Extrasolar Giant Planets: A New Perspective on Climate

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Opportunities for Climate Insights

- Atmospheric response to extreme and varying climatic forcing
- Clouds
- Atmospheric chemistry
- Dynamics
Symbols = planets with $M < 10 \text{ M}_{\text{Earth}}$
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interaction with sunlight

rotation
interaction with sunlight

thermal emission

rotation
interaction with sunlight

atmospheric chemistry

thermal emission

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Exoplanet Science

• Yesterday & Today: transiting planets -- mostly giants
• Today & Tomorrow: directly imaged planets
  • near term: gas giants, groundbased
  • longer term: terrestrial planets, space
Transiting Planets
Atmospheric Circulation of Transiting Giant Planets

courtesy Nikole Lewis
Spitzer light curves for HD 189733b

Knutson et al. (2007, 2009)

8 µm  24 µm
Doppler detection of winds on HD 209458b?

Snellen et al. (2010, Nature) obtained high-resolution 2 μm spectra of HD 209458b during transit with the CRIRES spectrograph on the VLT

Tentative detection of ~2 km/sec blueshift in CO lines during transit of HD 209458b

Interpreted as winds flowing from day to night at high altitude (~0.01-0.1 mbar)
we record pressure and temperature profiles along our three-dimensional atmospheric model for HAT-P-2b. Both theoretical light curves and spectra directly from atmospheric models for exoplanets, especially those on consistent treatment of radiative and advective processes. A shift in the hot spot highlights the importance of self-heating in the hot spot of the planet from the substellar longitude. This shift means the hottest portion of the planet will rotate into and which portion of that emergent flux would be directly toward an earth observer including limb darkening.

As the planet cools, while wind speeds have just reached their peak values causing an increase in the order of magnitude of the emergent flux from each point on the planet. This is a result of the lag between planet wide TiO/VO. This is a result of the lag between planet wide

Our cases with TiO/VO, which result in a smaller order of magnitude of the emergent flux from each point on the planet. This is a result of the lag between planet wide TiO/VO. This is a result of the lag between planet wide

Figure 4, the hot spot on is shifted eastward from the substellar longitude. This shift in the hot spot means that the hottest portion of the planet will rotate into secondary eclipse (bottom) from our models with (right) and without (left) TiO/VO. Temperatures represent average values weighted by cosine of the lapse rate and secondary eclipse in models with and without TiO/VO. The lack of strong rotational effects significantly between models with and without TiO/VO.
Direct Imaging

- Thermal emission (today)
- Reflected light (future)
Thermal Evolution

adapted from Burrows (2001, RvMP, 73, 79)
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Direct Imaging Advantages

- Planet light separated from primary star
- Large range of orbits, masses can be probed

Marois et al. (2008)
Atmospheric Models

chemical & physical properties

$T_{\text{eff}}, g, [\text{M/H}]$

clouds & dynamics

``$f_{\text{sed}}, K_{zz}$``
Atmospheric Models

chemical & physical properties

\( T_{\text{eff}}, g, [M/H] \)

clounds & dynamics

``f_{\text{sed}}, K_{zz}``

P

T

chemical & physical properties

\( T_{\text{eff}}, g, [M/H] \)

clounds & dynamics

``f_{\text{sed}}, K_{zz}``
Compare data to model set

1000/4.5/2/10^4 cloudy
cloudy
Thus all 3 planets are cool & cloudy
HR 8799 planets

- Detection of CH$_4$, CO, H$_2$O
- Hints of super-solar composition
- Clouds to cool temperatures
- Mixing, non-equilibrium chemistry
- Mass, $T_{\text{eff}}$ constraints
- Gravity-dependent cloud departure
Marley (2013)
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HR 8799 c
1100 K young giant planet

CO + trace? CH₄

Mg-silicates
Iron metal liquid
Perovskite
Corundum

CO

Mixing

Marley (2013)
Learning Horizontal Patchiness Important Too
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Meanwhile in Reflected Light

Color and albedo are functions of type and depth of clouds.

Clouds depend on BOTH internal heat flow (mass, age) and incident flux.
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photochemistry
Value of Directly Imaged Cool Giants

- Good synergy with solar system planets
- Know how to interpret spectra
- Photochemistry and winds less crucial to interpretation (no massive external forcing)
- Derive dynamics, composition, internal heat flow as function of planetary mass, orbit, insolation
I’ve lived in good climate and it bores the hell out of me. I like weather rather than climate.

–John Steinbeck
Weather on Brown Dwarfs

Apai et al. (2013)

Should be possible for planets too
Conclusions

• Exoplanets exhibit atmospheric and climatic forcings in novel new conditions
• Provide insight to role of clouds, dynamics, atmospheric chemistry, and radiative balance
• The future should bring many more planets
The Future: Climate on Directly Imaged Planets

(in five years there will be far more data for these objects than the hot Jupiters)
The Future: Climate on Directly Imaged Planets

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