High-Precision Radial Velocity Analysis of GJ 3090: Improved Mass Constraints and Detection of a New Signal

Pierrot Lamontagne

Abstract

The characterization of planets orbiting M-dwarf stars has emerged as a crucial frontier in exoplanetary science, offering unique insights into planetary formation and evolution processes. These cool, low-mass stars, which constitute most of our galaxy's stellar population, present ideal targets for detecting and characterizing potentially habitable worlds. The measurement of precise radial velocities (pRV) for M-dwarf systems is particularly valuable, as it enables the determination of planetary masses—a fundamental parameter for understanding planetary composition and formation mechanisms.

This thesis presents a comprehensive analysis of the GJ 3090 system using high-precision radial velocity data from two complementary instruments: the High Accuracy Radial velocity Planet Searcher (HARPS) [1] and the Near Infrared Planet Searcher (NIRPS) [2]. HARPS, operating in the visible spectrum with a resolution of R$\sim$115,000, has been a pioneering force in exoplanet detection since 2003. NIRPS, which recently began operations in 2022, extends observations into the near-infrared (0.95-1.8 μm), making it particularly well-suited for M-dwarf observations. The synergy between these instruments, capable of simultaneous observations, provides a powerful tool for disentangling planetary signals from stellar activity.

Our analysis employs state-of-the-art techniques to address the challenging task of separating planetary signals from stellar activity. We implement a multidimensional Gaussian Process (GP) framework that simultaneously models RV variations and activity indicators, including TESS photometry from 4 sectors and the novel ΔT indicator [3] derived from the spectra. This approach allows us to robustly constrain stellar activity while preserving genuine planetary signals.

Through this analysis, we achieve two significant results: First, we substantially improve the mass determination of GJ 3090 b, reducing the relative uncertainty from 22% [4] to 11%. Combined with its radius, this reveals GJ 3090 b as a low-density mini-Neptune, suggesting the presence of a substantial atmosphere. This precise mass determination is particularly timely as ongoing James Webb Space Telescope (JWST) observations aim to characterize the planet's atmosphere. The improved bulk density measurement will significantly enhance the reliability of atmospheric retrievals and composition analyses. Second, we report the detection of an additional radial velocity signal in the system, which we interpret as evidence for a second planet. The statistical significance of this detection is thoroughly evaluated through model comparison and false alarm probability analysis.

These findings contribute to our understanding of planetary system architecture around M-dwarfs and demonstrate the capabilities of modern precise radial velocity instruments and analysis techniques. The improved mass measurement for GJ 3090 b not only provides valuable constraints for planetary formation theories but also establishes crucial context for atmospheric characterization efforts with JWST. The detection of an additional signal highlights the potential for discovering multi-planet systems around M-dwarfs through careful analysis of high-precision RV data.

References

1. Pepe, F. *et al.* in *Optical and IR Telescope Instrumentation and Detectors* (eds Iye, M. & Moorwood, A. F. M.) (SPIE, Aug. 2000). http://dx.doi.org/10.1117/12.395516.

2. Étienne Artigau *et al.* *NIRPS first light and early science: breaking the 1 m/s RV precision barrier at infrared wavelengths* 2024. arXiv: 2406.08304 [astro-ph.IM]. https://arxiv.org/abs/2406.08304.

3. Artigau, *et al.* *The Astronomical Journal* **168,** 252. ISSN: 1538-3881. http://dx.doi.org/10.3847/1538-3881/ad7b30 (Nov. 2024).

4. Almenara, J. M. *et al.* **665,** A91. arXiv: 2207.14121 [astro-ph.EP] (Sept. 2022).