Three-dimensional atmospheric circulation of hot Jupiters on highly eccentric orbits

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Motivation – Current Exoplanet Population

"Planet Semi-Major Axis" vs "Planet Eccentricity" (488)
Motivation

Why study the atmospheric dynamics of exoplanets?
• Studying weather on extrasolar planets helps us understand ground- and space-based observations
• Varying parameters over a wide range helps us expand the theory of atmospheric circulation beyond the confines of the solar system

Why study eccentric exoplanets?
• Eccentric exoplanets are subject to highly time-variable heating
• Unlike exoplanets in circular orbits, these planets are likely non-synchronously rotating their host stars
• These orbital characteristics present a unique dynamical regime
For our models: Generic hot Jupiters on highly eccentric orbits

- Assume mass, radius, and gravity of generic hot Jupiter
- Atmospheric composition of 1x solar (without TiO/VO) in chemical equilibrium
- Varied parameters
  - *Eccentricity:* from circular (e=0.0) to highly eccentric (e=0.75)
  - *Semi-major axis* (orbital period)
    
    \[ a = 0.0313 \text{ AU}, 0.0497 \text{ AU}, 0.0789 \text{ AU} \]
SPARC Model Atmosphere
Substellar and Planetary Atmospheric Radiation and Circulation Model

MITgcm
• Solves 3-D primitive equations
  \[
  \frac{dv}{dt} = -\nabla \Phi - fk \times v
  \]
  \[
  \frac{\partial \Phi}{\partial p} = -\frac{1}{\rho}
  \]
  \[
  \nabla \cdot v + \frac{\partial \omega}{\partial p} = 0
  \]
  \[
  \frac{dT}{dt} = \frac{q}{c_p} + \frac{\omega}{\rho c_p}
  \]

Radiative Transfer
• Based on RT model by Marley and McKay (1999)
• Plane-parallel, two-stream
• Opacities binned using correlated-k method
Eccentric Extrasolar Planet Considerations

Distance varies with time

\[ r(t) = a(1 - e \cos E(t)) \]
\[ M(t) = E(t) - e \sin E(t) \]
\[ M(t) = n(t - \tau) \]

Planetary rotation rate is likely non-synchronous

- Use pseudo-synchronous formulation from Hut (1981)

\[ \tau_{\text{rot}} = \tau_{\text{orb}} \left[ \frac{(1+3e^2+3e^4/8)(1-e^2)^{3/2}}{1+15e^2/2+45e^4/8+5e^6/16} \right] \]
Effect of eccentricity

a = 0.0497 AU
Why the narrower jet?
Rossby Deformation Radius \( (L_R) \)

- Hz length scale for atmospheric phenomena affected by both rotation and buoyancy waves (gravity waves)
- Given at equator by

\[
L_R = \frac{NH}{f}
\]

where

- \( N = \) Brunt-Vaisala frequency
- \( H = \) scale height
- \( f = \) Coriolis parameter \( = 2\Omega \sin\phi \)

- By Hut (1981) formulation, rotation period proportional to orbital period, which in turn is inversely proportional to the deformation radius
Effect of orbital distance

Each run has $e=0.75$, pseudo-synchronous rotation

$a=0.0789$ AU

$a=0.0497$ AU

$a=0.0313$ AU
Hot Jupiter with $e=0.75$, $a=0.0789$ AU, $T_{\text{rot}}/T_{\text{orb}} = 1/9$

Equatorial superrotating jet maintained throughout orbit
What pumps the jet?
Eddy momentum flux

- *Eddy momentum flux*: contribution of momentum transport by *turbulent eddies*
- Calculate $u^*v^*$, the meridional flux of eastward momentum
  - $u^*$ and $v^*$ are the deviations of zonal and meridional winds from their zonal averages
  - If $u^*v^* > 0$, northward flux of eastward momentum
  - If $u^*v^* < 0$, southward flux of eastward momentum
What pumps the jet?
Eddy momentum flux

- Eastward momentum is being transported equatorward
- This flux maintains the equatorial jet against westward accelerations caused by advection, friction, and Coriolis forces
Observational Implications

- Peak temp lags peripase passage
- Dynamics shift hot spot east of SS point
- Depending on observing geometry, hot/cold sides rotate in/out of view at different times

→ Lightcurves will be shaped by both factors
Conclusions

• Eccentric hot Jupiters dominated by eastward flow at photospheric levels
  – Eastward displacement of the hottest regions from the substellar point
  – Superrotating jet maintained by eddies that transport eastward momentum to equator
• Rapid rotation rates due to pseudo-synchronization lead to
  – Small Rossby deformation radius
  – Multiple jets in atmosphere

*Future work:*
→ systematic study of dynamics and mechanisms
→ generation of model lightcurves and spectra
For our models: HD 189733b on eccentric orbits

**Planetary Parameters**
- $M_p = 1.13 \ M_J$
- $R_p = 1.138 \ R_J$
- $a = 0.0313 \ AU, 0.0497 \ AU, 0.0789 \ AU$
- $e = 0.0, 0.25, 0.50, 0.75$
- $g = 21.4 \ m \ s^{-2}$
- pseudo-synchronous rotation
- Atmospheric Composition:
  - H$_2$O (Tinetti et al. 2007)
  - CH$_4$ (Swain et al. 2008)
  - CO (Swain et al. 2009)

**Stellar Parameters**
- Stellar type = K1-K2
- $M_s = 0.8 \ M_{\odot}$
- $T_{\text{eff}} = 4980 \ K$