C/O Ratios in Exoplanetary Atmospheres

Nikku Madhusudhan
Princeton University

Collaborators: Drake Deming (U. Maryland), Joseph Harrington (UCF), Kevin Stevenson (UCF), Sarah Nymeyer (UCF), Christopher Campo (UCF), Peter Wheatley (WASP), Jasmina Blecic (UCF), Ryan Hardy (UCF), Nate Lust (UCF), David Anderson (WASP), Andrew Collier-Cameron (WASP), Christopher Britt (UCF), William Bowman (UCF), Leslie Hebb (WASP), Coel Hellier (WASP), Pierre Maxted (WASP), Don Pollacco (WASP), Richard West (WASP), Olivier Mousis (FNRS, France), Jonathan Lunine (Cornell), Torrence Johnson (JPL), Kevin Heng (ETH, Zurich), Julianne Moses (Space Sci. Inst), Channon Vischer (LPI), Erik Petigura (Berkeley), Geoff Marcy (Berkeley), Brice Demory (MIT), Kaspar von Braun (NExSci), Sukrit Ranjan (Harvard), David Charbonneau (Harvard)

Special thanks: Sara Seager, Adam Burrows, Marc Kuchner

Extreme Solar Systems II
Jackson Hole, WY. September 11-17, 2011
The Giant Planet Story is the Story of the Solar System

C/O = 0.5
(Working Hypothesis)

C/O ≥ 1
(Strange Territory)


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)”
Temperature Profiles of Planetary Atmospheres

Madhusudhan & Seager 2009
First Stringent Constraint on the C/O ratio of a Giant Planet Atmosphere

Surprises in the dayside atmosphere of hot Jupiter WASP-12b

A high C/O ratio and weak thermal inversion in the atmosphere of exoplanet WASP-12b

Nikku Madhusudhan (MIT/Princeton), Joseph Harrington (UCF), Kevin Stevenson (UCF), Sarah Nymeyer (UCF), Christopher Campo (UCF), Peter Wheatley (WASP), Drake Deming (NASA GSFC), Jasmina Blecic (UCF), Ryan Hardy (UCF), Nate Lust (UCF), David Anderson (WASP), Andrew Collier-Cameron (WASP), Christopher Britt (UCF), William Bowman (UCF), Leslie Hebb (WASP), Coel Hellier (WASP), Pierre Maxted (WASP), Don Pollacco (WASP), Richard West (WASP), 2011, Nature, 64, 469
Fit requires non-solar abundances

1. Low H$_2$O, Significant CH$_4$
2. No need for a thermal inversion
3. C/O $\geq$ 1

Madhusudhan et al. 2011, Nature, 64, 469
A Carbon-rich Atmosphere

Key Molecular Constraints

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

$\xi^2 = \chi^2/N_{\text{obs}}$

C/O $\geq 1$

Atmospheric Retrieval Techniques

Bayesian:
(Madhusudhan & Seager 2010 & 2011)

Grid-based:
(Madhusudhan & Seager 2009)

Madhusudhan et al. 2011, Nature, 469, 64
"NASA's Spitzer Reveals First Carbon-Rich Planet" - NASA/JPL News

“The Most Fanciful Planet Ever!”
Time Magazine

'Diamond exoplanet' idea boosted by telescope find
BBC

“Carbon-Rich Planet: A Girl's Best Friend?”
US News

“Scorching Hot Alien Planet Abounds With Carbon”
Space.com

“Exoplanet Strikes Carbon Pay Dirt”
Scientific American

“Astronomen staunen über zwei ferne Exoten”
Der Spiegel

“Carbon is King on a Hot Jupiter”
Sky & Telescope
Extreme depletion of water-ice in planetesimals
Madhusudhan et al. 2011b, in press; Lodders 2004
(See poster by E. Petigura)

C/O ≥ 1

Predominance of non-silicate rocks and interiors, water-poor
Gaidos (2000), Kuchner & Seager (2005), Bond et al. (2010)

Water-poor, C-rich Chemistry
Madhusudhan 2011 (submitted), Poster by J. Moses, Talk by K. Heng
New Candidate Carbon-rich Atmospheres
Potential solutions to two outstanding problems
Observational and Theoretical Efforts
Summary

• We have no idea if H$_2$O should be abundant in exoplanetary atmospheres? **We don’t even know the H$_2$O abundance in Jupiter**!

• C/O ratio controls the H$_2$O abundance and has major implications for planet formation, interiors, atmospheres, and for the search for life as we know it.

• We **CAN** measure C/O ratios for hot Jupiters better than for Jupiter. Hot Jupiters are abundant in gaseous H$_2$O, whereas Jupiter is below freezing.

• Latest observations are indicating C/O $\geq$ 1 in some hot Jupiter atmospheres. Need detailed follow-up and verification.

**Most Profound Question**