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

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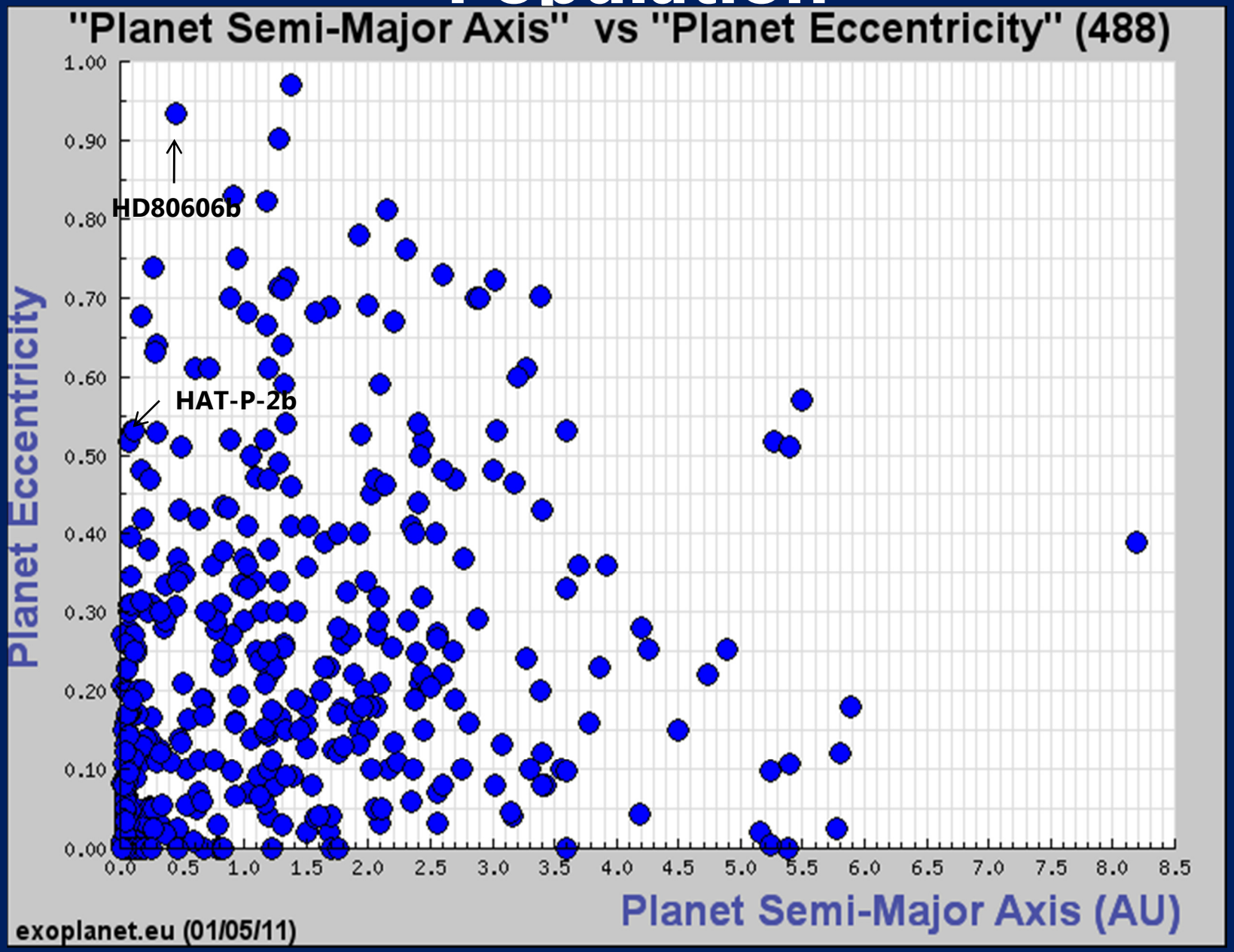
Motivation – Current Exoplanet Population



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 AU, 0.0497 AU, 0.0789 AU
  - *Rotational period:* pseudo-synchronous rotation using Hut (1981) formulation

SPARC Model Atmosphere

Substellar and Planetary Atmospheric Radiation and Circulation Model

MITgcm

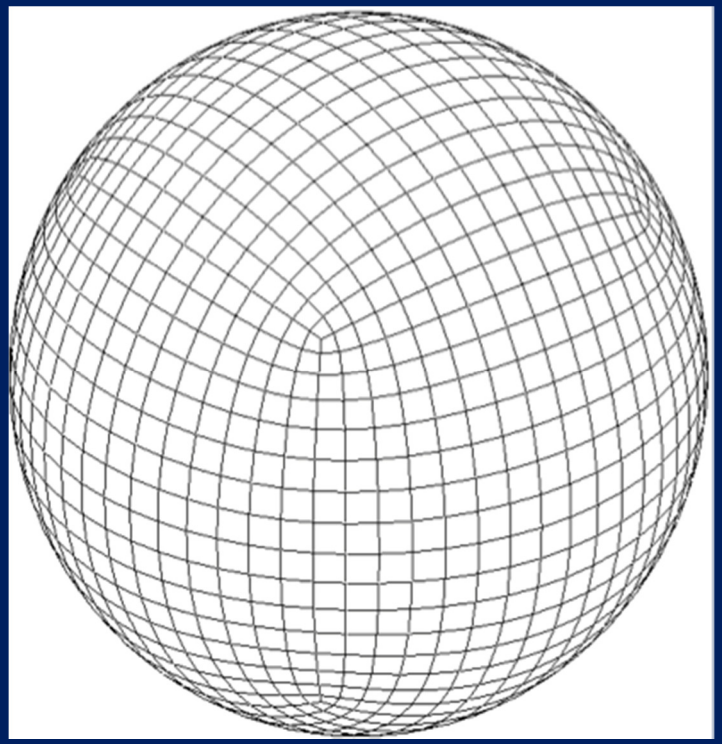
- Solves 3-D primitive equations

$$\frac{d\mathrm{v}}{dt} = -\nabla\Phi - f\mathrm{k} \times \mathrm{v}$$

$$\frac{\partial\Phi}{\partial p} = -\frac{1}{\rho}$$

$$\nabla \cdot \mathrm{v} + \frac{\partial\omega}{\partial p} = 0$$

$$\frac{dT}{dt} = \frac{q}{c_p} + \frac{\omega}{\rho c_p}$$



Cubed sphere grid

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

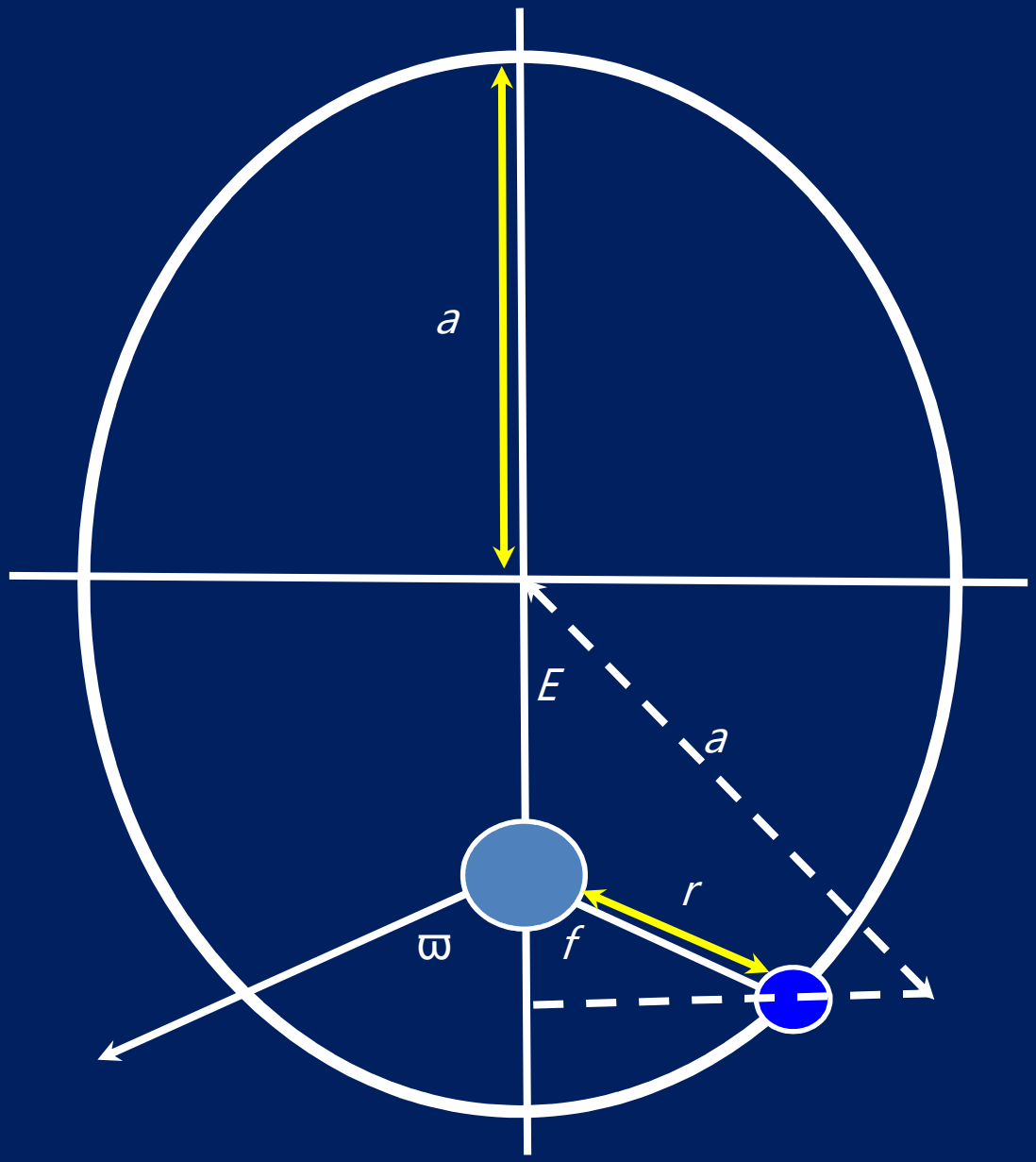
Distance varies with time

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

Planetary rotation rate is likely non-synchronous

- Use pseudo-synchronous formulation from Hut (1981)

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



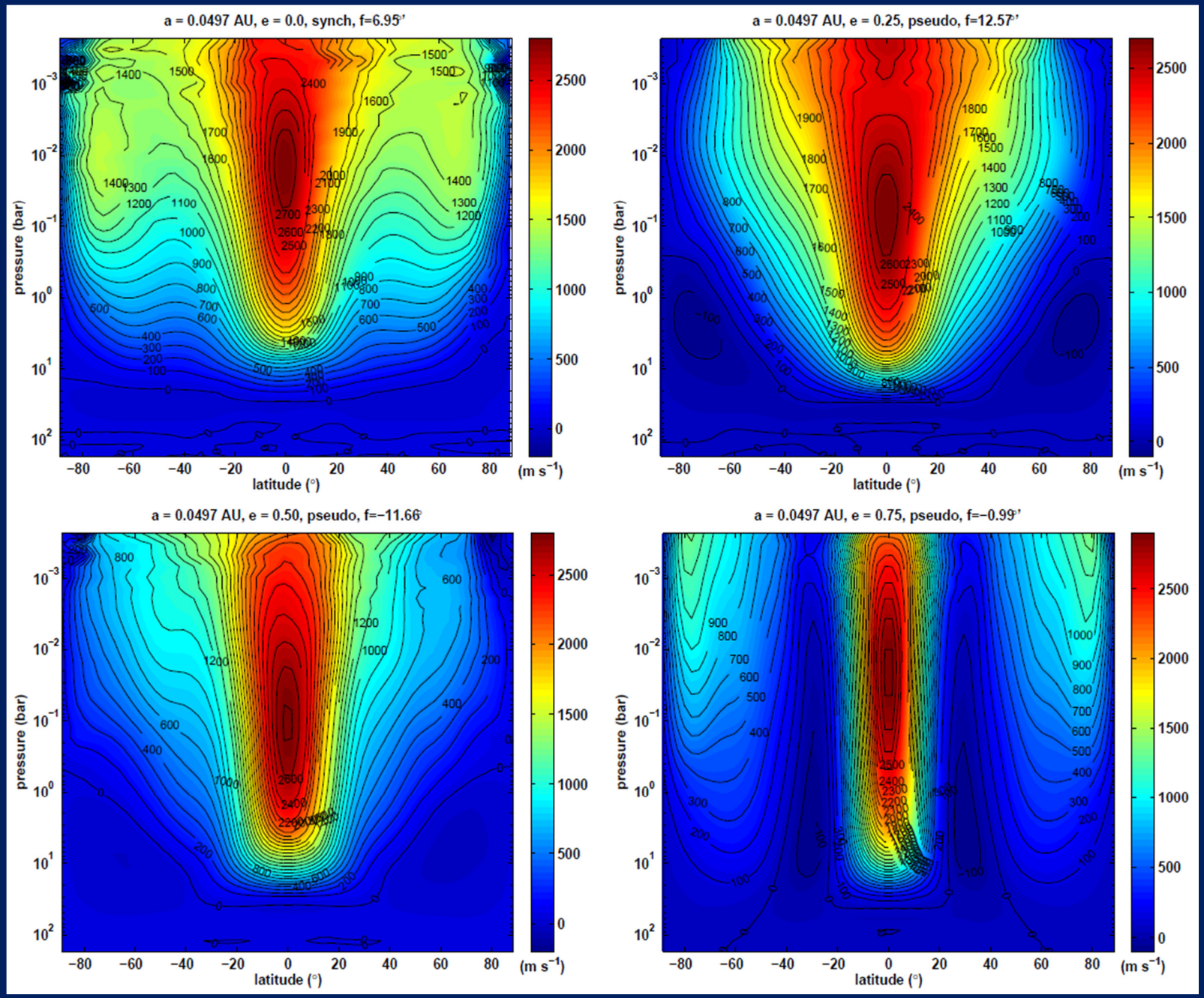
Effect of eccentricity
a = 0.0497 AU

e=0.0

e=0.25

e=0.50

e=0.75



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

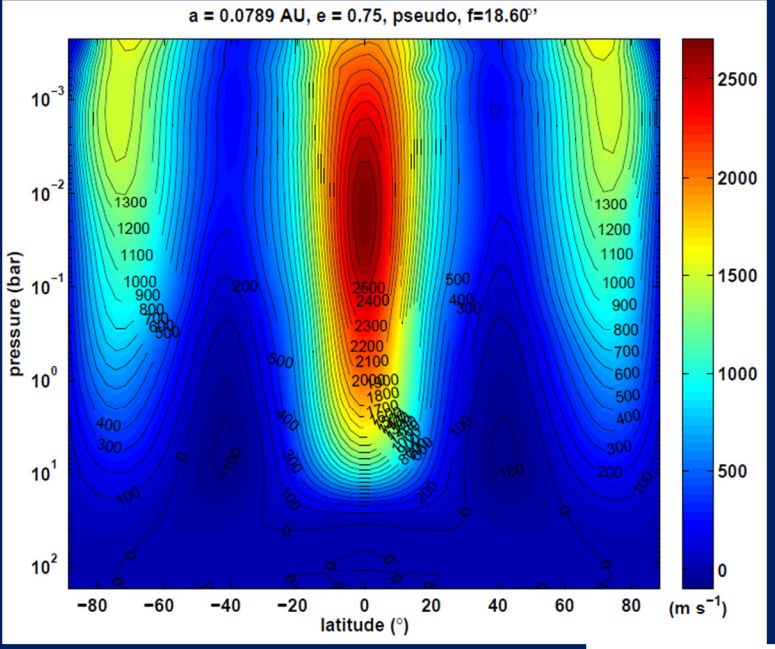
H = scale height

f = Coriolis parameter = $2\Omega \sin\varphi$

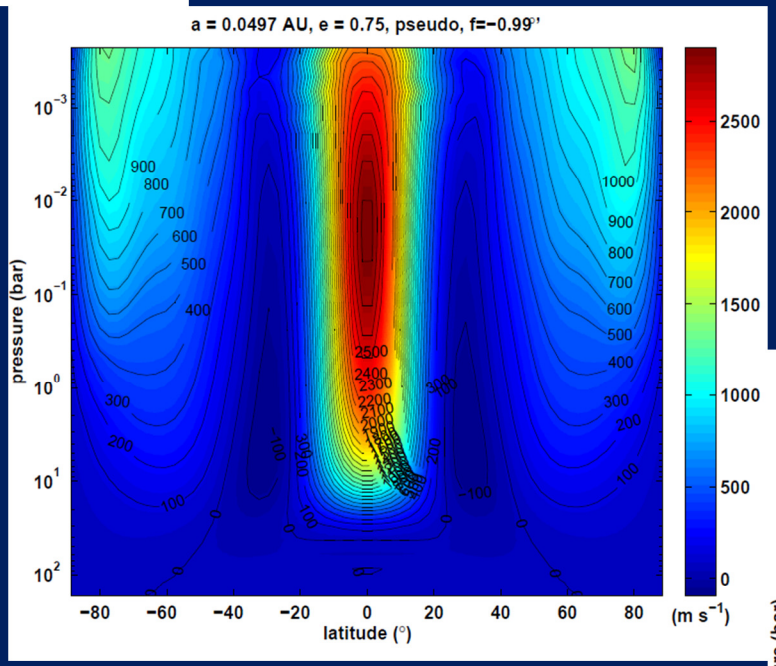
- By Hut (1981) formulation, rotation period proportional to orbital period, which in turn is inversely proportional to the deformation radius

Effect of orbital distance

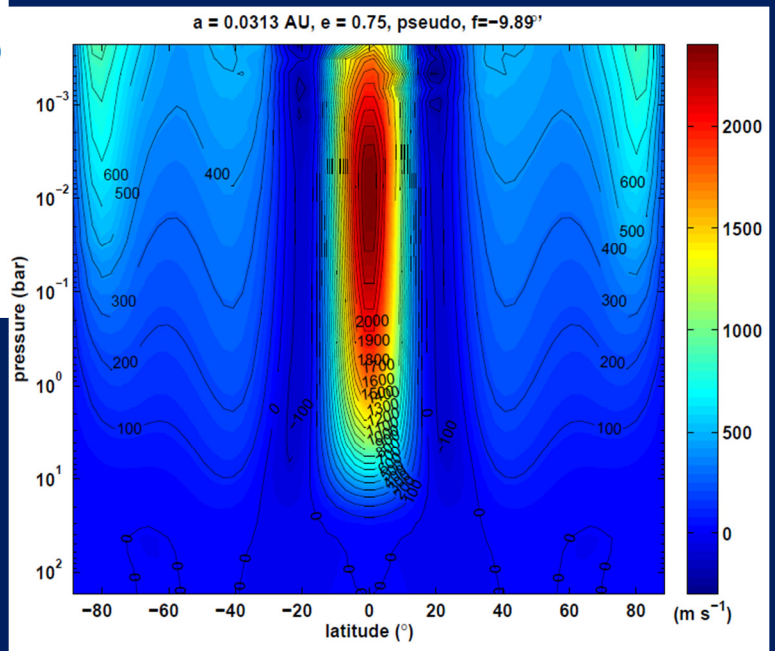
Each run has e=0.75, pseudo-synchronous rotation



a=0.0789 AU

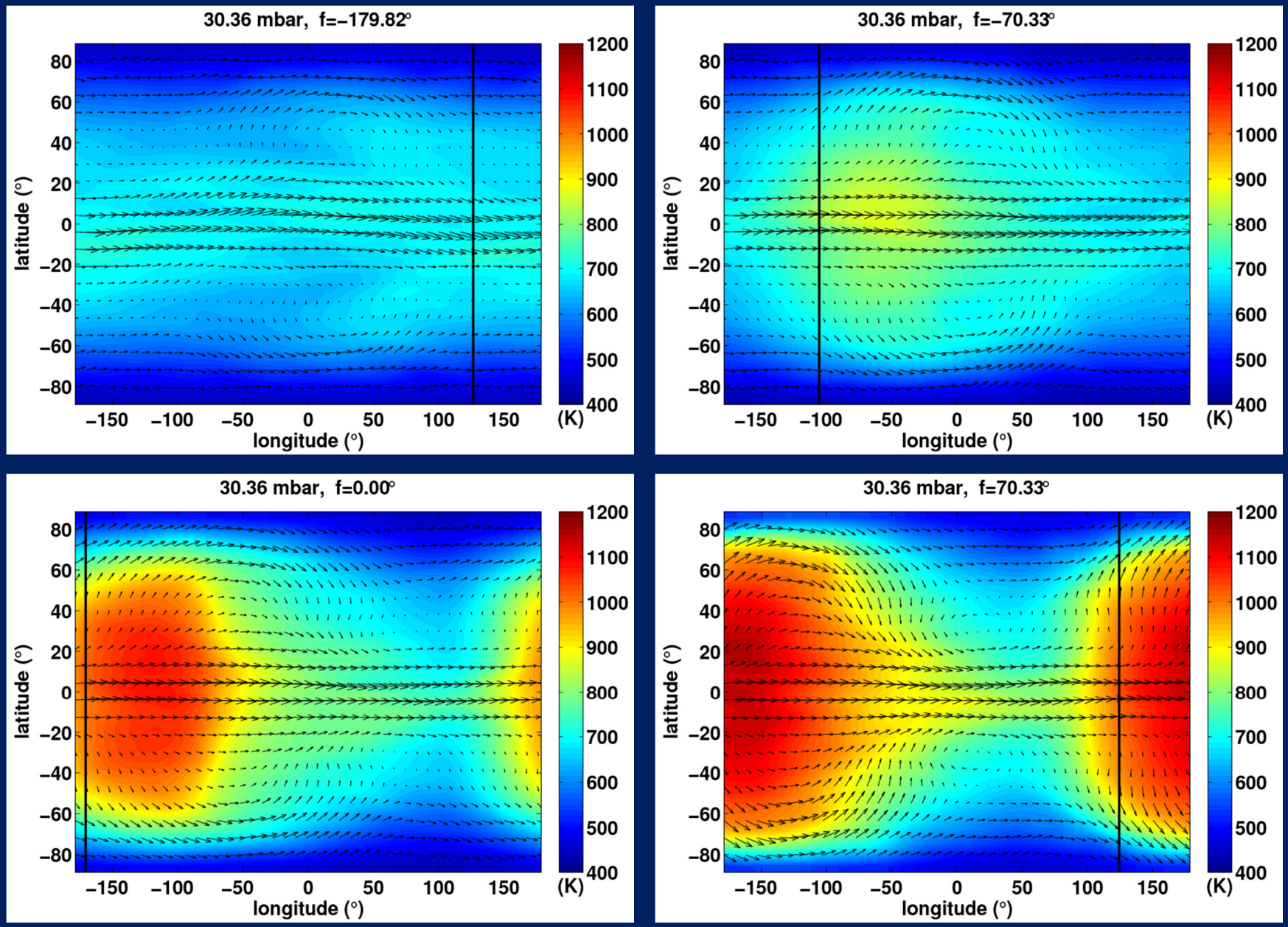


a=0.0497 AU



a=0.0313 AU

Hot Jupiter with **e=0.75, a=0.0789 AU, T_{rot}/T_{orb}= 1/9**



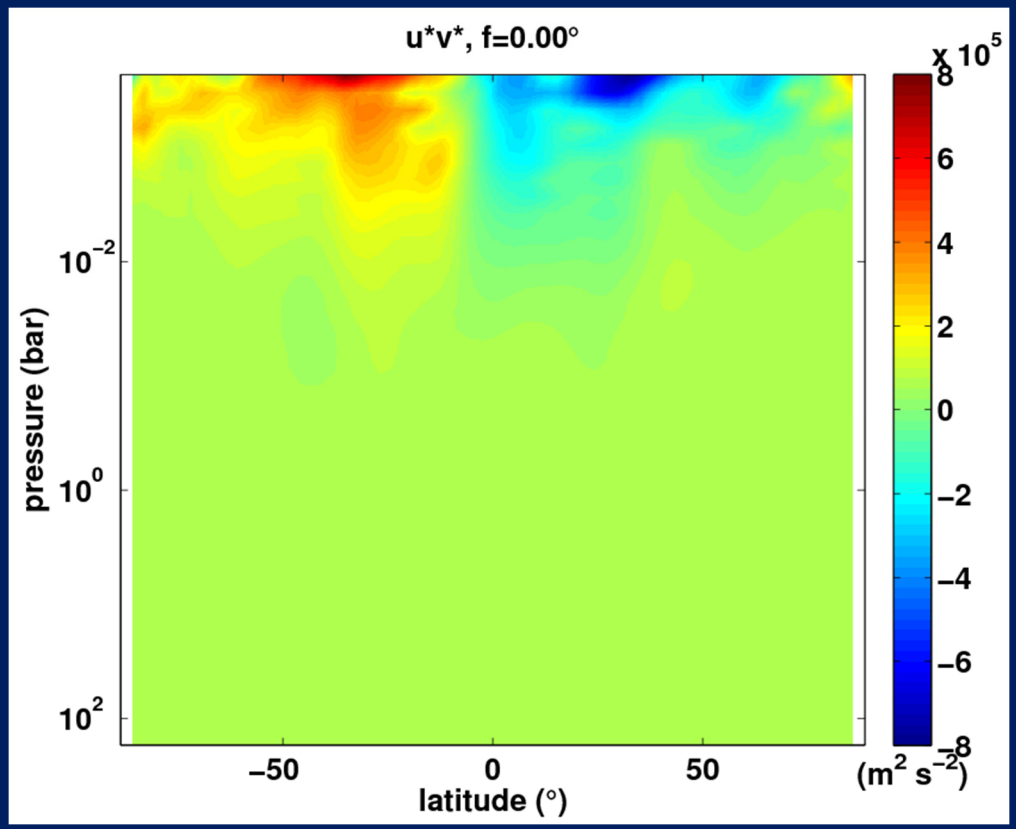
Equatorial superrotating jet maintained throughout orbit

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 meriodional winds from their zonal averages
  - If u*v* > 0, northward flux of eastward momentum
  - If u*v* < 0, southward flux of eastward momentum

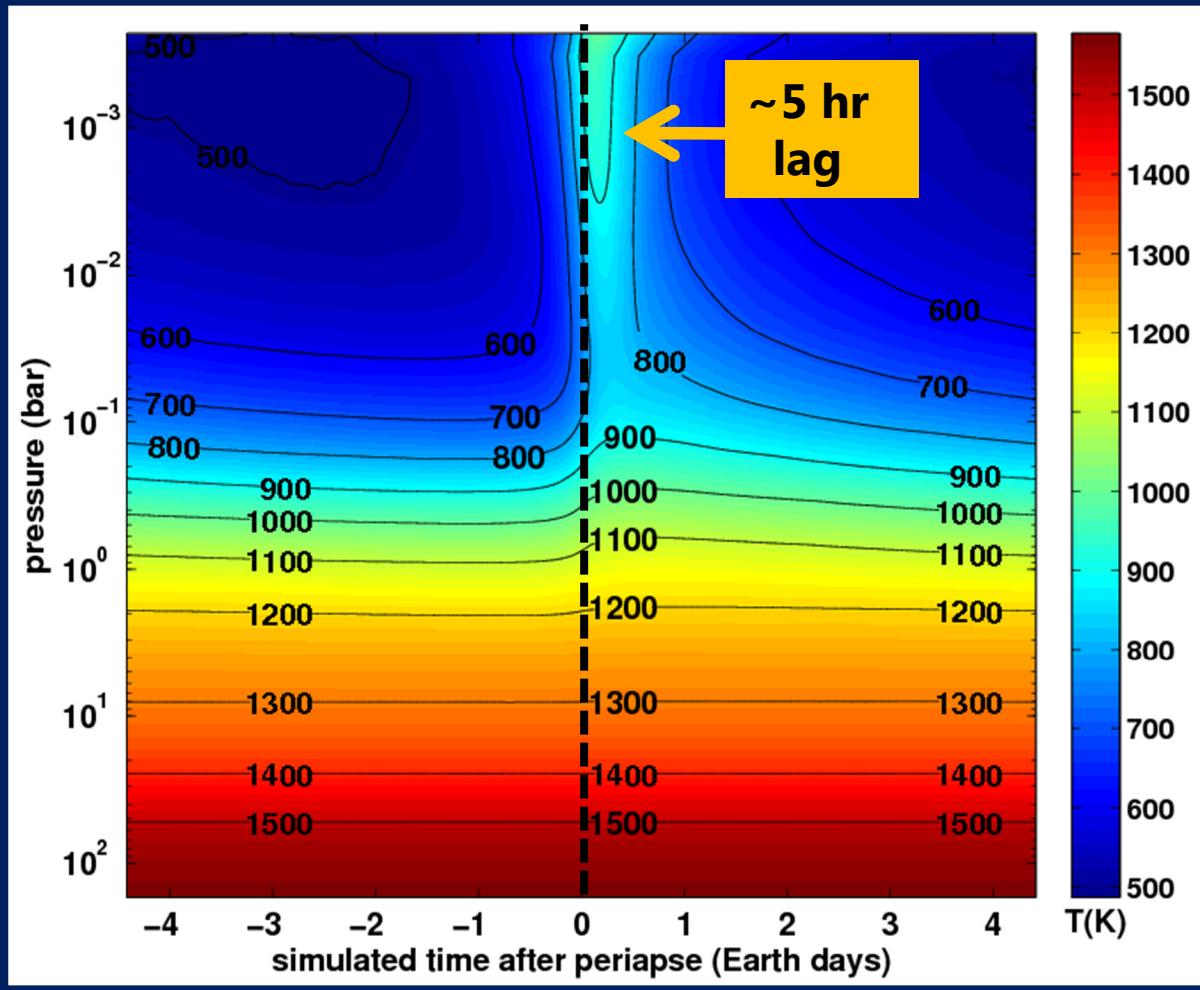
What pumps the jet?
Eddy momentum flux

- 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_2O (Tinetti et al. 2007)
- CH_4 (Swain et al. 2008)
- CO (Swain et al. 2009)

Stellar Parameters

Stellar type = K1-K2

$M_S = 0.8\ M_{Sun}$

$T_{eff} = 4980\ K$