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Evolution & Atmospheric Circulation of “Pegasi Planets”

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Abstract. About one-quarter of the extrasolar giant planets discovered so far have orbital distances smaller than 0.1 AU. Among those are the first genuine giant planet detected outside our solar system, 51 Peg b, and the first characterized extrasolar planet, HD 209458b (also in the Pegasus constellation). These “Pegasi planets” form a class of objects whose evolution and structure is strongly affected by stellar irradiation and tides. We show in particular that the radius of HD 209458b cannot be reproduced by conventional evolution models unless its atmosphere is assumed to be unrealistically hot. We argue that the combination of the synchronization by stellar tides and the strong irradiation yield an atmosphere that has significant temperature variations and strong winds. The kinetic energy thus generated can be transported in the deep interior and slow the planet's contraction. We also discuss the consequences of the atmospheric circulation on the chemistry.

1. Introduction

The detection of giant planets around solar-type stars has been a major discovery of the past decade. At the time of this conference, more than 100 extrasolar planets have been detected by radial velocity (see Marcy et al. 2000, 2003; Udry et al. 2003; and the discoverers' web pages). About one fourth of these have orbital distances smaller than 0.1 AU. This is for example the case of the first extrasolar giant planet to have been discovered, 51 Peg b (Mayor & Queloz 1995).

These objects, which we dub “Pegasi planets” (short for “51 Peg-like planets”) are interesting for several reasons. First, they are more likely to transit in front of their stars than is the case for more distant planets (the transit probability varies inversely with the planet's orbital radius, reaching ~10% for a planet at 0.05 AU around a solar-type star). When radial velocity data are used, the mass, density, and surface gravity can be characterized as well. Second, they are expected to be in synchronous rotation (Guillot et al. 1996). Third, the luminosity that they receive due to stellar radiation is much larger than their intrinsic luminosity, so the temperatures near the photosphere are known independently of the planet's prior history. Finally, planets inside 0.07 AU from their star appear to have near-circular orbits, which is interpreted as the effect of circularization by tides (Marcy et al. 1997). We can therefore infer enough bulk parameters of Pegasi planets to truly begin characterizing their interiors, dynamics, and evolution.

The perfect demonstration of the first point is the discovery of HD 209458b, a planet transiting in front of its star every 3.524 days (Charbonneau et al. 2000; Henry et al. 2000). The observed system consists of a G0V star and a planetary companion of mass $0.69 \pm 0.05\,\mathrm{M_J}$ ($\mathrm{M_J}= 1.89 \times 10^{27}$ kg is the mass of Jupiter) on a circular orbit ($e < 0.04$) at a distance of 0.047 AU, and a planetary radius at 1 bar estimated to be $1.349\,\overline{\mathrm{R}}_\mathrm{J}$, where $\overline{\mathrm{R}}_\mathrm{J} \equiv 70,000$ km is Jupiter's mean radius (Hubbard et al. 2001; see also Brown et al. 2001). This large radius, in relatively good agreement with theoretical predictions (Guillot et al. 1996), shows unambiguously that HD 209458b is a gas giant. Physical characterization of HD 209458b's atmosphere is discussed by Seager (2003).

However, we show hereafter that the problem of the evolution of HD 209458b, and of Pegasi planets in general, is more complex than previously believed. This article is based on the two articles by Guillot & Showman (2002; hereafter paper I) and Showman & Guillot (2002; hereafter paper II). We refer the reader to these articles for further details.

2. The Radius of HD 209458b

As we will show in the next section, the relatively large radius of HD 209458b is difficult to reproduce. In all the following discussion, we will assume conditions that maximize the calculated radii at any given time: we will assume that HD 209458b was formed *in situ* and that it possesses no central dense core. The reader should keep in mind that the presence of a core or a slow migration of the planet would lead to even smaller radii than calculated here.

2.1. The Standard Evolution Model

In the standard case, the evolution of a giant planet is governed by standard hydrostatic and thermodynamical equations, and by the energy conservation equation:

$$\frac{\partial L}{\partial m} = -T\frac{\partial S}{\partial t}, \tag{1}$$

where L is the planet's intrinsic luminosity, m is mass inside a given radius, T temperature, S specific entropy and t is time. Inside the planet, each layer contributes to the outward energy flux by a decrease of its specific entropy (this corresponds to a contraction and, in all but the earliest phases, a cooling).

The amount of energy lost by the planet per unit time is also set by the atmospheric "lid". The atmospheric boundary condition can be defined at a pressure P_0 and a corresponding temperature $T_0 = f(L_*, L, g)$, where L_* is the stellar luminosity received by the planet and g its gravity. Defining f involves solving a complex radiative transfer problem.

In the absence of such a model that would consistently account for both the intrinsic luminosity and stellar luminosity, the approach of Guillot et al. (1996)

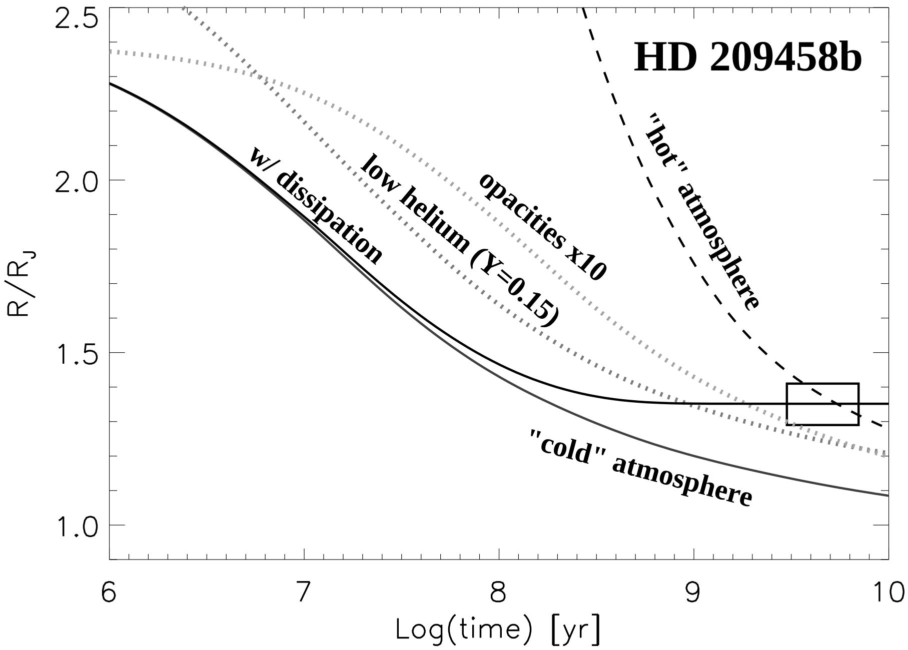

Figure 1. Radius of HD 209458b (in units of the radius of Jupiter) versus time under different assumptions (see text). The box indicates inferred radii and ages of HD 209458b.

was to use the result of a radiative transfer calculation for an isolated planetary atmosphere. Skipping the details of the procedure (see Paper I), this implies a relatively "hot" upper boundary condition of $T \approx 3400\,\mathrm{K}$ at $P = 10\,\mathrm{bar}$. The theoretical evolution for this "hot" atmosphere is shown in Figure 1 to appropriately reproduce the inferred age and radius of HD 209458b (Burrows et al. 2000).

However, detailed radiative transfer calculations have shown this approximation to overestimate the atmospheric temperatures of Pegasi planets by as much as 1000 K at pressures larger than a fraction of a bar (Seager & Sasselov 1998, 2000; Goukenleuque et al. 2000; Barman et al. 2001). We thus chose to calculate evolution models with an atmospheric boundary condition that was more appropriate to these atmospheric models, which led to a temperature of $T \approx 2400\,\mathrm{K}$ at $P = 3\,\mathrm{bar}$. In that case, the "cold" atmospheric boundary condition leads to a faster shrinking of the planet that is incompatible with the observations (see bottom curve in Figure 1).

Independent calculations by Bodenheimer et al. (2001) with an atmospheric boundary condition based on the Eddington approximation also yield a fast shrinking that is consistent with our results for the "cold" case.

We therefore feel that because the "cold" atmospheric boundary condition is preferable to the "hot" boundary condition, there is a problem in explaining

HD 209458b's radius. This problem is more acute when considering the possible presence of a central core, which would yield still smaller radii. We examine hereafter various possible explanations.

2.2. A Deeper Absorption of the Stellar Flux?

One possibility is that although part of the stellar flux is absorbed at low altitudes, a small fraction of it penetrates deep into the atmosphere. As a consequence, the temperature gradient in the radiative region, proportional to the energy flux to be transported, would be larger. The temperatures at deep levels would then also be larger than in our cold model.

While this mechanism should be carefully included by future evolution models, it appears that even the continuous opacities alone prevent the deep penetration of the stellar flux (see Paper I). Simulations of radiative transfer along a fixed temperature profile by Iro et al. (2002) show that 99.99% of the stellar flux is absorbed at a pressure $P < 10\,\mathrm{bar}$.

On the other hand, we stress the urgent need for more realistic atmospheric boundary conditions. All atmospheric models published so far assume boundary conditions that are incompatible with the results of the evolution models. In particular, the intrinsic flux of the planet was generally overestimated by orders of magnitude (it is only $\sim 10^{-4}$ of the received stellar radiation).

2.3. Other Alternative Explanations

Another explanation is to invoke a lower than solar abundance of helium. However, in the framework of the cold model, we found that in order to fit the observed radius, we need $Y \sim 0.15$, an extremely uncertain value (see Figure 1).

Also, the cooling could be slowed by a higher opacity in the inner radiative region. However, we used in our calculations Rosseland opacities by Alexander & Ferguson (1994) that account for the presence of grains and thus represent rather high values of this quantity. Figure 1 shows that an increase of these opacities by a factor ~ 10 is required for a marginal fit of the observed radius. We estimate that such an increase in opacities is unrealistic.

2.4. Non-Standard Models with Energy Dissipation in the Interior

Given these difficulties in reproducing the observed radius of HD 209458b, Bodenheimer et al. (2001) and paper I proposed a “non-standard” model in which the energy conservation equation inside the planet becomes

$$\frac{\partial L}{\partial m} = \dot{\epsilon} - T\frac{\partial S}{\partial t}, \tag{2}$$

where m is the mass inside any given level, and $\dot{\epsilon}(m)$ is the energy dissipated per unit time per unit mass at that level.

Bodenheimer et al. showed that the radius of HD 209458b can be explained by the dissipation of $\sim 10^{26}\,\mathrm{erg\,s^{-1}}$ deep in the planet. Figure 1 shows our result for the evolution of HD 209458b when including the dissipation of $\dot{E} \approx 1.8 \times 10^{26}\,\mathrm{erg\,s^{-1}}$ at the planet's center, using our cold boundary condition. Depending on where the dissipation takes place (in the outer layers or deeper), a whole series of evolution curves can be calculated, as described in Paper I.

Most of the problem is then to find an adequate source of energy. Bodenheimer et al. (2001) proposed that orbital circularization by tidal friction may dissipate an adequate quantity of energy within the planet. In the case of HD 209458b:

$$\dot{E} \approx 10^{28} e^2 \left(\frac{1\,\mathrm{Gyr}}{\tau_{\mathrm{circ}}}\right)\ \mathrm{erg\,s^{-1}}, \tag{3}$$

where e is the planet's eccentricity and τ_{circ} the circularization time scale. One first possibility is that $e \sim 0.1$ and $\tau_{\mathrm{circ}} \sim 1\,\mathrm{Gyr}$, in which case the energy could be provided by a slow circularization of the planet's orbit. A second possibility is that circularization proceeds on faster time scales, but that a non-zero eccentricity is forced by an unknown companion. According to published literature, the eccentricity of HD 209458b is $e < 0.03$, and no nearby, eccentric and massive companion has been detected (Mazeh et al. 2000; Henry et al. 2000; Charbonneau et al. 2000). The explanation is then only marginally possible. However, the situation would change if further observational studies confirm the previous conclusion of a very small eccentricity and/or lead to the detection of a close companion.

In papers I and II we propose that the missing energy source may simply lie in the extremely high stellar irradiation. As discussed hereafter, the strongly non-uniform irradiation tends to generate winds in the planetary atmosphere. This kinetic energy is expected to be transported to deeper levels, where it could be dissipated. Only about 1% of the irradiated stellar energy needs to be affected that way in order to reproduce the observations, a value which is in agreement with observations in the Earth's atmosphere. This can either be take the form of "weather noise", i.e. disorderly generation of kinetic energy in the atmosphere and its dissipation at deeper levels, or of a globally asynchronous rotation of the interior. In that case, paper II shows that the interior could be asynchronous by a factor of up to 2.

Finally, a last explanation invokes the generation of vertical shear instabilities in the atmosphere. These instabilities could force the temperature gradient to lie close to an adiabat and would effectively heat the deep planetary atmosphere. That case could then resemble the "hot case", the only difference being that heat would be advected in the atmosphere instead of being transported radiatively.

3. Atmospheric Circulation: Possible Regimes

The previous discussion shows the need of a good understanding of the characteristics of the atmospheres of Pegasi planets. Atmospheric models have previously always assumed a perfect redistribution of the absorbed stellar energy over the entire atmosphere. This allowed solving for the atmospheric temperature structure in only one dimension (radius) with a spatially averaged incident flux. Hereafter, we show that the real situation is much more complex and will require in the future the calculation of general circulation models properly including radiative transfer.

The expected physical structure of Pegasi planets is shown in Figure 2. At pressures less than 10 bars, where absorption of the intense stellar light and thermal radiation to space occur, models predict a stably stratified temperature profile (Seager & Sasselov 1998, 2000; Goukenleuque et al. 2000; Barman et al. 2001). This layer is underlain by another radiative (statically stable) region, extending to 100–1000 bars, that transports the intrinsic heat flux (Guillot et al. 1996). At even greater pressures, the opacities are large, and the intrinsic flux must be transported by convection.

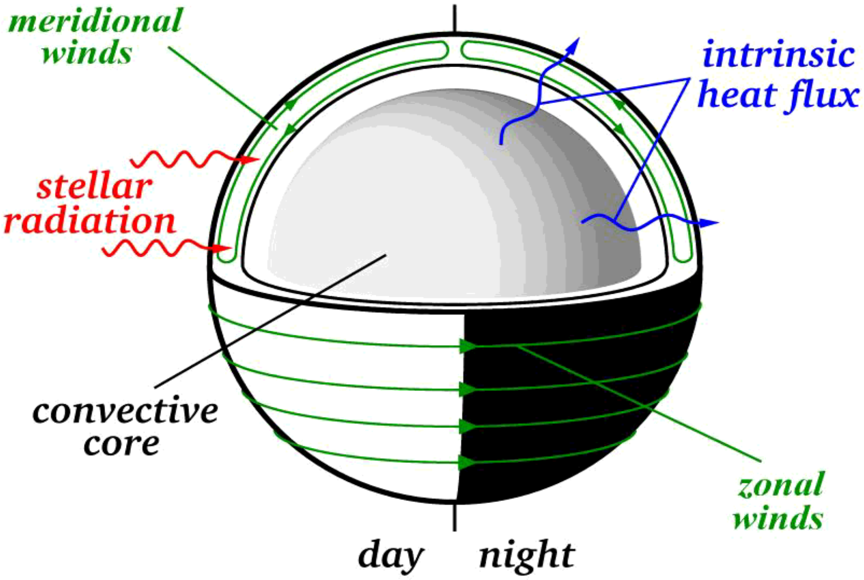

Figure 2. Conjectured dynamical structure of Pegasi planets: At pressures larger than 100–800 bar, the intrinsic heat flux must be transported by convection. The convective core is at or near synchronous rotation with the star and has small latitudinal and longitudinal temperature variations. At lower pressures a radiative envelope is present. The top part of the atmosphere is penetrated by the stellar light on the day side. The spatial variation in insolation should drive winds that transport heat from the day side to the night side (see text).

The rotational regime of the interior is constrained by considering the time scale to tidally despin the planet (Goldreich & Soter 1966):

$$\tau_{\rm syn} \approx Q \left(\frac{R^3}{GM}\right) (\omega - \omega_{\rm s}) \left(\frac{M}{M_\star}\right)^2 \left(\frac{a}{R}\right)^6, \tag{4}$$

where Q, R, M, a, ω and $\omega_{\rm s}$ are the planet's tidal dissipation factor, radius, mass, orbital semi-major axis, rotational angular velocity, and synchronous (or orbital) angular velocity. M_* is the star's mass, and G is the gravitational constant. Factors of order unity have been omitted. A numerical estimate for HD 209458b (with ω equal to the current Jovian rotation rate) yields a spindown time $\tau_{\rm syn} \sim 3Q$ years. Any reasonable dissipation factor Q (see Guillot et al. 1996; Marcy et al. 1997; Lubow et al. 1997) shows that HD 209458b should be led to synchronous rotation in less than a few million years, i.e. on a time scale much shorter than the evolution time scale. Like other Pegasi planets, HD 209458b is therefore expected to be in synchronous rotation with its 3.5-day orbital period.

An upper limit on the atmospheric wind speed can be derived from shear-instability considerations. We assume that no zonal winds are present ($u(P_{\rm core}) = 0$) in the convective core, a consequence of synchronization by tidal friction. The build-up of winds at higher altitudes in the radiative envelope is suppressed by Kelvin-Helmholtz instabilities if the shear becomes too large. This occurs when the Richardson number (R_i) becomes smaller than 1/4 (cf. Chandrasekhar 1961), i.e. when

$$R_i = \frac{N^2}{(du/dz)^2} < \frac{1}{4}, \tag{5}$$

where N is the Brunt-Vaisala frequency and du/dz the vertical wind shear.

The maximal wind speed at which Kelvin-Helmholtz instabilities occur can then be derived by integration of Eq. (5), from which it is derived that $u_{\rm max} \sim 3000\,{\rm m\,s^{-1}}$ at $P \sim 1\,{\rm bar}$, to be compared to the winds of Jupiter, Saturn, Uranus and Neptune which reach 100–500 $\rm m\,s^{-1}$. The expected speed of sound at these levels in HD 209458b is of order $2400\,{\rm m\,s^{-1}}$. A characteristic time scale for zonal winds to redistribute temperature variations over scales similar to the planetary radius R then stems from $\tau_{\rm zonal} \gtrsim R/u_{\rm max}$.

The radiative heating time scale can be estimated by a ratio between the thermal energy within a given layer and the layer's net radiated flux. In the absence of dynamics, absorbed solar fluxes balance the radiated flux, but dynamics perturbs the temperature profile away from radiative equilibrium. Close to optical depth unity, the radiative time scale is

$$\tau_{\rm rad} \sim \frac{P}{g}\frac{c_p}{4\sigma T^3}, \tag{6}$$

where c_p is the specific heat and g is the gravity.

At optical depths of order unity (or equivalently, pressure levels of order one bar), it is expected for HD 209458b that $\tau_{\rm zonal} \gtrsim \tau_{\rm rad}/5$ (where the inequality comes from the fact that we have derived only a *maximum* wind speed). The temperature difference between the night side and the day side and between the poles and the equator are therefore expected to be at least several hundred Kelvins. This is due to the fact that the atmospheres of Pegasi planets are considerably hotter than those of the planets of our solar system and that their radiative cooling is considerably faster. This is the case even though zonal winds can become relatively strong.

We have so far derived a maximum value of the zonal wind speeds. It is possible to estimate, using geostrophic equations, the winds that would balance radiative heating. Paper II shows that in a scenario in which radiative cooling and heating is balanced by horizontal advection, winds obeying the geostrophic equations may approach this upper limit of 3000 m/s above which shear instabilities would develop. This may provide a mechanism for advecting heat into the planetary interior, and lead to the hot deep atmosphere discussed in the previous section.

It should be noted however that the nature of the circulation is yet unknown. For example, radiative cooling and heating could be balanced by vertical motions. However, in this case, the vertical velocity of $\sim 20\,\mathrm{m/s}$ near 1 bar also implies by continuity a relatively large zonal velocity (~ 3000 m/s). Depending on the nature of the circulation, clouds could form and dissipate at different locations in the planet. In the case of a superrotating atmosphere with little vertical motion, clouds are expected to mostly form on the night side. If the radiative heating is balanced by vertical advection (as in a Hadley cell), clouds would tend to appear on the day side, close to the substellar point.

4. Disequilibrium Chemistry & Na in HD 209458b

The discovery of Na in the atmosphere of HD 209458b (Charbonneau et al. 2002) is a major observational feat. The fact that it is present in lower-than-expected abundances has already led to several theoretical interpretations in the literature. Here, we will simply point out a possible consequence of day/night temperature variations on the chemistry of this element.

Na has the property that it condenses into Na_2S at temperatures $\sim 1000\,\mathrm{K}$ for pressures $P \sim 1\,\mathrm{bar}$, or $T \sim 800\,\mathrm{K}$ for $P \sim 1\,\mathrm{mbar}$ (Lodders 1999). On the day side and probably on the terminator (although this would require further tests), the temperatures are expected to be high enough for condensation not to occur. Therefore, equilibrium chemistry predicts that this element should be present in atomic form.

However, consider the situation of an atmosphere with a colder night side and a relatively rapid zonal circulation such as discussed in the previous section. Furthermore, consider that parcels of air flow on approximatively isobaric surfaces. Air that is warm on the day side may become cold enough on the night side and lead to the condensation of Na_2S. Because at the pressures involved (bars to mbars) condensation and sedimentation are relatively fast (e.g., Rossow 1978), it is expected that solid grains of Na_2S are efficiently removed from the top of the atmosphere. If there is little upward advection on the day side, Na will be present in significantly smaller abundances than expected from a simple equilibrium calculation. While this does not necessarily constitute the definitive answer to the Na problem, it illustrates the ability of circulation to modify the abundances of sodium and other gaseous species relative to expectations from simple one-dimensional models. This applies both to species that condense and that are formed through a relatively slow ($\tau \gtrsim 1\,\mathrm{day}$) chemical reaction. We point out that advection could for example modify significantly the CH_4/CO ratio in the atmospheres of Pegasi planets compared to expectations from equilibrium chemistry.

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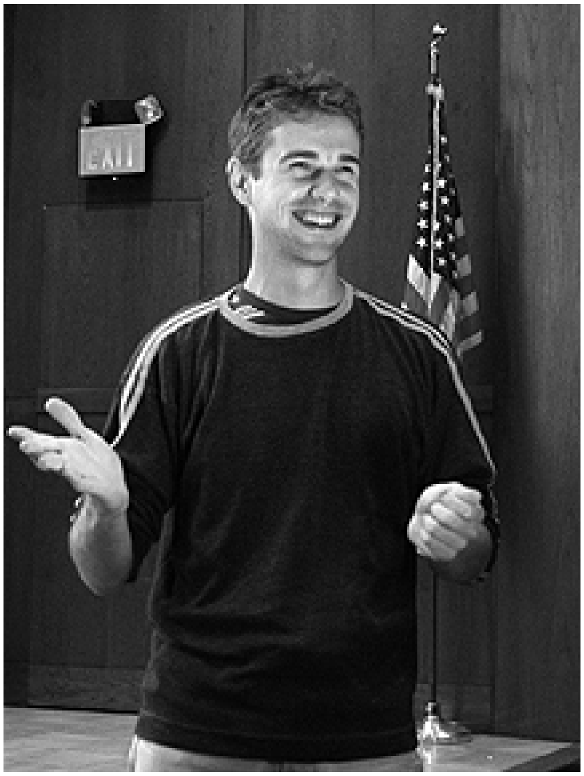

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