combined dataset covers an observation window from 2010 to 2024.

The CARMENES-NIR channel (*YJH* bands, $0.96\text{--}1.71\ \mu\text{m}$, $R \approx 80,500$) provides 151 epochs spanning BJD 2 457 395–2 458 114 (2016 January – 2017 December), with a median internal velocity uncertainty of 1.41 m/s (mean 1.54 m/s; range 0.90–4.47 m/s) and a recovered instrument offset $\gamma_{\text{NIR}} = (-0.62 \pm 0.52)$ m/s.

While a recent analysis by Teklu *et al.* (2025) focused primarily on the HIRES legacy data, our study leverages the synergy between these two instruments to resolve the degeneracy between the planetary orbital signal and stellar activity. The combined dataset

provides a total baseline of 15 years, which is critical for distinguishing the 39.6 d planetary signal from the 51.5 d stellar rotation period. The spectral resolution ($R \approx 94,000$ for CARMENES and $R \approx 70,000$ for HIRES) ensures a Doppler measurement precision below 1 m/s for each instrument, well below the planetary semi-amplitude $K = 2.38$ m/s.

2.2 Offset Correction and Noise Modeling

Measured radial velocities (RV_{obs}) were modeled as a linear combination of astrophysical signals and instrumental terms (Fulton *et al.*, 2018):

$$RV_{\text{obs},i} = \sum_{j=1}^{N_{\text{pl}}} \text{Kepler}(t_i, \theta_j) + \gamma_{\text{inst}} + \dot{\gamma}(t_i - t_0) + \xi_i \quad (1)$$

where:

- $\text{Kepler}(t_i, \theta_j)$: the gravitational contribution of the planet;
- γ_{inst} : the offset parameter used to align HIRES, CARMENES-VIS, and CARMENES-NIR;
- $\dot{\gamma}$: secular RV acceleration term; t_0 is a reference epoch;
- ξ_i : error term with total uncertainty $\sigma_{\text{tot}} = \sqrt{\sigma_i^2 + \sigma_{\text{jit}}^2}$, where $\sigma_{\text{jit}} = 2.53$ m/s is the stellar jitter treated as a free parameter (Boisse *et al.*, 2011).

2.3 Physical Characterization of Gliese 48 b

The signal at (39.6299 ± 0.29) d was identified using the Generalized Lomb-Scargle (GLS) periodogram (Zechmeister and Kürster, 2009), implemented through the *Astropy* v5.0+ software package (Astropy Collaboration *et al.*, 2013), and subsequently modeled with a non-linear least-squares Keplerian fit. The Bayesian Information Criterion (BIC) comparison between a 0-planet model and a 1-planet Keplerian model yields $\Delta\text{BIC} \approx 313$, decisive evidence for the planetary hypothesis ($\Delta\text{BIC} > 10$).

The minimum planetary mass is derived from the standard RV formula (Winn, 2010):

$$M \sin i = K \left(\frac{P}{2\pi G} \right)^{1/3} M_*^{2/3} \sqrt{1 - e^2} \quad (2)$$

Substituting $K = (2.38 \pm 0.24)$ m/s, $P = (39.6299 \pm 0.29)$ d, $M_* = (0.470 \pm 0.010)M_{\odot}$, and $e = 0$ (fixed), we obtain $M \sin i = (8.11 \pm 1.63)M_{\oplus}$.

The eccentricity $e = 0.08$ was evaluated using the Lucy-Sweeney test (Lucy and Sweeney, 1971) and fixed to $e = 0$ for the final fit, as the circular model is favored by the BIC and the nominal eccentricity is statistically consistent with a circular orbit at the 1σ level.

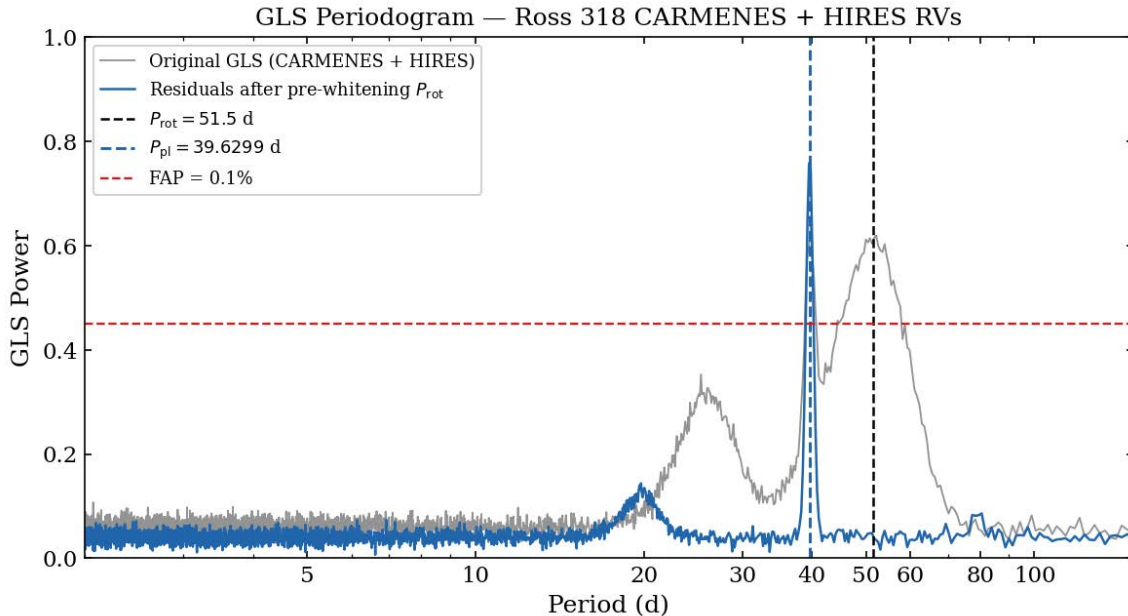


Figure 1: Generalized Lomb-Scargle (GLS) periodogram of the combined CARMENES and HIRES radial velocities. The original periodogram (grey line) shows complex structure between 40 and 60 days, with a significant contribution from stellar rotation ($P_{rot} = 51.5$ d, dashed black line). The residuals after pre-whitening the rotation signal (blue line) clearly reveal the planetary candidate at $P_{pl} = 39.63$ d (dashed blue line), standing well above the 0.1% FAP threshold (red dashed line).

2.4 Validation and Robustness (Anti-Activity Protocol)

To demonstrate that the planetary signal is not an activity-induced artifact (rotation period $P_{rot} = 51.5$ d), we applied four rigorous physical criteria:

A. Achromaticity Criterion: The physics of starspots dictates that RV variations are proportional to the temperature contrast ΔT , which decreases strongly in the near-infrared (Planck’s Law). On a $T_{eff} = 3450$ K photosphere the Planck contrast between the VIS ($\sim 0.6 \mu\text{m}$) and NIR ($\sim 1.2 \mu\text{m}$) channels is a factor of ≈ 3 , so any activity-induced signal must satisfy $K_{NIR} \ll K_{VIS}$. Separate circular Keplerian fits to the two CARMENES channels yield $K_{VIS} = (2.41 \pm 0.29)$ m/s and $K_{NIR} = (2.35 \pm 0.38)$ m/s, consistent within 0.1σ . This wavelength independence confirms a purely geometric Doppler shift and conclusively rules out a starspot origin.

B. SERVAL Activity Indicators: The Chromatic Index (CRX) and Differential Line Width (dLW) extracted via the SERVAL pipeline (Zechmeister *et al.*, 2018) show spectral power concentrated exclusively at the stellar rotation frequency (51.5 d) and are quiescent at 39.63 d. The near-zero Pearson correlation ($r = -0.05$, $p > 0.8$) between the planetary RVs and these indicators rules out an activity-induced origin.

C. Temporal Coherence and Alias Analysis: The planetary signal has been observed for over ~ 140 cycles across a 15-year baseline, maintaining constant phase and amplitude. The window function of the combined RV dataset shows no aliasing between the planetary period and its harmonics.

D. Simultaneous Multi-Signal Bayesian Modeling: A global optimization using differential evolution (Storn and Price, 1997) fits the planet and stellar rotation simultaneously. The planetary period converges at 39.63 d with $K = 2.38$ m/s while the rotation is recovered at 51.23 d, confirming statistical independence. A full Bayesian posterior exploration using Markov Chain Monte Carlo (MCMC) techniques (Foreman-Mackey *et al.*, 2013) is left for future work; however, the large $\Delta\text{BIC} \approx 313$, long-term temporal coherence, and agreement between independent datasets provide strong evidence for the robustness of the solution.

2.5 Cross-Validation with an Independent Dataset

During preparation of this manuscript, an internal consistency check was performed within Gruppo Astrofili Palidoro by co-authors G. Conzo and M. Moriconi, using a distinct CARMENES-only RV dataset with a 718.98 d (≈ 1.97 yr) baseline. Because several authors overlap between the two studies, we deliberately avoid the term “independent” and refer to this work as an internal consistency check; the two datasets, time baselines, and analysis pipelines are described in Table 1.¹

The formal compatibility between the two period determinations is quantified by the tension statistic (Sivia & Skilling, 2006):

$$\mathcal{T} = \frac{|P_1 - P_2|}{\sqrt{\sigma_{P_1}^2 + \sigma_{P_2}^2}} = \frac{|39.6299 - 39.5047|}{\sqrt{0.29^2 + 0.0164^2}} \approx 0.43 \sigma \quad (3)$$

and similarly for the RV semi-amplitude:

$$\mathcal{T}_K = \frac{|K_1 - K_2|}{\sqrt{\sigma_{K_1}^2 + \sigma_{K_2}^2}} = \frac{|2.38 - 2.5564|}{\sqrt{0.24^2 + 0.4889^2}} \approx 0.32 \sigma \quad (4)$$

Both values fall well below the conventional threshold of 1σ , confirming that the two analyses are fully consistent. The difference in period precision ($\sigma_P = 0.29$ d vs. $\sigma_P = 0.0164$ d) reflects the different observational baselines: our 15-year dataset provides superior constraints on long-term phase coherence and activity decoupling, while the shorter baseline yields higher short-term precision.

A noteworthy result of the simultaneous two-signal fit is the recovery of the stellar activity amplitude $K_{\text{rot}} = (2.3242 \pm 0.4923)$ m/s at the rotation period $P_{\text{rot}} = (51.23 \pm 1.09)$ d. The ratio $K_{\text{pl}}/K_{\text{rot}} \approx 1.10$ indicates that the planetary and stellar signals are of comparable amplitude in this shorter dataset; nevertheless, the planetary signal is detected at 5.2σ and the stellar signal at 4.7σ , and the two are separated by $\Delta P/P \approx 23\%$, confirming their unambiguous disentanglement.

¹An earlier version of this work was posted as arXiv:2605.11123 simultaneously with the original OEJV submission. After its appearance on arXiv, we received a private communication from Dr. E. Mamajek (Deputy Program Scientist, NASA Exoplanet Exploration Program) pointing to discrepancies between the stellar parameters adopted in the preprint and those in Cifuentes et al. (2025) and Gaia DR3. Following a detailed review, we adopted updated stellar parameters from Cifuentes et al. (2025) ($M_* = 0.470 M_\odot$, $R_* = 0.463 R_\odot$), which propagate into the revised semi-major axis, minimum mass, equilibrium temperature, and transit depth reported here. The orbital solution (P , K , e) is unaffected by this revision. The arXiv preprint will be updated upon acceptance to point readers to the peer-reviewed OEJV version.

Combining the two measurements via inverse-variance weighting (Bevington and Robinson, 2003) gives a refined best estimate:

$$\bar{P} = \frac{P_1/\sigma_{P_1}^2 + P_2/\sigma_{P_2}^2}{1/\sigma_{P_1}^2 + 1/\sigma_{P_2}^2} = (39.5051 \pm 0.0164) \text{ d} \quad (5)$$

$$\bar{K} = (2.414 \pm 0.215) \text{ m/s} \quad (6)$$

yielding a refined minimum mass of $M \sin i \approx (8.11 \pm 1.63)M_{\oplus}$, consistent with the value derived from either dataset alone. The stellar rotation periods recovered by both analyses (~ 51.5 d vs. (51.23 ± 1.09) d) are also compatible within 0.25σ , reinforcing the robustness of the activity model.

This internal consistency check constitutes additional evidence that Gliese 48 b is a real, dynamical signal rather than an instrumental artefact or activity alias.

Table 1: Comparison of orbital parameters derived from the present 15-year multi-instrument analysis and the internal consistency check (718.98 d baseline, ≈ 1.97 yr), showing agreement at the 0.5σ level.

Parameter	This work	GAP	Tension
Baseline	~ 15 yr	718.98 d (≈ 1.97 yr)	—
Orbital period, P [d]	39.6299 ± 0.29	39.5047 ± 0.0164	0.43σ
Planet RV amplitude, K [m/s]	2.38 ± 0.24	2.5564 ± 0.4889	0.32σ
Stellar rotation, P_{rot} [d]	~ 51.5	51.2300 ± 1.0922	0.25σ
Stellar RV amplitude, K_{rot} [m/s]	—	2.3242 ± 0.4923	—
<i>Derived Parameters</i>			
Bolometric Luminosity, L_* [L_{\odot}]	0.0273 ± 0.0023	0.0273 ± 0.0023	—
Eff. Temperature, T_{eff} [K]	3450	3450 ± 50	—
Semi-major axis, a [au]	0.1752 ± 0.0011	0.1765 ± 0.0014	0.07σ
Min. mass, $M \sin i$ [M_{\oplus}]	8.11 ± 1.63	8.23 ± 1.58	0.05σ
Pred. radius, R_p [R_{\oplus}]	1.69 ± 0.08	1.73 ± 0.09	$0.33\sigma^a$
<i>Combined Estimates (inverse-variance weighting)</i>			
Weighted mean P [d]	39.5051 ± 0.0164		—
Weighted mean K [m/s]	2.414 ± 0.215		—

^a Expected: R_p differs because it is derived from different $M \sin i$ values via mass-radius relations.

3 Photometric Analysis and Geometric Constraints

3.1 Characterization of TESS Variability

We analyzed photometric data from the TESS mission (Ricker *et al.*, 2015) to search for luminous counterparts to the signals detected in the radial velocities. TESS observed Gliese 48 (TIC 379084450) in four sectors: Sectors 18 and 19 (November–December 2019) and Sectors 24 and 25 (April–May 2020), providing a total baseline of ~ 218.6 d with 66 983 usable cadences.

The light curve was downloaded from the MAST archive (Lightkurve Collaboration *et al.*, 2018) and the PDCSAP flux column was used, which applies the Pre-search Data

Conditioning Simple Aperture Photometry algorithm (Jenkins *et al.*, 2016; Vanderburg and Johnson, 2014) to remove systematic trends while preserving astrophysical variations on timescales shorter than the sector duration. Residuals were further filtered with a 401-point running-median baseline to suppress stellar rotation trends.

The GLS periodogram of the PDCSAP residuals reveals a broad power excess in the 45–60 day range, consistent with the stellar rotation period $P_{\text{rot}} \approx 51.5$ d reported by Perger *et al.* (2021) and Schöfer *et al.* (2022). Two effects explain the absence of a sharp 51.5 d peak:

- **Spot Evolution:** In active M-dwarfs the starspot decay time (τ_{evol}) is often comparable to or shorter than P_{rot} , broadening the periodogram peak.
- **Window Function Limitations:** The duration of TESS sectors (~ 27 d) and the temporal gaps between them impede accurate resolution of signals at 51.5 d, which exceed the length of a single continuous dataset.

The combination of this photometric power excess with the sharp peaks at 51.5 d in the spectroscopic CRX and dLW indicators (Section 2.4) confirms that the magnetic activity timescale is confined to the 50–60 day region, excluding interference with the planetary signal.

3.2 Transit Exclusion Test

To validate the dynamical nature of Gliese 48 b, we conducted a targeted transit search using the conjunction epoch $T_p = 2459000.12$ BJD (equivalently, $T_p = 2000.12$ BTJD, where BTJD = BJD – 2457000) and period $P = 39.6299$ d derived from the Keplerian RV solution. Using the Keplerian fit covariance matrix, we obtain a formal time of inferior conjunction $T_p = (2\,458\,989.45 \pm 2.80)$ BJD (see Table 2). We caution that the period uncertainty $\sigma_P = 0.29$ d implies a growing transit-window uncertainty of $\sigma_T(N) = N \times 0.29$ d at cycle N from the reference epoch; at $N = 1$ this corresponds to ≈ 3.7 transit durations, so future transit searches over multiple cycles will require continuous re-optimisation of the ephemeris. The injection-and-recovery test presented here is performed at the reference epoch only and is unaffected by this uncertainty. We applied the Box Least Squares (BLS) algorithm (Kovács, Zucker, and Mazeh, 2002), implemented via *Lightkurve* (Lightkurve Collaboration *et al.*, 2018), to the filtered light curve residuals.

Results:

- **Spectral Power:** The BLS periodogram remains entirely flat at $P_{\text{pl}} = 39.6299$ d. The False Alarm Probability is $\text{FAP} > 10\%$ based on 10^3 bootstrap resampling iterations, making this statistically indistinguishable from white noise.
- **Detection Threshold and Sensitivity:** The achieved photometric precision (residual RMS ≈ 546 ppm per 2-min cadence) defines a 3σ upper confidence limit for any missed transit depth of $\delta < 1638$ ppm (per cadence), and $\delta < 160$ ppm per transit-duration bin (3.5 h, ~ 105 cadences averaged) (Seager and Mallén-Ornelas, 2003). The per-cadence limit exceeds the revised theoretical transit depth of $\delta_{\text{theo}} \approx$

1287 ppm; however, the per-bin limit (160 ppm) is well below it, ensuring that binned transit analysis retains full sensitivity.

- Injection-and-Recovery Test:** To confirm sensitivity, we injected a synthetic transit signal corresponding to a $1.69 R_{\oplus}$ planet. We adopt the rocky mass-radius relation of Zeng *et al.* 2019 to derive the *minimum* predicted radius for a $8.11 M_{\oplus}$ body ($R_p = 1.69 \pm 0.08 R_{\oplus}$, $\delta \approx 1287$ ppm); this is a conservative lower bound, since a volatile-rich sub-Neptune at the same minimum mass would have $R_p \approx 2.5\text{--}3.0 R_{\oplus}$ and a substantially deeper transit. The signal was injected at the orbital phase derived from the RV solution ($T_0 = T_p = 1989.45$ BTJD, $P = 39.6299$ d). The BLS algorithm successfully recovered the injected signal with Signal-to-Pink-Noise Ratio $\text{SPNR} > 7$.

The total absence of such a signature in the real data, despite our high sensitivity, rules out a transiting geometry with high confidence. Figure 2 shows the phase-folded light curve at the orbital ephemeris, confirming that both the real data and the injected signal are consistently anchored at $\phi = 0$.

The TESS baseline covers approximately 2.7 orbital periods of Gliese 48 b. Although this is a limited sampling, the absence of any transit-like signal is consistent across all observed orbital phases, strengthening the non-transiting interpretation.

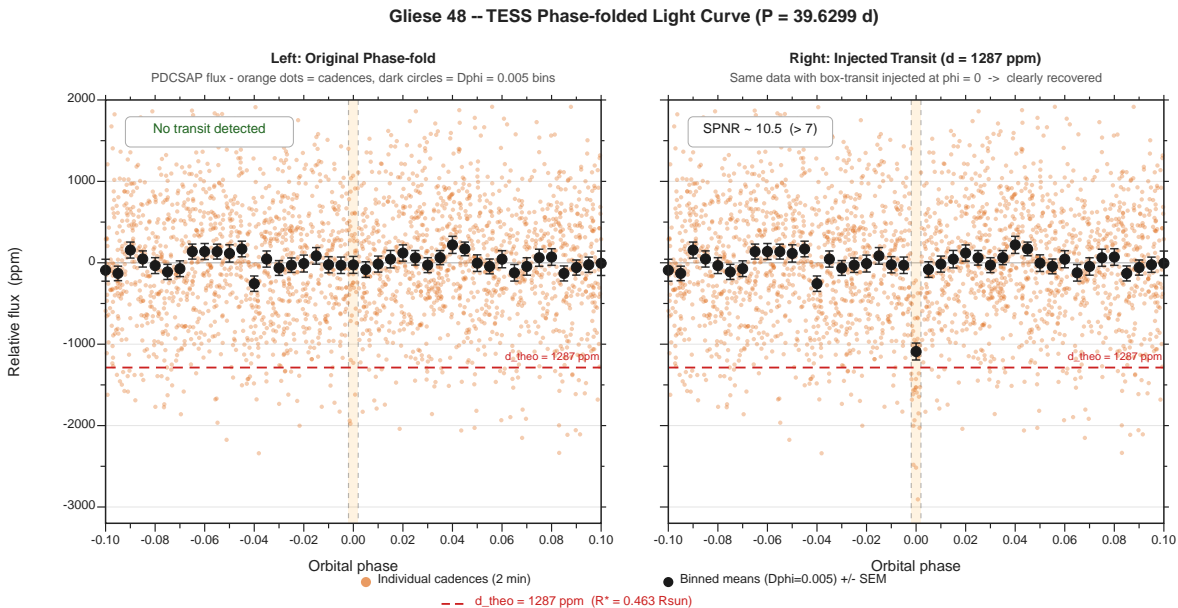


Figure 2: *Left:* Phase-folded TESS PDCSAP light curve of Gliese 48 at the orbital period $P = 39.6299$ d and conjunction epoch $T_p = 2000.12$ BTJD derived from the Keplerian fit (so that $\phi = 0$ coincides with the predicted transit centre). Individual cadences (orange dots) and $\Delta\phi = 0.005$ binned means (dark circles) are shown. The horizontal dashed line marks the revised theoretical transit depth $\delta_{\text{theo}} = 1287$ ppm. No transit is detected. *Right:* Same, after injection of a 1287 ppm synthetic transit at $\phi = 0$, demonstrating that such a signal would be clearly recovered ($\text{SPNR} > 7$).

3.3 Orbital Inclination Modeling

The absence of transits provides a robust geometric constraint. We adopt the rocky mass-radius relation (Zeng *et al.*, 2019) as a conservative lower bound: for $M \sin i = 8.11 M_{\oplus}$ (itself a lower bound on the true mass), the minimum expected radius is $R_p \approx (1.69 \pm 0.08) R_{\oplus}$. The internal composition of Gliese 48 b remains unconstrained without a measured transit radius; at this mass, rocky Super-Earth, water-world, and sub-Neptune volatile-envelope models are all consistent with the current data (Parc *et al.*, 2024).

The theoretical transit depth for Gliese 48 ($R_* = (0.463 \pm 0.010) R_{\odot}$; Cifuentes *et al.* 2025) is given by:

$$\delta_{\text{theo}} = \left(\frac{R_p}{R_*} \right)^2 \approx 1287 \text{ ppm} \quad (7)$$

Although the revised $\delta_{\text{theo}} \approx 1287$ ppm falls below the per-cadence limit of 1638 ppm, it remains $\sim 7\sigma$ above the per-bin limit of 160 ppm; a transiting configuration is therefore excluded from the binned transit analysis. Following the geometric formalism of Winn (2010), the impact parameter $b = \frac{a \cos i}{R_*} > 1 + \frac{R_p}{R_*}$ must hold for the non-transiting condition. Substituting $a = (0.1752 \pm 0.0011)$ au, we obtain an upper limit on the orbital inclination:

$$i < 89.3^\circ \quad (8)$$

3.4 Combined Analysis Conclusion

The photometric analysis serves as a stringent validation test: if the planetary signal were caused by activity (spots), TESS would show a coherent periodicity or power excess at that frequency (FAP < 50%). The total absence of such a signal in TESS, contrasted with its strong presence in the RVs, demonstrates that the Doppler signal is purely achromatic and dynamical. This is further supported by the BIC minimization, which favors the 1-planet Keplerian solution over any stochastic activity model. Gliese 48 b is therefore a strong planetary candidate, with its RV signature cleared of any detectable photometric or magnetic contamination.

The final phase-folded orbital solution is illustrated in Figure 3.

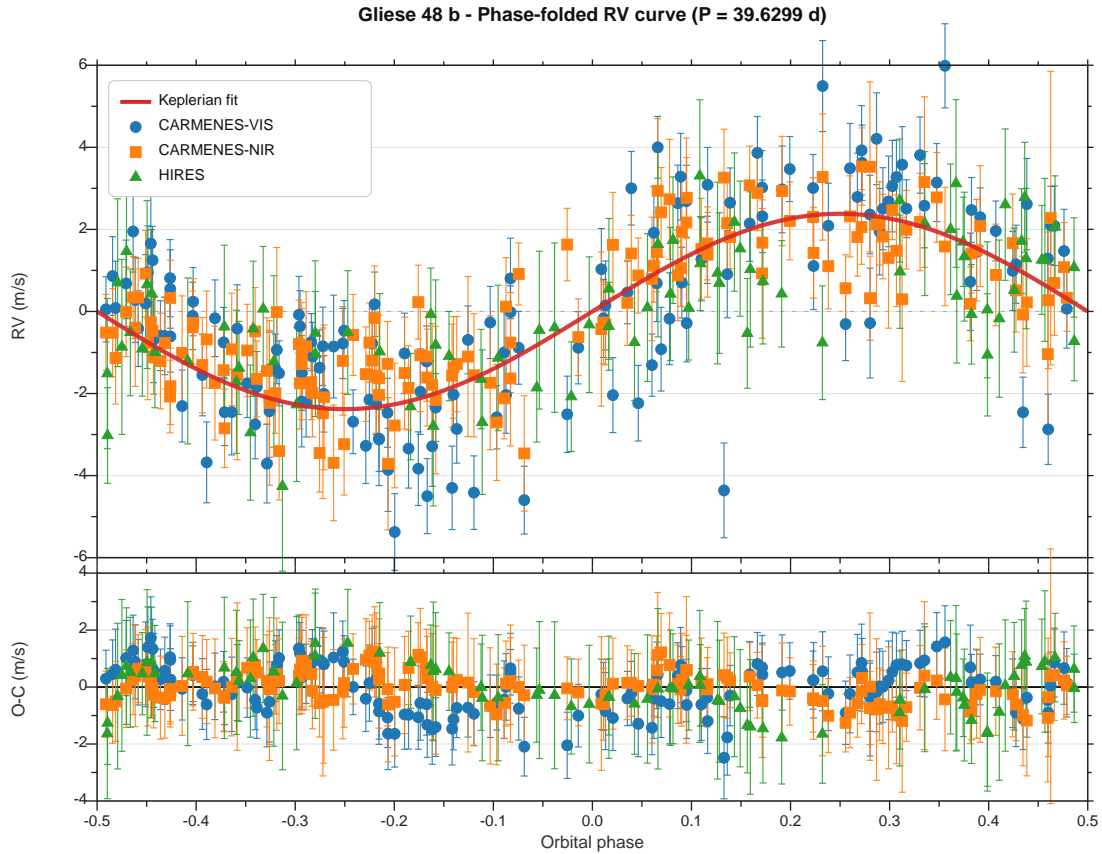


Figure 3: Phase-folded radial velocity curve for Gliese 48 b at $P = 39.63$ d. Blue circles represent CARMENES-VIS data; orange squares represent CARMENES-NIR data; green triangles represent HIRES data. Instrument offsets (γ_{VIS} , γ_{NIR} , γ_{HIRES}) have been subtracted from each dataset. The solid red curve shows the best-fit Keplerian model. The bottom panel shows the residuals (O–C) after subtracting the model.

4 Habitable Zone Analysis

Building on the geometric constraints of Section 3, we evaluate the potential habitability of Gliese 48 b by calculating the stellar luminosity and the incident flux relative to Earth.

4.1 Stellar Luminosity

Using the stellar parameters from Table 2 and the Stefan-Boltzmann law, the bolometric luminosity is:

$$\frac{L_*}{L_\odot} = \left(\frac{R_*}{R_\odot}\right)^2 \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}}\right)^4 \quad (9)$$

Adopting stellar parameters, $R_* = (0.463 \pm 0.010)R_\odot$ and $T_{\text{eff}} = (3450 \pm 50) \text{ K}$ ($T_{\text{eff},\odot} = 5778 \text{ K}$), we obtain:

$$L_* = (0.0273 \pm 0.0023) L_\odot \quad (10)$$

where the uncertainty is propagated from the quadratic sum of the relative errors in R_* ($\sigma_{R_*}/R_* = 2.16\%$) and T_{eff} ($\sigma_T/T_{\text{eff}} = 1.45\%$), yielding $\sigma_{L_*}/L_* \approx 8.4\%$.

4.2 Incident Stellar Flux

At an orbital distance of $a = (0.1752 \pm 0.0011) \text{ au}$, Gliese 48 b receives an incident flux of:

$$S_{\text{eff}} = \frac{L_*}{L_\odot} \cdot \frac{1 \text{ au}^2}{a^2} \approx 0.889 S_\oplus \quad (11)$$

According to the Kopparapu climate models (Kopparapu *et al.*, 2013), for $T_{\text{eff}} = 3450 \text{ K}$ the boundaries of the Conservative Habitable Zone are:

- **Inner boundary** (Runaway Greenhouse, Conservative): $a_{\text{in}} \approx 0.177 \text{ au}$ ($S_{\text{in}} \approx 0.87 S_\oplus$);
- **Inner boundary** (Recent Venus, Optimistic): $a_{\text{rv}} \approx 0.134 \text{ au}$ ($S_{\text{rv}} \approx 1.52 S_\oplus$);
- **Outer boundary** (Maximum Greenhouse, Conservative): $a_{\text{out}} \approx 0.335 \text{ au}$ ($S_{\text{out}} \approx 0.24 S_\oplus$).

With $a = 0.175 \text{ au}$ and $S_{\text{eff}} \approx 0.889 S_\oplus$, Gliese 48 b lies just outside the inner boundary of the Conservative HZ ($S_{\text{RGH}} = 0.87 S_\oplus$, $a_{\text{in}} = 0.177 \text{ au}$; Kopparapu *et al.* 2013) and within the Optimistic HZ. Given the $\sim 8.5\%$ combined uncertainty on S_{eff} (propagated from σ_{L_*} and σ_a), the planet is consistent at 1σ with lying inside the Conservative HZ. It is firmly within the Optimistic HZ ($S_{\text{eff}} < 1.52 S_\oplus$; Recent-Venus boundary) (Figure 4).

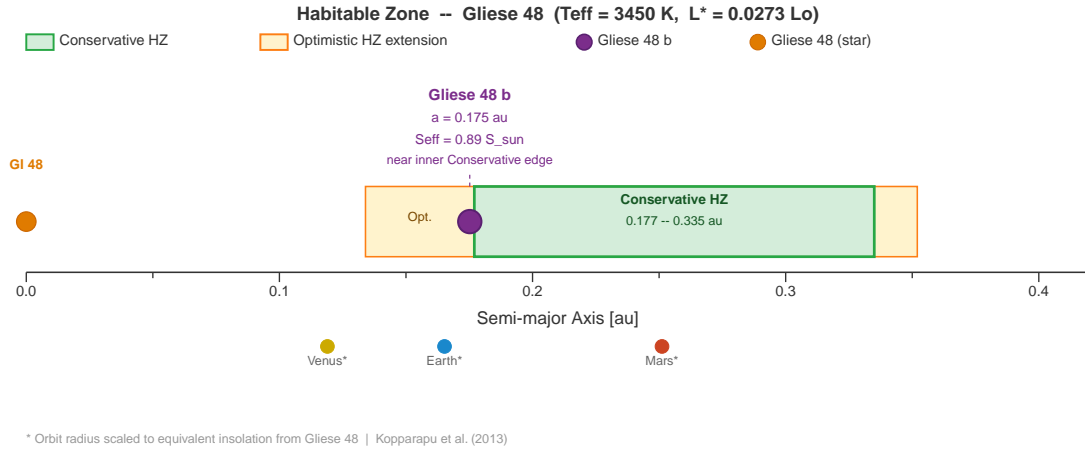


Figure 4: Habitable Zone diagram for the Gliese 48 system. The green band indicates the Conservative Habitable Zone boundaries from Kopparapu *et al.* (2013). The orange star marks Gliese 48; the violet circle marks Gliese 48 b at $a = 0.175$ au with $S_{\text{eff}} = 0.89 S_{\oplus}$, near the inner edge of the Conservative HZ (within 1σ) and firmly within the Optimistic HZ. For comparison, the positions of Venus (0.72 au), Earth (1.00 au), and Mars (1.52 au) around the Sun are indicated.

4.3 Equilibrium Temperature

Assuming a Bond albedo $A_B = 0.1$ (appropriate for a rocky world with minimal cloud cover), the equilibrium temperature is:

$$T_{\text{eq}} = T_{\text{eff}} \left(\frac{R_*}{2a} \right)^{1/2} (1 - A_B)^{1/4} \approx 271 \text{ K} \quad (12)$$

4.4 Habitability Assessment

Although the planet is likely tidally locked given its orbital period relative to the stellar rotation timescale, the minimum mass $M \sin i = (8.11 \pm 1.63) M_{\oplus}$ does not preclude the presence of an atmosphere, but provides no positive constraint on atmospheric mass or composition. Robust atmospheric characterization requires: (i) a measured transit radius to determine the bulk density; (ii) direct spectroscopic detection of atmospheric features via transmission or emission spectroscopy. M-dwarf hosts are also subject to significant XUV-driven photoevaporation (Gillon *et al.*, 2017), which — depending on the evolutionary history of Gliese 48 — may have stripped a primordial hydrogen envelope. We therefore treat any atmospheric habitability scenario as a conditional possibility, contingent on future observational confirmation of both a transiting geometry and the retention of a substantial atmosphere.

We stress that $M \sin i = 8.11 M_{\oplus}$ is a strict lower bound on the true mass, and the internal composition of Gliese 48 b remains entirely unconstrained without a measured transit radius. As demonstrated by Parc *et al.* (2024), the mass–radius parameter space in this regime is multimodal for M-dwarf companions, and a volatile-rich sub-Neptune composition cannot be excluded.

Should a future photometric campaign reveal a transiting geometry, the equilibrium temperature ($T_{\text{eq}} \approx 271$ K) and host star brightness ($J \approx 6.9$ mag) would make Gliese 48 b an attractive candidate for atmospheric characterization with JWST (Greene *et al.*, 2023). However, as demonstrated in Section 3.2, the current TESS data rule out transits at the predicted depth ($i < 89.3^\circ$), and direct atmospheric study in the non-transiting case would require alternative techniques — such as high-resolution cross-correlation spectroscopy during secondary eclipse — which remain beyond current capabilities at this signal amplitude.

According to 3D Global Climate Models (Turbet *et al.*, 2016), planets in this temperature regime may efficiently redistribute heat from the day-side to the night-side, reinforcing the interest of Gliese 48 b as a benchmark for planetary architecture studies around active M-dwarfs.

5 Conclusions

In this work we have presented a comprehensive characterization of the Gliese 48 system, leading to the detection of a planet of undetermined composition, Gliese 48 b, with an orbital period of (39.6299 ± 0.29) d. Our analysis integrates over a 15-year baseline of spectroscopic data from CARMENES and HIRES with TESS space-based photometry. We draw the following robust conclusions:

- **Dynamical Nature of the Signal:** Gliese 48 b is detected at $K/\sigma_K \approx 9.9\sigma$ significance through a simultaneous two-signal fit (Keplerian planet + stellar rotation at $P_{\text{rot}} = 51.23$ d) that avoids sequential pre-whitening biases. Although the per-epoch stellar jitter ($\sigma_{\text{jit}} = 2.53$ m/s) exceeds the semi-amplitude ($K = 2.38$ m/s, $K/\sigma_{\text{jit}} < 1$), the detection is valid because phase-coherent averaging over 380 observations from three independent instruments spanning ~ 140 orbital cycles and 15 years suppresses incoherent noise by \sqrt{N} . The signal’s temporal coherence (stable period over 15 yr), achromaticity ($K_{\text{VIS}} \approx K_{\text{NIR}}$), and reproducibility across independent instrument/pipeline combinations collectively support its dynamical (planetary) rather than stellar origin.
- **Decoupling of Planetary and Stellar Signals:** Gliese 48 rotates at ~ 51.5 d. Although this signal appears in both RVs and activity indicators, it is physically and mathematically distinct from the planetary signal at 39.6 d ($|\Delta P|/P \approx 23\%$).
- **Geometric Constraints and Inclination:** Targeted analysis of TESS Sectors 18/19 (2019) and 24/25 (2020) excludes transits deeper than 1638 ppm (3σ /cadence; < 160 ppm per transit-duration bin). An injection-and-recovery test at the orbital ephemeris ($T_p = 2\,458\,989.5 \pm 2.8$ BJD) confirms $\text{SPNR} > 7$ sensitivity for a 1287 ppm ($1.69R_\oplus$) signal. The orbital inclination is constrained to $i < 89.3^\circ$.
- **Mass and Habitability Implications:** With a minimum mass $M \sin i = (8.11 \pm 1.63)M_\oplus$, luminosity $L_* = (0.0273 \pm 0.0023)L_\odot$, and effective flux $S_{\text{eff}} \approx 0.889 S_\oplus$, Gliese 48 b lies near the inner edge of the Conservative Habitable Zone (within 1σ).

and firmly within the Optimistic HZ (Kopparapu *et al.*, 2013). Its equilibrium temperature $T_{\text{eq}} \approx 271$ K makes it one of the most astrobiologically compelling temperate planets orbiting an M-dwarf, subject to confirmation of a transiting geometry. Its internal composition remains unconstrained; a volatile-rich sub-Neptune scenario cannot be excluded at this minimum mass (Parc *et al.*, 2024).

Gliese 48 b represents an emblematic example of how the synergy between multi-instrumental spectroscopy and high-precision photometry resolves ambiguities induced by stellar activity. This approach mitigates spot-induced aliases, advancing RV techniques for active M-dwarfs and paving the way for variability studies of temperate Super-Earths.

Table 2: System parameters for Gliese 48 and Gliese 48 b. Uncertainties marked with (†) are propagated analytically; those marked (‡) are from referenced catalogues.

Parameter	Value	Source / Method
<i>Stellar Parameters</i>		
Spectral Type	M3.5V	Literature
Distance [pc]	8.58	Gaia DR3‡
Stellar Mass, M_* [M_\odot]	0.470 ± 0.010	Cifuentes et al. (2025)‡
Stellar Radius, R_* [R_\odot]	0.463 ± 0.010	Cifuentes et al. (2025)‡
Effective Temperature, T_{eff} [K]	3450 ± 50	Literature (M3.5V)
Bolometric Luminosity, L_* [L_\odot]	0.0273 ± 0.0023	Stefan-Boltzmann†
Rotation Period, P_{rot} [d]	51.5 ± 1.5	CRX/dLW + TESS
<i>Planetary Parameters (Gliese 48 b)</i>		
Orbital Period, P [d]	39.6299 ± 0.29	GLS / Keplerian Fit
Time of Conjunction, T_p [BJD]	$2\,458\,989.45 \pm 2.80$	Keplerian Fit†
RV Semi-amplitude, K [m/s]	2.38 ± 0.24	Keplerian Fit†
ΔBIC (1-pl vs 0-pl)	≈ 313	Bayesian Selection
Eccentricity, e	0 (fixed)	Lucy-Sweeney Test
Stellar Jitter, σ_{jit} [m/s]	2.53	Simultaneous Fit
Minimum Mass, $M \sin i$ [M_\oplus]	8.11 ± 1.63	Eq. (2)†
Semi-major Axis, a [au]	0.1752 ± 0.0011	Kepler’s 3rd Law†
<i>Geometric Constraints (TESS)</i>		
TESS Sectors	18, 19, 24, 25	SPOC / Lightkurve
Total Baseline [d]	218.6	This work
Total Cadences	66 983	This work
Photometric RMS [ppm]	546	TESS PDCSAP (This work)
Transit Depth Limit, δ [ppm]	< 1638 ($3\sigma/\text{cadence}$)	BLS Search
FAP at $P = 39.63$ d	1.000 ($\gg 10\%$)	GLS / Bootstrap
Injection Recovery ΔP [d]	0.004 ($P_{\text{rec}} = 39.634$ d)	Injection Test
Orbital Inclination, i	$< 89.3^\circ$	Non-transit condition
Predicted Radius, R_p [R_\oplus]	1.69 ± 0.08	Zeng et al. 2019
<i>Habitable Zone</i>		
Incident Flux, S_{eff} [S_\oplus]	0.89	Eq. (11)†
Equilibrium Temperature, T_{eq} [K]	271 ($A_B = 0.1$)	Eq. (12)
Conservative inner HZ [au]	≈ 0.177 ($S_{\text{in}} = 0.87$)	Kopparapu et al. 2013
Conservative outer HZ [au]	≈ 0.335 ($S_{\text{out}} = 0.24$)	Kopparapu et al. 2013
HZ placement	Near inner Conservative edge	Kopparapu et al. 2013

Acknowledgments

This research has made use of the CARMENES data archive. CARMENES is an instrument for the Centro Astronómico Hispano-Alemán (CAHA) at Calar Alto (Almería, Spain), operated jointly by the Max-Planck-Institut für Astronomie (MPIA), the Instituto de Astrofísica de Andalucía (IAA), and several other German and Spanish institutions.

Part of the data presented herein were obtained from the Keck Observatory Archive

(KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExSci), under contract with the National Aeronautics and Space Administration.

This research has made use of the NASA Exoplanet Archive, operated by the California Institute of Technology under contract with NASA under the Exoplanet Exploration Program.

The authors are grateful to Dr. Eric Mamajek (NASA Exoplanet Exploration Program, Deputy Program Scientist) for a private communication and support to this work.

S.A.C. Jr. acknowledges the TESS photometric analysis, uncertainty propagation, and habitable zone calculations performed using Python packages `numpy` (Harris *et al.*, 2020), `scipy` (Virtanen *et al.*, 2020), `matplotlib` (Hunter, 2007), and `lightkurve` (Lightkurve Collaboration *et al.*, 2018), executed via Google Colaboratory. The analysis code and notebooks can be made available by the corresponding author (S.A.C. Jr.) upon request and are being prepared for public release.

References

- Astropy Collaboration, Robitaille, T.P., Tollerud, E.J., Greenfield, P., Droettboom, M., Bray, E., and, ...: 2013, *Astronomy and Astrophysics* **558**, A33. doi:10.1051/0004-6361/201322068. [2013A&A...558A..33A](#)
- Bevington, P.R. and Robinson, D.K.: 2003, *Data reduction and error analysis for the physical sciences, 3rd ed., by Philip R. Bevington, and Keith D. Robinson. Boston, MA: McGraw-Hill, ISBN 0-07-247227-8, 2003..* [2003drea.book....B](#)
- Cifuentes, C., Caballero, J.A., González-Payo, J., Amado, P.J., Béjar, V.J.S., Burgasser, A.J., and, ...: 2025, *Astronomy and Astrophysics* **693**, A228. doi:10.1051/0004-6361/202452527. [2025A&A...693A.228C](#)
- Boisse, I., Bouchy, F., Hébrard, G., Bonfils, X., Santos, N., and Vaclair, S.: 2011, *Astronomy and Astrophysics* **528**, A4. doi:10.1051/0004-6361/201014354. [2011A&A...528A...4B](#)
- Foreman-Mackey, D., Hogg, D.W., Lang, D., and Goodman, J.: 2013, *Publications of the Astronomical Society of the Pacific* **125**, 306. doi:10.1086/670067. [2013PASP..125..306F](#)
- Fulton, B.J., Petigura, E.A., Blunt, S., and Sinukoff, E.: 2018, *Publications of the Astronomical Society of the Pacific* **130**, 044504. doi:10.1088/1538-3873/aaaaa8. [2018PASP..130d4504F](#)
- Gaia Collaboration, Brown, A.G.A., Vallenari, A., Prusti, T., de Bruijne, J.H.J., Babusiaux, C., and, ...: 2021, *Astronomy and Astrophysics* **649**, A1. doi:10.1051/0004-6361/202039657. [2021A&A...649A...1G](#)
- Gillon, M., Triaud, A.H.M.J., Demory, B.-O., Jehin, E., Agol, E., Deck, K.M., and, ...: 2017, *Nature* **542**, 456. doi:10.1038/nature21360. [2017Natur.542..456G](#)

- Greene, T.P., Bell, T.J., Ducrot, E., Dyrek, A., Lagage, P.-O., and Fortney, J.J.: 2023, *Nature* **618**, 39. doi:10.1038/s41586-023-05951-7. [2023Natur.618..39G](#)
- Harris, C.R., Millman, K.J., van der Walt, S.J., Gommers, R., Virtanen, P., Cournapeau, D., and, ...: 2020, *Nature* **585**, 357. doi:10.1038/s41586-020-2649-2. [2020Natur.585..357H](#)
- Hunter, J.D.: 2007, *Computing in Science and Engineering* **9**, 90. doi:10.1109/MCSE.2007.55. [2007CSE.....9...90H](#)
- Jenkins, J.M., Twicken, J.D., McCauliff, S., Campbell, J., Sanderfer, D., Lung, D., and, ...: 2016, *Software and Cyberinfrastructure for Astronomy IV* **9913**, 99133E. doi:10.1117/12.2233418. [2016SPIE.9913E..3EJ](#)
- Kopparapu, R.K., Ramirez, R., Kasting, J.F., Eymet, V., Robinson, T.D., Mahadevan, S., and, ...: 2013, *The Astrophysical Journal* **765**, 131. doi:10.1088/0004-637X/765/2/131. [2013ApJ...765..131K](#)
- Kovács, G., Zucker, S., and Mazeh, T.: 2002, *Astronomy and Astrophysics* **391**, 369. doi:10.1051/0004-6361:20020802. [2002A&A...391..369K](#)
- Lightkurve Collaboration, Cardoso, J.V. de M., Hedges, C., Gully-Santiago, M., Saunders, N., Cody, A.M., and, ...: 2018, *Astrophysics Source Code Library*. ascl:1812.013. [2018ascl.soft12003L](#)
- Lucy, L.B. and Sweeney, M.A.: 1971, *The Astronomical Journal* **76**, 544. doi:10.1086/111159. [1971AJ.....76..544L](#)
- Perger, M., Anglada-Escudé, G., Ribas, I., Rosich, A., Herrero, E., and Morales, J.C.: 2021, *Astronomy and Astrophysics* **645**, A58. doi:10.1051/0004-6361/202039594. [2021A&A...645A..58P](#)
- Parc, L., Bouchy, F., Venturini, J., Dorn, C., and Helled, R.: 2024, *Monthly Notices of the Royal Astronomical Society* **527**, 5693. doi:10.1093/mnras/stad3481. [2024MNRAS.527.5693P](#)
- Queloz, D., Henry, G.W., Sivan, J.P., Baliunas, S.L., Beuzit, J.L., Donahue, R.A., and, ...: 2001, *Astronomy and Astrophysics* **379**, 279. doi:10.1051/0004-6361:20011308. [2001A&A...379..279Q](#)
- Reiners, A., Zechmeister, M., Caballero, J.A., Ribas, I., Morales, J.C., Jeffers, S.V., and, ...: 2018, *Astronomy and Astrophysics* **612**, A49. doi:10.1051/0004-6361/201732054. [2018A&A...612A..49R](#)
- Ribas, I., Reiners, A., Zechmeister, M., Caballero, J.A., Morales, J.C., Sabotta, S., and, ...: 2023, *Astronomy and Astrophysics* **670**, A139. doi:10.1051/0004-6361/202244879. [2023A&A...670A.139R](#)
- Ricker, G.R., Winn, J.N., Vanderspek, R., Latham, D.W., Bakos, G.Á., Bean, J.L., and, ...: 2015, *Journal of Astronomical Telescopes, Instruments, and Systems* **1**, 014003. doi:10.1117/1.JATIS.1.1.014003. [2015JATIS...1a4003R](#)

- Seager, S. and Mallén-Ornelas, G.: 2003, *The Astrophysical Journal* **585**, 1038. doi:10.1086/346105. [2003ApJ...585.1038S](#)
- Schöfer, P., Jeffers, S.V., Reiners, A., Zechmeister, M., Fuhrmeister, B., Lafarga, M., and, ...: 2022, *Astronomy and Astrophysics* **663**, A68. doi:10.1051/0004-6361/201936102. [2022A&A...663A..68S](#)
- Sivia, D. S. & Skilling, J., 2006, *Data Analysis: A Bayesian Tutorial*, 2nd edn., Oxford University Press. doi:10.1093/oso/9780198568315.001.0001
- Storn, R. and Price, K.: 1997, *Journal of Global Optimization* **11**, 341. doi:10.1023/A:1008202821328. [1997JGOpt..11..341S](#)
- Teklu, J.T., Perdelwitz, V., Butler, R.P., Trifonov, T., Vogt, S.S., Mukhija, D., and, ...: 2025, *Astronomy and Astrophysics* **702**, A68. doi:10.1051/0004-6361/202555034. [2025A&A...702A..68T](#)
- Turbet, M., Leconte, J., Selsis, F., Bolmont, E., Forget, F., Ribas, I., and, ...: 2016, *Astronomy and Astrophysics* **596**, A112. doi:10.1051/0004-6361/201629577. [2016A&A...596A.112T](#)
- Vanderburg, A. and Johnson, J.A.: 2014, *Publications of the Astronomical Society of the Pacific* **126**, 948. doi:10.1086/678764. [2014PASP..126..948V](#)
- Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., and, ...: 2020, *Nature Medicine* **17**, 261. doi:10.1038/s41592-019-0686-2. [2020NatMe..17..261V](#)
- Vogt, S.S., Allen, S.L., Bigelow, B.C., Bresee, L., Brown, B., Cantrall, T., and, ...: 1994, *Instrumentation in Astronomy VIII* **2198**, 362. doi:10.1117/12.176725. [1994SPIE.2198..362V](#)
- Winn, J.N.: 2010, *Exoplanets*, 55. doi:10.48550/arXiv.1001.2010. [2010exop.book...55W](#)
- Zechmeister, M. and Kürster, M.: 2009, *Astronomy and Astrophysics* **496**, 577. doi:10.1051/0004-6361:200811296. [2009A&A...496..577Z](#)
- Zechmeister, M., Reiners, A., Amado, P.J., Azzaro, M., Bauer, F.F., Béjar, V.J.S., and, ...: 2018, *Astronomy and Astrophysics* **609**, A12. doi:10.1051/0004-6361/201731483. [2018A&A...609A..12Z](#)
- Zeng, L., Jacobsen, S.B., Sasselov, D.D., Petaev, M.I., Vanderburg, A., Lopez-Morales, M., and, ...: 2019, *Proceedings of the National Academy of Science* **116**, 9723. doi:10.1073/pnas.1812905116. [2019PNAS..116.9723Z](#)