Modeling Exoplanetary Atmospheres

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Methods for Characterizing the Atmospheres of Transiting Planets

- Direct Imaging
- Transits

Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear
Amplitude: ~0.1%
Time Scale: 1-5 hours

Transit
See radiation from star transmitted through the planet’s atmosphere
Transit depth: ~1%
Absorption feature: ~0.01%
Time Scale: 1-5 hours

Orbital Phase Variations
See cyclical variations in brightness of planet
Amplitude: ~0.01-0.1%
Time Scale: 30-100 hours

Direct Imaging
Spectroscopy of thermal infrared light emitted by the planets

- Jupiter, 1969
- HD 189733b, ~2008

Exoplanet atmospheres is running **40-50 years** behind solar system atmospheres
Infrared Brightness Maps in Thermal Emission

- Jupiter, 1972
  Key et al., 5 \( \mu \text{m} \)

- HD 189733b, 2007
  Knutson et al., 8 \( \mu \text{m} \)
Planets Can Be Categorized

- Planets can generally be grouped (we think) based on where their atmospheres came from
  - **Primary**: Accreted from the protoplanetary disk
    - Jupiter, Saturn, Uranus, Neptune, similar exoplanets
    - Atmosphere can be most of planet’s total mass
  - **Secondary**: Outgassed from the planet’s interior
    - Venus, Earth, Mars, Titan, similar exoplanets
Two Aspects of Studying Atmospheres

• Understand Atmospheric Physics (and Chemistry)
  • Absorption and Emission of Radiation
  • Circulation: Advection of Energy

• Connect to Planetary Origins
  • Atomic and Molecular Abundances
  • Connect to Formation Location and/or Stellar Abundances
Connecting to Origins for Giant Planets

Connection to the Solar System
(Atreya et al. 2020)

Giant planet C/O ratio
Oberg et al. (2011)

Giant planet metal-enrichment
(Fortney et al. 2013)
Flavors of Models

1D Radiative/Convective Equilibrium (RCE)
- Most akin to classical “stellar atmosphere modeling”
- Specify all the physics and chemistry and iterate to the “solution”
- Compute large grids over $T_{\text{eff}}$ (or $T_{\text{eq}}$), gravity, abundances, cloud parameters

1D Inverse Models (“Retrieval”)
- Bayesian data-driven framework to yield constraints on temperature structure + abundances
- “Millions of models”
- Builds on Earth science methods but was rediscovered by astrophysicists (sigh)

3D Dynamical Models
- Radiation + Hydrodynamics
- “GCM”: General (or Global) Circulation Model
- Essential, since irradiated and/or cloudy atmospheres are inherently 3D
- Rad-tran and chemistry simplified vs. 1D RCE
Making a 1D RCE Model

Abundances
Chemistry
Opacities
Incident stellar energy
Intrinsic energy
Radiation/Convection
Atmospheric pressure-
Temperature profile
Spectrum
1D RCE Model Allow for Predictions and Explorations of Parameter Space

Pressure-Temperature profiles from Marley & Robinson (2015)

Emission spectra from Morley et al. (2014)
Fitting a Spectrum Via Retrieval

Figure courtesy of Mike Line (ASU)
Typical Hot Jupiter Retrieval Outcome

hot Jupiter HD 209458b
Line et al. (2016)
3D GCM Models

- This is a tricky business
- Unlike the solar system, you can’t “see” the dynamics
- Dynamics be inferred from time-series photometry or spectroscopy

Showman, Fortney, et al. (2009)
Diverse Atmospheres Across Day to Night

Parmentier et al. (2016)

Kataria et al. (2015), WASP-43b
Looking ahead: Reflection spectra of Exo-earths

Wavelength (µm) vs. $F_p/F_*$

- Rayleigh scattering
- $N_2$
- $O_3$
- $O_2
- $H_2O$

$H_2O$ cloud:
- $\tau$, $f_c$
- $dp$

Gases:
- $N_2$, $O_2$
- $H_2O$, $O_3$

Feng et al. (2018)

Top of atmosphere:
- $P_t$
- $P_0$

Surface:
- $A_s$, $g$, $R_p$
Sorting out the challenges for assessing atmospheric abundances of biosignatures

Feng et al. (2018)
Current Challenges for Models

- Umm...well...sometimes it isn’t clear what observations to trust
- Clouds
  - Condensation, coagulation, sedimentation, transport, vaporization, in 1D or 3D
  - Not a solved problem for the Earth
- Incomplete molecular opacities at high temperatures and high resolution
  - Important role for lab astro
- Phase space for small planets is phenomenally larger in terms of possible chemical abundances

- We’ve spent considerable time and effort on assessing the known unknowns
- What about the *unknown* unknowns?

We’ve spent several decades mastering stellar atmospheres. Many more decades will be needed for exoplanet atmospheres.