

Understanding the Structure and Starspot of the TOI-3884 System through Spot-Crossing Transits

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Spot-crossing transits, where a planet crosses in front of the host star's spots, provide a rare opportunity to directly investigate the temperature, size, and distribution of spots. However, such events are typically random and difficult to observe intentionally. Among these, the TOI-3884 system, where a super-Neptune planet is orbiting a mid-M-dwarf, is a unique system in which the transit light curves persistently exhibit spot-crossing features. This is due to the unique configuration of the system, where the stellar pole faces the observer, and the planet in a polar orbit transits in front of a large spot located near the pole. However, two previous studies on this system (Alemenara et al. 2023, Libby-Robert et al. 2024) have reported some parameter discrepancies. Moreover, the absence of stellar brightness variations in TESS light curves, which would be expected if a large spot exists near the pole, contributed to the uncertainty in understanding the system prior to our study.

To better understand the dynamical structure and spots' characteristics of the TOI-3884 system, we performed multiple transit observations of TOI-3884b using the MuSCAT series, optical multi-band photometers. Additionally, to obtain better quality stellar brightness modulation, we conducted optical photometric monitoring observations of the star TOI-3884 using the LCO 1m telescopes/Sinistro.

From the transit observations, we found time-dependent variations in the shape of the spot-crossing light curves, suggesting that the spot is not fixed at the pole but rather moves with the stellar rotation. Monitoring observations revealed that the star has a rotation period of ~ 11 days, with a brightness variation of around 3%, which aligns with the results from the spot-crossing transits. As a result, we resolved inconsistencies in previous studies and more precisely constrained the range of parameter values for the stellar inclination, spot position, and size. Additionally, simultaneous multicolor photometry confirmed that the spot temperature is ~ 200 K lower than the photospheric temperature.

The obtained constraints on the TOI-3884 system's structure and spot characteristics provide valuable observational insights for future observations, such as spectroscopic observations planned with JWST. Furthermore, this study's constraints on spot location and temperature are important, especially given the lack of general knowledge of typical spot characteristics for M-dwarfs. If TOI-3884 is not an exceptional star, this work suggests that large spots near the poles might be a common feature of such M-dwarfs. This has important implications for atmospheric studies of exoplanets, as the presence of polar spots could affect the atmospheric constraint from transmission spectroscopy. This work highlights the importance of further theoretical and observational investigations into the characteristics of starspots.

Keywords: Starspot, M-dwarf, TOI-3884, Transit