Scientific Frontiers in Research on Extrasolar Planets
ASP Conference Series, Vol. 294, 2003
D. Deming and S. Seager, eds.

Atmospheric Circulation of "Pegasi" Planets

Adam P. Showman
Department of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721; showman@lpl.arizona.edu

Tristan Guillot
Observatoire de la Côte d'Azur, Laboratoire Cassini, CNRS UMR 6529, 06304 Nice Cedex 4, France; guillot@obs-nice.fr

Abstract. We examine the atmospheric circulation of giant planets within 0.1 AU of their stars and discuss the implications for current and future measurements of their planetary radii, horizontal temperature variability, and clouds. Previous radiative-transfer and evolution models of such planets assume a homogeneous atmosphere. Simple arguments suggest, however, that at the photosphere the day-night temperature differences and wind speeds may reach $\sim 500\,\mathrm{K}$ and $\sim 2\,\mathrm{km\,sec^{-1}}$, respectively. Three-dimensional, nonlinear numerical simulations of the atmospheric circulation of HD209458b produce winds exceeding $1\,\mathrm{km\,sec^{-1}}$ that blow the hottest regions away from the substellar point, which has important implications for the infrared light curves of these planets. Furthermore, we show that kinetic energy produced in their atmospheres can be transported into the interiors at a rate great enough to affect the long-term evolution. If the interiors of these planets are close to synchronous rotation and the energy is dissipated locally in the interior, this source of energy could be significant enough to explain the (large) radius of HD209458b.

1. Introduction

About one-fifth of the giant planets discovered around other stars are orbiting at distances less than 0.1 AU from their stars. The detection of HD209458b in transit (Charbonneau et al. 2000; Henry et al. 2000; Brown et al. 2001), with an implied radius of 1.35 Jupiter radii, heralds a new era in characterization of these so-called "Pegasi" planets. An understanding of upcoming measurements of albedo, day-night temperature differences, and radii of Pegasi planets will require knowledge of possible atmospheric circulation regimes. Horizontal temperature variability and cloud abundance depend on the geometry and intensity of the atmospheric circulation, which will affect the infrared light curve and albedo. And an understanding of the radius will require knowledge of the circulation — the radius represents the planet's history of cooling and contraction, which is affected by the circulation through the circulation's influence on temperature profile, cloud abundance, and internal energy transport. In fact, evolution models of HD209458b that use realistic atmospheric temperatures predict a radius that is too small, which suggests that some heat source is missing from the calculations (Guillot and Showman 2002). The best hypothesis is that kinetic energy produced by the atmospheric heat engine is transported into the interior, where it counteracts the loss of energy that causes planetary contraction.

Here we present simple order-of-magnitude arguments and three-dimensional, fully nonlinear simulations of the atmospheric circulation of HD209458b to constrain (i) the nature of the circulation, including wind speeds, day-night temperature differences, and cloud structure, and (ii) the magnitude and depth of kinetic energy production and transport, which is crucial in evaluating whether the atmospheric heat engine can "inflate" the radius of HD209458b enough to satisfy its (large) measured value. The presentation is based on Showman and Guillot (2002) and Guillot and Showman (2002), to which we refer the reader for details. Also, see Guillot and Showman (2003).

2. Atmospheric Circulation of Pegasi Planets

The intense starlight incident upon the surface of Pegasi planets leads to a deep radiative zone extending from near the photosphere to pressures of 100–1000 bars (Guillot and Showman 2002), below which the structure is convective. The globally averaged absorbed and radiated fluxes are $\sim 10^5\,\mathrm{W\,m^{-2}}$, which is $\sim 10^4$ times greater than the intrinsic flux of $\sim 10\,\mathrm{W\,m^{-2}}$. The short radiative time constants ($\sim$ 1 day near the photosphere) implies that large day-night temperature differences are likely even if the wind speeds are fast.

Simple arguments suggest that the interiors of Pegasi planets are in near-synchronous rotation (3.5 days for HD209458b) (Guillot 1996). In planetary atmospheres, rotation inhibits the horizontal expansion of fluid structures past a critical size determined by the strength of the Coriolis accleration. For Jupiter, these critical length scales, the deformation radius and Rhines length, are $\sim$ 2000 and $\sim 10,000\,\mathrm{km}$, respectively, which is similar to the sizes of many of the jets and vortices that dominate the flow. For Pegasi planets, however, these length scales are closer to the planetary radius, which suggests that the circulation is likely to have characteristic length scales approaching the planetary radius. Furthermore, we expect that the dominant force driving the circulation is the intense dayside heating and nightside cooling, and the global scale of this forcing again suggests that a global-scale circulation may dominate.

An order-of-magnitude estimate of day-night temperature difference ΔT and horizontal wind speed v can be obtained as follows. Wind speeds less than $\sim 2\,\mathrm{km\,sec^{-1}}$ imply that the global-scale circulation of Pegasi planets should be approximately geostrophic, i.e., consist of a balance between horizontal pressure-gradient and Coriolis accelerations. This balance implies that the horizontal wind at the photosphere is related to the horizontal temperature contrast (basically because the winds are balancing the horizontal pressure gradients that result from the horizontal temperature gradients). This can be written

$$v \sim \frac{R}{fa}\Delta T\,\Delta\ln p \tag{1}$$

where R is the gas constant, $f \approx 3 \times 10^{-5}\,\mathrm{sec^{-1}}$ is the Coriolis parameter, $a \approx 10^8$ m is the planetary radius, ΔT is the characteristic horizontal temperature difference, and $\Delta \ln p$ is the difference in log-pressure between the base of the circulation and the photosphere, which is ~ 3.

The dayside heating and nightside cooling is balanced by advection

$$\frac{v\Delta T}{a} \sim \frac{q}{c_p} \tag{2}$$

where q/c_p is the magnitude of the mean heating rate in K sec^{-1}. Using $q/c_p \sim 10^{-3}$–$10^{-2}\,\mathrm{K\,sec^{-1}}$, appropriate to regions close to 1 bar (which is near the photosphere), these equations imply that at the photosphere $v \sim 0.6$–$2\,\mathrm{km\,sec^{-1}}$ and $\Delta T \sim 200$–$500\,\mathrm{K}$.

One could imagine balances other than those we have considered (e.g., including inertial accelerations in Eq. (1) or balancing heating/cooling against vertical rather than horizontal advection in Eq. (2)), but for the parameter values relevant to HD209458b, the predicted speeds and temperature contrasts are similar to those above (Showman and Guillot 2002). The greatest caveat is the fact that v and ΔT should depend (perhaps strongly) on depth, which is not included in this simple analysis. Numerical simulations, however, can include these effects.

We performed three-dimensional, fully nonlinear numerical simulations of the atmospheric circulation of HD209458b using the EPIC model (Dowling et al. 1998), which solves the primitive equations in spherical geometry using finite-difference methods. We solved the equations within the radiative layer from 0.01 to 100 bars assuming the planet's interior is in synchronous rotation with the 3.5-day orbital period. The radius, surface gravity, and rotation rate of HD209458b were used (10^8 m, $10\,\mathrm{m\,sec^{-2}}$, and $\Omega = 2.1 \times 10^{-5}\,\mathrm{sec^{-1}}$, respectively).

The intense insolation was parameterized with a simple Newtonian heating scheme, which relaxes the temperature toward an assumed radiative-equilibrium temperature profile with a time constant of 3×10^5 sec (equal to the expected radiative time scale at a pressure of about 5 bars). The chosen radiative-equilibrium temperature profile was hottest at the substellar point (0° latitude, 0° longitude) and decreased toward the nightside; it is this day-night difference that drives all the dynamics in the simulation. The simulations were performed with a horizontal resolution of 64×32 with 10 layers evenly spaced in log-pressure.

Despite the motionless initial condition, winds rapidly develop in response to the day-night heating contrast (Figure 1), reaching an approximate steady state after ~ 400 Earth days. Winds exceed $1\,\mathrm{km\,sec^{-1}}$, but despite these winds, a horizontal temperature contrast is maintained. The dayside (longitudes $-90°$ to $90°$) is on average hotter than the nightside, but dynamics distorts the temperature pattern in a complicated manner. A strong equatorial jet develops with weaker structure at high latitudes. As expected, the jets and gyres that exist are broad in scale, with a characteristic width of the planetary radius.

The temperature patterns in Figure 1 show that Earth-based infrared measurements can shed light on the circulation of Pegasi planets. In Figure 1 (bottom), the superrotating equatorial jet blows the high-temperature region downwind. The highest-temperature region is thus *not* at the substellar point but lies eastward by about 60° in longitude. The maximum and minimum temperatures would thus face Earth *before* the transit of the planet behind and in front

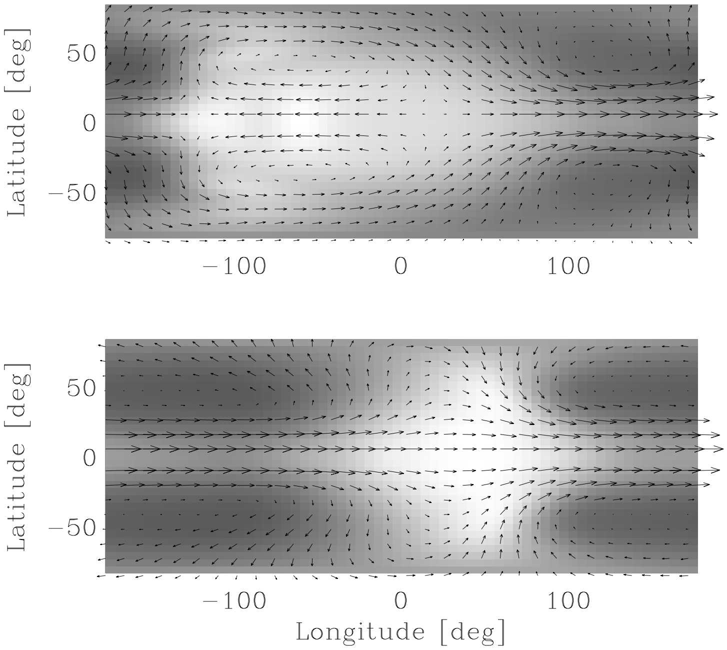

Figure 1. Simulation of atmospheric circulation on HD209458b after 42 and 466 Earth days (top and bottom, respectively). Panels depict pressure on an isentrope (greyscale) and winds (vectors) at a mean pressure near 0.4 bars. The maximum wind speeds are 937 (top) and 1541 $\mathrm{m\,sec^{-1}}$ (bottom), and the greyscale spans 0.3–0.5 bars. Greyscale is such that, on an isobar, white regions are hot and dark regions are cold. Substellar point is at 0° latitude, 0° longitude.

of the star, respectively. On the other hand, if a broad westward jet existed instead, the maximum and minimum temperatures would face Earth *after* the transits. Therefore, an infrared light curve of the planet throughout its orbital cycle would help determine the direction and strength of the atmospheric winds.

As the simulation begins, the net atmospheric angular momentum is nearly zero (relative to a synchronously rotating state), so regions of both eastward and westward winds exist (Figure 1, top). As the simulation evolves, however, eastward angular momentum is transported from the interior into the atmosphere, and an eastward superrotating jet results (Figure 1, bottom). The exchange that produces this jet may depend on particular parameter values, and more analysis is needed before robust predictions can be made.

Because upgoing and downgoing air generally have different kinetic energies and momenta, vertical motion can lead to exchange of energy and momentum between the atmosphere and interior. In the simulation, kinetic energy is transported from the atmosphere into the interior at a rate that reaches 2500 $\mathrm{W\,m^{-2}}$ (Figure 2). This downward transport of kinetic energy is $\sim$ 1% of the absorbed stellar flux and is great enough to affect the radius of HD209458b (Guillot and Showman 2002). Although the simulation described here does not determine the kinetic energy's fate once it reaches the convective interior, we expect that tidal

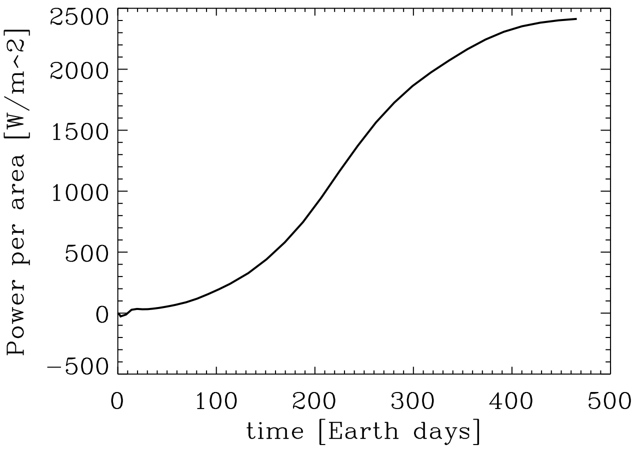

Figure 2. Globally-averaged flux of kinetic energy across the model's bottom isentrope (at $\sim$ 100 bars), which is the interface between the radiative layer and the convective interior in the model.

friction, Kelvin-Helmholtz instabilities, or other processes could convert these winds to thermal energy. This may help explain the large radius of HD209458b.

Although clouds were not included in the simulations, several endpoint scenarios are possible. In one scenario, dayside heating is balanced by horizontal advection of cold air from the nightside (e.g., if a strong east-west jet exists), with little vertical motion occurring. As air flows from nightside to dayside, the starlight it absorbs increases its temperature by up to $\sim$ 300 K. Any clouds would therefore sublimate, leading to a cloud-free dayside. As the air returned to the nightside, it would cool, so nightside clouds might exist. In a second scenario, dayside heating is balanced by upwelling of lower-entropy air from the planet's interior instead of advection of cold air from the nightside. Because the rising air would carry condensable (e.g., silicate) vapors, clouds could form on the dayside. These scenarios illustrate the importance of dynamics in determining the cloudiness, hence albedo and extent of starlight absorption, and show that the cloud layer may not be global, as has sometimes been assumed.

References

Brown, T. M., Charbonneau, D., Gilliland, R. L., Noyes, R. W., & Burrows, A. 2001, ApJ, 552, 699

Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45

Guillot, T., Burrows, A., Hubbard, W.,B., Lunine, J. I., & Saumon, D. 1996, ApJ, 459, L35

Guillot, T., & Showman, A. P. 2002, A&A, 385, 156

Guillot, T., & Showman, A. P. 2003, these proceedings

Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, L41

Showman, A. P., & Guillot, T. 2002, A&A, 385, 166

Adam Showman