Investigation of thermal processes during mass accretion and subsequent radioactive heating of a protoplanet

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Introduction

Investigating how stars and planetary systems form is key to understanding them in their current state. Here I modeled the formation and subsequent heating by radioactive decay of an Earth-like planet.

Methods

This is a very simple model, with no mass or energy loss. All of the initial potential energy possessed by the accreting material was retained and converted into thermal energy. This energy was then increased over time up to the current time of 4.5 billion years by including radioactive heating.

The model was divided into two parts. The first involved "building the planet" by accreting material in 1000 equal mass increments up to the current mass of ~6.0 x 10^{27} g. The protoplanet was given an initial radius of 6.4x10^6 cm (64 km) and a constant density of 5.5 g cm^{-3}. As each layer was added to the protoplanet, the potential energy was calculated as such:

$$U = \frac{GMm}{R}$$

Where G is the gravitational constant, M is the total mass of the planet, m is the mass of each layer, and R is the total radius of the protoplanet. The potential energy was then converted into heat by calculating:

$$T = \frac{U}{mCp}$$

where T is temperature in Kelvin, and $Cp = 10^7\ erg\ g^{-1}\ K^{-1}$ is the specific heat.

The second part of the model involved adding heat due to radioactive decay. The current value for the heating rate within carbonaceous chondrite meteorites is 4 x 10^{-8} erg g^{-1} s^{-1}, with a half-life of 1 billion years. This was used to calculate the heating rate at the time that accretion (and thus the corresponding temperature increase) was terminated, and heating due to radioactive decay was initiated. This heating continued until 4.5 billion years after the start of the accretion process.

Results

The temperature profiles at the end of formation and at the current time of 4.5 billion years are plotted in figures 1 and 2. In figure 1, formation was terminated after 10 million years, and heating due to radioactive decay began at that time. In figure 2, formation was terminated after 100 million years. At the end of formation, the surface temperature of the planet came out to be 62 615 K. When heating by radioactive decay started after 10 million years, the final surface temperature came out to be 66 494 K. When it did not start until after 100 million years, this rate was lower and resulted in a final temperature of 65 467 K.

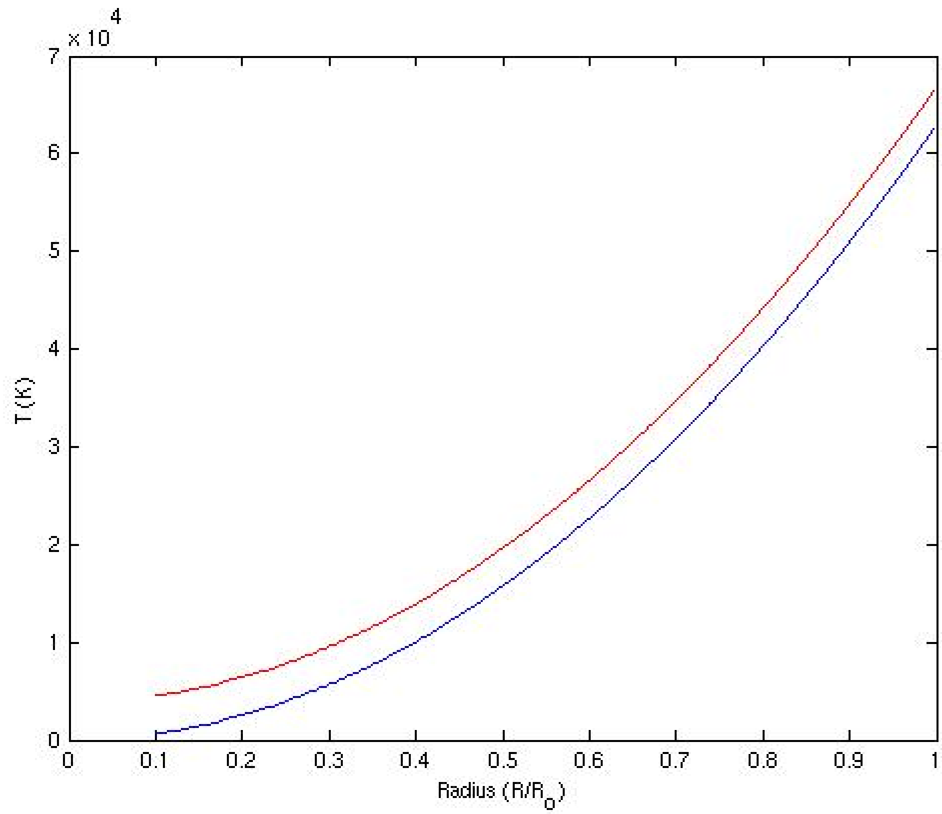

Figure 1: This figure shows the temperature profiles of the planet at two different times; the blue (bottom) curve represents the temperature right at the 10 million year formation, and the red (top) curve represents the temperature at the current time of 4.5 billion years.

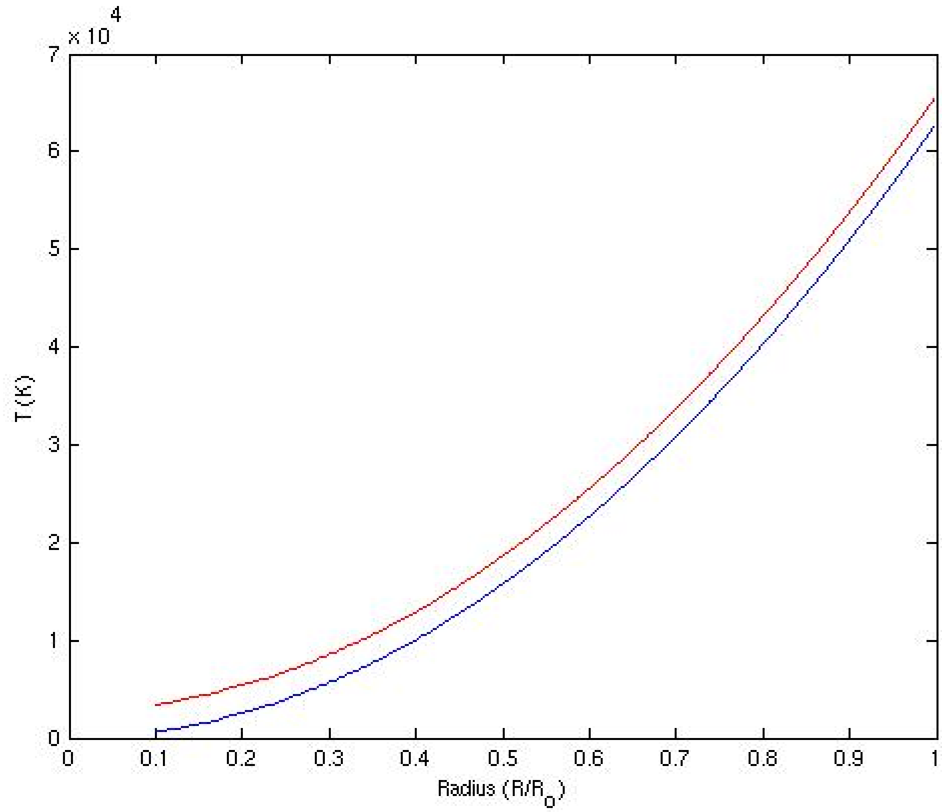

Figure 2: This plot is similar to figure 1, with planet formation ending after 100 million years instead of 10 million years. Again, the blue (bottom) curve shows the temperature profile of the planet just after formation, and the red (top) curve shows the temperature profile at the current time of 4.5 billion years.

Conclusions

For this simple model, the energy was converted completely into heat, thus increasing the temperature of the surface of the planet as it grew. The temperature only increased by a few hundred Kelvin as a result of radioactive heating, so this is not a significant contributor to the temperature of a planet (at least not in the way it is modeled here). When formation did not cease until after 100 million years as opposed to 10 million, the decay rate had decreased by a larger amount, and therefore the final surface temperature profile was slightly lower than it was for the 10 million year formation time.