A HOT SPIN STABILITY LIMIT FOR TERRESTRIAL PLANETS.

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Introduction. During the late stages of planet formation, terrestrial planets can be significantly heated by large impacts. In addition, the growing planets are expected to have been in, on average, rapidly rotating states [1]. High energy, high angular momentum post-impact states are likely to be common during the giant impact phase of accretion.

The nature of such high energy, high angular momentum planets has not been well studied. It is generally assumed that a planet is corotating, with the potential for a distinct disk of material in orbit. However, we show that there is a hot spin stability limit (HSSL) for terrestrial planets, where the planet cannot maintain a corotating state. Such planets form a continuous mantle-atmosphere-disk (MAD) structure, where the corotating center of the structure transitions smoothly to a sub-keplerian outer region. The existence of this heretofore unrecognized state of terrestrial planets has important implications for understanding young planets and for the origin of our Moon [2].

In order to define the HSSL boundary for terrestrial planets, we have developed a new code (HERCULES) that is capable of calculating the equilibrium structure of rotating planets of any composition. Here, we use the HERCULES code to examine the dependence of the HSSL boundary on the total mass, total angular momentum, and the thermal profile of the planet. We also examine the likelihood of exceeding the HSSL during solar system formation.

HERCULES planet structure code. HERCULES is a semi-analytical code designed to find the equilibrium internal structure of rotating planets. The planet is modeled as a series of concentric, constant density layers. An iterative scheme is then used to find a self-consistent solution for the shape of each layer. The equatorial radius of each layer is adjusted to conserve mass, and the rotation rate is adjusted to conserve angular momentum. The mass of different material layers (e.g. core, mantle, atmosphere) is conserved separately.

The HERCULES code is based on an approach designed for studying the structure of Jupiter [3]. However, this model was limited to planets that have small rotational flattening [4, 5]. We have used the work of [4] to extend the concentric layer model to be able to model planets with extreme rotational flattening. The new code allows us to explore the structure of the hot, rapidly rotating planets formed during accretion.

The results of the HERCULES code agree very well with the internal structure of isolated planets modeled using smooth particle hydrodynamic (SPH) methods. Importantly, HERCULES does not suffer from the well-known problems with SPH at boundaries with large density contrasts.

The structure of hot, rapidly rotating planets. Consider a planet that is undergoing a gradual heating. The planet expands with increasing internal energy. For sufficiently slowly rotating planets, the body remains corotating; however, for planets with sufficient angular momentum, the outer edge of the planet reaches a limit where the co-rotating angular velocity approaches the keplerian orbital velocity (Fig. 1). We define this transition as the *hot spin stability limit* (HSSL) for a planet. Beyond the HSSL, the outer portions of the structure have sub-keplerian velocities.

For a corotating planet below the HSSL, the structure that conserves both angular momentum and mass is unique. Beyond the HSSL, the shape and mass distribution within the structure is degenerate and depends on the radial angular momentum distribution. However, a post-HSSL planet cannot adopt a corotating state without losing angular momentum or cooling. Post-HSSL planets can form a continuous mantle-atmosphere-disk (MAD) (Fig. 1, 3A) where the planet is continuous in density and rotational velocity from the lower mantle out to the disk-like outer regions making large scale mixing possible.

The HSSL boundary. We have defined the HSSL boundary using HERCULES and the GADGET2 SPH codes. The angular momentum required to exceed the HSSL depends on both the mass of the body and the thermal structure. The actual thermal structure depends on the mechanism of energy and angular momentum deposition that led to the planet exceeding the HSSL. For illustrative purposes, we have considered a simple end member case where the mantle of the body is on a single isentrope (Fig. 2). The HSSL is exceeded at lower angular momentum for higher entropy planets.

Exceeding the HSSL in giant impacts. The HSSL can be exceeded in the post-impact states of giant impacts (Fig. 3). In order to exceed the HSSL, a post-impact state must have (i) a high degree of vaporization and (ii) sufficient angular momentum. Determining the fraction of impacts meets these requirements is difficult, as most simulations of the giant impact phase do not track angular momentum. However, based on N-body models of planet formation, a large fraction of final terrestrial planets are rapidly rotating [1] and ~40% of terminal giant impacts have sufficient specific impact energy to provide the required thermal state (based on [6]). Therefore, some terrestrial planets likely exceeded the HSSL during accretion.

Conclusions. A hot spin stability limit for terrestrial planets has important implications for understanding the properties and processes on young planets, including collisional cross sections and the pressures and temperatures of core formation. The isotopic and elemental composition of our Moon can be quantitatively explained by partial condensation from a well-mixed post-HSSL Earth [2].

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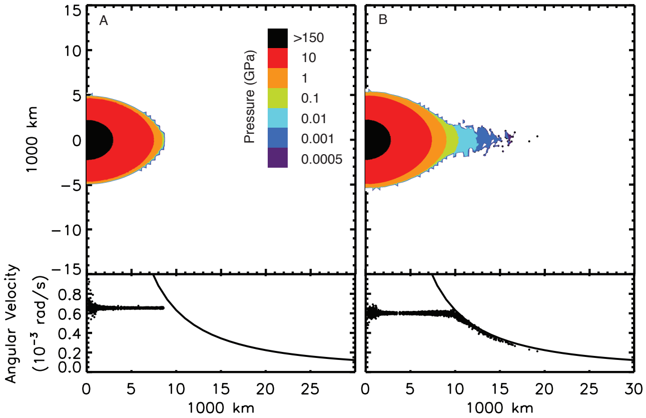

Figure 1: Pressure contours of slices parallel to the rotation axes (upper panels) and angular velocity profiles in the midplane (lower panels) of isolated Earth-mass SPH planets. The black line indicates a keplerian orbit. A and B show a planet below and above the HSSL respectively. The planets have mantles with constant entropies of 5 kJ/K/kg (A) and 5.5 kJ/K/kg (B) and 2.45 times the present day Earth-Moon angular momentum.

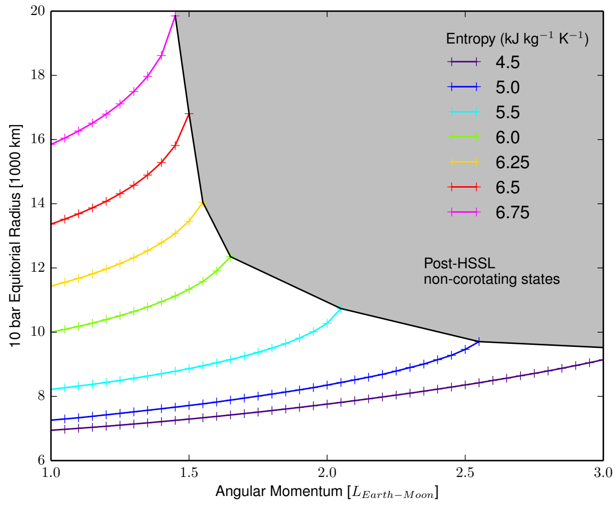

Figure 2: The HSSL boundary for Earth mass planets with constant entropy mantles. The black line indicates the transition from corotating planets to post-HSSL structures with planets below the line being in corotation. Colored lines indicate the equatorial radius of HERCULES planets of varying mantle entropies. The radius of the planet is defined by the 10-bar pressure contour.

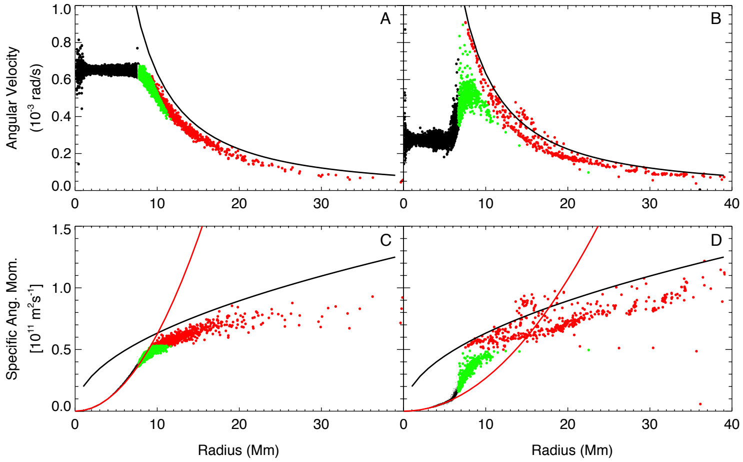

Figure 3: Midplane profiles of SPH post-impact planets for a high energy, high angular momentum impact after [7] (A, C) and a lower energy, present-day angular momentum impact after [8] (B, D). A, C show a post-HSSL post-impact continuous MAD structure whereas B, D show a discontinuous planet and disk. Black points have density >1 g cm^{-3}. Green and red points vary in their specific angular momentum. Lines indicate a keplerian orbit (black) and the angular momentum for corotating material (red).