EARLY ACCRETION AND ITS EFFECT ON THE THERMAL HISTORY OF MARS.

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Introduction

Thermal evolution models provide insights into a wide spectrum of questions related to the evolutionary history of Mars ranging from the processes of core, crust and mantle separation, to formation of the hemispherical dichotomy and the Tharsis region [1]. Accretion models of Mars [2] in the 1970's based on the work on [3] estimated a timescale of accretion of Mars between 100 – 1500 Myrs. Thus, early thermal evolution models of Mars [4] assumed cold post-accretion initial temperatures. Dynamical modeling by [5] suggested significant heating by large impacts during accretion, leading thermal modelers (e.g. [2]) to construct models for an initially hot Mars. Most thermal models until now have retained the assumption of ~100 Myr accretion timescale, and consequently have considered heating only by long-lived radionuclides. Another category of models computed thermal histories of early Mars by taking into account the impact energy and/or the heat of core formation [5,6]. Theoretical support for rapid accretion was provided by recognition of "runaway growth," that allowed bodies in a planetesimal swarm to attain large sizes before velocities are stirred up, in a shorter interval of time than previously recognized [7,8]. Plausible swarm parameters allow runaway embryos to grow as large as Mars on a timescale ~1 Myr or a hundredth of the time thought by [3]. [9] suggested that Mars might be a surviving embryo produced by runaway growth. The idea of faster accretion and differentiation is supported by a host of isotopic systems [10,11,12,13,14]. Hf-W systematics indicate that accretion, core segregation, and large-scale silicate melting on Mars was complete by ~10 Myrs with respect to CAI formation. A possible explanation for silicate depletion (relative to metal sulfide) and planetary density for Earth and Mars might be the lack of a protracted accretion stage (that produces giant impacts) for Mars [15]. The fast accretion of Mars in timeframes of ~1 Myr brings into play a significant role for 26Al in early thermal evolution, since the heat generated per unit mass per unit time by this radionuclide is greater than the combined heat produced by all other short- and long-lived radionuclides, for at least the first 5 Myrs after CAI formation.

Accretion and its effect on the thermal history of planetesimals

[16,17] put forward the first thermal model that takes into account the heat budget during the accretion process. We showed that the nature of the accretion process profoundly affects thermal history for Asteroid 6 Hebe. In contrast to results from instantaneous accretion models (that assume the asteroid to be fully formed at the start of the simulation), [17] show that it is possible for an asteroid to reach its peak temperature during accretion. The times at which different depth zones within the asteroid attain peak metamorphic temperatures may increase from the center to the surface in certain cases, whereas in instantaneous models the opposite relation is observed. Instantaneous accretion models predict a dominance of type 6 material; in incremental models, the volume of high-grade material in the interior may be significantly lower. Depending upon the times at which accretion initiates and ends, the thermal history of Hebe is found to vary. The variation of thermal history with the nature of the process of accretion is observed since the timescale of accretion and the timescale of decay of the heat source are comparable. The thermal history of Mars, in contrast, to Hebe, would involve a host of complexities including core formation, crust separation, mantle and core convection, impacts, etc.: Yet, the study of Hebe points to why it is necessary to evaluate the effect of early accretion on Mars.

Present Approaches and the early thermal history of Mars

The classical Mars thermal models [1] start out with a differentiated planet with a mantle and a crust and an assumed initial temperature of 1500 – 2000 K: so such models give no information about the early thermal history, but instead try to address problems related to the long term cooling of the planet. Mantle convection is thought to shape the cooling history of planetary interiors. The simplest picture is a planet that cools monotonically with time. As discussed in detail in [18], these scenarios make several assumptions, and have certain drawbacks. For example, it is assumed that convection heat flux is proportional to temperature, since mantle viscocity is proportional to temperature. Approximately, every 100 K increase in temperature doubles the heat flux. However, convection scaling laws do not explicitly account for melting. The deviation is greater and will be crucial factor when modeling the early thermal history of Mars. Also, this form of convection does not take into account any phase transitions, differentiation or compositional layering. The last two factors will be critical if Mars accreted early and 26Al was still live. Thus, differentiation at, say 2 Myrs., will produce a large difference in the heat generated per unit time per unit volume between the core and the mantle (because the core will not have any live 26Al and the mantle will have considerable 26Al abundance.)

Approaches

We have approached the problem in two ways:

Model A: We have modeled Mars using an incremental accretion thermal model with Stu Weidenschilling incorporating results from the multizone accretion code.

Model B: We have also reevaluated [18] taking into account the effect on 26Al in a scenario of early accretion of Mars.

Methods: Model A

We use a finite element code to solve the heat transfer equation. The radius of Mars is assumed to increase according to the output of the multizone accretion code [19], taking into account the heat released by impacts. Half of the total energy generated by impact is assumed to uniformly dissipate in the accreted layer. We take into account the heat released by the decay of short-lived (26Al, 60Fe) as well as long-lived (U, K, Th) radionuclides. The planet is assumed to stay undifferentiated through the first 5 Myrs relative to CAI formation.

Results: Model A

We constrain maximum temperatures produced in a model of incremental accretion as a function of time at which accretion initiates with respect to CAI formation (T[acc]) and the duration of the accretionary epoch (T[dur]). The minimum time required to accrete a Mars-size body at its orbital location is ~0.9 Myrs according to the multizone code [19]: this sets the lower limit for T[dur]. For values of T[acc] < 2 Myrs, the maximum temperature is much higher than the melting point of silicates. Temperature profiles in each of these cases show that the entire planet will experience temperatures that produce complete melting. For values of T[acc]> 2 Myrs, maximum temperatures are greater than the melting temperature, but the temperature profiles indicate that though the upper mantle of the planet would melt completely, the central portion undergoes partial silicate melting/metamorphism. Impact energy deposited in the outer layers of the planet (from the surface to a depth of 1000 km) produces high temperatures in this region while the lower abundance of 26Al (for T[acc]>2 Myrs) prevents heating in the central portion.

Fig.-1 show post-accretionary temperature profiles for various accretionary scenarios to be significantly different from one another and from the assumption of constant interior temperature used in most thermal models of Mars.

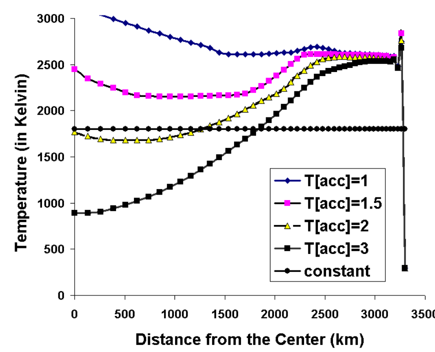


Figure-1: The planetary temperature profile after the end of accretion assuming that it accretes by runaway accretion in 1 Myrs (T[dur]=1 Myr). The time at which accretion initiates is taken as a variable and results of runs are shown for T[acc]=1, 1.5, 2 and 3 Myrs. For T[acc] =0, i.e. if accretion of Mars starts at CAI formation, very high temperatures are produced that are beyond the scale of the plot (indicating that the planet would melt completely). Impact produces high temperatures nearer to the surface, whereas 26Al causes heating in the planetary interior. Thus, when T[acc] increases, the maximum temperature at the center is seen to decrease. For reference, we show a post accretion temperature of T= 1800 K used in a thermal model that assumes an initially hot Mars.

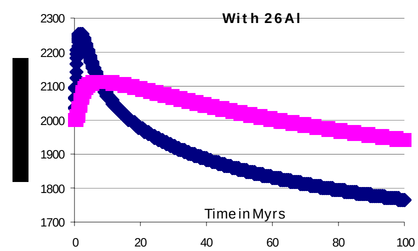
Methods: Model B

Accretion is assumed to initiate 2 Myrs after CAI formation [20]. Two model calculations are made to bracket upper and lower limits of accretion time: Mars is thus assumed to accrete in 1 and 10 Myrs., respectively. Accretion is assumed to be instantaneous. The simulation initiates after accretion is complete. Mars is assumed to be partitioned into a core and mantle with an initial temperature of 2000 K. Specific heat of the core and mantle are taken to be constant at 840 J/kg/K and 1200 J/kg/K, respectively. The heat flux from the mantle in a plate tectonics regime is approximated from [18,21]. The core is assumed to be isothermal. Heating is assumed to take place by short-lived (26Al, 60Fe) and long-lived (K, U, Th) radionuclides. The Al content of the crust was approximated from the composition of Martian dust as measured by Mars Pathfinder [22]. The Al content of the undifferentiated mantle after core formation and the bulk planet were approximated from geochemical models of [23]. Viscocity is assumed to be temperature dependent with a reference viscocity of 1020 K at 1573 K [18].

Results: Model B

The interior of early Mars is believed to have undergone uniform heating and has been the basis of uniform initial temperature assumptions in Mars thermal models. However, redistribution of radionuclides during differentiation may cause inhomogeneous heating of the crust and mantle particularly when 26Al is potent. Thus, 26Al and 60Fe will be partitioned into the mantle and core, respectively after core formation, causing the mantle temperature to increase significantly compared to the underlying core. A plate tectonic regime (without 26Al) is thought to drive core convection as shown by [18]. However, in the case of a hotter mantle overlying the core, core convection is unlikely to occur. A plate tectonic regime must first lose excess heat released by 26Al decay, until the mantle is cooler than the core. At such time, core convection can initiate causing a magnetic field on Mars. Thus, the onset of a magnetic field and of the plate tectonic episode on Mars would not be simultaneous but staggered in time, in a scenario of fast accretion. If the duration of accretion of Mars is ~10 Myrs., plate tectonics does drive core convection from the outset as shown previously by [18].

(a) With 26Al heating



(b) Without 26Al heating

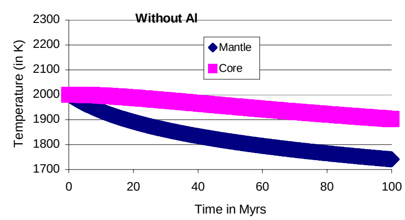


Figure 2: The plots summarizes core and mantle temperatures as a function of time with respect to CAI formation with (a) and without (b) including the effect of 26Al, respectively. The first 100 Myrs are shown in order to highlight the effect of 26Al on the early evolution of Mars. A plate tectonic regime is assumed to have existed for the mantle: hence, heat loss from the mantle is quick. Time is shown in Myrs. and temperature in K. The accretion of Mars is assumed to be complete 3 Myrs after CAI formation. Note that the temperature of the mantle sharply increases at the early stages of the simulation due to preferential heating of the mantle by 26Al, in case of (a). At this time, the mantle is hotter than the underlying core, and the core is assumed to gain heat by conduction from the overlying mantle. In a scenario, where 26Al is not considered (b), the temperatures of the mantle and core decrease monotonically as was shown by [18].

Future Work

The drawback of the model A is the assumption of an undifferentiated planet: in reality, Fe-FeS melting and silicate melting will probably initiate during the accretion process. Model A does account for the latent heats of melting, but not the physical segregation of the core and crust. On the other hand, Model B starts model with a fixed initial temperature and a planet differentiated into a core and a mantle.

Thus, the complexity of the accretion process is not taken into account. In future, we hope to work on an integrated model that calculates the heat budget during accretion and takes into account the differentiation process.

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