Mapping the 3D Structure of Exoplanet Atmospheres using Transit Spectroscopy

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Credit: D. Spiegel
Rauscher & Menou (2010)
Methods of Transit Spectroscopy

Eclipse mapping
3D structure of dayside

Transit mapping
3D structure of terminator

E. Rauscher: 3D mapping

Orbital (rotational) phase curves
2D structure in longitude and pressure

Phase-dependent high-resolution spectroscopy
2D structure in longitude and pressure
The geometries are different, but both techniques share the same basics

- **Eclipse mapping**
- **Transit mapping**

**How to access 3D info:**
- Latitude and longitude come from the shape of the light curve
- Depth into the atmosphere comes from spectral differences

**Methods to extract 3D info:**
- Model-independent
- Model-informed
Basic concepts of 3D mapping

1. The 3D info comes from the shape and wavelength-dependence of the light curve
2. Extracting that info requires applying assumptions
Eclipse mapping: a cartoon example
Eclipse mapping: a cartoon example
Eclipse mapping

- How to access 3D info:
  - Latitude and longitude come from the shape of the light curve
  - Depth into the atmosphere comes from spectral differences
Eclipse mapping: a more complex example

Figure 1. Representation of a cataclysmic variable star with the Roche-lobe filling secondary star, the accretion disk, and the compact white dwarf indicated.
Eclipse mapping: a more complex example

Baptista (2000)
Eclipse mapping: a more complex example

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Baptista (2000)
Eclipse mapping: a more complex example

Baptista (2000)
Horne (1985)

Nuances in creating eclipse maps
Nuances in creating eclipse maps

Horne (1985)

Map used to make light curve
Maximally uniform reconstruction

OR?
Nuances in creating eclipse maps

- Methods to extract 3D info:
  - Model-independent
  - Model-informed

E. Rauscher: 3D mapping
Eclipse mapping
The first (and only) *Spitzer* eclipse map

See also Williams et al. (2006); Rauscher et al. (2007)
... but it’s complicated … what’s the right map to use?

\[ \Gamma_{SH,3}(\phi, \theta) = \sum_{l=0}^{3} I_l Y_l^0(\phi - \Delta \phi, \theta - \Delta \theta), \]

Spherical harmonics

OR?

A physical assumption about how the planet should look

\[ \Gamma_2(\phi, \theta) = \begin{cases} I_1 \cos^{\alpha} \phi \cos^{\gamma} \theta + I_0 & \text{if } \phi \geq 0 \\ I_1 \cos^{\beta} \phi \cos^{\gamma} \theta + I_0 & \text{if } \phi < 0, \end{cases} \]

de Wit et al. (2012)
“Eigen-mapping”: a model-independent method

orthogonal on the planet  $\leftrightarrow$ NOT orthogonal in the data

$\Psi_0(\theta, \phi) \leftrightarrow \lambda_0(t)$

$\Psi_1(\theta, \phi) \leftrightarrow \lambda_1(t)$

$\Psi_2(\theta, \phi) \leftrightarrow \lambda_2(t)$

$\Psi_3(\theta, \phi) \leftrightarrow \lambda_3(t)$

\ldots \ldots \ldots

Majeau et al. (2012)
“Eigen-mapping”: a model-independent method

Spherical harmonic light curves, $F_l^m(t)$

- $\Psi_0(\theta, \phi) \leftrightarrow \lambda_0(t)$
- $\Psi_1(\theta, \phi) \leftrightarrow \lambda_1(t)$
- $\Psi_2(\theta, \phi) \leftrightarrow \lambda_2(t)$
- $\Psi_3(\theta, \phi) \leftrightarrow \lambda_3(t)$

Majeau et al. (2012)

Principal Component Analysis

Identifies orthogonal and maximally informative light curves

From: https://medium.com/analytics-vidhya
"Eigen-mapping": a model-independent method

Spherical harmonic light curves, $F_l^m(t)$

$\Psi_0(\theta, \phi) \leftrightarrow \lambda_0(t)$

$\Psi_1(\theta, \phi) \leftrightarrow \lambda_1(t)$

$\Psi_2(\theta, \phi) \leftrightarrow \lambda_2(t)$

$\Psi_3(\theta, \phi) \leftrightarrow \lambda_3(t)$

\[ E_n(t) = \sum_{l=1}^{l_{\text{max}}} \sum_{m=0}^{\pm l} \lambda_{n,l,m} F_l^m(t) \]

"Eigen-curves", $E_n(t)$

Majeau et al. (2012)

Rauscher et al. (2018)
"Eigen-mapping": a model-independent method

"Eigen-maps", $Z_n(\theta, \phi)$

$Z_n(\theta, \phi) = \sum_{l=1}^{l_{\text{max}}} \sum_{m=0}^{\pm l} \lambda_{n,l,m} Y_l^m(\theta, \phi)$

Challener & Rauscher (2022)
ThERESA code available on github

"Eigen-curves", $E_n(t)$

Rauscher et al. (2018)
The *first* eclipse map with JWST!

JWST ERS Transiting Exoplanets Team, Coulombe et al. (2023)
The first eclipse map with JWST!

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Credit: NASA/JPL-Caltech (K. Miller/IPAC)

JWST ERS Transiting Exoplanets Team, Coulombe et al. (2023)
But what about a 3D map?

Thermal emission comes from different layers in the atmosphere

Credit: Himawary/Simon Proud/Vivien Parmentier
3D Eclipse Mapping Methods:

1. Eclipse light curve at each wavelength

2. Use “eigencurves” (Rauscher et al., 2018) to make map at each wavelength
3D Eclipse Mapping Methods:
Model-independent spectral-spatial groups

1. Eclipse light curve at each wavelength

2. Use “eigencurves” (Rauscher et al., 2018) to make map at each wavelength

3. Combine into 3D spatial + spectral map

4. Use clustering to identify similar regions (“groups”) and their representative spectra (“eigenspectra”)

Mansfield et al. (2020)
3D Eclipse Mapping Methods: Model-independent spectral-spatial groups

OR

Temperature-pressure parameterization

**Stay tuned!**

- 3D map of WASP-18b
- More maps:
  - WASP-43b
  - GTO/GO targets
- More techniques
  - parameterizations linking temperature structure to physics
  - what parts of a map we can't see (null space)

3. Place temperature maps at different pressures
4. Use radiative transfer to match measured spectra

Mansfield et al. (2020)

Challener & Rauscher (2022)
Transit mapping
How spatial structure shows up in transit

Dayside facing us
How spatial structure shows up in transit

Dayside facing us

Nightside facing us

E. Rauscher: 3D mapping
How spatial structure shows up in transit

Dobbs-Dixon et al. (2012)

Fortney et al. (2010)

hotter = puffier

cooler = compact

Leading and Trailing terminators ≠

Eastern and Western terminators
How spatial structure shows up in transit

Different 3D models with different structures predict different offsets

Dobbs-Dixon et al. (2012)
How spatial structure shows up in transit

Dobbs-Dixon et al. (2012)

Fortney et al. (2010)

E. Rauscher: 3D mapping
How spatial structure shows up in transit

1. Physical morphology changes shape of light curve

2. Differing opacities make this wavelength-dependent
How do we measure 3D structure in transit?

Instead of brightness variations, there are effective radius variations

\[ \Psi_0(\theta, \phi) \]

\[ \Psi_1(\theta, \phi) \]

\[ \Psi_2(\theta, \phi) \]
How do we measure 3D structure in transit?

Instead of brightness variations, there are effective radius variations

\[ \Psi_0(\theta, \phi) \leftrightarrow \lambda_0(t) \]

\[ \Psi_1(\theta, \phi) \leftrightarrow \lambda_1(t) \]

\[ \Psi_2(\theta, \phi) \leftrightarrow \lambda_2(t) \]

Instead of deviations from uniform brightness, there are deviations from uniform radius

Line & Parmentier (2016)

von Paris et al. (2016)

E. Rauscher: 3D mapping
3D Transit Mapping Methods: Model-independent

Fit $R_p(\lambda)$ for leading and trailing limbs

Espinoza & Jones (2021)
3D Transit Mapping Methods: Model-independent

Fit $R_p(\theta, \lambda)$ with Fourier series
Get atmospheric profiles at all locations

Fit $R_p(\lambda)$ for leading and trailing limbs

Espinoza & Jones (2021)

Simulated NIRISS/SOSS limb spectra

JWST limb constraints (through limb spectra)

Grant & Wakeford (2022)
3D Transit Mapping Methods:

- **Model-independent**
  - Parameterized structure

- **Parameterize 3D atmospheric structure and run retrieval on spectral light curves**

- **Fit $R_p(\theta, \lambda)$ with Fourier series**

- **Get atmospheric profiles at all locations**

**Espinoza & Jones (2021)**

- Simulated NIRISS/SSS limb spectra

**MacDonald & Lewis (2022); see also Nixon & Madhusudhan (2022)**

- Fit $R_p(\lambda)$ for leading and trailing limbs

**Grant & Wakeford (2022)**

- Observer's Perspective
  - Star
  - Ray Path
  - Observer

- Observer's Perspective
  - Leading and trailing limbs
Mapping the 3D Structure of Exoplanet Atmospheres

- How to access 3D info:
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With JWST we can measure atmospheres in 3D!