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Analysis of transits and habitability of exoplanets with Pico dos Dias Observatory

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Abstract. The question of the existence of life beyond Earth has driven astrophysical research, with the search for extraterrestrial life focusing on exoplanets. The Habitable Zone (HZ) is a key concept, based on our knowledge of Earth, that indicates the orbital region in which the temperature could permit liquid water on the surface of a planet with an atmosphere, assuming inner and outer edges of 100 and 0 °C, respectively. Detecting transits using differential photometry is an effective technique for identifying and characterizing exoplanets, allowing for the estimation of parameters such as the planetary radius relative to the star and the orbital period. In 2024 and 2025, we observed planetary transits at the Pico dos Dias Observatory (OPD/LNA) with the 1.6m Perkin-Elmer telescope and the SPARC4 instrument (griz bands - SDSS). Targets were selected via ExoClock, with priority given to terrestrial planets orbiting red dwarf stars, which are relevant for the search for potentially habitable exoplanets, such as L 98-59d and GJ 1132b. Gas giants, such as Qatar-2b, were also observed to optimize telescope time management. By using the BATMAN (Kreidberg, 2015) and ECLIPSE (Valio, 2003) codes, we obtained a mean radius for Qatar-2b of $R_p = 1.25 \pm 0.01 R_J$ in griz (BATMAN). We also detected a stellar spot with a mean radius of $R_{spot} = 14842 \pm 1115$ km and a mean color temperature of $T_{color} = 3435 \pm 231$ K in griz (ECLIPSE). Such results are crucial for the accurate characterization of exoplanets and contribute to the knowledge base of planetary populations, providing support for future investigations into habitability.

Resumo. O tema da existência de vida fora da Terra tem impulsionado a pesquisa astrofísica, com o foco da busca por vida extraterrestre nos milhares de exoplanetas descobertos orbitando outras estrelas, para além do Sistema Solar. A Zona Habitável (ZH) é um conceito-chave que indica a faixa orbital em que a temperatura pode permitir água líquida na superfície de um planeta com atmosfera, considerando bordas interior e exterior de 100 e 0 °C, respectivamente. Embora a definição de ZH tenha um viés terrestre, os reais limites para a vida cósmica são desconhecidos, tornando a caracterização de exoplanetas, em relação a seus interiores, superfícies e atmosferas, um passo fundamental. A detecção de trânsitos por fotometria diferencial é uma técnica eficaz para identificar e caracterizar esses mundos, permitindo estimar parâmetros como o raio planetário em relação à estrela e o período orbital. Em 2024 e 2025, observamos trânsitos planetários no Observatório do Pico dos Dias (OPD/LNA) com o telescópio 1,6m Perkin-Elmer e o instrumento SPARC4 (bandas griz - SDSS). Os alvos foram escolhidos via ExoClock, com prioridade para planetas terrestres de estrelas anãs vermelhas (tipos K e M), relevantes para a busca por exoplanetas potencialmente habitáveis, como L 98-59d e GJ 1132b. Gigantes gasosos, como Qatar-2b, também foram observados para otimizar o tempo de telescópio. Aplicando os códigos BATMAN (Kreidberg, 2015) e ECLIPSE (Valio, 2003), obtivemos um valor médio do raio de Qatar-2b de $R_p = 1,25 \pm 0,01 R_J$ em griz (BATMAN), e também detectamos uma mancha estelar de raio médio $R_{spot} = 14842 \pm 1115$ km e temperatura de cor média $T_{spot} = 3435 \pm 231$ K em griz (ECLIPSE). Tais resultados são cruciais para a caracterização precisa de exoplanetas e contribuem para a base de conhecimento sobre a população planetária, fornecendo subsídios para futuras investigações sobre habitabilidade.

Keywords. Planet-star interactions – Stars: activity – Astrobiology

1. Introduction

Over the last few decades, scientific attention on exoplanets—planets orbiting stars outside the Solar System—as potentially habitable environments has expanded due to the increasing number of discoveries: 6061 confirmed as of 12/11/2025 (NASA Exoplanet Science Institute). Furthermore, the diversity in the architecture of planetary systems and the estimated existence of billions of rocky planets in the Milky Way justify the importance of considerable investments in giant telescopes and satellites dedicated to the detection and characterization of these worlds, such as the future PLATO (PLAnetary Transits and Oscillations of stars) mission, in which Brazil participates.

Planets with approximately 2 terrestrial radii ($R_\oplus$) and 10 Earth masses ($M_\oplus$), depending on their density, are classified as super-Earths or sub-Neptunes (Lichtenberg & Miguel, 2025). This boundary between rocky and gaseous objects accounts for the majority of planets in the Galaxy. Despite this, exoplanet detection methods, such as planetary transits and radial velocities, have an observational bias toward planets with large radii that are closer to the host star, as they are more easily identified. For example, Hot Jupiters possess dimensions comparable to Jupiter but orbital periods of only a few days.

In this work, we present some results for the transit event of the gas giant Qatar-2b observed in 2024, analyzed in the author's Master's dissertation (Bellecerie-Fonseca, 2025).

2. Detecting exoplanets: transits

Among the various methods for detecting and confirming exoplanets, the photometric transit method is the most successful. It consists of monitoring the light curve of a star during a planetary eclipse event, which occurs when the planet transits the stellar disk. Various system parameters, such as mass, radius, and orbital period, can be obtained by combining transit results with those from the radial velocity method.

A transit is defined by the relationship between its depth—the flux variation in the stellar light curve ΔF_*—and the planetary radius relative to its star R_p/R_* (Equation 1). Stellar heterogeneities such as spots and faculae, which are consequences of magnetic activity, may be detected during observations, especially during deep transit events.

$$\text{Depth} = \Delta F_* = \left(\frac{R_p}{R_*}\right)^2 \quad (1)$$

In 2024 and 2025, we selected targets for multi-band photometry via the the international collaborative ExoClock project (Kokori et al., 2023), which supports the preparation of the ESA's ARIEL mission. Observations were carried out using the 1.6m Perkin-Elmer telescope equipped with the SPARC4 instrument (Simultaneous Polarimeter And Rapid Camera in 4 bands) (Rodrigues et al., 2024), which features four cameras covering bands corresponding to the griz filters of the SDSS (Sloan Digital Sky Survey). Priority was given to Earth-sized and super-Earth planets orbiting red dwarf stars (spectral types K and M), though gas giant transits were also observed to optimize the available telescope time. Data reduction was conducted using the SPARC4 pipeline (Martioli et al., 2025), including bias and flat-field calibration, and differential photometry.

For all targets, transit modeling with the BATMAN (Kreidberg, 2015) and ECLIPSE (Valio, 2003) codes in Python yielded precise estimates of the planetary radius, inclination, and mid-transit times, which were compared with literature values. Figure 1 shows the i' band observation of the Qatar-2b transit on 04/27/2024, fitted with BATMAN. Figures 2 and 3 show the results in the r' band using the ECLIPSE code, applied with Markov-Chain Monte Carlo (MCMC) using 70 walkers, 200 iterations, and 50 burn-in interactions.

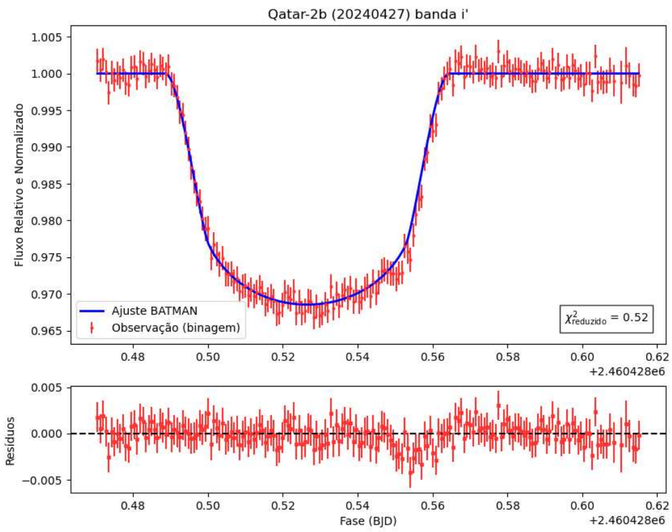

Figure 1. BATMAN fit in the i' band with respective residuals for the binned data of stellar normalized flux as a function of the phase observed in BJD.

The planet is a Hot Jupiter orbiting a red dwarf star with an effective temperature of T_{eff} = 4645 ± 50 K (Yalçınkaya et al., 2024) and a mass of M_* = 0.743 ± 0.021$M_\odot$ (Mancini et al., 2024). Mancini et al. (2014) and Močnik (2017) observed multi-wavelength transits and detected spots on the host star. We confirmed the Jupiter-like dimensions of Qatar-2b (Table 1) and

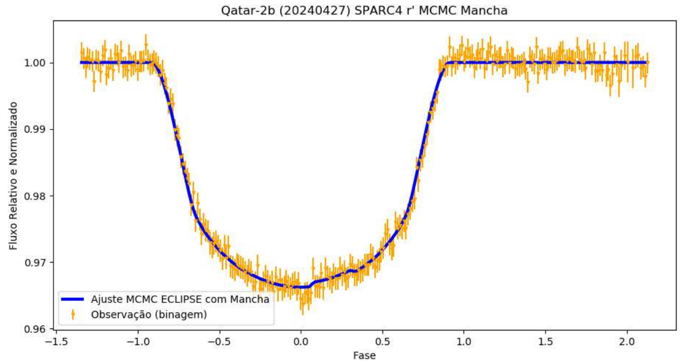

Figure 2. ECLIPSE fit in the r' band for 70 walkers, 200 iterations, and 50 burn-in interactions. The normalized flux is binned and shown relative to the transit phase; a spot is observed shortly after the midpoint.

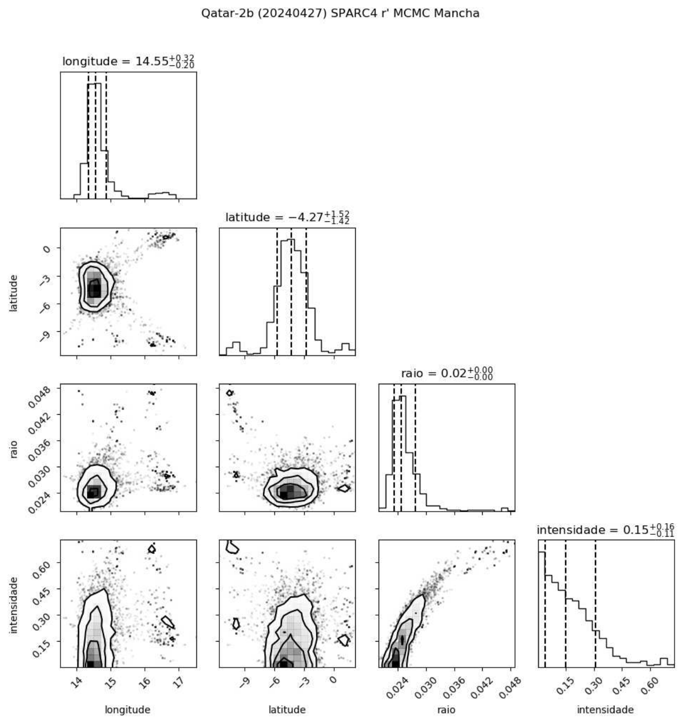

Figure 3. Corner plot of the ECLIPSE fit in the r' band for 70 walkers, 200 iterations, and 50 burn-in interactions. Results are shown for the latitude and longitude of the spot (in degrees), and the radius and intensity relative to the stellar radius and mean stellar disk intensity.

detected a stellar spot shortly after the transit midpoint (Figure 2 and Table 2). Additionally, we analyzed the variation of transit depth relative to the observed band; a larger R_p was found in the g' band than in the redder bands, suggesting an atmosphere dominated by hydrogen molecules (H_2) and helium atoms (He), consistent with Mancini et al. (2014).

3. Conclusions and perspectives

Our findings on transit observations of terrestrial and gas giant planets using the ground-based 1.6m telescope at Pico dos Dias Observatory demonstrate the high photometric performance achievable with SPARC4. These observations provide updated transit parameters for the ExoClock database and contribute to

Table 1. Results of BATMAN e ECLIPSE codes for Qatar-2b. R_p (R_J) is the planetary radius in comparison to Jupiter and i is the orbital inclination of the orbit.

	R_p (R_J)		i (°)	
Reference	1.254 ± 0.013	Mancini et al. (2014)	86.12 ± 0.08	Mancini et al. (2014)
SPARC4	BATMAN	ECLIPSE	BATMAN	ECLIPSE
g'	1.254 ± 0.013	$1.323^{+0.022}_{-0.015}$	89.49 ± 0.45	$86.90^{+0.45}_{-0.57}$
r'	1.248 ± 0.013	$1.257^{+0.002}_{-0.001}$	88.41 ± 0.21	$89.21^{+0.19}_{-0.56}$
i'	1.243 ± 0.013	$1.251^{+0.005}_{-0.017}$	87.74 ± 0.25	$88.59^{+0.34}_{-0.29}$
z'	1.245 ± 0.013	$1.237^{+0.007}_{-0.006}$	88.26 ± 0.28	$88.77^{+0.46}_{-0.97}$

Table 2. ECLIPSE results for the modeled stellar spot in Qatar-2, including radius R_{spot} and color temperature T_{color} in each observed band.

SPARC4	R_{spot} (km)	T_{color} (K)
g'	24294^{+4614}_{-2388}	3642^{+472}_{-314}
r'	13496^{+1775}_{-1208}	3374^{+540}_{-362}
i'	13496^{+5048}_{-1742}	3349^{+540}_{-529}
z'	14576^{+2877}_{-1753}	3243^{+536}_{-479}

our understanding of planetary populations and the broader investigation of habitability. During the PhD project, we aim to characterize more exoplanets by conducting multi-wavelength observations with SPARC4, spectroscopy with the SOAR telescope, and analyzing data from the PLATO satellite.

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