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Super-dense remnants of gas giant exoplanets

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Abstract

The masses that have been observed for three large exoplanets, Kepler-52b, Kepler-52c, and Kepler-57b, are between 30 and 100 times the Earth mass, which implies densities higher than iron planets of the same sizes. We propose that these planets could represent the naked solid cores of gas giants that would have lost their atmospheres, for instance during their migration towards their star, and investigate the conditions under which the density of these cores could remain close to their initial highly pressurized state.

1. Introduction

Among more than 2300 candidates of transiting exoplanet systems that have been identified by NASA's Kepler mission [1], ten planets are more massive than iron cores that would have the same size. A re-analysis of the data lead to the conclusion that the mass of the smallest of them is actually not known, but that the mean density of the three largest reported planets Kepler-52b, Kepler-52c, and Kepler-57b, which are between 30 and 100 times the Earth's mass, is indeed higher than an iron planet of the same size [3]. We investigate the feasibility of these intriguing observations, and propose that these planets could represent the naked solid cores of gas giants that would have lost their atmosphere, for instance, during their migration towards their stars.

2. The relaxation of a naked core

Following the accretion of a gas giant, its huge and dense primordial atmosphere imposes extremely high pressures, up to the order of TeraPascals, on the solid core. This state is assumed to be in equilibrium with associated finite strains. The radial distribution of the density and the incompressibility of highly pressurized silicates are calculated by extending the method employed by [5] and [2] to very high pressure conditions, using the Kean formulation of the equation of state [6]. The equivalent description of metallic materials is performed through the Mie-Grüneisen-Debye theory, which provides comparable results to both ANEOS and Thomas-Fermi-Dirac formulations up to a few tens of TPa [2]. The mechanical effects induced by the loss of the massive atmosphere are described by a pressure unloading of the solid core surface, and by a consequent increase of volume and decrease of the density. Following the methods employed to investigate the deformation of the Earth's mantle by surface loads [4], the evolution of the unloading and associated decompression processes, is assessed by the convolution of a time-dependent source, the extensive surface stress, with the time varying viscoelastic response of the spherical planet to a unit-step stress function.

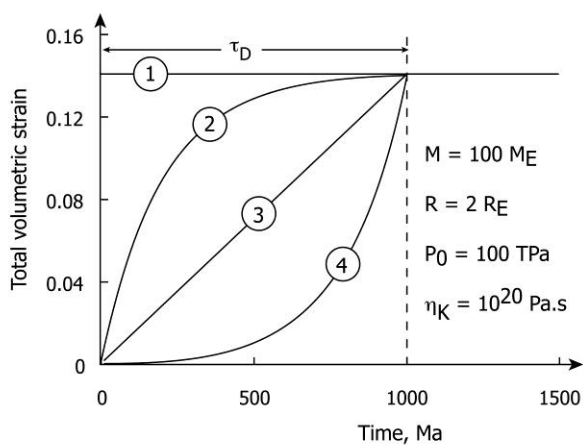

Figure 1: The temporal evolution of the cumulated volumetric strain induced by atmospheric unloading of a (100 Earth's mass, 2 Earth's radius) planet. Labels 1 to 4 refer to the four atmospheric loss scenarii described in the text.

The temporal evolution of the total volumetric strain is displayed in Figure 1 for four scenarii of atmospheric pressure unloading, which would be applied on the surface of K-52b, c, and K-57 b like planets. Case 1 corresponds to a sudden (1 Ma long) impulse-like blow-off of the initial atmospheric pressure (100 TPa in the example). Cases 2 and 4 consider a t_D = 1 Ga long evolution during which the rate of pressure loss either decreases or increases as a function of time (cases 2 and 4, respectively), and case 3 corresponds to a constant pressure loss over time. The pressure unloading scenario governs the temporal evolution of the volumetric strain for times smaller than the source duration, but it does not significantly influence the final strain value. Whatever the unloading history, a ~ 14% cumulated strain is attained at the end of the atmospheric loss. This volumetric change corresponds to a radius increase lower than 5%. This result suggests that large planetary cores may stay in an almost unrelaxed state for billions of years, provided that their internal equilibrium pressure, and hence finite strain incompressibility, is of the order of magnitude of the unloading surface stress.

6. Summary and Conclusions

Previous studies have demonstrated that similar mass and radius relationships could be found for Super-Earths and mini-Neptune. Our results lead us to propose that a third family can also be considered, i.e., that a few "planets" discovered close to their stars are in fact the remnants of the inner core of gaseous exoplanets, and that the very dense objects discovered recently by Kepler might be such bodies. The approach summarized here is reasonable as long as the planetary core is very massive (at least a few tens of Earth mass). To the first order of approximation, the mean pressure inside a spherical planet, and hence its incompressibility, scales with the square of its surface gravity. For large and massive planets such as Kepler-52b, c and Kepler-57b, the high pressure incompressibility at equilibrium derived from equation of state calculations (i.e. for a zero surface pressure after unloading) is of the same order of magnitude, or larger, than the former maximum atmospheric pressure load. For smaller, e.g. Earth-like planets, the decompression history will strongly depend on the ratio between the initial atmospheric load and the incompressibility in the equilibrium state. If this ratio is larger than one, it is expected that the planet will decompress until it reaches its gravitational equilibrium. In the latter case, the decompressed state is strongly dependent on the age of the planet. The older the planetary system is, the larger the decompression of naked cores should be. This must be taken into account if one wants to study a very dense object. A careful study of the nature of these small objects, potentially still away from equilibrium, requires the age of the system to be known. Also, a planet so close to its star that its surface temperature is very high may reach the new gravitational equilibrium much quicker since the viscosity is very much temperature dependent. Additional parameters to mass and radius, such as their age, their distance to the star, or the bulk composition of the system will have to be incorporated in future models to confirm that we may be observing the fossilized cores of giant exoplanets. This first study strongly suggests that such occurrences are indeed possible.

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