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HEAT TRANSPORT IN GIANT (EXO)PLANETS: A NEW PERSPECTIVE

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ABSTRACT

We explore the possibility that large-scale convection is inhibited over some regions of giant planet interiors, as a consequence of a gradient of composition inherited from either their formation history or particular events like giant impacts or core erosion during their evolution. Under appropriate circumstances, the redistribution of the gradient of molecular weight can lead to double diffusive layered or overstable convection. This leads to much less efficient heat transport and compositional mixing than large-scale adiabatic convection. We show that this process can explain the abnormally large radius of the transit planet HD 209458b and similar objects and may be at play in some giant planets, with short-period planets offering the most favorable conditions. Observational signatures of this transport mechanism are a large radius and a reduced heat flux output compared with uniformly mixed objects. If our suggestion is correct, it bears major consequences on our understanding of giant planet formation, structure and evolution, including possibly our own Jovian planets.

Subject headings: convection — hydrodynamics — planetary systems — planets and satellites: general

Online material: color figures

1. INTRODUCTION

Over 200 extrasolar giant planets have now been discovered by radial velocity surveys. Fourteen of these planets have been observed transiting their parent star, allowing an accurate determination of their radius and mean density. For half of these objects, notably the first ever discovered transit HD 209458b, the predicted theoretical radius lies several σ's (up to $\sim$20%) below the observed mean value (Baraffe et al. 2005). The various scenarios proposed so far to solve this discrepancy have been rejected on either observational or theoretical arguments (Levrard et al. 2007) or lack an identified robust mechanism to convert surface kinetic energy into thermal energy at depth (Showman & Guillot 2002). A fair conclusion of these studies is that an important physical mechanism is probably missing in our present description of at least some short-period planets, for which we have a radius determination, but possibly of all extrasolar or even solar giant planets.

According to the conventional core-accretion model for planet formation (Pollack et al. 1996), planets are believed to have a substantial enrichment in heavy elements compared with their parent star, with a total of $\sim$40 $M_\oplus$ for a Jupiter-mass object (Alibert et al. 2005). Observational constraints of Jupiter and Saturn show that these planets do have a significantly enhanced Z-abundance compared with the Sun, with a global mean mass fraction $Z = M_Z/M_p \approx 10\%$–20% (Saumon & Guillot 2004). In all these calculations, the big planetesimals are generally supposed to drown to the core during the early phase of solid accretion, while the smaller ones are distributed *uniformly* throughout the envelope, leading to a uniform heavy element abundance. This is a rather simplistic description of the planet internal structure, which implies (1) well-defined interfaces between the central core and the (highly diffusive) H/He rich envelope and (2) very efficient large-scale thermal convection throughout the entire gaseous envelope. The observed atmospheric abundances of Jupiter and Saturn, however, seem to require the redistribution of a subsequent fraction of heavy elements in the interior of these planets (Guillot et al. 2004). In this Letter, we explore the consequences of the presence of an initial compositional gradient in the envelope, as a result of either early planetesimal accretion or subsequent core erosion, and of the resulting less efficient heat transport and compositional mixing on the fate of gaseous planets. We show that layered convection, if it occurs as a result of this compositional gradient, might be the lacking physical mechanism to explain the transiting planet's abnormally large radii.

2. LAYERED SEMICONVECTION

The presence of a positive compositional gradient, i.e., a gradient of mean molecular weight $\nabla_\mu = [(d \ln \mu) / (d \ln P)] > 0$, tends to stabilize the fluid against convective instability according to the Ledoux stability condition:

$$\nabla_{\rm ad} > \nabla_T + \frac{\chi_\mu}{\chi_T} \nabla_\mu, \tag{1}$$

where ∇_T and $\nabla_{\rm ad}$ denote the usual temperature and adiabatic gradients, respectively, and $\chi_\mu = [(\partial \ln P) / (\partial \ln \mu)]_{\rho, T}$, $\chi_T = [(\partial \ln P) / (\partial \ln T)]_{\rho, \mu}$. In most of the giant planet interiors, superadiabaticity is extremely small, with $\nabla_T - \nabla_{\rm ad} \lesssim 10^{-8}$, so a small molecular weight gradient over a typical mixing length size region can significantly affect and even damp out convection. In convective systems where buoyancy effects of (destabilizing) heat and (stabilizing) composition are opposed, the process leads generally to quasi-static, uniformly mixed convective layers separated by small diffusive interfaces with steep gradients, $\nabla_\mu \gg 1$. Such stable layered convection is indeed observed in some areas of the Earth's oceans, due to the presence of the stabilizing salt gradient (thermohaline convection) leading to a stratified steplike temperature profile with stable boundary layers (Schmitt 1994). Laboratory experiments have also confirmed this layering (Fernando 1989). Once formed, the stratification is stable provided that the compositional gradient remains large enough at the interfaces to satisfy equation (1). Would such a stratification occur in planetary interiors, the layered part of the interior can be considered as a *semiconvection* zone with a reduced efficiency to transport the internal heat and composition flux compared with large-scale

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convection. One may argue that the conditions in planetary interiors differ from the ones in the oceans or in the experiments. Characteristic thermal diffusivity in H/He planetary interiors, dominated by electronic transport in the central, ionized parts, and by molecular motions in the outer envelope, lies in the range $\kappa_T \approx 10^{-1}$ to 10^{-2} cm^2 s^{-1}, while the kinematic viscosity is $\nu \approx 10^{-3}$ to 10^{-2} cm^2 s^{-1} (Stevenson & Salpeter 1977a). The characteristic Prandtl number thus ranges from $\mathrm{Pr} = \nu/\kappa_T \approx 10^{-2}$ to 1. These values do not differ by large factors from the ones characteristic in the oceans or in laboratory experiments, Pr ≈ 1–10, in contrast to the ones characteristic of stellar conditions ($\mathrm{Pr} < 10^{-6}$). Therefore, a layering process in giant planet interiors cannot be excluded, and it is worth exploring the consequences on the planet evolution. Such layered convection may occur near the discontinuity in composition at the boundary of the central rocky-icy core or in chemically inhomogeneous regions in the interior, reminiscent of the early planetesimal accretion episodes.

There is presently no widely accepted description of semiconvection. Water-salt experiments (Fernando 1989) show that a series of quasi-static convective layers separated by diffusive interfaces develop when a balance is reached between the variation of potential energy (i.e., of buoyancy) due to mixing at the interface and the kinetic energy of the eddies available at the interface. This translates into a critical Richardson number $\mathrm{Ri} = lg\Delta\rho/\rho\langle v^2\rangle$ of order 1–10, where $\Delta\rho \simeq \rho(\Delta T/T)$ is the density contrast between the diffusive and convective layers, g is the gravity, and $\rho\langle v^2\rangle$ is the kinetic energy of the convective flow, of characteristic average length scale l and rms velocity $\sqrt{\langle v^2\rangle}$. Guided by experimental results (Linden & Shirtcliffe 1978) and energetic arguments, Stevenson (1979), in a wave description of semiconvection, showed that should layers form as a result of small-scale wave breaking whereupon the compositional gradient is redistributed, they would be stable if

$$(\kappa_T + \nu)(\nabla_T - \nabla_{\rm ad}) < (D + \nu)\nabla_\mu, \text{ i.e., } \mathrm{Pr} \gtrsim \tau^{1/2}, \qquad (2)$$

where the inverse Lewis number $\tau = \mathrm{Le}^{-1} = D/\kappa_T$ is the ratio of the solute microscopic diffusivity to the thermal diffusivity. The Spruit (1992) stability condition is less restrictive, since layered formation is supposed to always occur and is given essentially by equation (1). Under Jovian planet conditions, typical values are $D \approx 10^{-3}$ to 10^{-4} cm^2 s^{-1} (Stevenson & Salpeter 1977a), and then $\tau \sim 10^{-2}$, so that, according to this criterion, diffusive layers could be at least marginally stable in giant planet interiors. It is worth noting that the molecular to thermal diffusivity ratio is the same for a H/He mixture under Jovian interior conditions as for salty water, $\tau \approx 10^{-2}$, so that the extent of the solute versus thermal layer is about the same. Since, according to experiments and condition (2), this ratio is the relevant criterion for stability of the layers, this adds some support to the planetary case. In a layered convection stratification, heat is carried away from the interfaces by descending and ascending plumes in the overturning regions while transport across the interface occurs by diffusion. Because of the boundary layers, only a part of the fluid transports heat efficiently. On average, one has "convective-like" motions having a much shorter length scale than for ordinary convection. The *thermal* thickness of the diffusive layers, δ_T, is determined by a balance between the thickening due to diffusion and the entrainment due to convective motions so the convective time, $\sim l/v$, in the mixed layer of size l must be comparable to the thermal diffusion time, $\sim\delta_T^2/\kappa_T$, across the boundary layer (Fernando 1989). This yields $\delta_T \approx (\kappa_T l/v)^{1/2}$ and $\delta_X \approx (Dl/v)^{1/2}$ for the thickness of the heat and compositional interfacial layers, respectively. The number N of layers is of course very uncertain. It can be crudely estimated as follows. The heat flux f transported by convection in each mixed layer is the mass flux carried by the plumes fed from the diffusive layers, and thus of width comparable to these layer thickness, times the energy variation across the convective layer, $T\delta S \approx T(l\nabla S)$:

$$f = \frac{1}{l}(\rho v \delta_T)(T\delta S) = \rho c_p \kappa_T \frac{l}{\delta_T}\frac{T}{H_P}(\nabla - \nabla_{\rm ad}). \qquad (3)$$

For a semiconvective region extending over a planet-size region, the total number of layers is thus given by

$$N \approx \frac{F_{\rm tot}}{f} = \frac{L/4\pi R^2}{\rho c_p \kappa_T \frac{T}{H_P}(\nabla - \nabla_{\rm ad})}\frac{\delta_T}{l}. \qquad (4)$$

Using characteristic numbers for Jovian planet conditions (with $l \sim H_P$), one gets $N \sim 10^5$–10^6 as a rough estimate. If convection is inhibited, however, the smaller heat flux and larger superadiabaticity require less layers.

3. EFFECT ON THE EVOLUTION

We have conducted calculations following the evolution of a template Jupiter-mass planet, representative of HD 209458b and similar short-period planets, with a global metal content $M_Z = 40\ M_\oplus$, including a $6\ M_\oplus$ core, i.e., $M_Z/M_p = 13\%$ ($Z \simeq 6\ Z_\odot$), in agreement with previously mentioned planet formation models and Jupiter and Saturn's observational constraints. The amount of heavy elements is distributed initially throughout the planet following a gradient, distributed within a certain number of boundary layers N where condition (1) is fulfilled. The layers are located within the inner ~30% by mass (60% in radius) of the planet, where H and He are fully ionized, to ensure high enough thermal conductivity. The present calculations have been done with $N = 50$ and 100; the width of each boundary layer corresponds to $\delta_T \approx 10^3$ cm $\sim 10^{-6} H_P$. A larger number of layers would be computationally too difficult to resolve correctly. These boundary layers are separated by larger convective, mixed layers, with a uniform composition ($\nabla\mu = 0$), where the usual mixing-length formalism applies. The sizes of the boundary and mixed layers (δ_T, δ_X, l) obey the aforementioned relationships. The heat flux F_T and solute flux F_Z in the boundary layers are calculated with the appropriate diffusion equations: $F_T = \rho c_p \kappa_T \nabla T$, where $\kappa_T = [(16\sigma T^3)/(3\rho^2 c_p)]\,(\kappa_c^{-1} + \kappa_r^{-1})$ and κ_c, κ_r denote the conductive (Potekhin 1999) and radiative (Rogers et al. 1996; Ferguson et al. 2005) mean opacities, respectively, and $F_Z = \rho D \nabla Z$, where $\nabla Z = -(Z/\chi) H_P^{-1} \nabla_\mu$, with $\chi = [(\partial \ln \mu)/(\partial \ln Z)]$, is the mean concentration gradient across the layer. Conduction remains efficient enough in the thin boundary layers to fulfill condition (1). Because diffusion limits the heat transport, the internal heat flow of the planet is significantly reduced compared with that of a fully convective object. The signatures of double-diffusive convection in a planetary interior are thus a reduced heat output and a larger radius compared with an object where heat is transported efficiently by large-scale convection. This is illustrated in Figure 1, which compares the evolution of the radius and thermal intrinsic luminosity of the planet in both cases. The excellent agreement with the otherwise un-

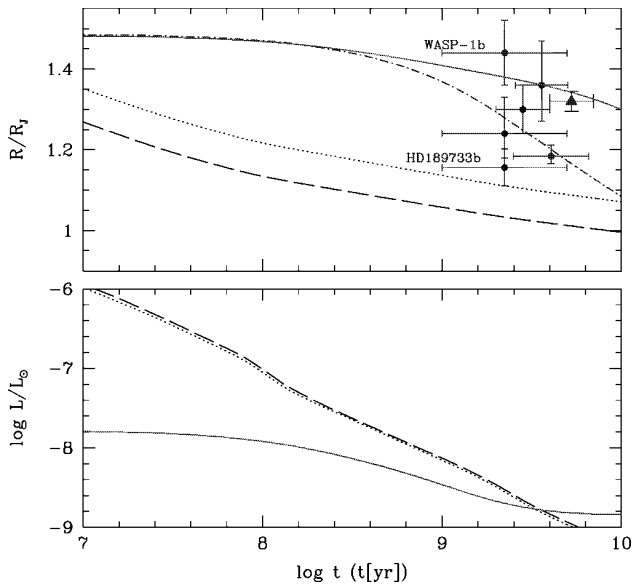

FIG. 1.—Evolution of the radius and the intrinsic luminosity of a Jupiter-mass ($1\ M_J$) planet orbiting at 0.05 AU of a Sun-like star, from the same initial conditions. All calculations include the effect of the stellar irradiation on the planet structure and evolution. (1) Effect of a core and metal enrichment. *Dotted line*: Adiabatic interior, no core, $Z = Z_\odot$. *Long-dashed line*: Adiabatic interior, central dunite core $M_c = 6\ M_\oplus$, metal enrichment $Z_{\rm env} \simeq 6\ Z_\odot$ in the envelope. (2) Effect of layered convection (same M_c and $Z_{\rm env}$). *Solid line*: Layered convection for $N = 100$ layers. *Dot-dashed line* (*upper panel*): $N = 50$ layers. The observed values of the seven planets with abnormally large radii, HD 209458b (*triangle*), WASP-1b, XO-1b, OGLE-TR-56b, Tres-2, HAT-P-1b, and HD 189733b, with masses ranging from 0.5 to 1.3 M_J, are displayed with their most recent 1 σ error bar determinations. [*See the electronic edition of the Journal for a color version of this figure*.]

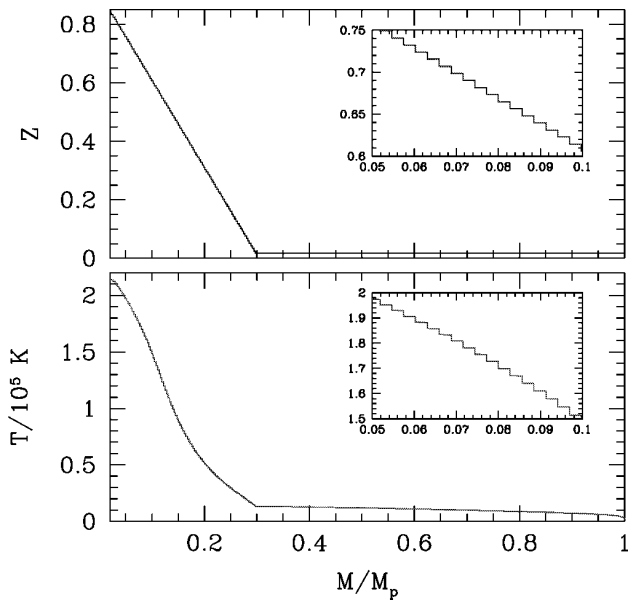

FIG. 2.—Internal heavy element and thermal profiles at 5 Gyr for the case of 100 convective + diffusive layers distributed in the inner 30% by mass of the planet. The global heavy element mass fraction of the planet is $Z = M_Z/M_p = 0.13$, including the central core ($M_{\rm core} = 2\%\ M_p$). Note the steplike T and Z distributions, as portrayed in the inner subsets. [*See the electronic edition of the Journal for a color version of this figure*.]

explained observed radii of HD 209458b and similar irradiated planets suggests that diffusive convection might be taking place in the interior of at least certain giant planets. As seen, the expected luminosity at young ages is more than 1 order of magnitude fainter than that of a fully convective planet evolving from a comparable initial state. The observational confirmation of the present scenario would be either the determination of an exoplanet temperature or luminosity at young ages[3] or the observation of an inflated radius for a transiting planet at large enough orbital distance, $a \gtrsim 0.1$ AU for a solar-type parent star, for stellar irradiation not to affect the planet's internal structure. Figure 1 also illustrates the dependence of the evolution on the number of layers. Less boundary layers imply larger convective layers and thus more efficient heat transport, as illustrated by the more rapidly decreasing radius in the 50-layer calculations.

A key question is to know whether diffusive interfaces can persist on timescales comparable to the characteristic time for the evolution of the planet. According to the aforementioned critical Richardson number criterion, supported by experiments (Fernando 1989), a quantitative argument is that if the average kinetic energy in the convective layers is smaller than (a fraction of) the potential energy wall of the interface, convection cannot penetrate deeply into this interface, and significant entrainment across the interface cannot occur. This implies that the molecular diffusion timescale is long enough. This latter can be estimated for the entire stack of layers, distributed over a region of size L in the planet (presently $L \sim 10^9$ cm). The flux of elements across an interface is $F_Z \approx \rho D\ (\delta Z/\delta_X)$, where $\delta Z \approx (l/L)\ \Delta Z$ is the jump in the element mass fraction at each interface while ΔZ is the total variation over the entire semiconvective region. The timescale to redistribute the entire gradient over the entire region is then $t \approx (\rho L \Delta Z/F_Z) \approx (L^2/D)\ (\delta_X/l) \approx 10$ Gyr. This admittedly crude estimate shows that the stable diffusive convection configuration might last long enough to affect substantially the evolution. With the typical value $D = 10^{-3}$ cm^2 s^{-1}, about 10% of the initial gradient ΔZ has been transported by diffusion over a Gyr, as confirmed by our numerical calculations. In principle, the compositional gradient thus remains large enough during the evolution for the Ledoux criterion to remain valid in a majority of layers. In other words, the temperature jump at interfaces is too small to offset the molecular weight stabilization of interfaces $[(\Delta T/T) \lesssim (\Delta\mu/\mu)]$. The composition and temperature profiles in our calculations at 5 Gyr are portrayed in Figure 2, with $\delta Z/\Delta Z \approx 1\%$ and $\Delta T \approx 10^3$ K at each diffusive interface. Note that, if layers form in sequence through turbulent entrainment or from sporadically breaking internal waves generated by oscillatory instabilities, interfaces may be dynamically renewed with time, if some compositional gradient or stirring effects remain present. Such a process occurs in laboratory systems and oceans.

Different reasons can be advocated for the cause of the initial compositional gradient. This latter can be inherited from the formation process. Large incoming planetesimals could disseminate part of their constituents, iron, silicates, ices, by ablation and break-up as they penetrate the building gaseous envelope (Iaroslavitz & Podolak 2007). Note also that accretion will not proceed homogeneously as capture mechanisms differ for the gas (H, He), ice (essentially C, O, N), and rock (silicates

[3] For short-period, irradiated planets, however, the intrinsic flux of the planet, $\sigma T_{\rm eff}^4$, is smaller than the absorbed and reflected contributions of the incident stellar flux, $\sim (R_\star/a)^2 \mathcal{F}_\star$. For long-period planets or for planed telescopes like the LBT or the *JWST*, dedicated to infrared planet searches, however, the planet intrinsic luminosity can be determined.

and iron) components. This will substantially increase the compositional gradients before the core is reached. As mentioned earlier, even modest gradients can easily offset superadiabatic excess over planet-size regions, preventing large-scale convective motions. A compositional gradient might also result from disruption and redistribution of the core due to a giant impact or erosion at the core-envelope interface because of metallic hydrogen high diffusivity, leading to a core diluted into a fraction of the planet (Stevenson 1982; Guillot et al. 2004). The redistribution of these elements might be partially inhibited by diffusive processes, forming diffusive interfaces because of the opposite buoyancy effects of heat and composition. Furthermore, when accreting the envelope, part of the outermost regions of the protoplanet might be nearly isothermal (Mizuno 1980), which favors the stability of a compositional gradient. Interestingly, when distributing the layers in the *outer* 10% by mass (~15% by radius) of the planet, where *radiative* thermal diffusivity starts to dominate over conductive diffusivity, we get an effect similar to the one portrayed in Figure 1. The situation for the formation of diffusive convection is particularly favorable for short-period exoplanets for several reasons. First of all, a substantial fraction of the gaseous envelope has been eliminated by evaporation (Baraffe et al. 2006), leading to a larger metal fraction. Second of all, for short-period exoplanets, the numerous collisions tend to eject the gas, leading to a larger enrichment in planetesimals than for the other planets. Third of all, the higher internal temperatures for short-period, irradiated planets, favor (1) ionization of the various elements and thus the thermal conductivity and (2) solubility of the core material into the envelope. At last, because of the stellar irradiation, the outer layers of short-period planets are isothermal and not adiabatic.

4. CONCLUSION AND PERSPECTIVE

The aim of the present Letter is to suggest an alternative, possibly important energy transport mechanism in giant planet interiors and to explore its effects on the evolution. These calculations provide a consistent description of the evolution of giant planets, *with a metal enrichment in agreement with observational constraints*, in case heat is transported by layered convection. Assuming an initial compositional stratification within a certain number of double-diffusive interfaces, diffusive and convective transport in the respective layers are calculated consistently during the evolution. Only the outermost 40% in radius (70% in mass) of the planet can convect freely. These calculations, however, cannot be expected to give an accurate description of the onset and stability of layered convection. There is presently no accurate treatment of this mechanism under conditions characteristic of giant planets. The only attempt to study the onset of double-diffusive layer formation at low Prandtl numbers ($Pr < 1$) (Merryfield 1995) remains inconclusive. Indeed, insufficient numerical resolution and artificially enhanced viscous and molecular diffusivities in the simulations might suppress small-scale motions/instabilities and the formation of a statistically steady state of intermittent diffusive layers. Simulations of vertical salinity in water, $Pr = 7$, on the other hand, well reproduce the experiments and confirm the formation of quasi-static convective layers separated by diffusive interfaces above a critical Richardson number (Molemaker & Dijkstra 1997.

Even though the present calculations rely on some uncertain ground, the agreement with the puzzling and otherwise unexplained observed radius of HD 209458b and other abnormally large exoplanets leads to the conclusion that layered convection might be taking place in at least some planets and could explain their particular properties. This transport mechanism yields a much reduced heat escaping rate compared with a homogeneous adiabatic structure. Even if a stable layered configuration does not occur, overstable modes of convection (fulfilling eq. [1] but not eq. [2]), due to the presence of opposite diffusive processes (composition and heat) of different efficiencies, can lead to the growth of small-scale fluid oscillations (Stevenson & Salpeter 1977b; Stevenson 1979). Overstability, however, is more similar to an enhanced diffusion process than to a convective mixing process, with a much smaller energy transport efficiency, as shown by experiments (Stevenson & Salpeter 1977b). The onset or persistence of layered or overstable (oscillatory) convection might require optimal conditions, inherited from particularly favorable formation or evolution histories (e.g., late accretion of large unmixed planetesimals or giant impacts stirring up completely the planet interior). The present Letter suggests that, under such appropriate conditions, the heat transport mechanism in giant planet interiors can be severely affected, decreasing the efficiency of or even inhibiting large-scale convection. This should motivate 3D investigations of convection in the presence of a stabilizing compositional gradient under conditions suitable to giant planets and the search for transits at larger orbital distances.

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