How Does Spectral Resolution Influence Net Doppler Shifts?

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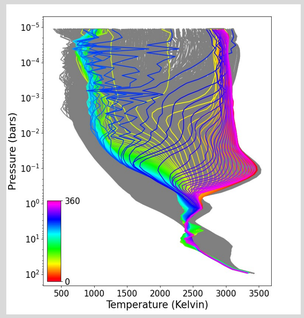
Introduction

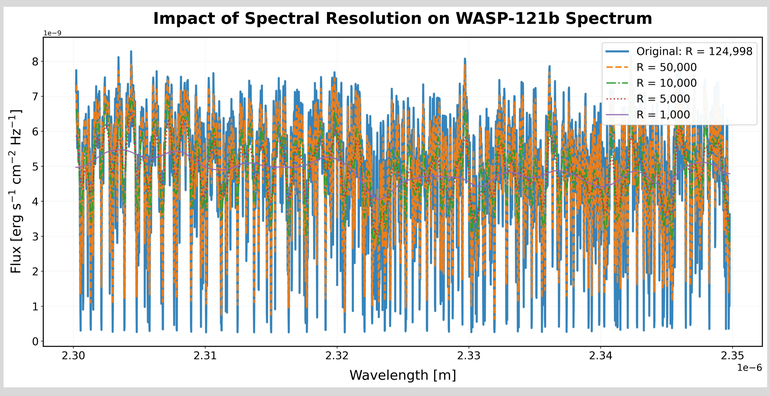
- Purpose: To investigate how spectral resolution and planetary magnetic fields influence our ability to measure the atmospheric dynamics in exoplanets
- We generate synthetic observations by post-processing 3D General Circulation Models (GCMs) (Rauscher & Menou, 2013), systematically degrading spectral resolution to assess its impact on wind retrievals.



Key Exoplanet Properties (Bourrier et al., 2020):

Mass	1.16 M_J
Radius	1.75 R_J
Orbital Period	1.27 days
Semi-Major Axis	0.026 AU
Equilibrium Temp	2350 K

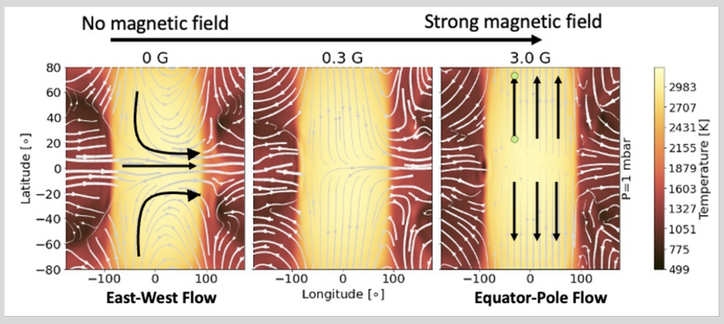
- Model: Pressure-temperature profiles of WASP-121b across longitude 0° to 360° (Beltz et al., 2024):
  - Strong dayside thermal inversion (0.1 - 10^{-3} bar) driven by TiO and VO absorption
  - The eastward equatorial jet presents on the both day and night sides
- Phase-resolved, high-resolution spectroscopy isolates the planet's Doppler shift signal:
  - Enables mapping of winds, chemistry, and temperature structure (Birkby, 2018)
  - Models are detrended to match instrumental resolution for direct composition



Left: Reduced resolution lowers detectable line numbers, affecting the measurement of Doppler shift

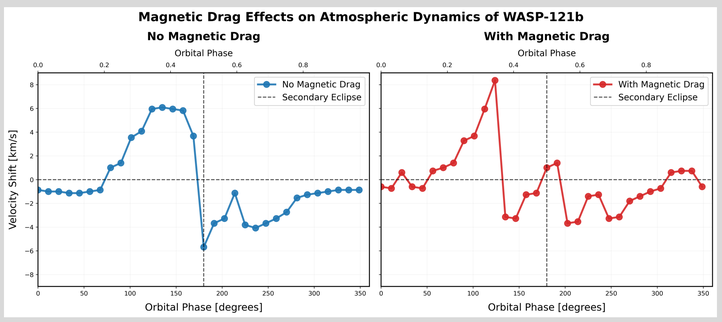
Cross-Correlation

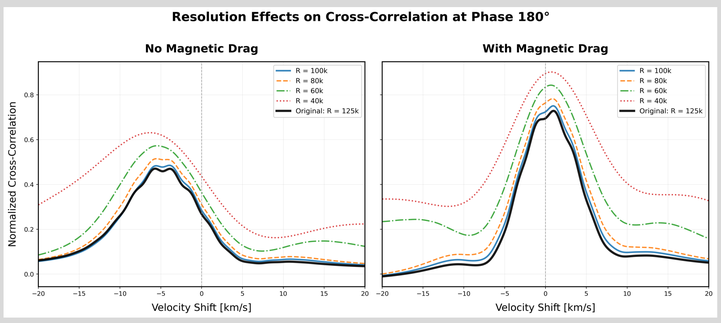
- Cross-correlation matches theoretical templates to observed data to detect exoplanet atmospheres (Birkby, 2018)
- Wind speeds are measured by matching between Doppler-off (static) and Doppler-on (including winds and rotations) spectra. The CCF peak indicates where features match best, showing the net wind speed
- Atmospheric models are compared between:
  - Drag-free (no magnetic field)
  - Drag-on (with magnetic field)
- Our approach is motivated by GCM studies which show that magnetic drag can slow atmospheric winds and alter global circulation patterns (Rauscher & Menou, 2013)



Left: Wind patterns under different magnetic field strengths (Beltz et al., 2024)

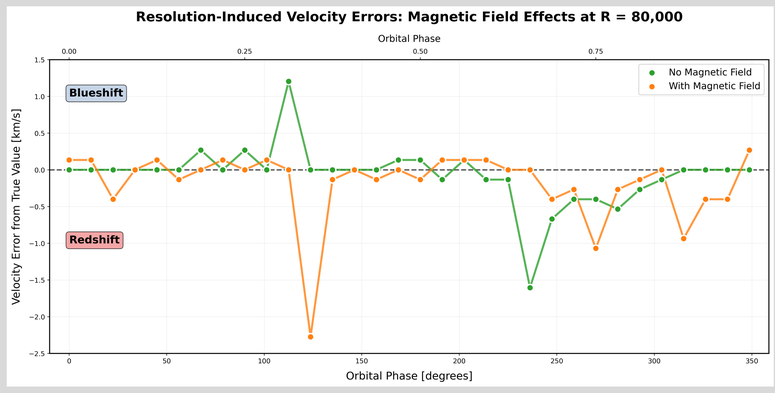
Right: Drag-free model shows smooth Doppler shifts from organized atmospheric flow. Magnetic drag model exhibits chaotic patterns from wind-expression



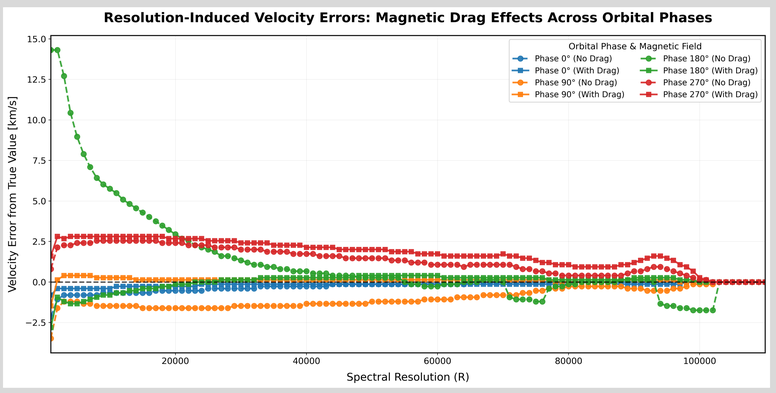


Left: Resolution effects: Lower spectral resolution broadens CCF peak, increasing detection strength at the cost of velocity precision

Phase-Resolved Doppler Shifts



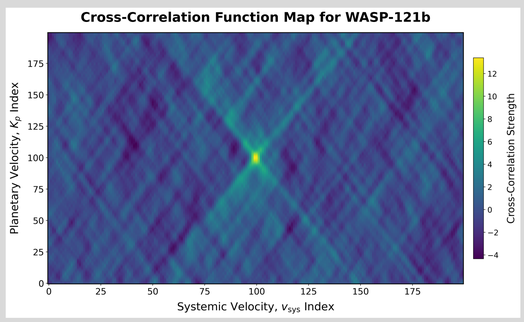
- Velocity differences show strong dependence on orbital phase and magnetic activity levels, with systemic variations across the orbit
- Magnetic drag produces larger velocity shifts compared to drag-free model and creates sharper, less predictable changes at specific phases
- Drag-free models maintain more consistent and smoother velocity variations throughout the orbital period



- Velocity retrieval errors increase significantly below R = 20k
- Magnetic drag suppresses wind variability, resulting in smaller, more consistent phase deviations

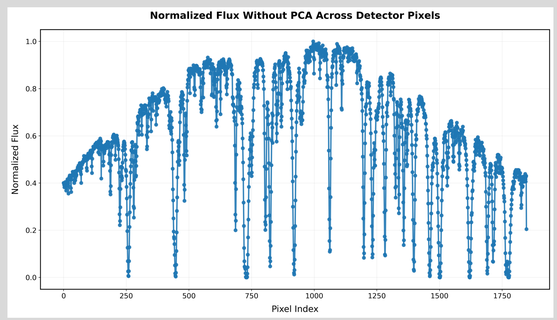
Scope Open-Source Package

- The planet's observed spectrum is convolved with several instrumental and atmospheric effects:
  - Radial Velocities: Doppler shifts from the planet's orbit and stellar motion
  - Blaze Function: Wavelength- and order- dependent grating efficiency (Kim et al., 2025)
  - Telluric Absorption: Atmospheric molecular absorption affecting ground-based observations (Smette et al., 2015)
  - Signal-to-Noise: Photon statistics and detector limitations
- All factors are modeled within the Scope package (Savel et al., 2025)
- Example of the Scope output:



Above: Cross-correlation function map showing the detection strength of WASP-121b across systemic and planetary velocities

Below: Transmission spectrum signal across package pixels before PCA detrending



Future Work

- Compare wind velocities from raw GCMs vs Scope-processed spectra
- Test different resolution values within the Scope framework
- Test different magnetic field strengths within the Scope framework
- Quantify biases by comparing retrievals from 1D and 3D atmospheric models

References

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- Birkby (2018), arXiv:1806.04617
- Bourrier et al. (2020) , A&A, 635, A205
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- Savel, A. B., Bedell, M., Kempton, E. M.-R., et al. 2025, arXiv:2411.07303
- Smette et al. (2015), A&A, 576, A77