Stellar Activity or a Planet? Revisiting dubious planetary signals in M-dwarf systems

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Resumen / GJ581, una estrella M3V, inicialmente se pensaba que albergaba seis planetas. Sin embargo, el periodo de rotación estelar recientemente determinado (132.3 ± 6.3 días), que es el doble y el cuádruple de los periodos orbitales de los dudosos planetas d ($P_{\rm orb}$: 66.8 días) y g ($P_{\rm orb}$: 36.5 días), respectivamente, introduce una incertidumbre respecto al origen de estas señales periódicas. Nuestro objetivo es confirmar o refutar la naturaleza planetaria de las señales de velocidad radial (RV) atribuidas a estos planetas analizando 718 puntos de datos de RV, que constituyen el conjunto de datos más extenso hasta la fecha, y los indicadores espectroscópicos de actividad estelar. Identificamos 4 señales periódicas mediante un análisis de frecuencias de las series temporales de: 5.37 d(planeta b), 12.9 d(planeta c), 66.3 d(planeta d), and 3.15 d(planeta e), que se modelan utilizando modelos Keplerianos, seguido de un análisis de estabilidad temporal que indica la presencia de una señal inducida por la actividad estelar con un período de 66.3 días. Para confirmar la naturaleza de esta señal periódica, debemos emplear un modelo kepleriano junto con procesos Gaussianos (GP) de manera simultánea. Adicionalmente, actualizamos el periodo de rotación estelar de GJ581 mediante un análisis de indicadores de actividad, empleando un modelo de GP, obteniendo un valor de $P_{\rm rot} = 132^{+1.82}_{-1.71}$ días, mejorando la precisión respecto al valor de la literatura.

Abstract / GJ581, an M3V star, was initially thought to harbor six planets.However, the recently determined stellar rotation period (132.3 ± 6.3 days), being twice and four times the orbital periods of putative planets d ($P_{\rm orb}$: 66.8 days) and g ($P_{\rm orb}$: 36.5 days), respectively, introduces uncertainty regarding the origin of these periodic signals. Our aim is to confirm or refute the planetary nature of the radial velocity (RV) signals attributed to these planets by analyzing 718 RV data points, constituting the most extensive dataset to date, and the spectroscopic stellar activity indicators. We identify four periodic signals by performing a frequency analysis on the RV timeseries: 5.37 d(planet b), 12.9 d(planet c), 66.3 d(planet d), and 3.15 d(planet e). The RVs are modeled using Keplerian models, followed by a temporal stability analysis, which indicates the 66.3 d signal is induced by stellar activity. To confirm the nature of this periodic signal, we must employ a simultaneous Keplerian and Gaussian Process (GP) model. Additionally, we update the stellar rotation period of GJ581 through an analysis of activity indicators, employing GP regression modeling, obtaining a value of $P_{\rm rot} = 132^{+1.82}_{-1.71}$ days, improving the accuracy compared to the literature value.

Keywords / stars: activity — planets and satellites: detection — techniques: radial velocities

1. Introduction

Stellar activity is one of the main causes of false positives in exoplanet detection. Specifically, the presence of magnetic fields affects the shape of spectral lines inducing periodic (or quasi-periodic) radial velocity (RV) variations that can mimic planetary signals in RV measurements. Some studies (Boisse et al., 2011; Gorrini et al., 2022) have shown that these activity signals tend to manifest at the stellar rotation period and its harmonics. Consequently, it becomes crucial to distinguish between these activity-induced signals and authentic planetary signatures in RV measurements, especially in cases where planetary orbital periods closely align with the stellar rotation period.

GJ581 is an M3 dwarf with a reported stellar rotation period of approximately 132.5 ± 6.3 days (Suárez Mascareño et al., 2015). Initially, it was claimed that GJ581 hosted six planets: b ($P_{\rm orb}$: 5.37 days; Bonfils et al., 2005), c ($P_{\rm orb}$: 12.9 days; Udry et al., 2007), d ($P_{\rm orb}$: 66.6 days; Mayor et al., 2009), e ($P_{\rm orb}$: 3.15 days; Mayor et al., 2009), f ($P_{\rm orb}$: 433 days; Vogt et al., 2010), and g ($P_{\rm orb}$: 36.6 days; Vogt et al., 2010). Remarkably, planets d and g are harmonics of the stellar rotation period, this raises doubts as to whether these periodic signals are really planets or are an artifact of signals induced by stellar activity. In addition, previous independent studies have cast doubt on some of the number of detected exoplanets. Tuomi (2011) analyse the combined RVs from HARPS and HIRES spectrographs using Bayesian tools and strongly supported only four companions, arguing against GJ581 f and g. However, Tuomi (2011) acknowledge that it cannot be definitively concluded that the solution proposed by by Vogt et al. (2010) is not real.

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Furthermore, Robertson et al. (2014), corrected the available radial velocity data for activity and suggested that the GJ581 d signal could be an artifact of stellar activity.

In this study, we reanalyze the RV data together with the stellar activity in order to confirm or rule out the planetary nature of the RV signature attributed to the GJ581 system. Utilizing the most recent radial velocity measurements available, we present the details of the data employed in Section 2, while Section 3 outlines the methodology used to determine the stellar rotation period. In section 4 we analyze the radial velocity measurements by using periodograms, Keplerian models, and a temporal stability analysis of the signal. Finally, Section 5 discusses the preliminary results obtained from this analysis.

2. Spectroscopic Data

2.1. Radial Velocities

We employed RV timeseries data from multiple spectrographs, including 412 RV datapoints from HIRES (High-Resolution Echelle Spectrometer, Butler et al., 2017), 54 RV datapoints from CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs, Ribas et al., 2023), and an additional 252 spectra from HARPS (High-Accuracy Radial velocity Planetary Searcher, Mayor et al., 2003). The RVs for HARPS were derived using NAIRA (New Algorithm to Infer RAdial-velocities; Astudillo-Defru et al., 2017b), which employs spectra to construct high signal-to-noise ratio (S/N) stellar and telluric templates, enabling precise RV computations for M dwarfs. In total, our dataset comprises 718 RV data points for GJ581.

2.2. Spectroscopic Activity Tracers

We also calculated spectroscopic activity indicators using the HARPS data. The S-index was computed following the methodology outlined in Astudillo-Defru et al. (2017a), Hα index values were derived according to the method of Gomes da Silva et al. (2011), and for the Na I D lines, we adopted the approach detailed in Astudillo-Defru et al. (2017b). We use the S-index values provided by Butler et al. (2017) for the HIRES dataset. For the CARMENES dataset, we utilize the Hα and Na I D index values provided by the Ribas et al. (2023).

3. Stellar Rotation Period

The stellar rotation period can be derived by modeling spectroscopic activity indicators through Gaussian Process (GP) regression, employing a quasi-periodic kernel (e.g., Rajpaul et al., 2015; Faria et al., 2016) given by:

$$\Sigma_{ij} = \eta_1^2 \exp\left[-\frac{|t_i - t_j|^2}{\eta_2^2} - \frac{\sin^2\left(\frac{\pi|t_i-t_j|}{\eta_3^2}\right)}{2\eta_4^2}\right] \tag{1}$$

Here, Σ_{ij} represents the covariance matrix. There are four hyper-parameters typically linked to physical characteristics. η_1 correlates with the data points, n_2 is linked to an aperiodic timescale representing the active region lifetime on the stellar surface, η_4 is associated with the periodic timescale, representing the distribution of active regions on the stellar surface (Camacho et al., 2023). The final hyperparameter, η_3, refers to the quasi-periodicity of the kernel and represents the stellar rotation period.

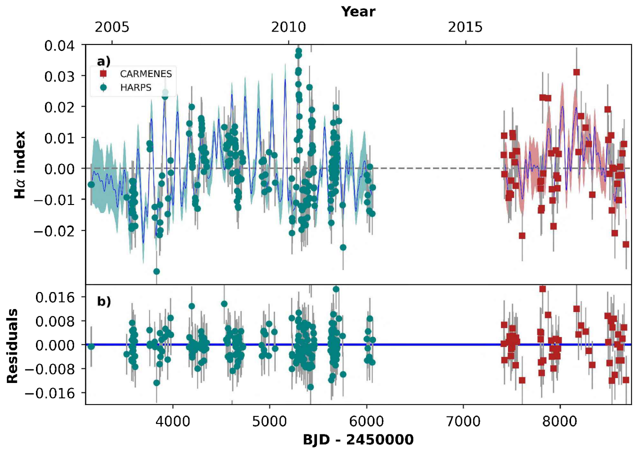

Fig. 1. Hα time series modeled with a GP using a quasi-periodic kernel. *a)* Model showing the GP resulting from the median of the hyper-parameters' posteriors (blue curve). The colored zone depicts the model 1-σ confidence. *b)* Residual of the fit.

In our analysis, we use the Gaussian Process (GP) modeling capability of RadVel (Fulton et al., 2018) to model the Hα timeseries obtained from HARPS and CARMENES data using a quasi-periodic kernel. This yields a estimate of GJ581's stellar rotation period, $P_{\rm rot} = 132^{+1.82}_{-1.71}$, improving the accuracy compared to the literature value. The Hα index timeseries with the GP models is shown in Fig. 1.

In addition, we applied GP modeling on the S-index timeseries obtained from HARPS and HIRES. Employing the same kernel and hyperparameter priors, this analysis yielded an estimate for the stellar rotation period of $P_{\rm rot} = 130^{+4.52}_{-3.75}$, which aligns well with the value derived from our Hα modeling.

4. Doppler measurements and orbital analysis

4.1. Identifying periodic signals

For the RV analysis, we employed the Generalized Lomb-Scargle (GLS) periodogram (Zechmeister & Kürster, 2009) to the RVs and residuals, as depicted in Fig. 2. This analysis successfully identified periodic signals corresponding to planets b, c, and e, with orbital periods of 5.368862 ± 0.00007, 12.9181 ± 0.0014, and 3.14893 ± 0.00015 days, respectively. Furthermore, it was detected a periodic signal with an orbital period of 66.263 ± 0.098 days, attributed to planet d, which is of particular interest. Notably, the periodogram does not exhibit any additional significant signals that could be attributed to the other planetary candidates from the

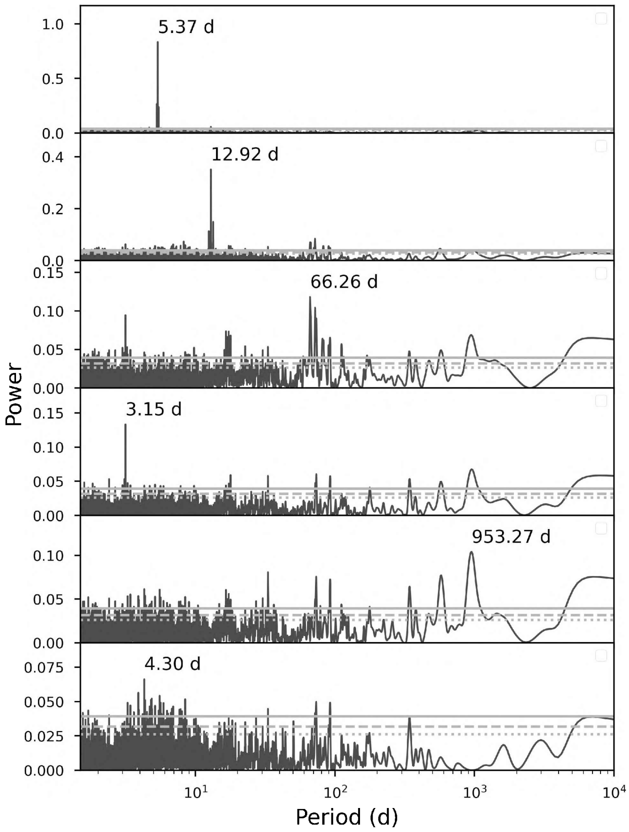

Fig. 2. GLS periodograms of GJ581 RV time series and residuals. The gray solid, dashed and dotted horizontal lines represent the 0.3%, 4.6%, and 31.7% False Alarm Probability (FAP) levels corresponding to a 3σ, 2σ, and 1σ detection threshold, respectively.

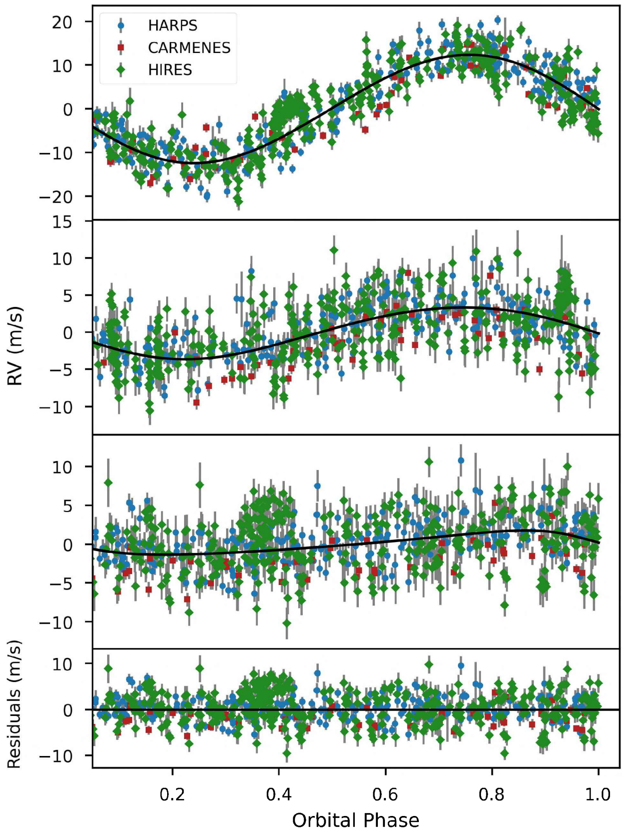

Fig. 3. *Top Three Panels:* Phase-folded RV curves for planets b, c, and e in the GJ581 planetary system, derived from HARPS (blue circles), HIRES (green diamonds), and CARMENES (red squares) datasets. The black lines in each panel represent the best-fitting RV models. *Bottom Panel:* Residual of the 3-Keplerian model.

literature: f(P_{orb} : 433d) and g(P_{orb} : 36.6d), as shown in the last two panels of Fig. 2.

4.2. Keplerian Models

We utilized a 3-Keplerian model to analyze the radial velocity data for the initial three planetary companions orbiting GJ581, employing the Pyaneti software (Barragán et al., 2022). The model incorporates uniform priors for all orbital parameters, including orbital period (P), time of inferior conjunction (T_{conj}), parametrization of eccentricity (ew_1 and ew_2), argument of the periastron (ω), and the semi-amplitude of the RV curve (K). To transform K into the planetary masses we assume a stellar mass of 0.31 ± 0.02 $M_{\odot}$ (Encyclopaedia of exoplanetary systems*). These parameters were fitted by using the Monte Carlo Markov Chain method included in Pyaneti.

In Figure 3, we present the phase-folded RV curves for the planets with orbital periods of 3.15 days, 5.37 days, and 12.9 days.

Furthermore, Table 1 provides some of the orbital parameters for the respective planets within the GJ581 planetary system, derived from the Keplerian model applied to the combined RV dataset.

4.3. Temporal Stability Analysis

We analyzed the temporal stability of the residual signal of the 3-Keplerian model using the stacked Bayesian Lomb-Scargle (sBGLS) periodogram, as introduced by Mortier & Collier Cameron (2017). This analysis is based on the principle that stellar activity signals are variable and incoherent. The underlying concept is that the power or probability of a periodic signal being present in the data, particularly a planetary signal, should increase as more observations are added. The top panel of Figure 4 depicts the sBGLS periodogram of the RVs of GJ58 around the orbital period of planet b (5.3 days). As expected, the level of confidence in the detection of a planetary signal increases as more data is added.

However, bottom panel of Fig.4 shows the sBGLS periodogram of the residual signal from Fig. 3. Notably, the probability associated with the 66-day signal attributed to planet d does not consistently increase with the growing number of observations. Instead, an

*https://exoplanet.eu/catalog/gj_581_b--301/#publication_8432

Table 1. Orbital period (P), Semiamplitude (K), eccentricity (e), and mass (M_p) values of each confirmed planet in the GJ581 system, derived from the 3-Keplerian model using the latest dataset.

Parameter	**GJ581 b**	**GJ581 c**	**GJ581 e**
Period [days]	5.36861 ± 0.00002	12.91800 ± 0.00042	3.14880 ± 0.00004
K [m/s]	12.39 ± 0.07	3.49 ± 0.07	1.5 ± 0.1
e	0.0274 ± 0.0058	0.0601 ± 0.0235	0.3075 ± 0.0537
M_p ($M_\oplus$)	15.5 ± 0.6	5.8 ± 0.2	1.56 ± 0.08

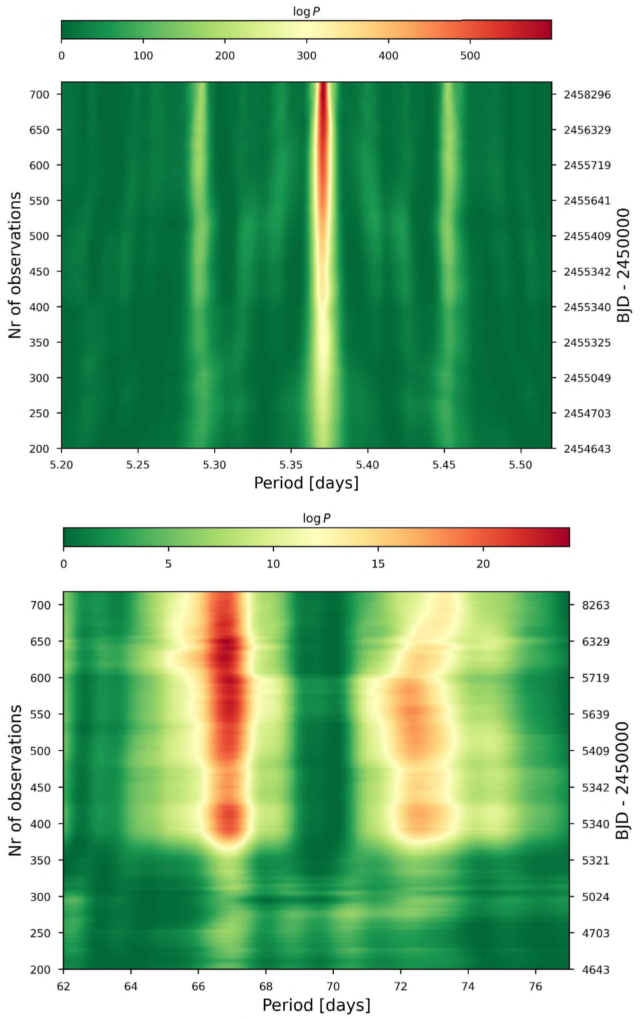

Fig. 4. *Top:* sBGLS periodogram of the RV time series of GJ581 around 5.3 days. *Bottom:* sBGLS periodogram of the third RV residuals around 68 days. The number of observations is plotted against period, with the color scale indicating the logarithm of the probability, where redder is more likely.

irregular pattern emerges, accompanied by another signal around 72 days, suggesting the presence of a signal induced by stellar activity.

5. Discussion and Future work

While our analysis suggests that the periodic signal attributed to planet d may not originate from a planetary source, but rather indicates the presence of a signal induced by stellar activity, a conclusive determination requires further statistical analysis. Additionally, planets b, c, and e exhibit consistent and coherent signals in our analysis, aligning with planetary signals expectations, which supports their existence. The next step is to conduct a simultaneous Keplerian model and activity indicator analysis using Gaussian Process regression with a quasi-periodic kernel. This approach aims to discern whether the observed periodic signal d can be accurately described by stellar activity.

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