S384 - TMA03

Time-Series Photometric Analysis of XO-2Nb from the S384 Observing Campaign

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1 Abstract

This report presents a photometric analysis of the transiting exoplanet XO-2Nb using time-series observations from the PIRATE telescope. The dataset was processed with HOPS to generate a light curve, and transit modelling yielded an orbital period $P_{ORB} = 2.61585982$ days, mid-transit time $T_{mid} = 2460700.47875 \pm 0.00038$, planet-to-star radius ratio $R_p/R_* = 0.1013 \pm 0.0010$, inclination $i = 88.0°$, and scaled semi-major axis $a/R_* = 7.93$. Assuming a stellar radius of $R_* \approx 0.97\,R_\odot$, the planetary radius was estimated as $R_p \approx 0.98\,R_{Jup}$. The final light curve displayed minimal red noise and an autocorrelation coefficient of 0.14, confirming the robustness of the fit. While no anomalies were detected, the results contribute to the long-term monitoring of XO-2Nb and confirm the suitability of PIRATE and HOPS for exoplanet transit studies.

2 Introduction

Transiting exoplanets are a cornerstone of modern planetary science, offering insight into stellar structure and properties. Several exoplanet detection techniques have been developed, the most widely used being the transit method, which measures periodic dips in stellar brightness as a planet crosses its host star, and the radial velocity method, which detects Doppler shifts in a star's spectral lines. Other approaches such as direct imaging, astrometry, and gravitational-microlensing all allow for a detection of exoplanets with a range of orbital distances, masses, and system geometries, outside of what can be measured by the main two methods. The objective of this project was to confirm the transit parameters of XO-2Nb using new photometric data obtained using the PIRATE telescope and HOPS, while still keeping an understanding of uncertainties and limitations of the dataset.

This investigation focuses on XO-2Nb, a well characterised hot Jupiter orbiting the K-dwarf XO-2N, part of the XO-2 wide binary system. Discovered via transit photometry in the XO survey by Burke et al. (2007), XO-2Nb has a short orbital period of $P_{ORB} \approx 2.6$ days, mass $M \approx 0.57 M_{Jup}$, and radius $R \approx 0.97 R_{Jup}$. The transit depth and high inclination angle produce a typical U-shaped curve indicative of a near-central transit. The exoplanet's orbital properties were later refined by Damasso et al. (2015) using HARPS-N radial velocity data, which confirmed orbit shape using eccentricity values and improved constraints on the stellar and planetary parameters.

XO-2N, the host star, is a metal rich late-G/early-K dwarf with a temperature $T_{eff} \approx 5332$K (Damasso et al. 2015), radius $R \approx 0.976 R_\odot$ (Sing et al. 2012), and metallicity $[Fe/H] \approx +0.45$ (Burke et al. 2007). It resides in a rare wide binary configuration with XO-2S, located $31''$ (arcseconds) away from each other. Both stars are known to host planetary systems, offering a unique comparative framework for studying planet formation in chemically similar environments. Teske et al. (2013) performed an elemental abundance analysis of both stars, finding abundances of not only carbon and oxygen, but also iron and nickel, which contribute to the high metallicity values given above.

While XO-2Nb is dynamically similar and shares many properties with other well-known hot Jupiters, its presence in a binary where both stars host planets makes it uncommon. The Rossiter-McLaughlin effect observations performed by Narita et al. (2011) suggest a small eccentricity consistent with zero, and a likely spin orbit alignment of the exoplanet, also confirming an inclination value $i \sim 90°$. Transmission spectroscopy by Sing et al. (2012), combined with narrowband photometric measurements placed XO-2Nb as the first hot Jupiter with evidence of both sodium and potassium in its atmosphere. The combined findings from observations performed of this exoplanet and its system make it incredibly unique and worth exploring further.

3 Method

The primary dataset selected for this analysis was obtained on the night of the 24th of January 2025, through utilisation of the PIRATE telescope and spans approximately 9.5 hours of continuous observation, which includes coverage of both pre-ingress and post-egress, essential for the purposes of baseline correction. The dataset was chosen for being comprehensive and of high quality, providing the best results throughout all of the observing nights assigned to my team. It was comprised of 571 FITS images taken with an R filter, each with a 50.0s exposure time, beginning at 19:58, and ending at 05:38 the next morning.

Initial calibration of raw frames was conducted using common reduction techniques such as bias correction, flat fielding and alignment. These steps were handled within HOPS using reference master frames from a set of calibration frames. The light curve extraction was performed using HOPS, where an ensemble of comparison stars was manually selected using data from SIMBAD and the HOPS interface, with selection criteria focused on proximity to the target star, similarity in magnitude (ΔMag within ± 0.25) and colour ($\Delta Colour$ within ± 0.05), as well as photometric stability. A breakdown of the selected comparison stars can be seen in Table 1:

Table 1: Comparison star choice for XO-2Nb

Star Name	**Gmag**	**GBP–GRP**	ΔMag	ΔColour	**Stability**
XO-2Nb	11.18	0.84			Stable
XO-2Sd	11.09	0.85	0.09	0.01	Stable
TYC 3413-187-1	11.35	0.84	0.17	0.00	Stable
TYC 3413-11-1	11.40	0.87	0.22	0.03	Stable
TYC 3413-319-1	11.34	0.84	0.16	0.00	Stable
TYC 3413-104-1	11.28	0.83	0.10	0.01	Stable

Differential aperture photometry was carried out using an aperture radius of 12.0 for the target and each comparison, selected manually to encompass the the entire stellar profile while minimising background contamination. Utilising the built-in HOPS MCMC transit fitting tool, detrending functions were applied in order to reduce the impact of airmass variations and any background discrepancies that may have occurred. The resulting model produced an initial best fit, from which key parameters were explored using 5,000 MCMC iterations. Key transit parameters fitted include the mid-transit time T_{mid}, radius ratio R_p/R_*, inclination i, and scaled semi-major axis a/R_*. The quality was evaluated and the autocorrelation coefficient examined to ensure it fell within the permitted thresholds.

In order to further refine the image, adjustments were made to discard any frames displaying significant tracking errors, cloud cover effects or distorted PSFs, and an evaluation of the comparison planet selection and aperture settings was performed to improve autocorrelation values and maximise the stability of the extracted light curve.

4 Results

The final detrended light curve derived for XO-2Nb displays a clear, symmetric, U-shaped transit profile, which is typical of a hot Jupiter crossing a main sequence K-dwarf star. This aligns with expectations and previously published observations of the system from Burke et al. (2007) and Damasso et al. (2015), affirming the reliability of observational data. The light curve was produced after careful calibration of the raw dataset, where I decided to exclude a total of four frames of lower quality, all exhibiting anomalies, but found the choice of comparison stars and aperture settings to be satisfactory, as any other choice produced significantly higher autocorrelation values. The final photometry is presented in Figure 1, revealing a clean transit, with both ingress and egress well-resolved.

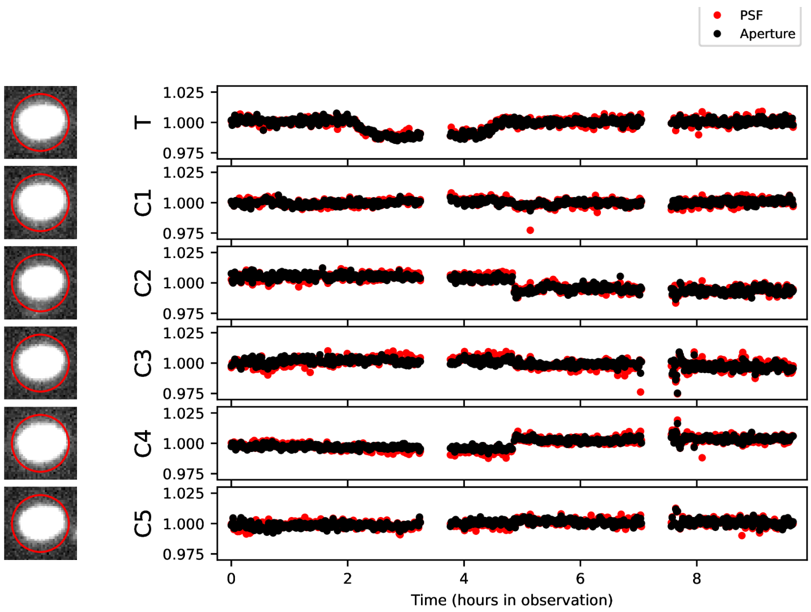

Figure 1: Final Photometry

As a means of enhancing the overall light curve symmetry and minimising residuals, comparison stars C2 and C4 were eliminated due to their divergent trends. The remaining comparisons showed photometric stability, and the best fit model demonstrates low scatter with no significant correlated noise, confirmed by an autocorrelation of 0.14. The final fitting, shown in Figure 2, shows excellent agreement with the observed data, and confirms that the chosen aperture and detrending parameters were appropriate.

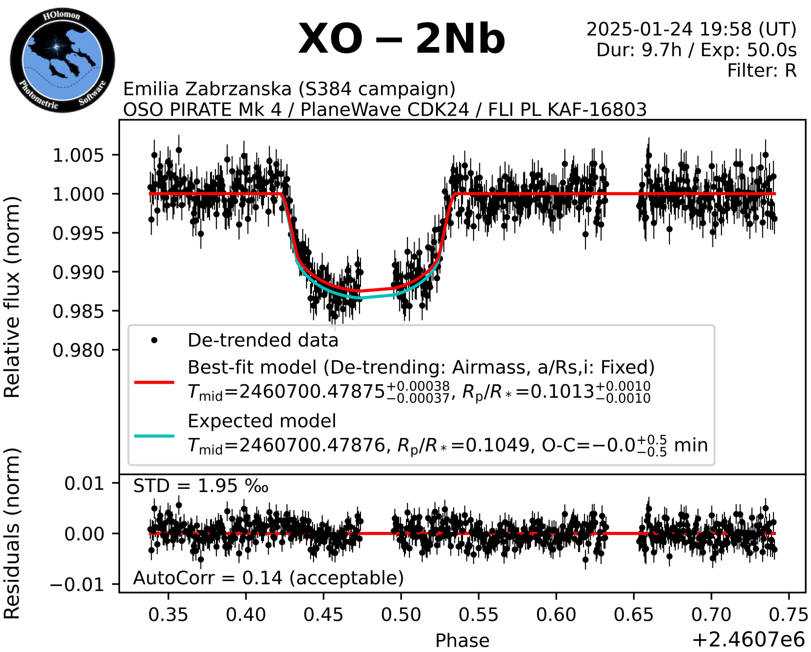

Figure 2: Detrended Model

In this analysis, several orbital parameters were established, allowing for direct comparison with values reported in literature. The orbital period was set to $P_{ORB} = 2.61585982$ *days*, in excellent agreement with the values of $P(d) = 2.61585922 \pm 0.00000028$ from Damasso et al. (2015), and $P(d) = 2.61586178 \pm 0.00000075$ from Sing et al. (2012). Both sources match to within a few microseconds, reflecting the high precision of our values, and the stable nature of XO-2Nb's orbit across multiple epochs. While the mid transit time of $T_{mid} = 2460700.47875 \pm 0.00038$ did differ from that reported by Sing et al. (2012), (BJD 2455981.46036 ± 0.00013), this can be expected due to the time between observations. The inclination of $i = 88.0°$ however, is consistent with the high values speculated by Narita et al. (2011) and aligns well with values of 87.96° from Damasso et al. (2015) and 88.8° from Sing et al. (2012). This supports the observed flat-bottomed transit shape we see in Figure 2, and coupled with our fixed eccentricity of zero, is consistent with XO-2Nb having a circular orbit. The scaled semi-major axis was also fixed, at $\frac{a}{R_*} = 7.93$, which closely matches the value of 7.928 reported by Damasso et al. (2015).

A key fitted parameter was the planet to star radius ratio, $\frac{R_p}{R_*} = 0.1013 \pm 0.0010$, which translated to a transit depth of:

$$\delta = (\frac{R_p}{R_*})^2 \tag{1}$$

$$\delta = (0.1013)^2 \approx 0.0126 \tag{2}$$

This 1.26% fractional dimming is in agreement with the 1.10% reported by Damasso et al. (2015), falling well within the expected range for hot Jupiters.

Assuming a stellar radius of $R_* = 0.97\, R_\odot$, the planetary radius is therefore:

$$R_p = 0.1013 \times 0.97\, R_\odot \approx 0.98\, R_{\text{Jup}} \tag{3}$$

This is consistent with the previously published value of $0.98 \pm 0.03\, R_{\text{Jup}}$ by Burke et al. (2007).

Overall, the fixed, fitted, and derived parameters, along with the resulting transit geometry, show excellent consistency with the physical and observational expectations for a gas giant. The model reproduces the key features of the light curve with accuracy, and the parameters obtained are tightly aligned with those reported previously. The short orbital period, absence of detectable eccentricity, and large planetary radius all reinforce confidence in the reduction and modelling process employed in this investigation. Taken together, these demonstrate the robustness of the data quality and methodology, confirming the observations are reliable and precise.

5 Conclusions

The analysis of XO-2Nb produced a radius ratio, inclination, and derived planetary radius closely matching literature values, with all key fitted parameters falling within the expected uncertainties of those reported by Burke et al. (2007) and Damasso et al. (2015), not only confirming the robustness of the current analysis, but also reaffirming its classification as a typical hot Jupiter. The symmetric, U-shaped light curve produced using PIRATE and modelled with HOPS confirms the reliability of both the observational setup and the data reduction process, while the low autocorrelation coefficient validates the quality of the photometric extraction and fitting.

Although no anomalies were detected, this dataset extends the observational baseline for XO-2Nb and contributes to its long-term monitoring. The rejection of frames affected by tracking issues, and the exclusion of unsuitable comparison stars underscore the importance of careful data selection and reduction in ground-based photometry. Some assumptions were made during modelling, included fixing the orbital eccentricity to zero and not fitting any darkening coefficients, due to the exclusion of dark frames from the calibration set. The analysis was also limited by the use of single band photometry, as only R-band images were available for consideration.

These results highlight the effectiveness of the PIRATE telescope and HOPS for exoplanet transit analysis. Future work could focus on multi-band transit observations, repeated monitoring across epochs, or joint analyses with radial velocity data to further refine planetary properties.

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6 Part B

6.1 Describe how in your view the teamworking phase of the project affected the findings you reported on in Part A. (3 marks)

I believe the team working phase played an important role in shaping the findings reported in Part A. In weeks 1 and 2 of the project, although each pair assigned to the observing nights was given complete freedom in their initial target selection, our group collaborated well to finalise a list of suitable targets through active forum discussions and a dedicated team meeting. Everyone contributed constructively, offering feedback and support, which enhanced my understanding of the project goals and strengthened my confidence going into the data-analysis phase of the project.

6.2 Reflect on the data-analysis phase of the project where you worked for yourself, and contrast this with the planning phase of the project where you worked as a member of a team. Which approach was more beneficial, and why? (3 marks)

While I believe both phases had their strengths, the data-analysis phase was more beneficial for my personal development, especially in terms of skills gained and confidence building. I became proficient in using HOPS and troubleshooting any issues that arose, as well as being able to carefully plan out my time and work to what worked best for me, not having to conform to my team. The autonomy and hands on practice obtained were helpful at illustrating what my future work may be like for my postgraduate degree and any further research I undertake.

6.3 If you could change one element of the observational astronomy project, what would that be, and why? (4 marks)

If I could change one thing, it would be to introduce more individual checkpoints during the team working phase, as while forum discussions and meetings were helpful, contributions were uneven at times, leading to delays in compiling final target shortlists. I think laying out clearer expectations of what each person has to do would improve efficiency of the collaborative process and reduce pressure on more engaged team members. This could also be the option of working completely individually, as while I could get heavily involved during the first week of the project, I was unable to meet with the team during any of their proposed times in week 2, leaving me to catch up on what had been discussed in my absence.