Using Transmission Spectroscopy to determine Rotational and Atmospheric Dynamics of Hot Jupiters

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Artist’s concept of a Hot Jupiter. Image credit: NASA, ESA, G. Bacon STScI
What is an Exoplanet?

Kepler Orrery IV showing the systems discovered & confirmed by KST. Video Credit Ethan Kruse
What is a Hot Jupiter?

Artist’s concept of a Hot Jupiter. Image credit: NASA, AMES, JPL-Caltech
3D General Circulation Model

- Models a simplified version of the radiative transfer process
- Creates a 3D temperature, pressure, and wind speeds map of the planet
Project Overview

• GOAL: Determine the rotation rate of HD189733b

• Model transmission spectra for 12 rotation models
3D GCM Rotation Models

\[ P_{\text{rot}} = 18.1 \text{ days} \]

\[ P_{\text{rot}} = 2.22 \text{ days} \]

\[ P_{\text{rot}} = 2.69 \text{ days} \]

\[ P_{\text{rot}} = 1.45 \text{ days} \]

\[ P_{\text{rot}} = 3.42 \text{ days} \]

\[ \text{max} V_{\text{los}} = 11.2 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 13.5 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 10.3 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 13.4 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 11.4 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 10.7 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 10.8 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 10.9 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 11.1 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 11.5 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 11.7 \text{ km/s} \]

\[ \text{max} V_{\text{los}} = 11.0 \text{ km/s} \]
What is Transmission Spectroscopy?

Transmission spectrum of atmosphere. Image credit: ESO
Transmission Spectrum Model

• Using the results of the GCM, models the transmission spectrum for a given atmospheric structure and composition

Project Overview

• GOAL: Determine the rotation rate of HD189733b

• Model transmission spectra for 12 rotation models:
  – Account for different sources of Doppler shift & broadening
Doppler Effects

Project Overview

• GOAL: Determine the rotation rate of HD189733b

• Model transmission spectra for 12 rotation models:
  – Account for different sources of Doppler shift & broadening
  – Account for limb darkening in model
Limb Darkening Effects

Impact parameter $b > 0$

Impact parameter $b = 0$

MDI Quick-Look Intensitygram: 2011.01.11 00:00

MDI INTENSITYGRAM IMAGE OF THE SUN.
IMAGE CREDIT: STANFORD UNIVERSITY
Creating Model Spectra

Model spectra comparing various sources of Doppler shift, with limb darkening
Summary

• Creating spectra with different Doppler shift sources, also with limb darkening
• Comparing model spectra with observed spectra to further constrain rotation rate of HD 189733b
Thanks!

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Summary

• Creating spectra with different Doppler shift sources, also with limb darkening

• Comparing model spectra with observed spectra to further constrain rotation rate of HD 189733b
Limb Darkening Effects Comparison

Comparison between the output of the old model, where the star is modeled as a perfect black body, and the new model which accounts for limb darkening (model where planet is at the center of the star).
Spectral Features

Important Equations

• Doppler Shift: \( \nu = \nu_0 (1 \pm \nu/c) \)

• Doppler Broadening: \( FWHM = \gamma_D \sqrt{\ln 2} \)
  where \( \gamma_D = \nu_0 \sqrt{2kT/(mc^2)} \)

• Planck Function: \( B(T, \nu) = (2\hbar \nu^3/c^2)(\exp(\hbar \nu/kT - 1)^{-1} \)

• Limb Darkening: \( I(\mu) = 1 - u_1(1 - \mu) - u_2(1 - \mu)^2 \)
  \( I_{tot} = \pi(1 - u_1/3 - u_2/6)n_s^2 \)
  where \( u_1 = 0.077, u_2 = 0.311, \) and \( n_s = 1000 \) (pixels/R_*)
My 3D GCM

Primitive equations of meteorology:
(with pressure as vertical coordinate)

\[
\frac{dv}{dt} + \frac{u \tan \phi}{R_p} \mathbf{k} \times \mathbf{v} = -\nabla_p \Phi - f \mathbf{k} \times \mathbf{v},
\]

horiz. & vert. mom.

\[
\frac{\partial \Phi}{\partial p} = -\frac{1}{\rho},
\]

continuity

\[
\frac{\partial \omega}{\partial p} = -\nabla_p \cdot \mathbf{v},
\]

energy

\[
\frac{c_p}{\rho} = \frac{\omega}{\rho} + Q,
\]

Standard two-stream, double-gray radiative transfer:

\[
F_{\text{vis}}(P) = (1 - A) \mu_0 F_{\text{inc}} \exp \left( - \frac{1}{\mu_0} \int_0^\infty \kappa_{\text{vis}} du \right)
\]

\[
= (1 - A) \mu_0 F_{\text{inc}} \exp \left( - \frac{1}{\mu_0} \kappa_{\text{vis}} \frac{g}{P} \right)
\]

\[
F_{\text{up, IR}}(P) = \int \left( 1 - \exp \left( - \frac{1.66}{g} \int \kappa_{\text{IR}} dP \right) \right) \frac{d\sigma T^4}{dP} dP
\]

with transition to flux-limited diffusion at high optical depth:

\[
F_{\text{IR}} = \frac{16 g \sigma T^3}{3 \kappa_{\text{IR}}} \frac{dT}{dP}
\]

Rauscher & Menou (2010, 2012)