A new view of hot Jupiters

Explaining the anomalous sizes of close-in giant planets via coupling between day-night currents and tides

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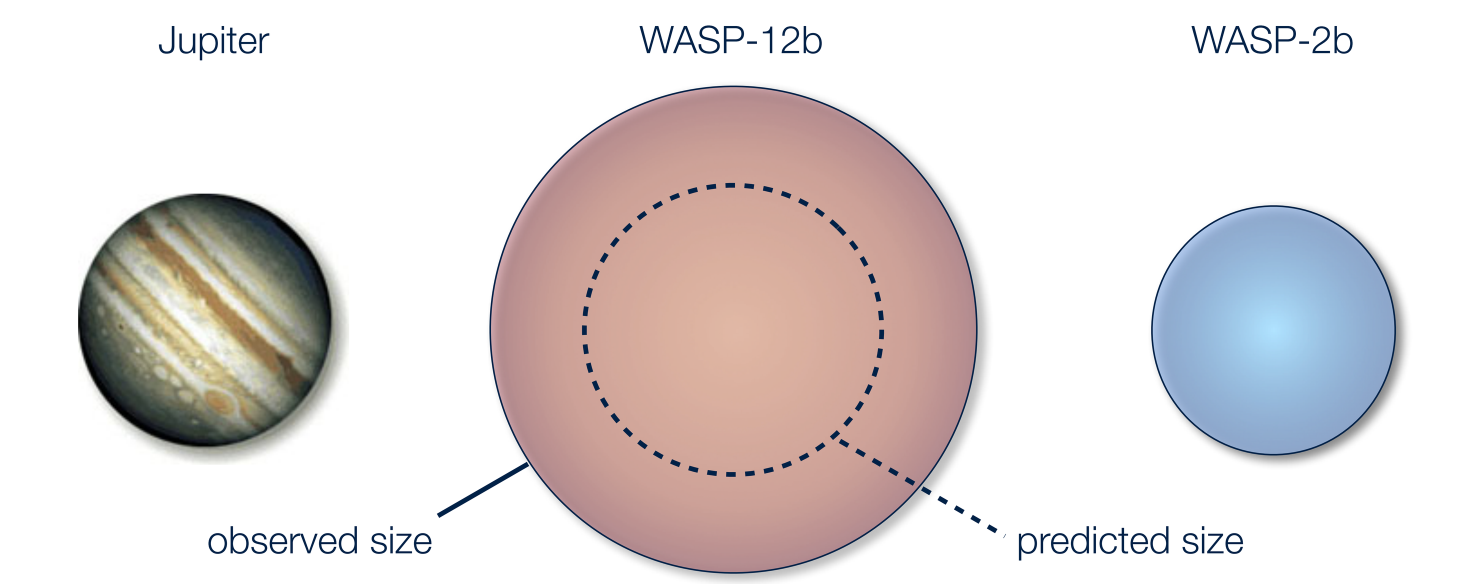
Anomalous sizes

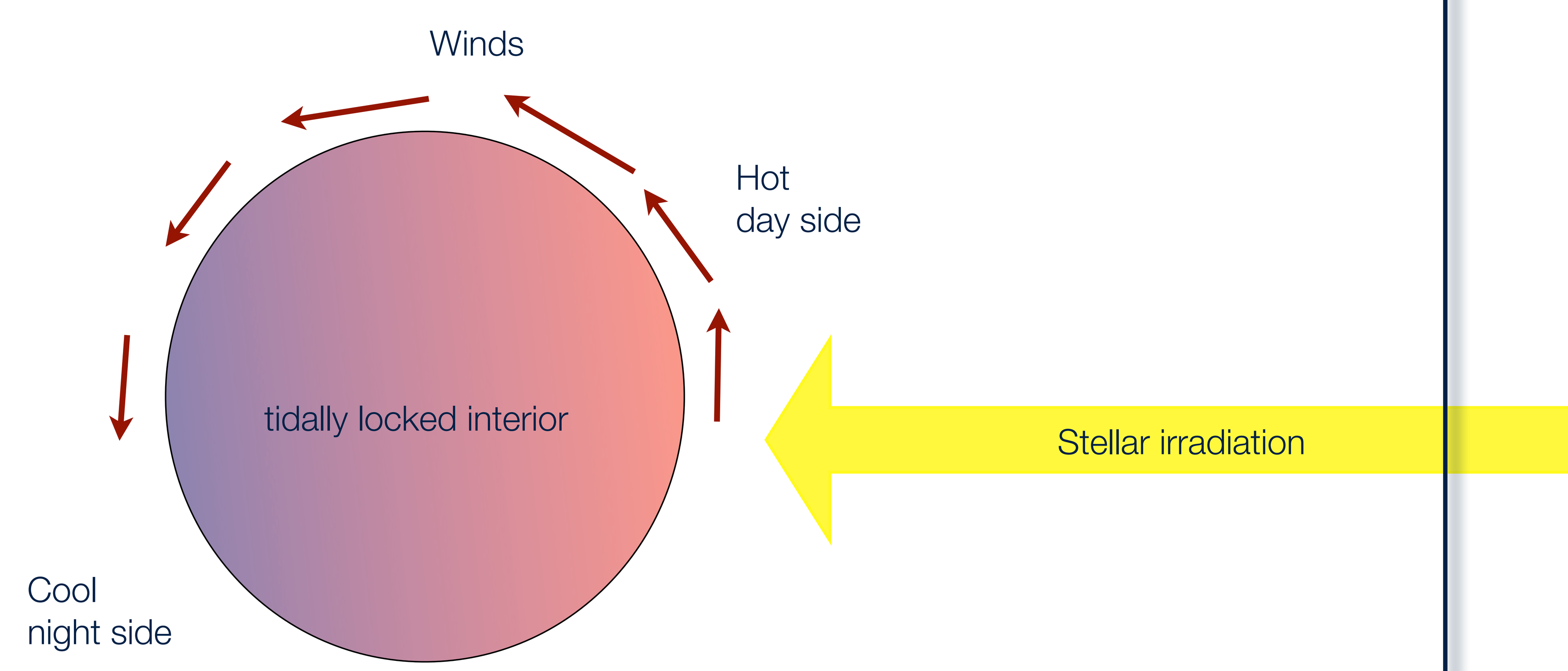


Close-in gas giant planets are strongly affected by their host star. They receive intense **irradiation** from it, and undergo strong **tidal interactions** with it. As a result:

- the *outer layers* of the atmosphere are heated up and expand, causing the planet's radius to increase compared to the non-irradiated case;
- the bulk of the planet is expected to be tidally locked;
- the large day-night temperature contrast gives rise to strong winds (advection)

Even accounting for the effects of irradiation on the outer layers, many close-in gas giant planets are **much larger** than predicted, sometimes reaching 2 Jupiter radii. The anomalously large planets also tend to be the most strongly irradiated, with equilibrium temperatures above 1500 K.

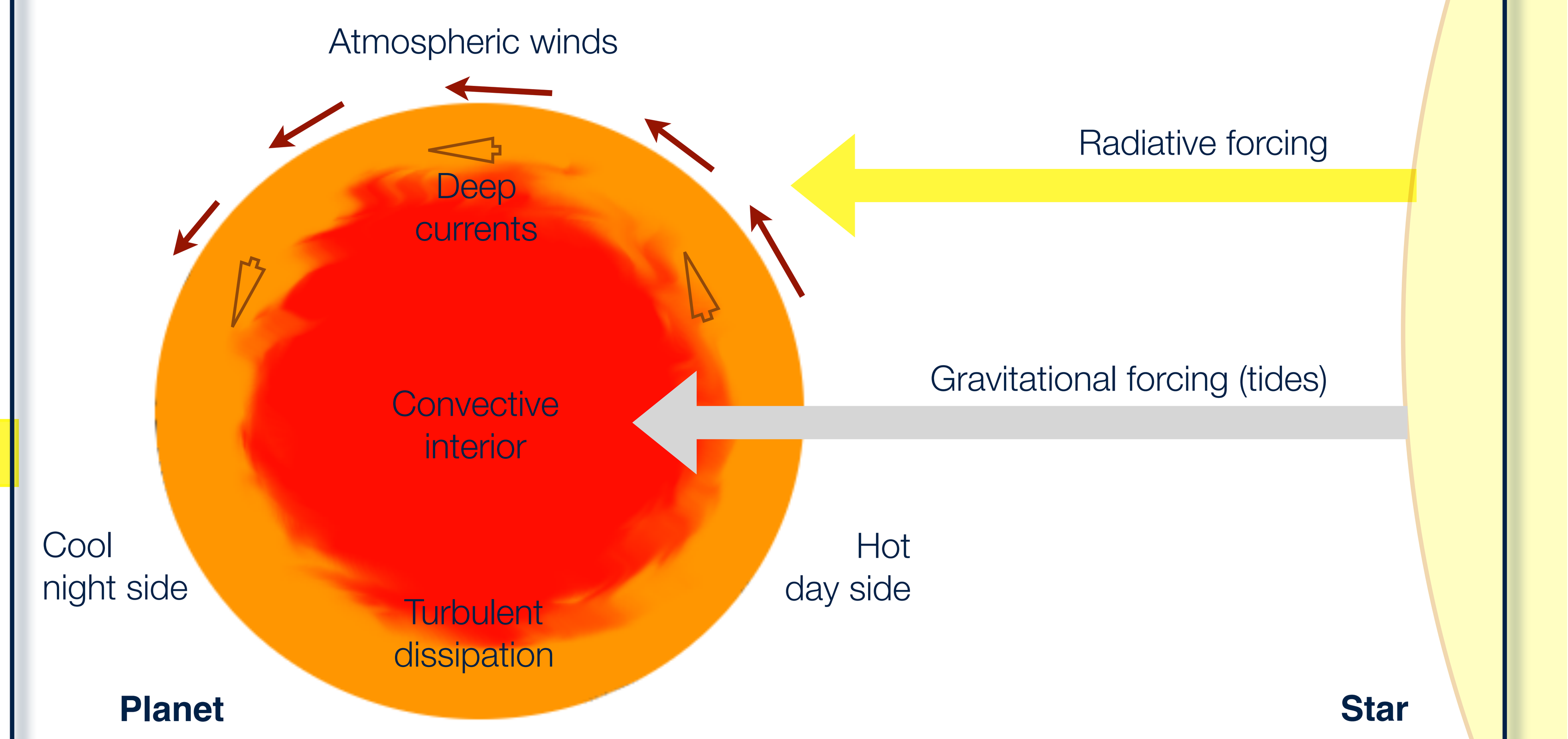
The standard picture



Close-in gas giant planets are expected to be tidally locked in synchronous rotation. Typical models assume that the heat is carried from the day side to the night side by winds in the atmosphere of the planet. The atmosphere is modeled as a shallow, mobile layer surrounding the tidally locked interior, but not interacting with it. In such a model, the incident radiation can only heat the outer layers of the atmosphere.

An additional source of internal heat is then needed to explain the observed sizes of the largest exoplanets. Various possibilities have been suggested (unseen companions, anomalously high opacities or opacity gradients, ...), but none successfully applies to the entire population.

Our model



In our model, close-in gas giant planets are trapped in an **advection/tide steady state**. The turbulent drag from atmospheric winds drives deep currents that couple with tidal forces. This allows the atmosphere to function as a **heat engine**, injecting energy into the interior of the planet to feed tidal dissipation. This injection of energy leads to an increase in radius.

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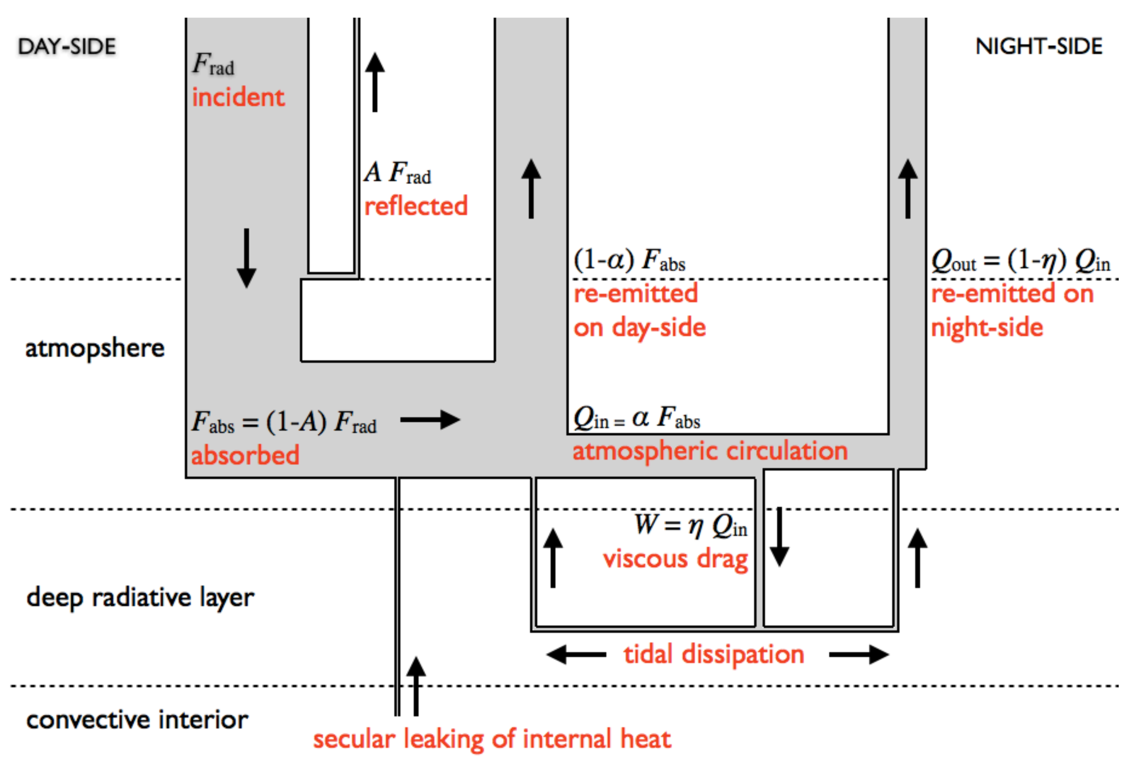
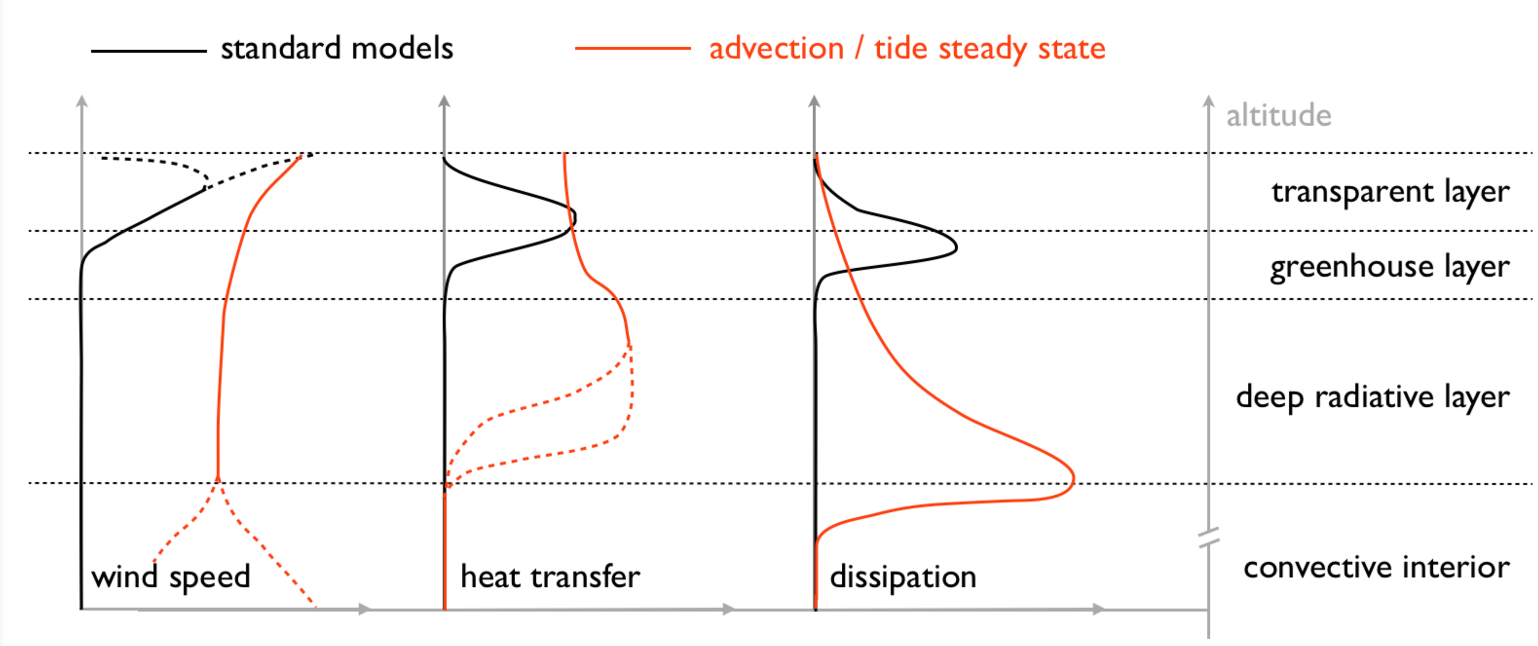
Energetics



Showman & Guillot (2002, Astron. & Astroph.) first pointed out that, if a small fraction of the energy of the incident stellar flux could be converted into mechanical energy **deep** enough in the planet's interior, the inflated radii of hot Jupiters could be explained.

We propose that the coupling of advection and tides via **viscous drag** could provide the necessary mechanism to inject energy into the deeper layers and dissipate it. By comparing the timescales for the different processes involved, we show that viscous drag acting on the day-night atmospheric circulation is sufficient to establish deep **currents** that are then dissipated by tides. We then estimate the proportion of incident energy dissipated by this process using a heat engine analogy, as illustrated above, and find that it corresponds to the prescription of the Showman-Guillot scenario.

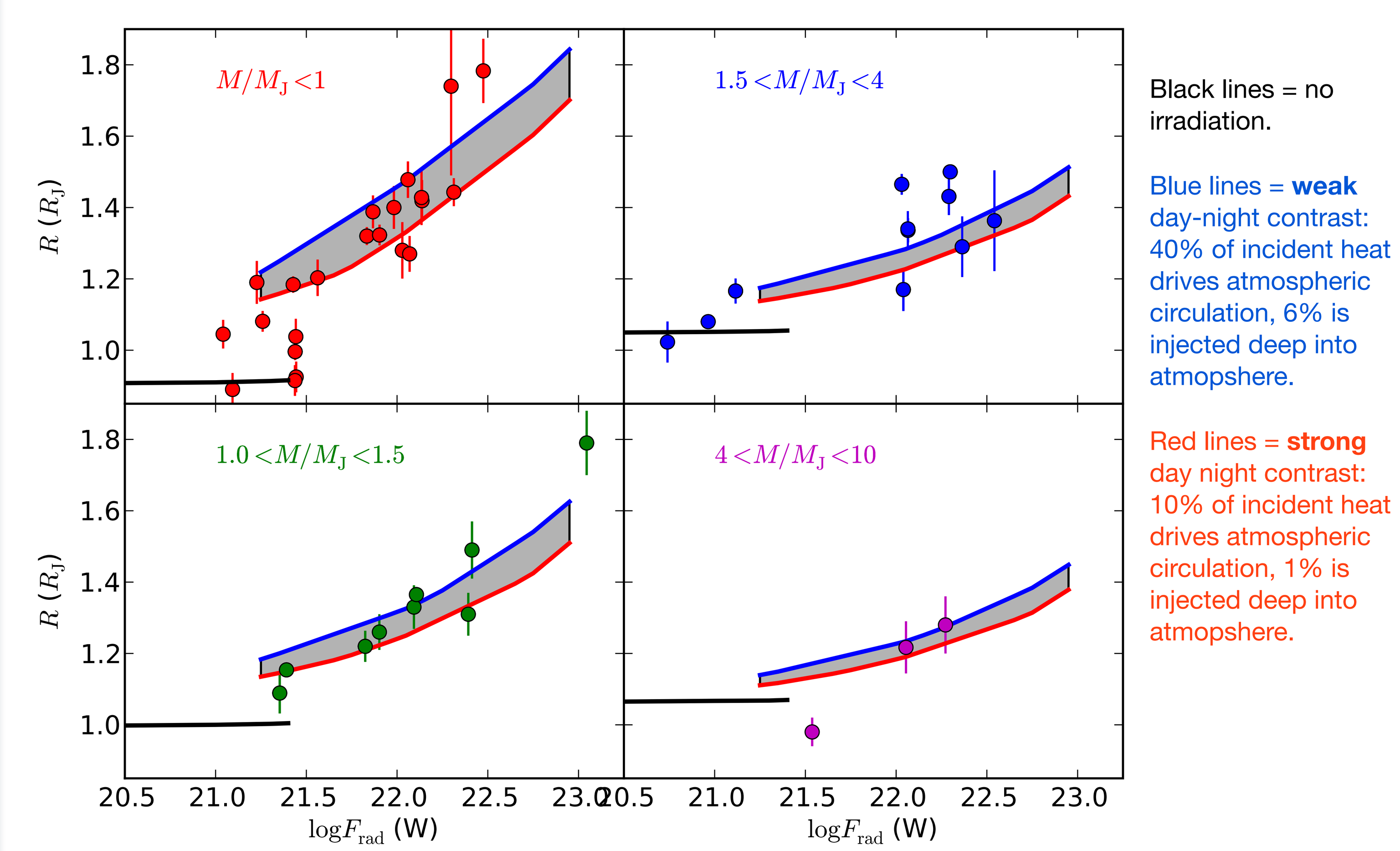
Wind-speed, heat transfer and dissipation



The above diagram shows a summarises, in schematic fashion, the key differences between standard models and our proposed scenario, in terms of wind speed, heat transfer and dissipation, as a function of depth in the planet.

Standard models assume a circulating atmosphere floating on, but decoupled from, a tidally locked interior. In the advection/tide steady state, advection extends much deeper into the planet, and the interior is kept slightly out of tidal equilibrium. The dissipation of mechanical energy takes place far below the depth where atmosphere becomes opaque, and is due to the turbulent dissipation of the advection current by tidal forces.

Comparison with observations



The above diagram shows the observed radii of hot Jupiters as a function of incident irradiation, in four mass bins, superimposed on the predictions of our model. Despite the simplistic nature of our treatment, the predictions are in striking agreement not only with the observed radii, but also with their dependence in incident stellar irradiation and planet mass. To our knowledge, no other scenario has similar predictive power over the entire hot Jupiter population.

In summary, hot Jupiters may be constantly "whipped up" by the competing radiative and gravitational forcing of their host star.