From Exoplanets To Exoworlds

Kevin Stevenson
May 8th, 2015
Sagan/Michelson Fellows Symposium
Collaborators

- Jacob Bean (UChicago)
- Laura Kreidberg (UChicago)
- Jean-Michel Désert (UC-Boulder)
- Jonathan Fortney (UCSC)
- Michael Line (UCSC)
- Caroline Morley (UCSC)
- Nikku Madhusudhan (Cambridge)
- Adam Showman (LPL)
- Tiffany Kataria (Exeter)

Funding Sources

- Sagan Fellowship
  - Support for this work was provided by NASA through the Sagan Fellowship Program and administered by NExScI.
- HST
  - Part of this work was based on observations made with the NASA/ESA Hubble Space Telescope that were obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.
- Spitzer
  - Part of this work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.
Current Questions in Exoplanet Characterization

Atmospheric thermal structure

Atmospheric chemistry

Atmospheric dynamics
Have we definitively detected a thermal inversion in the atmosphere of a hot-Jupiter?

Atmospheric chemistry

Atmospheric dynamics
Knutson et al. (2008) simultaneously measured one secondary eclipse in all four Spitzer/IRAC channels
- Divided time between channels
- Observing strategy was suboptimal
- Predicted emission spectrum ≠ measured Spitzer photometry points
- Prototypical exoplanet for atmospheric thermal inversions
  - Spawned numerous investigations to explain the source of purported inversion
HD 209458b – Circa 2014

• Diamond-Lowe et al. (2014)

• Reanalysis of 2005 data
  • 4 secondary eclipses
  • State-of-the-art analysis techniques
  • BLISS mapping
HD 209458b – Circa 2014

• Diamond-Lowe et al. (2014)

• Reanalysis of 2005 data
  • 4 secondary eclipses
  • State-of-the-art analysis techniques
  • BLISS mapping

• Analysis of previously-unpublished 2007, 2010 & 2011 data
  • 3.6, 4.5 & 8.0 μm light curves
  • More efficient observing mode
No evidence for an atmospheric thermal inversion in HD 209458b.
Results confirmed by Evans et al. (2015).
No definitive detection of thermal inversion in any exoplanet.
Current Questions in Exoplanet Characterization

Have we definitively detected a thermal inversion in the atmosphere of a hot-Jupiter?

Have we definitively detected a carbon-rich atmosphere for a hot-Jupiter?

Atmospheric dynamics
Carbon-rich planet:
- C/O > 1
- Low [H\textsubscript{2}O]
- High [CH\textsubscript{4}]

Oxygen-rich planet:
- C/O ~ 0.55 (Solar)
- High [H\textsubscript{2}O]
- Low [CH\textsubscript{4}]

Spawned numerous investigations
- Formation scenarios
- Classification schemes
- Diamond planets
WASP-12b – Carbon-Rich Planet?

**Planet**
- Mass: 1.39 M$_J$
- Radius: 0.83 R$_J$
- Eq. Temperature: 2500 K
- Orbital Period: 1.09 days

**Host Star**
- Mass: 1.35 M$_\odot$
- Radius: 1.57 R$_\odot$
- $T_{\text{eff}}$: 6300 K (G0V)
- Distance: 267 pc

**Observations**
- Published and unpublished data
- Spitzer & HST
- 1.1 – 10 μm

---

**Crossfield et al. (2012)**

**Cowan et al. (2012)**
• C-Rich: Best fit to available data
• O-Rich: Poor fit assuming thermochemical equilibrium, requires 5x less H$_2$O and 100x more CO$_2$ relative to solar composition (physically implausible).
• Isothermal: 2930 K, $7.3 \times 10^6$ times less probable
WASP-12b – Transmission Spectrum

• Observed 6 transits with HST/WFC3
  • 3 transits with G141 (1.2 – 1.7 μm)
  • 3 transits with G102 (0.8 – 1.2 μm)
• 7σ detection of H₂O at planet terminator

Kreidberg et al. (Submitted)
Kreidberg et al. (Submitted)

Temperature (Kelvin)

H₂O Abundance (log₁₀ VMR)

-8  -7  -6  -5  -4  -3  -2  -1

C/O = 0.55 model
C/O = 1.00 model
1σ uncertainty from FULL retrieval

10 mbar
1 mbar
0.1 mbar
Have we definitively detected a thermal inversion in the atmosphere of a hot-Jupiter?

Have we definitively detected a carbon-rich atmosphere for a hot-Jupiter?

What parameters affect the heat redistribution efficiency from dayside to nightside?
Cooler planets typically exhibit more efficient heat redistribution.
WASP-43b – White WFC3 Phase Curve

- PC Max. 40 ± 3 minutes before eclipse
- PC Min. 34 ± 5 minutes after transit
- Asymmetric shape (10σ confidence)
- Eclipse Depth: 461 ± 5 ppm

Stevenson et al., Science (2014c)
Planet Emission Spectrum

Phase = 0.15

H$_2$O

Relative Flux (ppm)

Wavelength ($\mu$m)

Brightness Temperature Maps

1.21 $\mu$m

1.42 $\mu$m

1.63 $\mu$m

Thermal Profile

Pressure (bar)

Temperature (K)

K. B. Stevenson (2014)
3.6 & 4.5 μm Spitzer Phase Curves

PRELIMINARY RESULTS
Conclusions

- HD 209458b does not have a thermal inversion at the pressure levels probed by Spitzer.
  - No definitive detection of a thermal inversion in any hot-Jupiter atmosphere to date.

- Carbon-rich status of WASP-12b is debatable.
  - Secondary eclipse photometry favors C-rich scenario.
  - Primary transit spectroscopy favors O-rich scenario.

- WASP-43b HST/WFC3 + Spitzer/IRAC phase curves
  - Heat redistribution efficiency is not strictly $T_{eq}$ dependent.