How Does Spectral Resolution Influence Net Doppler Shifts?

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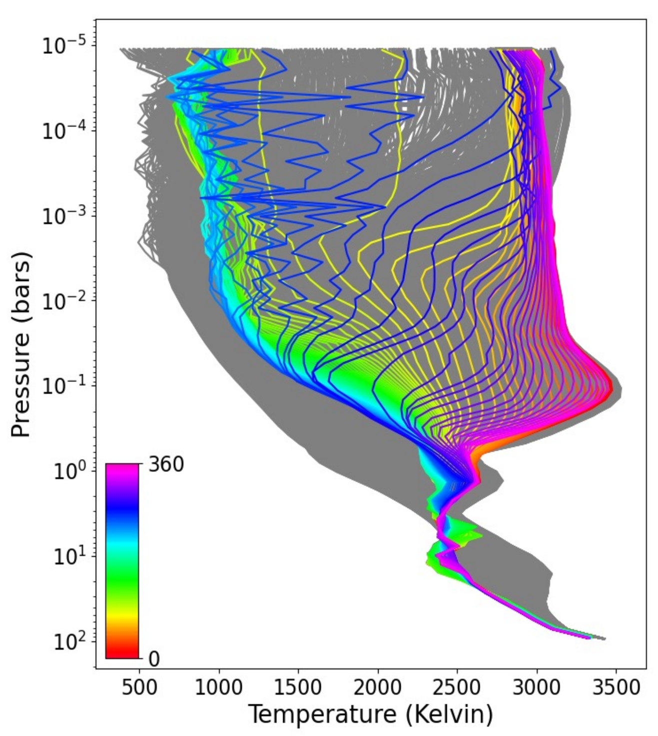
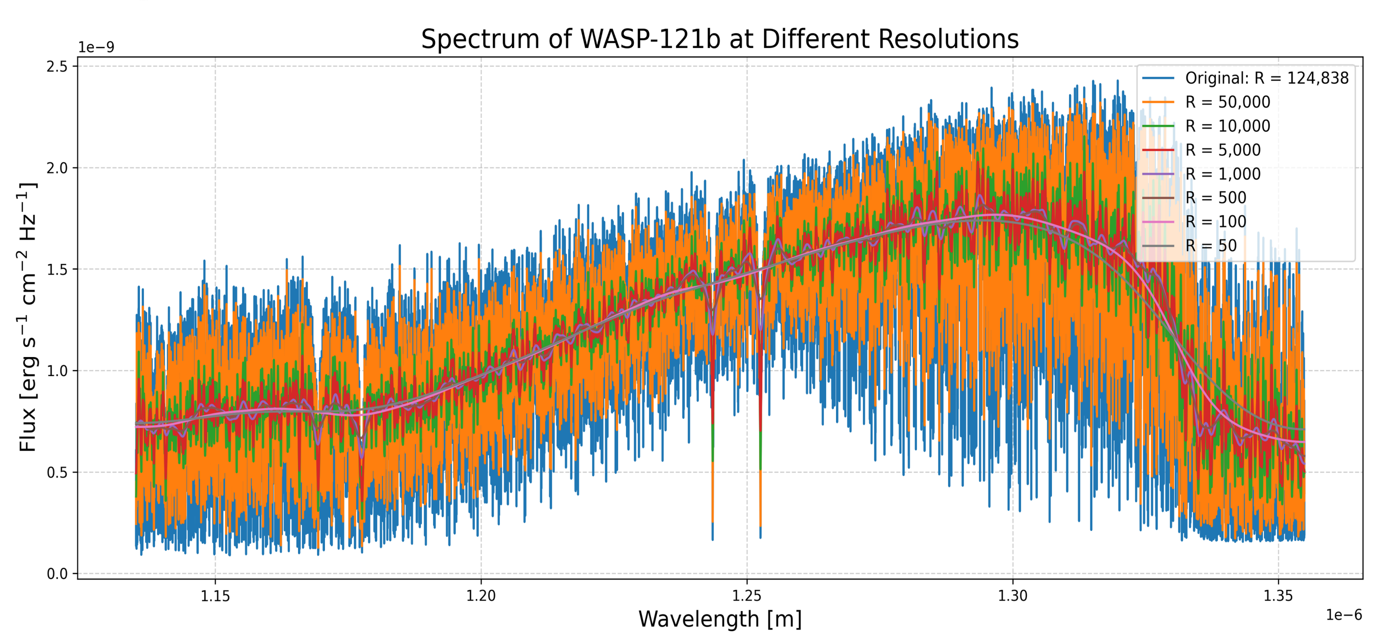
Introduction

- WASP-121b is an ultra hot Jupiter with a mass of 1.16 M_J and a radius of 1.75 R_J. It orbits its star every 1.27 days at a distance of 0.026 AU. Its equilibrium temperature is 2341.32 K (Bourrier et al., 2020).



Left: Pressure–temperature profiles of WASP-121b across longitudes from 0° to 360° (Beltz et al., 2024).
- A thermal inversion on the dayside between ~0.1 and 10^{-3} bar arises from the absorption of TiO (titanium monoxide) and VO (vanadium oxide).
- The eastward equatorial jet is present on both the day and night sides, driving the strongest wind speeds in the upper atmosphere.

- Thermal emission from the planet reveals its atmospheric composition and temperature structure (Birkby, 2018).
- Phase-dependent emission variations trace winds, thermal inversions, and magnetic effects.
- Exoplanet light is extremely faint compared to its star, making detection challenging.
- High-resolution spectroscopy separates the planet's light into many sharp lines unique to molecules, improving detection.
- Because many instruments have a range of resolution, scientists smooth high-resolution model to match the measurements.

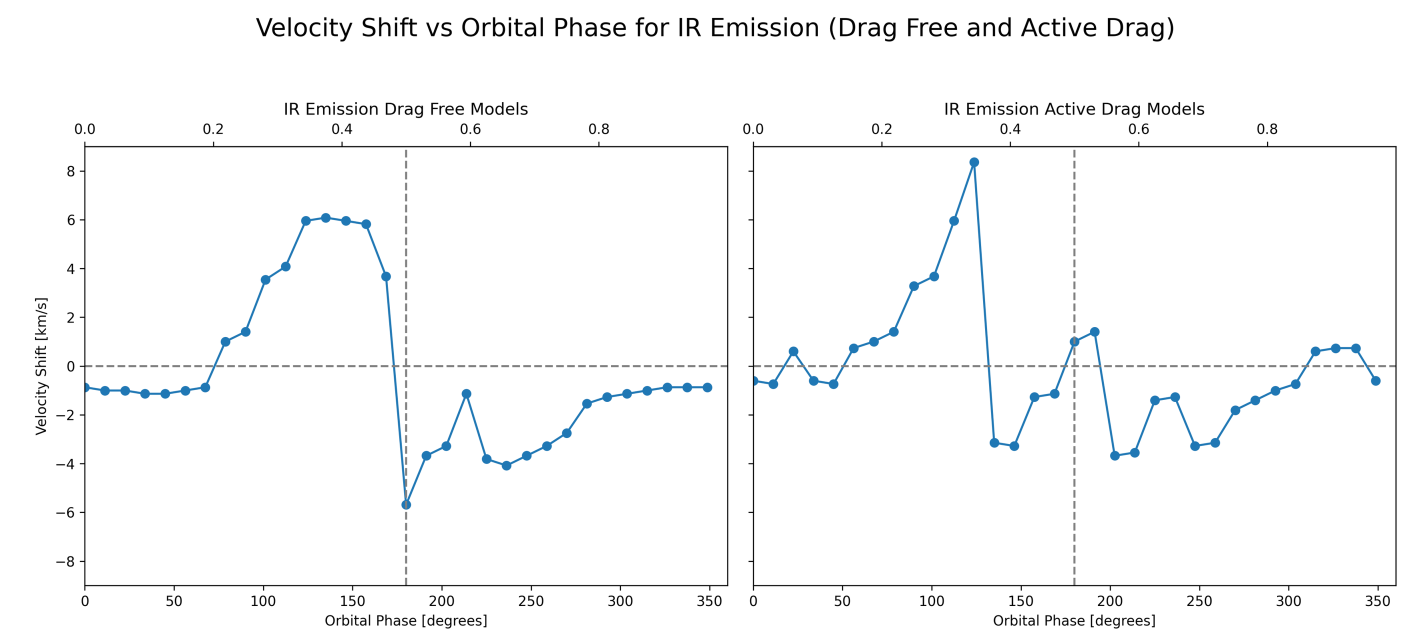


Above: Spectrum of WASP-121b at different resolutions.

- Reduced resolution lowers detectable line numbers, impacting Doppler shift and wind speed measurements.
- The cross-correlation function (CCF) compares two signals to find the best alignment, used to detect molecular species and velocity shifts.
- The CCF peak indicates where features match best, revealing motion through Doppler shifts in spectral lines.

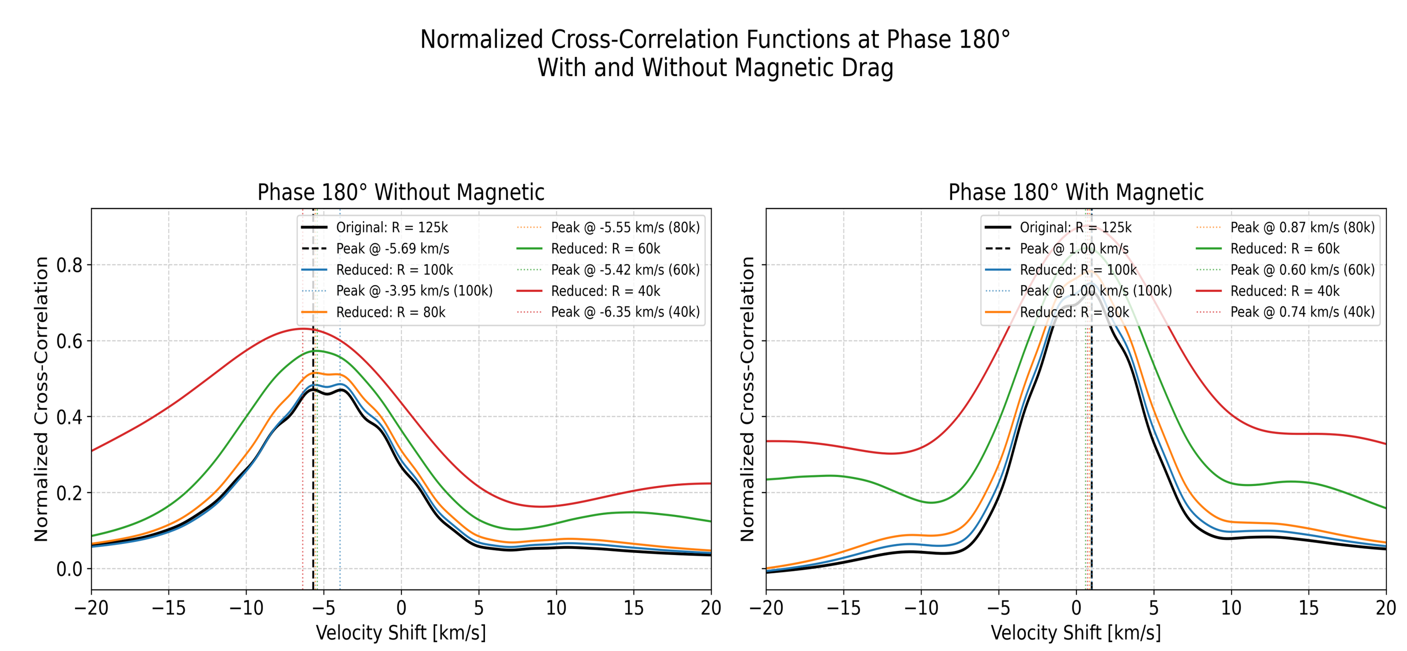
Cross-Correlation

- Compare between two atmospheric models:
  – Drag-free (no magnetic field)
  – Active drag (with magnetic field)



Above: Velocity shifts in IR emission vs. orbital phase for WASP-121b, comparing drag-free and magnetic drag models.

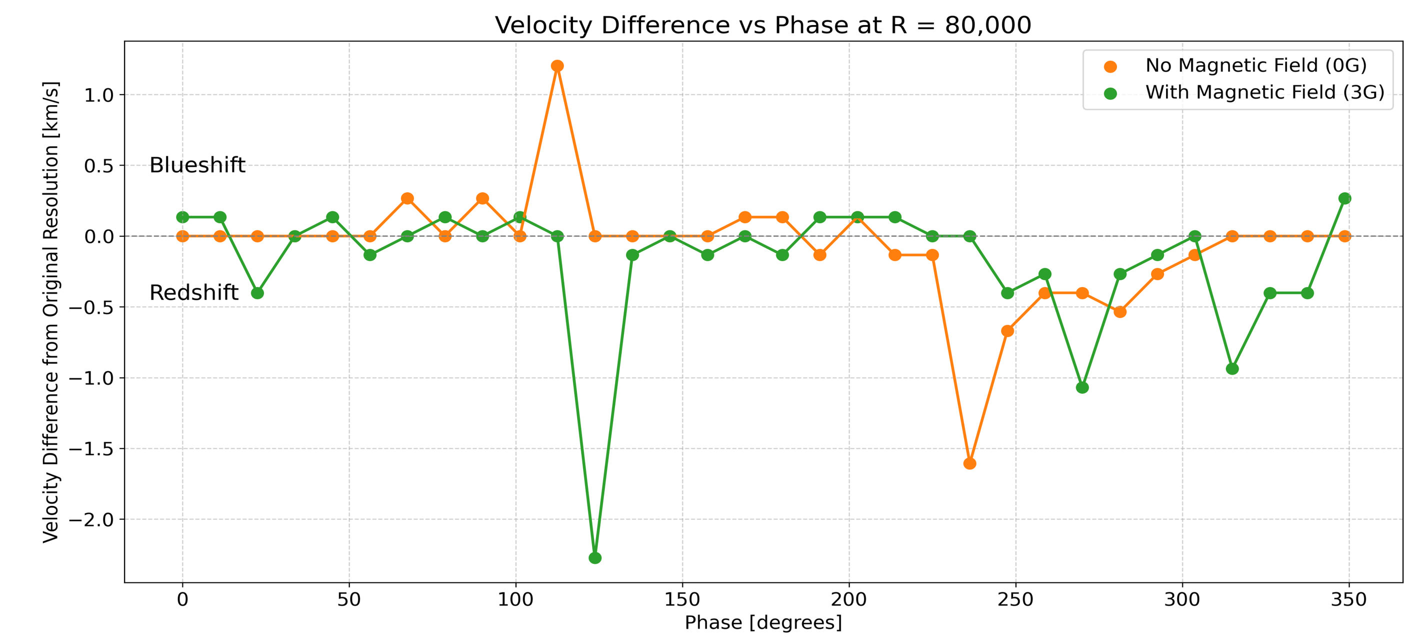
- Drag-free models produce smoother and more symmetric Doppler shifts, with peak velocities reaching around ±6 km/s.
- Magnetic drag slows atmospheric winds, reducing the overall Doppler shift amplitude.
- Magnetic effects disturb the wind pattern, making the atmospheric motion less smooth and more chaotic.
- Sharp red-to-blue transitions appear near phase 135° in drag-included models, showing sudden changes in wind direction.



Above: Normalized CCF at Phase 180 for Both Magnetic Models

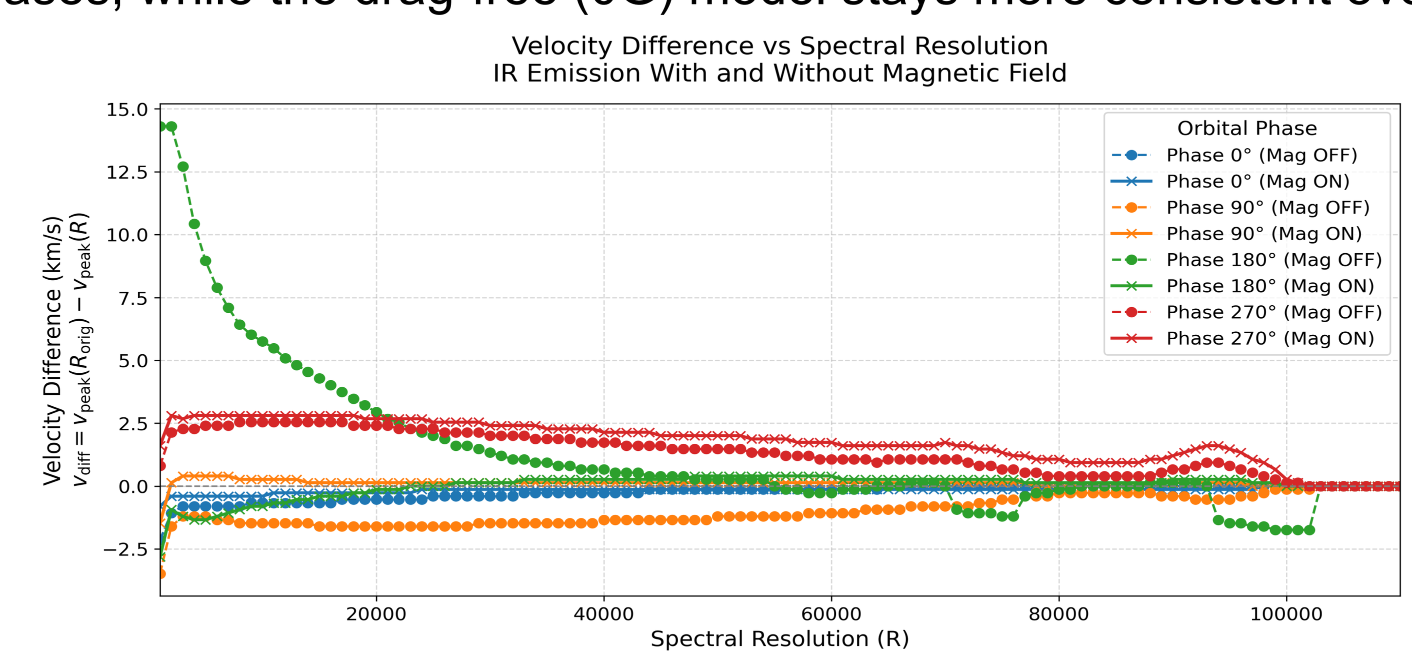
- Lower spectral resolution broadens and smooths the normalized CCF, increasing its peak value but reducing the precision of the velocity shift.
- Different magnetic fields change the shape and symmetry of the CCF peak across orbital phases
- Magnetic drag increases sensitivity to spectral resolution by suppressing winds, leading to larger and more asymmetric velocity deviations.

Shifts



Above: Velocity Difference from Original High-Resolution Value at R = 80,000 Across Orbital Phase

- Velocity differences vary with orbital phase and magnetic activity.
- Magnetic drag causes bigger shifts in velocity compared to the drag-free case.
- Magnetic drag can cause sharper or less predictable shifts at certain phases, while the drag-free (0G) model stays more consistent overall.



Above: Velocity Difference from Original High-Resolution Value vs Spectral Resolution

- Velocity retrieval errors increase as spectral resolution decreases, especially below R = 20,000.
- Magnetic drag suppresses wind variability, leading to smaller and more consistent deviations across phases.
- At phase 180°, low resolution mixes signals from both sides of the planet, making velocity measurements less accurate.

Future Work

- Study wavelength dependence of velocity retrieval accuracy.
- Simulate observational noise for realistic instrument conditions.
- Assess impacts of different instruments and spectral resolutions.
- Develop more realistic models to improve Doppler shift interpretations