Atmospheric Retrieval for Super-Earths:
Uniquely Constraining the Composition with Transmission Spectroscopy

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Benneke & Seager, 2011, ApJ, subm.

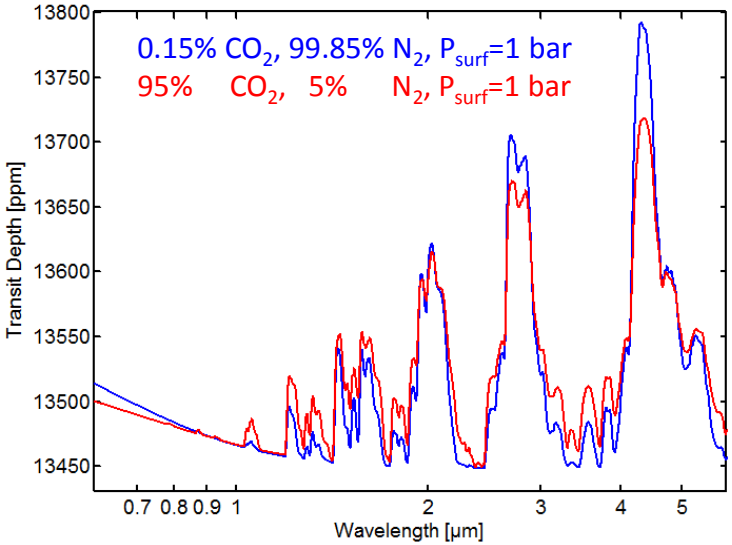
Take-Away Messages

- Developed a new retrieval method to infer atmospheric composition and surface or cloud-top pressure from transmission spectra of *super-Earth* atmospheres
- Transmission spectra *uniquely* constrain compositions of well-mixed atmospheres if observations are sufficient to quantify
  1. Broadband transit depths in features of absorbers in the visible/infrared
  2. Slope and Offset of Rayleigh scattering signature
- Even a strong detection of molecular absorption in NIR (>10σ) may be insufficient to determine whether the absorber is main constituent or minor species in atmosphere

Motivation

- Recent efforts to observe transmission spectrum of GJ1214b (Bean et al., Croll et al.)
  - Observational characterization of super-Earths may be feasible in near-future
- Current practice is to compare observations to model spectra of pre-conceived atmospheric scenarios (Miller-Ricci and Fortney, 2010)
  1. Potentially several scenarios matching the data
  2. We might not understand planets that disagree with our ideas

Transmission spectra for two scenarios of clear N_2-CO_2 atmospheres



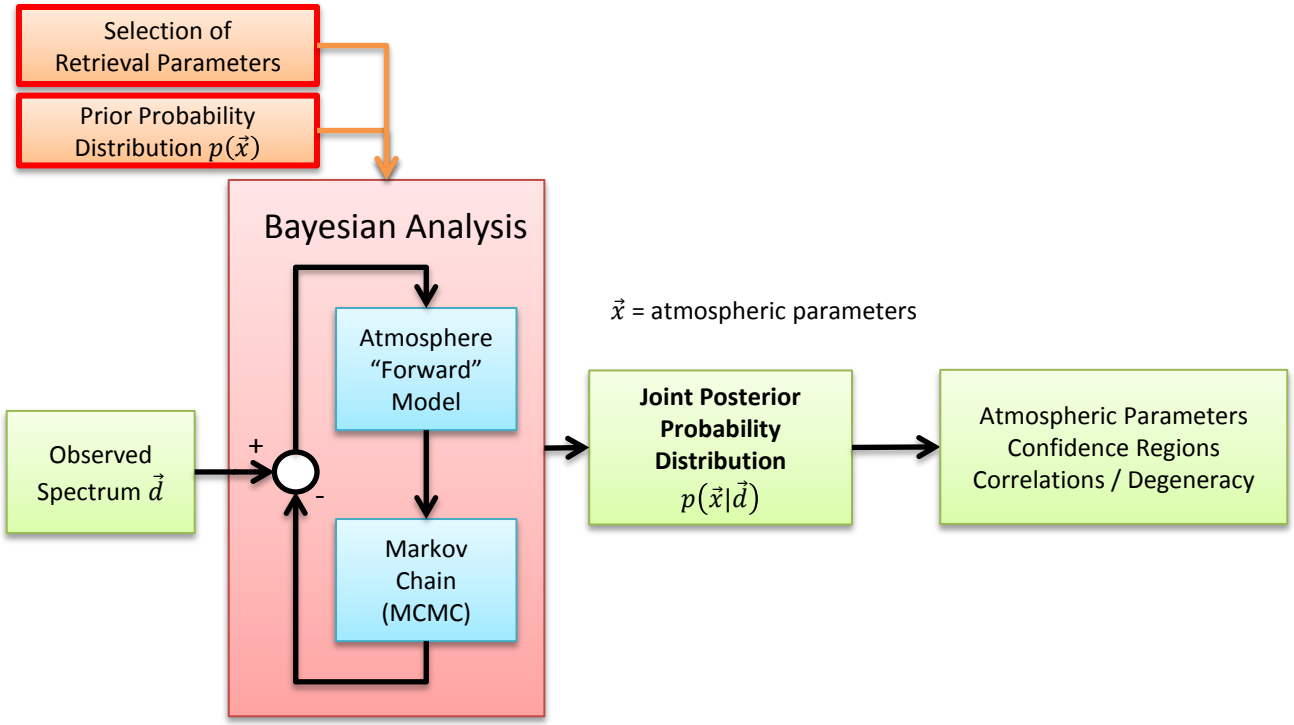
Identified needs

Tool to constrain atmosphere parameters from super-Earth transmission spectra independently of pre-conceived planetary scenarios

Conceptual understanding of what features in spectrum need to be observed to make conclusive statement about atmosphere

Overview of Retrieval Approach

Inference of atmospheric parameters directly from observational data by conducting Bayesian analysis using an atmosphere "forward" model combined with the MCMC technique



Atmosphere model employs no assumptions on elemental composition, or formation and evolution scenarios

Advantage over "classical" gradient-based retrieval methods (e.g. Rogers, 2000; Lee et al., 2011):

- Makes full use of available information / Does not assume Gaussian errors on atmospheric parameters
- Multi-modal solutions possible

Forward Model & Retrieval Parameters for Atmospheres of General Composition

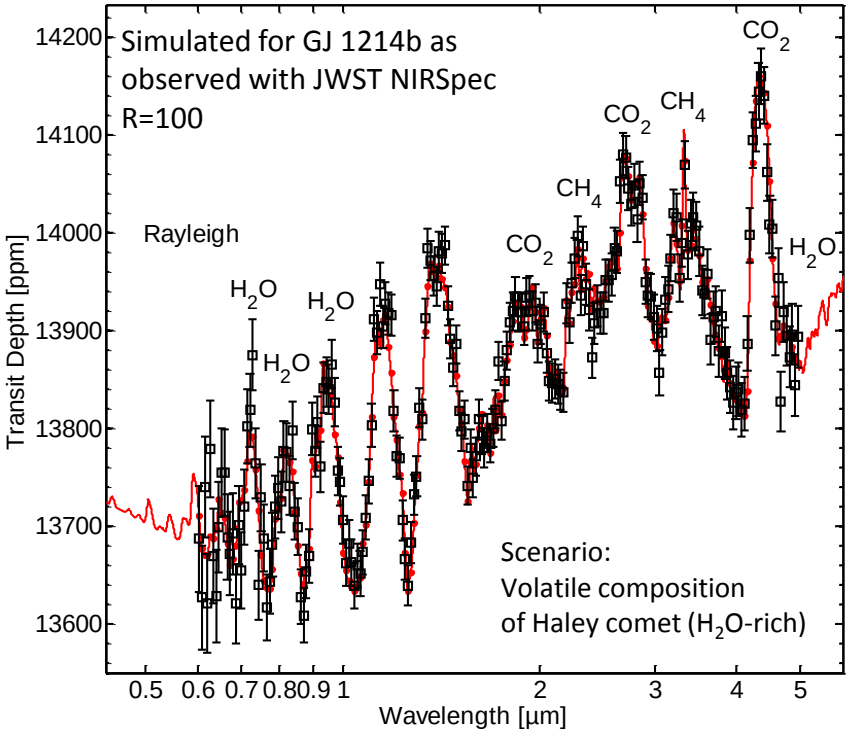
Atmosphere near terminator is treated as well-mixed with composition and thickness described by free parameters:

- Volume mixing ratios of all potentially-present molecular gases
- Surface pressure (ground or upper cloud deck)
- Planetary radius at 10 mbar level
- Planetary Bond albedo

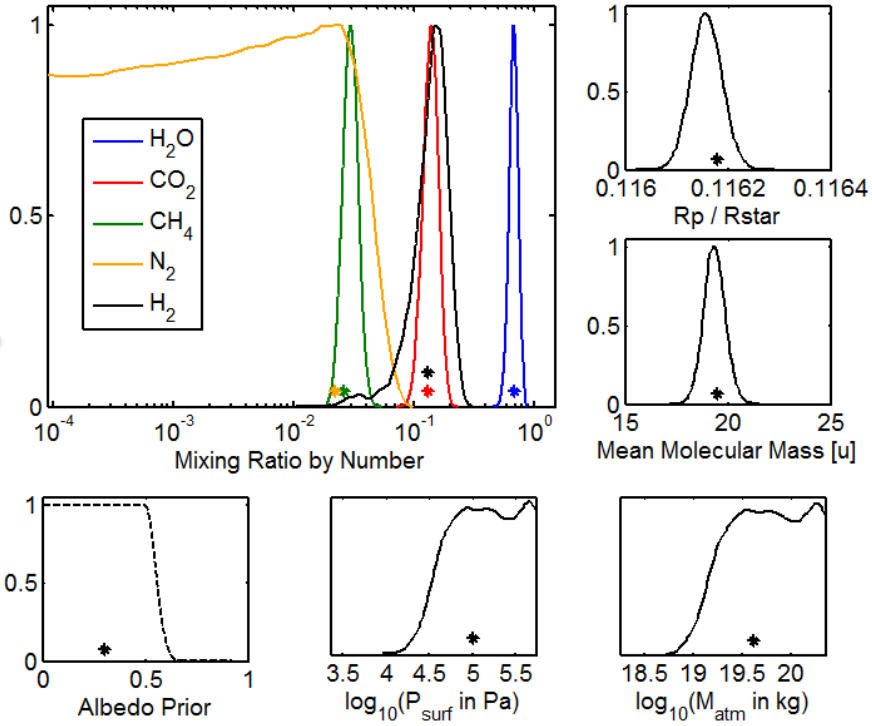
Vertical temperature profile consistent with composition and albedo using gray radiative-convective model (Guillot, 2010 + convective adjustments)

Numerical Results: Retrieval from Synthetic Transmission Spectra of GJ 1214b

Input: Transmission spectrum



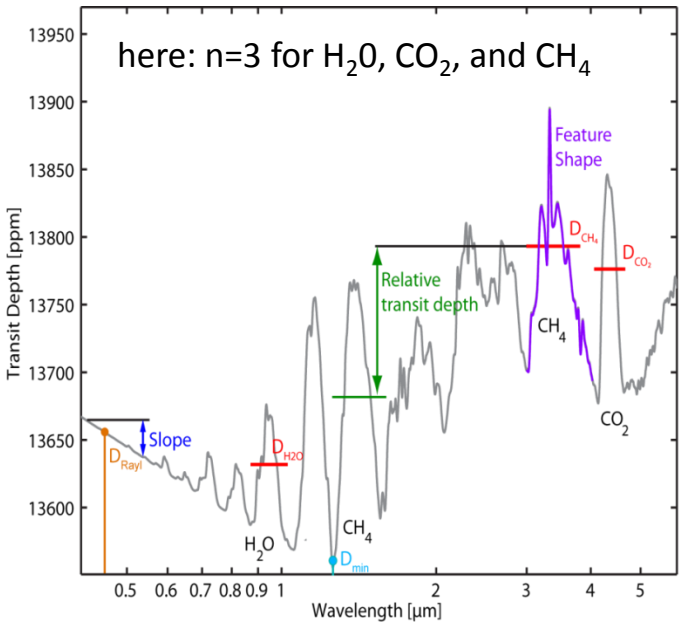
Output: Marginalized posterior probability density of atmospheric parameters (normalized)



* = values used to simulate observations

- Low-noise observations of transmission spectrum can provide unique constraints on atmospheric composition for all planetary compositions studied

Conceptual Overview: Unique Constraints on Composition



n+4 independent pieces of information

n+4 atmospheric properties

Transit depths in feature of absorber #1

Transit depths in feature of absorber #n

Relative abundances of absorbing gases

Slope of Rayleigh scattering signature

Shapes of individual features

Relative transit depth in features of same molecule

$$H|_{r=R_P} \approx \frac{dR_P}{d(\ln \sigma)}$$

Mean molecular mass

Transit depth offset of Rayleigh slope (D_{Rayl})

Sum of all mixing ratios equals 1

Lowest transit depth D_{min}

For thin atmospheres

Surface / cloud-top pressure

n mixing ratios of absorbers

2 mixing ratios of spectrally-inactive gases (e.g. N_2 and H_2+He)

Planetary radius $R_{p,10}$

- Transmission spectrum of atmosphere with *n* absorbers contains *n+4* independent pieces of information
- It can *uniquely* constrain atmospheric composition for well-mixed atmosphere with up to 2 spectrally-inactive gases

Take-Away Messages

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- Transmission spectra *uniquely* constrain compositions of well-mixed atmospheres if observations are sufficient to quantify
  1. Broadband transit depths in a feature of each relevant absorbers in visible/NIR
  2. Slope and Offset of Rayleigh scattering signature
- Even a strong detection of molecular absorption in NIR (>10σ) may be insufficient to determine whether the absorber is main constituent or minor species in atmosphere