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Uneven Cooling: The influence of atmospheric dynamics on the thermal evolution of gas giants

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Abstract. Planets cool and contract as they age, with a cooling rate that depends on the efficiency with which they can transport heat out to space, first through the convective interior and then radiatively out through the atmosphere. The bottleneck for this cooling is the radiative-convective boundary (RCB), where the heat transport is the least efficient. Due to differential heating and atmospheric dynamics, the depth of the RCB can vary with latitude and longitude, meaning that the actual global cooling rate may differ from what would be calculated assuming a spherically symmetric RCB, as in 1D evolutionary models. Here we present models of the deep atmosphere of a generic hot Jupiter, calculate inhomogeneity in the RCB, and determine the resulting effect on the global thermal evolution. Although this issue can apply to any differentially heated gas giant, we focus on the hot Jupiter class of planet because: 1) the thick radiative zones above their deep RCBs can have a stronger influence on deforming the surface of the RCB than would generally be the case for a less-irradiated planet, and 2) an uneven RCB should increase the cooling rate, potentially exacerbating the mismatch between the large radii measured for some hot Jupiters and the smaller radii expected from evolutionary models.

Keywords. hydrodynamics, radiative transfer, planets: general, stars: evolution

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Context. The evolutionary cooling rate of a planet is set by the flux at the boundary between its inner, convective region and its outer, radiative atmosphere (the radiative-convective boundary, RCB) and is easy to calculate if the temperature, pressure, and opacity at the RCB are known (Arras & Bildsten 2006). Hot Jupiters are a class of gas giants on close-in, circular orbits around their host stars and are assumed to be tidally locked into synchronous rotation, such that they experience strongly asymmetric heating. It has been proposed that the depth of the RCB should vary between their permanent day and night sides, allowing a hot Jupiter to cool more efficiently through its night side (Guillot & Showman 2002; Budaj *et al.* 2012; Spiegel & Burrows 2013). However, our 3D atmospheric circulation models predict that winds can efficiently homogenize day-night temperature differences in the deep atmosphere, near the RCB, leading to a temperature structure varying primarily in latitude but not longitude (e.g., Showman *et al.* 2009; Rauscher & Menou 2012). Since at deep pressures we still see a non-uniform temperature structure (maintained by the circulation pattern), uneven cooling could occur.

Model description. Informed by our 3D circulation models, we use a 2D model for the deep atmosphere, with pressure as the vertical coordinate and latitude as the horizontal, under the assumption that there is no significant longitudinal variation in the temperature structure. We built our model with standard radiative transfer (two-stream double-gray,

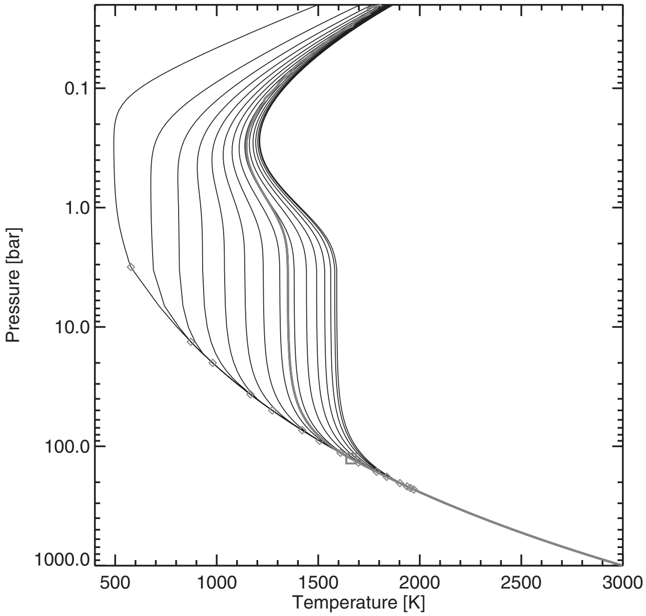

Figure 1. Temperature-pressure profiles from our model atmosphere. The black lines are at latitudes ranging from near the equator (hottest profile) to near the pole (coldest profile), with a pink diamond marking the location of the radiative-convective boundary. The thick blue line is calculated by our code, assuming a globally averaged stellar flux. The RCB for this 1D model is marked by the blue square. (The temperature increase high in the atmosphere is a result of our choice to have the infrared absorption coefficient scale linearly with pressure while the optical coefficient is constant. This region effectively acts only as an upper boundary condition.)

transitioning to flux-limited diffusion at high optical depth), dynamical heat transport based on local conditions, a standard adjustment of convectively unstable regions to the adiabatic lapse rate, and a matrix solution method to reach local flux equilibrium (radiative and dynamic). We then self-consistently calculate the global cooling luminosity, by integrating over the uneven flux escaping from the non-uniform RCB.

Initial results. We are testing the code without any dynamical heat transport before including the influence of atmospheric circulation on the temperature structure. This places an upper limit on how much the cooling luminosity through an uneven RCB could differ from what would be calculated by a 1D, uniform model. In the particular example shown in Fig. 1, the cooling rate through the uneven RCB is 30% higher than through the uniform RCB, implying faster evolutionary cooling and a smaller radius than would otherwise be predicted, and further exacerbating the problem of bloated hot Jupiter radii.

References

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