Characterizing exoplanet atmospheres with multi-wavelength transmission observations

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Extra-solar Planets:

Diversity:
- Jupiter-sized planets at $T \gtrsim 1500 \text{ K}$.
- Super-Earth planets with $M \gtrsim 2 \, M_{\text{Earth}}$.
- Earth analogs (Jenkins et al. 2015).

Transiting Exoplanets:

Transit depth $= \frac{\Delta F}{F} \approx \left( \frac{R_p}{R_s} \right)^2$

Eclipse depth $= \frac{\Delta F}{F} \approx \frac{F_p}{F_s}$
UV Observations:

Color vs. activity:

Fossati et al. 2013
WASP-13: UV Observations

Very inflated exoplanet (Skillen et al. 2009, Gomez Maqueo Chew 2013)

$log R'_\text{HK} = -5.263$
(Knutson et al. 2010)

HST/COS
G140L FUV

Fossati et al. 2015
WASP-13: Age Estimation

\[
\frac{\text{CIV 1548}}{\text{CI 1657}} = 7.607(\pm 0.150) - 1.838(\pm 0.041) \times \log(\text{Age [Myr]})
\]

Stellar age:
5.0 +/- 2.1 Gyr

Fossati et al. 2015
WASP-13: Activity Estimation

For WASP-13 the $\log R'_{HK}$ value is not a good measure of the stellar activity.

This is most likely caused by ISM absorption.

Fossati et al. 2015
Exoplanet Atmospheric Modeling:

Optical/IR Observations:

Transiting systems:

Atmospheric characterization:

Transmission/emission spectra:

Modeling:
The Problem of Exoplanet Atmospheric Modeling:

- Low S/N observations.
- Photometry: few, broadband points. (e.g., Spitzer)
- Spectra: low resolution, span. (e.g., Hubble’s WFC3)

Two approaches:

Forward Modeling:
- Physically-motivated (+)
- Self-consistent (+)
- Non-exhaustive (−)
- Not necessarily unique solution (−)

Retrieval (e.g., Bayesian):
- Statistically robust (+)
- Data driven (+)
- Computationally intensive (−)
- Not necessarily self-consistent (−)

Either way, we need to know the physics well.
Atmospheric Modeling:

The problem:

Our solution:
- Radiative Transfer
- Thermo-chemical equilibrium
- (Bayesian) Statistics

Radiative Transfer:
- Atmospheric model
- Species databases
- Observing geometry

Atmospheric model:
- Temperature
- Species abundances

Bayesian Atmospheric Radiative Transfer (BART) project.
Cubillos, Blecic, Harrington et al.
Atmospheric Modeling:

Bayesian Atmospheric Radiative Transfer (BART):

- Open-source Open-development.
- Documented.
- User interaction at the ‘Python’ level.
- Modular, independent, sub-modules:
  - Thermochemical-equilibrium chemistry.
  - Radiative-transfer.
  - Bayesian statistics.

github.com/exosports/BART

Init:

Run:

Markov Chain

Atmospheric-Model Generator

Radiative Transfer

Spectrum Integrator

Thermochemical Equilibrium Abundance

Species Abundances

Detector filters

Line-transition databases

CIA absorption

(Kurucz) Stellar model
Radiative Transfer:

The radiative-transfer equation describes how light propagates, as it travels through a medium:

\[
\frac{dI_\nu}{ds} = -\kappa_\nu (I_\nu - B_\nu(T))
\]

Not really new science, ... but must be efficient (if MCMC).

• Each species has an specific absorption pattern in the spectrum.

The Transit code:

• Solves 1D, line-by-line radiative-transfer equation.
• Produces transmission (transit) or emission (eclipse) spectra.
• Open-source, documented.

Inputs:

• One-dimensional atmospheric model \((T, p, \text{abundances})\).
• Species opacity databases.
Radiative Transfer:

Opacity databases:

- Collision-induced absorption (CIA, Borysow et al., Richard et al. 2012):
  - Smooth variation.
  - Main species: H₂, He.

- Quantum electronic, rotational, vibrational transitions (Rothman et al. 2010, 2013):
  - Discrete lines/bands.
  - Main species: H₂O, CH₄, CO, CO₂, NH₃, C₂H₂, C₂H₄, ...

![HAT-P-11b Transmission Spectra](image)
Atmospheric Model:

Temperature-profile model:
Three-stream Eddington approximation
(Parmentier & Guillot 2014):

• Stellar ($T_{\text{irr}}$) and internal ($T_{\text{int}}$) heating sources.
• IR ($\kappa_{\text{IR}}$) and optical mean opacities ($\kappa_v$).

Thermochemical-Equilibrium Abundance (TEA) code (Blecic et al. 2015a):

• Calculate species abundances (for given $T$, $p$).
• Gibbs free energy minimization.
• Python open-source code:

```
github.com/dzesmin/TEA
```
Radiative Transfer:

Transmission spectra:

- $\text{H}_2\text{O} : 1 \times 10^{-3}$
- $\text{CO} : 1 \times 10^{-4}$
- $\text{CH}_4 : 1 \times 10^{-4}$
- $\text{CO}_2 : 1 \times 10^{-4}$
Radiative Transfer: Validation

Our models agree to a few percent with those of C. Morley (in prep.).
Statistical Package:

Multi-Core Markov-chain Monte Carlo (MC³):  (Cubillos et al. 2015a, in prep.)

• **General** package for model-parameter estimation.
• Single/Parallel processor (MPI).
• Python/C open-source project:
  [github.com/pcubillos/mccubed](https://github.com/pcubillos/mccubed)

• Differential-Evolution MCMC *(Braak 2006).*
• Gelman-Rubin MCMC convergence *(Gelman & Rubin 1992).*
Statistical Package:

Multi-Core Markov-chain Monte Carlo (MC³):
(Cubillos et al. 2015a, in prep.)

github.com/pcubillos/mccubed

HD 209458b Spitzer 4.5 um phase curve:
HAT-P-11b: Transit Observations

Neptune-like planet:
• 26 $M_{\text{Earth}}$, 4.7 $R_{\text{Earth}}$.
• 900 K equilibrium temperature.
• 5-day orbit period.
(Bakos et al. 2010)

Transit observations:
• Kepler 0.64 um.
• Hubble’s WCF3 1.1–1.7 um.
• Spitzer 3.6 & 4.5 um.
(Fraine et al. 2014)

Atmospheric characterization with the SCARLET code:
Benneke et al.
BART fitting parameters:

- H$_2$O, CH$_4$, CO, and CO$_2$ abundances (4 pars).
- Temperature-profile params (3 pars).
- Altitude at 0.1 bar (1 param).

Started from equilibrium abundances.
HAT-P-11b: Results

- Constrained the 0.1-bar radius to: $29,750 \pm 200$ km.
- Determined $\sim 100 \times$ super-solar abundance of H$_2$O.
- CH$_4$, CO, CO$_2$ remained unconstrained.

Replicate the work of Fraine et al. (2014).
Conclusions:

• Models can be as complex as the data allow.
• Current exoplanet data is limited in wavelength coverage, wavelength resolution.

Tools for exoplanet characterization:

• We developed an open-source, statistically-robust code to model exoplanet spectra and characterize planetary atmospheres.
• The retrieval analysis has been validated and can reproduce previous results on Neptune planet HAT-P-11b. [github.com/exosports/BART]

Future development:

• Add Haze/Clouds and Rayleigh models.
• Add chemical disequilibrium: photo-chemistry, vertical mixing.
• Future instrument simulations: JWST & ELTs.