Characterizing the Atmospheres of Extrasolar Planets

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1795 Confirmed Exoplanets as of 16 June 2014
Kepler first 16 months: Batalha et al. (2013)
Most known planets have sizes between Earth and Jupiter.
Most known planets are close to their host stars
Most known planets are hotter than Earth
So…. based on our Solar System experience, most known exoplanets should have hot, thick atmospheres

But what do we really know about these atmospheres, and how do we know it?
Characterizing Exoplanet Atmospheres

- Planetary bulk density tells you something about volatile content
- Transit and eclipse photometry and spectra can provide information on atmospheric composition, clouds, atmospheric temperatures, longitudinal variations
- Spectroscopy of directly imaged planets can provide information on atmospheric composition, clouds, temperatures
Mass versus radius relation provides some clues to bulk composition and mass fraction of volatiles, but there are degeneracies from Howard et al. (2013).
Spectroscopy of Directly Imaged Planets

Directly imaged planets tend to be young, hot, large planets far from their host stars.

from Konopacky et al. (2013)
Characterizing Exoplanet Atmospheres Through Transits and Eclipses

Primary Eclipse
Measure size of planet
See star’s radiation transmitted through the planet atmosphere

Secondary Eclipse
See planet thermal radiation disappear and reappear

Figure by S. Seager
Atmospheric Absorption During Transit

from Deming et al. (2013)
Atmospheric Absorption During Eclipse

from Swain et al. (2009)
Vertical temperature profile from eclipse photometry and spectra

Madhusudhan et al. (2010)
Phase variations give you information on longitudinal $T$ variations.

Knutson et al. (2007)
HD 189733b
3D General Circulation Models of Exoplanets

from Showman et al. (2009)
High Spectral Resolution Observations

From Snellen et al. (2010). Cross correlation study identifies CO from the planet → can even determine high-altitude winds!

HD 209458b
Thermospheric Photochemistry on Exoplanets

from Koskinen et al. (2013); see also García-Muñoz (2007); Yelle (2004)

Hot, expanded thermosphere undergoing hydrodynamic escape can have heavy species dragged along with the escaping hydrogen.
Evidence for Clouds/Hazes

HD 189733b transit observations
Sing et al. (2011)

GJ 1214b (Kreidberg et al. 2014)

WASP-12b transit observations
Sing et al. (2013)

Kepler -7b (Demory et al. 2013)
What are these clouds? Need help from theory

[top] from my 2014 proposal
[left] from Morley et al. (2013)
Model fit via retrievals

from Lee et al. (2012)

Model fit via “first principles” → Spectral modeling from Caitlin Griffith

from Moses et al. (2011)
Models from a temperature retrieval but realistic chemistry from Moses (2014)

Reliable error bars matter!
Given observational challenges and limited spectral data at this stage, theoretical modeling is crucial to advancing our understanding of exoplanet atmospheres.
Equilibrium Chemistry: “Warm” Giant Exoplanet
Photochemistry/Quenching: “Warm” Giant Exoplanet
Equilibrium Chemistry: “Cool” Giant Exoplanet
Photochemistry/Quenching: “Cool” Giant Exoplanet
Observational Consequences of Disequilibrium Chemistry

Top: Moses (2014); Bottom: Miller-Ricci Kempton et al. (2012)
Thermochemical Equil. vs Metallicity, Elemental Ratios

500 K
100 mbar
C/O = 0.46

500 K
100 mbar
C/O = 0.46

500 K
100 mbar
C/O = 0.46

1200 K
100 mbar
C/O = 0.46

1200 K
100 mbar
C/O = 0.46

1200 K
100 mbar
C/O = 0.46

800 K
100 mbar
C/H = 300x solar

800 K
100 mbar
C/H = 300x solar

800 K
100 mbar
C/H = 300x solar

from Moses et al. (2013b)
Super Earth/Mini Neptunes: Fct. of Metallicity

from Moses et al. (2013b)
Observational Consequences of Metallicity & Clouds

Top: from Moses et al. (2013)

High metallicity causes transit spectra (right) to look flat and causes different molecular features to appear in emission spectra (top)

Bottom: from Knutson et al. (2014)

Optically thick clouds cause transit spectra (below) to look flat and emission spectra (left) to resemble blackbody emission

GJ 436b
Conclusions

• Increasingly sophisticated observations and data-analysis procedures are helping to define atmospheric composition, thermal structure, cloud properties on exoplanets

• Determining atmospheric composition from transits may be difficult for small exoplanets, due to high mean molecular weight atmos. and potential high clouds; acquiring good eclipse spectra will be key

• Need something like EChO, FINESSE 2.0, JWST to get eclipse spectra

• Need good theoretical models to define missions, predict what we can observe, interpret observations