Elemental Abundances in Exoplanetary Atmospheres

Nikku Madhusudhan
Institute of Astronomy, Cambridge

Collaborators: Drake Deming (U. Maryland), Peter McCullough (STScI), Nicolas Crouzet (U. Toronto), Jacob Bean (U. Chicago), Joseph Harrington (U. Central Florida), Kevin Stevenson (U. Chicago), Avi Mandell (NASA Goddard), Jean-Michel Desert (Caltech), David Anderson (Keele Univ., UK), Laura Kriedberg (U. Chicago), Heather Knutson (Caltech), Pierre Maxted (Keele, UK), Julianne Moses (Space Sci. Inst), Olivier Mousis (CNRS, France), Jonathan Lunine (Cornell), Torrence Johnson (NASA JPL), Sukrit Ranjan (Harvard), David Charbonneau (Harvard)

Aug 1, 2014

Planetary Systems Across the HR Diagram

Image Credits: ESA – C. Carreau
Atmospheric abundances in Jupiter

C/O ≥ 1  
(Strange Territory)

C/O = 0.5  
(Working Hypothesis)

H₂O abundance is not known for Jupiter

Owen et al 1999; Bolton et al. 2010
JUNO Mission
Launch - August 5, 2011, Cape Canaveral, Florida
Mission: To Understand the Origin and Evolution of Jupiter
Journey: 1.7 billion miles, 5 years

Goal #1: “Juno will determine how much water is in Jupiter’s atmosphere, which helps determine which planet formation theory is correct (or if new theories are needed)”
We can measure O/H and C/O ratios in hot Jupiters better than we can for Jupiter!
Implications for Planet Formation

Image Credits: NASA
Exoplanets Conducive for Atmospheric Characterization

Directly imaged planets
Marois et al. 2008

Transiting planets
Primary Eclipse
Measure size of planet
See star's radiation transmitted through the planet atmosphere

Secondary Eclipse
See planet thermal radiation disappear and reappear

Learn about atmospheric circulation from thermal phase curves
Atmospheric Spectra of Transiting Exoplanets

\[ \delta_{\text{transit}} = \left( \frac{R_p}{R_s} \right)^2 \]


Deming et al. 2013, Madhusudhan et al. 2014
Spectral Signatures of hot Jupiter Atmospheres
Spectral Signatures of hot Jupiter Atmospheres

![Graph showing spectral signatures with various chemical compounds like H$_2$O, CO, CH$_4$, and TiO, with identifiers for HST WFC3, Spitzer IRAC, and Ground-based Facilities.](image-url)
Example

Croll et al. (2011)

Campo et al. (2011)

López-Morales et al. (2010)
Model Fit to Photometric Data

Madhusudhan et al. 2011, Nature, 64, 469
First measurement of atmospheric C/O in a giant planet

Key Molecular Constraints

- $\text{H}_2\text{O}/\text{H}_2 \leq 6 \times 10^{-6}$
- $\text{CH}_4/\text{H}_2 \geq 8 \times 10^{-6}$

$\text{C/O} \geq 1$

Adapted from Madhusudhan et al. 2011, Nature, 469, 64

Data from Lopez-Morales et al. 2010; Croll et al. 2010; Campo et al. 2011
No Water Detected on the Dayside of WASP-12b

Also see Stevenson et al. 2014
Observations of Exoplanet Atmospheres

C/O Ratios in Hot Jupiter Atmospheres

New Advances with HST Spectroscopy

Deming et al. 2013

HD209458b

Deming et al. 2013

XO-1b

Madhusudhan et al. 2012

WASP-17 b

Mandell et al. 2014

WASP-12 b

WASP-19 b
Multi-instrument Spectra of Hot Jupiters
(HST + Spitzer + Ground-based observations)

• Sub-solar H$_2$O abundances
• High C/O ratio

More data coming ...

Stevenson et al. 2014, Madhusudhan et al. 2014 (in prep)
H$_2$O in Transmission Spectra

Madhusudhan et al. 2014a
High-precision H$_2$O Measurements

Madhusudhan et al. 2014a
What is causing the Low $\text{H}_2\text{O}$ Abundances
What is causing the Low H$_2$O Abundances?

Clouds/Hazes?  Low O/H?
Implications of C/O Ratio
1. Influence of C/O on Atmospheric Chemistry

A Two-dimensional Classification Scheme for hot Jupiter Atmospheres

2. Implications for Planet Formation

Image Credits: NASA
Influence of C/O on Planetesimal Composition

Madhusudhan, Mousis, Lunine, & Johnson 2011
Constraints on Protoplanetary Conditions

Gas Accretion Model

Predictions:
1. Nearly Stellar C/H
2. Sub-stellar O/H

Oberg et al. 2011
Ali-Dib et al. 2014

Depleted Disk Model

Predictions:
1. Stellar or super-stellar C/H
2. Stellar or Sub-stellar O/H

Madhusudhan et al. 2011b
Atmospheric Compositions of Lower Mass Planets
Characterizing Atmospheres of hot Neptunes (GJ 436b)

Clouds in the hot Neptune GJ 436b ($T \approx 750$ K)

$M_s = 0.4 \, M_\oplus, \, R_s = 0.5 \, M_\oplus, \, T_{\text{eff}} = 3500$ K, M3 V

$M_p = 22.2 \, M_E, \, R_p = 4.3 \, R_E, \, T_{\text{eq}} \approx 750$ K

Stevenson et al. 2010
Madhusudhan & Seager 2011
Characterizing Super-Earth Atmospheres (GJ 1214b)

\[ M_p = 6.55 \pm 0.98 \, M_E \]
\[ R_p = 2.678 \pm 0.13 \, R_E \]
\[ T_{eq} = 400 - 550 \, K \]

Key Merit: Orbits an M Dwarf
\( (M = 0.16 \, M_\odot, \, R = 0.2 \, R_\odot) \)

Clouds in the super-Earth GJ 1214b (T ≈ 550 K)

60 HST orbits

Kreidberg et al. 2014
Future Observational Facilities

The James Webb Space Telescope

- JWST: NIRSpec and MIRI (0.6-24 μm), R~3000
- E-ELT: METIS (2.9-5.3 μm) R -> 10^5 + N-band

The Future from Ground:
European – Extremely Large Telescope

Hedges and Madhusudhan (in prep)
Conclusions

• Currently hot Jupiters provide the best targets for atmospheric spectroscopy of exoplanets
  - We can measure H$_2$O better in hot Jupiters than in solar system giant planets

• The sum-total of existing data of exoplanetary atmospheres are indicating low H$_2$O abundances

• Clouds or Formation conditions?