Three-Dimensional Atmospheric Circulation of hot Jupiters on highly eccentric orbits

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Introduction

Of the over 400 exoplanets detected to date, approximately one-tenth of these are on highly eccentric orbits (e> 0.5). Such planets experience highly time-variable stellar heating throughout their orbit, undergoing 'flash-heating' events as the planet approaches periapse. Because a number of these eccentric planets transit their host stars as seen from Earth, we are able to probe their atmospheres to better understand their thermal structure, composition, and dynamics. Still, little is known about eccentric planets' atmospheric dynamical regime. Therefore, we use a three-dimensional atmospheric circulation model that includes radiative transfer (the MITgcm/SPARC model, see [1] and [2]) to study generic hot Jupiters over a wide range of eccentricities. Here we present a few results of one particular simulation, which places the hot Jupiter exoplanet HD189733b in a highly eccentric, pseudo-synchronous orbit.

Model Setup

HD189733b is a hot-Jupiter exoplanet in a circular ($e = 0.0$) orbit around its parent star. For our simulation, we assume the mass ($\mathrm{M_P} = 1.13\mathrm{M_J}$), radius ($\mathrm{R_P} = 1.138\mathrm{R_J}$), gravitational constant (g=21.4 ms^{-2}) of HD189733b with an atmospheric composition of 1×solar (excluding TiO/VO) in chemical equilibrium. However, the simulation presented here sets the orbital period at 4 times the nominal value (∼8.8 days) and the eccentricity at 0.75, such that the semimajor axis is 0.0497 AU, ∼1.5 times the nominal value, and the ratio of maximum to minimum stellar flux is almost 50. Because eccentric planets are likely non-synchronously rotating their host stars, we calculate the rotation rate of the planet assuming the pseudo-synchronous relationship derived in [3] to be 24.5 hours. The simulation utilizes a cubed-sphere grid with a horizontal resolution of C32 (∼64×128 in latitude and longitude) and a vertical pressure range from 170 bar to 20 μbar split into 40 levels with even log spacing.

Global Temperature and Global Winds

Because our model is three-dimensional, we can analyze properties of the atmosphere as a function of pressure. **Figure 1** shows the average global temperature as a function of time from periapse passage. Temperatures remain fairly constant below 1 bar. However, in the uppermost layers of the atmosphere, peak temperatures are reached ∼5 hours after periapse passage. **Figure 2** shows the zonal-mean zonal wind profile of our simulation at periapse. A strong eastward jet is located at the equator, with peak winds exceeding 2500 m/s. Because of the rapid rotation of the planet, strong midlatitude jets develop as well, with speeds of approximately 1200 m/s. The width of the jet is also determined by the Rossby deformation radius, $\mathrm{L_R = NH/f_0}$. Here, N is the Brunt-Vaisala frequency, H is the scale height of the atmosphere, and $\mathrm{f_0}$ is the Coriolis parameter. Therefore, the width of the jet depends on both the planetary rotation rate and the atmospheric stratification.

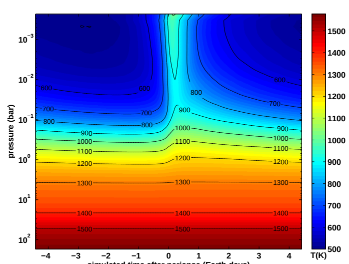

Figure 1: *Average temperature as a function of time relative to periapse passage for generic hot Jupiter simulation (e=0.75, pseudo-synchronous rotation, $T_{rot}/T_{orb} =\sim 1/9$). The temperatures represent averages over latitude and longitude as a function of pressure. On average, peak global atmospheric temperatures and winds are reached ∼5 hours after periapse passage.*

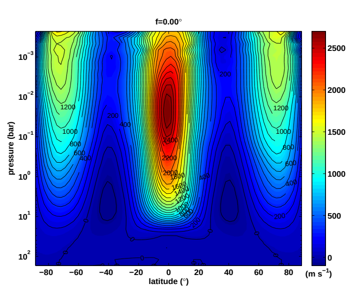

Figure 2: *Zonally-averaged zonal wind of generic hot Jupiter at periapse (true anomaly, f=0.0). The colorbar denotes the strength of the winds in units of ms^{-1}. Contours are spaced by 100 ms^{-1}. Notice the presence of a strong jets at the equator and also at the midlatitudes. A zonal-average refers to an average over longitude. Winds that are zonal move east/west.*

Winds

Like other eccentric exoplanets, this planet experiences a 'flash-heating' event as it passes through periapse. **Figure 3** shows the wind and temperature structure for the simulation at 30 mbar, which corresponds approximately with the level of the photosphere in the infrared, from apoapse (top panel) to beyond periapse (bottom-right panel). Like the circulation of HD189733b in its circular orbit (see [1]), the flow maintains a superrotating jet at the equator throughout its orbit. At apoapse, the temperature structure is fairly uniform in longitude. As the planet approaches periapse (second panel) temperatures rise to ∼900 K at the equator, and a high-amplitude eddy structure with a warm, chevron-shaped feature develops. This chevron-shaped feature is prominent at periapse (third panel), and extends in both latitude and longitude hours after periapse (bottom panel). The chevron shape indicates that turbulent eddies are transporting momentum equatorward (see **Figure 4**).

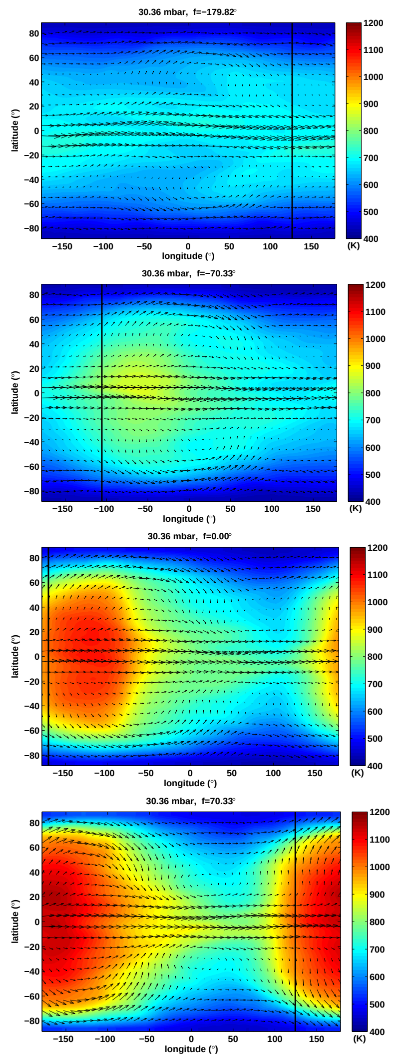

Figure 3: *Wind and temperature profiles at a pressure of the 30 mbar, from apoapse (first panel) to ∼5 hours after periapse (fourth panel). These profiles are snapshots taken 4.4 days before periapse (first panel), 5 hours before periapse (second panel), at periapse (third panel) and 5 hours after periapse (fourth panel). Colorscale indicates temperature, and arrows denote wind direction and wind strength. The solid vertical lines indicate the longitude of the substellar point. Note the chevron-shape of the heating event at periapse, particularly prominent in the mid-latitudes.*

Eddy Flux and Momentum Transport

To understand the transport of zonal (east-west) momentum through the atmosphere, one can also calculate the eddy flux, which quantifies the contribution of transport by turbulent eddies. Here, we calculate u^*v^*, the meridional flux of eastward momentum, where u^* and v^* are the deviations of zonal and meridional winds from their zonal averages. Positive (negative) values of u^*v^* indicate a northward (southward) flux of *eastward* momentum, or, analogously, a southward (northward) flux of *westward* momentum. **Figure 4** shows the zonally-averaged meridional eddy momentum flux at periapse, which shows that eastward momentum is being transported equatorward. This flux maintains the equatorial jet against westward accelerations caused by advection, friction, and Coriolis forces.

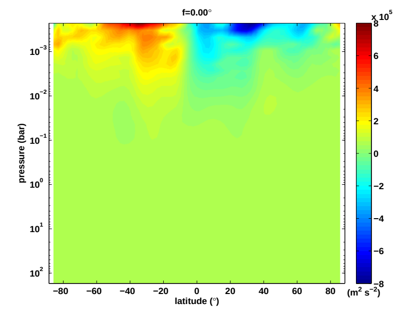

Figure 4: *Zonally-averaged meridional eddy flux of eastward eastward momentum at peripase, shown as a function of latitude and pressure. Negative values indicate southward transport, while positive values indicate northward transport. Here, eastward momentum is being transported toward the equator.*

Synopsis and Implications

– As in published models with zero eccentricity, our high-eccentricity circulation model is dominated by eastward flow at photospheric levels which cause an eastward displacement of the hottest regions from the substellar point.

– The rapid rotation rates associated with pseudo-synchronization at high eccentricity leads to a small Rossby deformation radius and hence multiple jets in the atmosphere.

– Global-mean temperatures and day-night temperature differences peak not at periapse but several hours afterward.

– Standing eddies formed by the strong day-night heating contrast induce a flux of momentum from midlatitudes to the equator, helping to maintain the superrotating equatorial jet. The eddy magnitudes and momentum fluxes peak just after periapse passage leading to variations in the zonal-mean flow throughout the orbit.

– The spatial and temporal variations of the temperature structure have strong implications for light curves; the observed time of peak IR flux will depend on the orientation of the planet's orbit with respect to Earth.

Future Work

This poster shows only one case of interest in our study of generic eccentric hot Jupiters. We are conducting a systematic survey of the influence of orbital semi-major axis, eccentricity, and planetary rotation rate on the dynamics, and will report on these results in the future.

References

[1] The M.I.T. General Circulation Model, http://mitgcm.org
[2] Showman et al. (2009), *ApJ*, 699, 564
[3] Hut (1981), *A&A*, 99, 126