Importance of the accretion process in asteroid thermal evolution:
6 Hebe as an example

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(Received 8 July 2002; revision accepted 23 October 2002)

Abstract—Widespread evidence exists for heating that caused melting, thermal metamorphism, and aqueous alteration in meteorite parent bodies. Previous simulations of asteroid heat transfer have assumed that accretion was instantaneous. For the first time, we present a thermal model that assumes a realistic (incremental) accretion scenario and takes into account the heat budget produced by decay of 26Al during the accretion process. By modeling 6 Hebe (assumed to be the H chondrite parent body), we show that, in contrast to results from instantaneous accretion models, an asteroid may reach its peak temperature during accretion, the time at which different depth zones within the asteroid attain peak metamorphic temperatures may increase from the center to the surface, and the volume of high-grade material in the interior may be significantly less than that of unmetamorphosed material surrounding the metamorphic core. We show that different times of initiation and duration of accretion produce a spectrum of evolutionary possibilities, and thereby, highlight the importance of the accretion process in shaping an asteroid’s thermal history. Incremental accretion models provide a means of linking theoretical models of accretion to measurable quantities (peak temperatures, cooling rates, radioisotope closure times) in meteorites that were determined by their thermal histories.

INTRODUCTION

Thermal and Accretion Models

Asteroid thermal models have been used to describe quantitatively the geologic evolution of asteroids and planetesimals in attempts to link their formation to measurable parameters in meteorites. The heat transfer equation is the basis for most model calculations (for a detailed discussion, see Ghosh and McSween [1998]) with assumptions that address uncertainties in initial conditions (e.g., asteroid temperature at the beginning of the simulation), boundary conditions (e.g., nebular ambient temperature, asteroid emissivity), and model parameters (e.g., specific heat capacity, thermal diffusivity, presence of regolith, voids, or ice).

Asteroids, the parent bodies of meteorites, are planetesimals that formed in the early solar nebula. The current population of the asteroid belt comprises a small fraction of the original mass of bodies in that region, depleted by collisional and dynamical processes over the age of the solar system. However, much of the thermal and chemical evolution of the asteroids occurred during the first few million years of their history, while heat sources were present presumably in the form of short-lived radionuclides. During this time, the planetesimal population was evolving as bodies accreted from dust suspended in the nebular gas evolved into objects hundreds of kilometers in size. Because heating and growth occurred on comparable timescales, the thermal evolution of asteroids must be considered in the context of bodies that are not static but are growing. The present work attempts to combine such a thermal model with constraints on growth rates from a dynamical model of planetesimal accretion.

Planetesimal Evolution in Terms of Accretion Physics and Heat Transfer

The process of the formation of planets from dust particles can be divided into three regimes:
Coagulation of $\mu$m-Sized Grains into km-Sized Bodies

In this size range, particle velocities are controlled by the drag forces exerted by the nebular gas. Collisions occur during settling toward the nebular midplane and radial migration, which may be influenced by turbulence. Sticking, at this stage, is due to non-gravitational sticking processes such as “van der Waals bonding,” “interlocking of grains,” etc. (Weidenschilling and Cuzzi 1993). The actual mechanism is obscure because it depends on mechanical properties of the aggregates, which are poorly constrained. In the case of a heat source uniformly distributed per unit mass, the amount of heat retained is proportional to the ratio of surface area to volume or directly proportional to the radius (heat is lost from the surface by radiation). Given the canonical ratio of $^{26}$Al/$^{27}$Al in calcium-aluminum rich inclusions (CAIs) and the chondritic abundance of Al, internal heating is not enough to cause a significant difference in temperature from the ambient nebula at this stage.

Formation of Asteroid-sized Bodies and Planetary Embryos from km-Sized Planetesimals

For bodies larger than about 1 km, mutual gravitational perturbations are stronger than drag forces. Eccentricities and inclinations are excited, leading to the crossing of orbits and collisions. Colliding bodies may be shattered, but enough energy is dissipated in impacts for the fragments to remain bound by gravity. Accretion of an ensemble of bodies is a complex interplay of the distributions of mass and velocity—the rate of collisions, which cause the masses of the bodies to grow, is controlled by the relative velocities. Velocities in turn, are determined by the masses through their gravitational perturbations. Simulations of accretion are an iterative process. In each timestep, the number of collisions and changes in the mass distribution are calculated, then the perturbation rate for the new mass distribution is computed to yield a new velocity distribution (Wetherill and Stewart 1993).

One problem with such simulations is the tendency for some bodies to undergo “runaway growth.” Gravitational focusing increases the collision cross-section (and, thus, the rate of mass accretion), of the larger bodies. The first bodies to reach a critical size grow much more rapidly than their less-fortunate neighbors. Their growth stalls when they deplete the available matter near their orbits, and their perturbations stir up the relative velocities of the smaller bodies decreasing the gravitational focusing. The planetesimal swarm typically develops a bimodal size distribution with a gap between lunar-sized to Mars-sized embryos and a power-law distribution of smaller bodies. This process produces an inhomogeneous swarm of planetesimals, the smaller bodies of which vary in size and velocity distribution with the distance of the embryos' orbits. To model this stage, we use a multi-zone accretion code. The planetesimal swarm is divided into a series of zones in semi-major axis. Populations of different zones can interact, both collisionally and gravitationally, where their orbits cross. Details of the model are given by Weidenschilling et al. (1997). At this stage of growth, planetesimals are large enough to retain heat generated in their interiors. The timescale of the accretion process is typically $\sim$1 Myr, thus, the rate of heat generation by $^{26}$Al (and possibly other short-lived nuclides, if present) changes significantly. Thermal evolution patterns are influenced by accretional histories, as explored in this paper. Collisional heating is not effective in the smaller (non-runaway) size range of the population that is ancestral to the present asteroids due to low impact velocities during accretion (discussed below).
Using Thermal Models to Link Accretion Models with Meteoric Measurements

The first step in linking meteorite measurements with accretion models is to identify specific meteorite parent bodies. Accretion models enable focusing on bodies of specific size and location at given heliocentric distances. In meteorite thermal models, the radius of the parent body is a particularly crucial parameter. During the last decade, developments in spectroscopy have helped to identify of possible parent asteroids for some meteorite classes (Binzel and Xu 1993; Gaffey and Gilbert 1998).

The second step in linking meteorite measurements with accretion models is to evaluate the dependence of an asteroid’s thermal history on the accretion process. Although several heat sources for asteroids have been proposed (Wood and Pellas 1988), a growing consensus exists that the decay of $^{26}\text{Al}$ (a radionuclide with a short half-life of 0.72 Myr) and high decay energy provided the heat for melting and metamorphism (Huss et al. 2001). Until now, heat transfer models have assumed, for ease of computation, that asteroid accretion was instantaneous, i.e., the asteroid attained its full size in an instant (e.g., Miyamoto et al. 1981; Bennett and McSween 1995; Akridge et al. 1998; Ghosh and McSween 1998). Instantaneous accretion models are based on the assumption that the accretion process does not have thermal consequences. If this assumption were true, it would be impossible to link meteoritic measurements to accretion history using asteroid thermal models. In this work, we test the validity of instantaneous accretion in thermal models, and find that its approximation may introduce considerable differences in the results, since it ignores the period during which $^{26}\text{Al}$ was most potent as a heat source.

Thermal models for partly melted asteroids are exceedingly complex because the heat source ($^{26}\text{Al}$) migrates during calculation (Ghosh and McSween 1998). A recent study by Merk et al. (2002) explores the effect of accretion on the thermal history of melted planetesimals and comes to conclusions similar to ours—although, an idealized accretion scenario is used, and complexities during melting (like the migration of $^{26}\text{Al}$ during differentiation) are ignored. The parent bodies of chondrites that did not melt offer a better constrained example. The present work uses asteroid 6 Hebe to illustrate a thermal model that incorporates incremental accretion. Hebe and H chondrites are spectrally similar (Gaffey and Gilbert 1998) and the location of Hebe near the $\nu_0$ and 3:1 resonances allows the transfer of meteoroids into Earth-crossing orbits (Morbidelli et al. 1998). Thus, asteroid Hebe is considered to be the probable parent asteroid of H chondrites (Gaffey and Gilbert 1998). We have modeled its thermal history using thermophysical constraints (peak temperature, specific heat capacity) from H chondrites and have compared the modeled metallographic cooling rates and isotope closure ages with those measured for H chondrites.

METHODOLOGY

Thermal Model

We solve the heat transfer equation for a spherical asteroid using the finite element method (Ghosh and McSween 1998) and a moving boundary is used to implement incremental accretion. The presumed heat source is the decay of $^{26}\text{Al}$ with an initial ratio of $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ at the time of formation of CAIs (Huss et al. 2001). Temperature- and composition-dependent specific heat capacity is incorporated (Ghosh and McSween 1999) and a radiation boundary condition is used. Impact energy (discussed below) is added to the near-surface layers according to a formulation from Melosh (1990). The thermal diffusivity of regolith ($1 \times 10^{-9} \text{m}^2 \text{s}^{-1}$) is assumed to be $1/100$th that of rock ($10^{-7} \text{m}^2 \text{s}^{-1}$). The asteroid grows from a nucleus having a 0.5 km radius to the radius of Hebe at 92.5 km (Gaffey and Gilbert 1998). The radius’ rate of growth through time is assumed to be constant for each evaluated case. Table 1 and Fig. 1 provide explanations of the assumptions made in each case with growth rates validated from results of the multizone accretion code (Figs. 2, 3, and 4) of Weidenschilling et al. (1997). The initial nucleus and the accreting mass is assumed to be H-chondritic in composition. The ambient nebular temperature is assumed to be 292 K. Many parent bodies experienced breakup and reassembly (Scott and Rajan 1981), and the present model assumes that any such event happened after geochemical closure was attained.

Obtaining a Match for Peak Temperature for Hebe

The peak temperature at the asteroid center is governed by the time of initiation of accretion ($T_{\text{init}}$, defined as the time interval between formation of CAIs and a 0.5 km radius body) and the duration of accretion ($T_{\text{dur}}$, defined as the time for Hebe to grow from initial to final radius). By adjusting $T_{\text{init}}$ and $T_{\text{dur}}$, we sought to produce the peak temperature for H6 chondrites, estimated at 1223 K (McSween et al. 1988). Various accretion scenarios can produce this peak temperature. We ran 6 test cases (Table 1) with $T_{\text{init}}$ varying for 0.7 to 3 Myr and $T_{\text{dur}}$ varying from 6.6 to 0.3 Myr (Fig. 5), all of which satisfy the peak temperature constraint. For comparison, we also made a run assuming instantaneous accretion (i.e., $T_{\text{dur}} = 0$) for $T_{\text{init}} = 3.13$ Myr. Using selected runs (Cases 1, 2, 4, and 6), Fig. 1 summarizes the differences in the thermal history of Hebe under different accretionary scenarios.

Accretion Model

These cases exemplify some of the many growth histories that are possible during stochastic accretion. We have used the multizone accretion code (Weidenschilling et al. 1997) to
compute the growth of planetesimals in the inner solar system from 0.5 to 4 AU for model times up to 5 Myr. This simulation does not include perturbations by Jupiter—we assume that it formed at a later time by delayed core-accretion (Pollack et al. 1996). If Jupiter formed early, by gravitational instability in the solar nebula (Boss 1997), its perturbations would have interfered with accretion in the asteroid region. In that case, it is difficult to account for the growth of planetesimals even to the size of present asteroids (Kortenkamp and Wetherill 2000a, b). While the code can account for fragmentation, computational demands make it impractical for such large simulations. Current findings assume that all collisions result in coalescence—this should be a good approximation at this stage of evolution. A typical output of the code is shown in Fig. 2. We take the results in the zone between 2.4 and 2.5 AU, the present location of Hebe, as representative of its plausible growth histories. The code treats bodies larger than $2 \times 10^{24}$ g (roughly the size of Ceres), as discrete entities, keeping track of their masses and orbital parameters individually (Fig. 3). As discussed above, such large bodies presumably formed in the asteroid region, but were removed later by Jupiter’s perturbations. Bodies of Hebe’s size (or any asteroid smaller than Ceres) are too numerous to be treated as individuals. Instead, they are represented through a statistical approach given that the population of logarithmic size bins each span a factor of 2 in mass.

We calculate the median and largest values of planetesimal mass in Hebe’s zone, in addition to the first and third quartiles of the mass distribution, as functions of time. The results, summarized in Fig. 4, trace the evolution of the swarm, with the largest body growing fastest, and the growth rate falling off for the third, second, and first quartiles, respectively. The growth rates of the various quartiles can be taken to be statistically representative of the accretion histories of individual bodies of asteroidal size. This helps to bracket possibilities for Hebe’s growth history—it could not grow faster than the largest body in the swarm. The median history, with $T_{dur}$ of a few Myr, is the most probable. But, variations by a minimal factor around the mean accretion rate are possible for a body of any given size. Bodies of Hebe’s size were present in the swarm at all times after the first ~0.1 Myr, presumably up to the time that Jupiter was formed and

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_{init}$ (Myr)</th>
<th>$T_{dur}$ (Myr)</th>
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<tbody>
<tr>
<td>Case 1</td>
<td>0.7</td>
<td>6.6</td>
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<tr>
<td>Case 2</td>
<td>1.2</td>
<td>5.0</td>
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<tr>
<td>Case 3</td>
<td>1.7</td>
<td>3.5</td>
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<td>Case 4</td>
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<tr>
<td>Case 5</td>
<td>2.6</td>
<td>1.2</td>
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<tr>
<td>Case 6</td>
<td>3.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Instantaneous</td>
<td>3.13</td>
<td>0</td>
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Fig. 1. The distribution of temperature in 6 Hebe as a function of time and at various stages of its growth is shown for 4 selected scenarios (cases 1, 2, 4, and 6). The time required for Hebe to grow from a radius of 0.5 km to its final size varies from 6.6 Myr in case 1 to 0.3 Myr in case 6. The grayscale temperature intervals correspond to zones of types 3 (<870 K), 4 (870–970 K), 5 (970–1023 K), and 6 (1023–1223 K) metamorphism, respectively. Note that when the duration of accretion is long (case 1 and 2), peak temperature is attained in the asteroid center during accretion and the metamorphic zones are deeply buried. Also, cases 1 and 2 produce a lower proportion of type 6 material as compared to cases 4 and 6.
Fig. 2. Size distribution of bodies accreted in the inner solar system at a model time of $10^6$ years from the multizone accretion code. Numbers of bodies are plotted in logarithmic intervals of mass and semimajor axis. The simulation spans a range from 0.5 to 4 AU in heliocentric distance. The swarm has a total mass of 5 Earth masses (the asteroid region is assumed to be depleted in mass at a later time after Jupiter’s formation) with surface density proportional to $R^{-3/2}$, where $R$ = distance from the sun. At the start of the simulation all bodies are assumed to be located in the smallest mass bin corresponding to radii = 0.5 km. After 1 Myr, runaway growth produces protoplanetary embryos of mass $\sim 10^{27}$ g out to 2.5 AU.

Fig. 3. Mass versus semimajor axis for bodies with masses larger than $2 \times 10^{24}$ g, which are treated as discrete objects in the simulation. Runaway growth stalls at $\sim 10^{27}$ g; this limit is insensitive to heliocentric distance. However, the growth time is a strong function of distance, and no large bodies have formed beyond 3.5 AU. Horizontal bars give the range from perihelion to aphelion; most of the large bodies have very low eccentricities at this stage.
ceased accretion. Accretion timescales increase with heliocentric distance, therefore, bodies in the inner belt would have formed more rapidly than in the outer belt. Additional variations in accretional history due to the stochastic nature of the process would also exist. One can imagine two bodies reaching the same size at the same time by different paths: one by gradual accumulation of small projectiles, the other by the sudden merger of two bodies, each containing half the final mass. We do not deal with such variations in our modeling. The thermal evolution of any asteroid depends on both its size and accretional history—such variations may explain why Vesta differentiated, while the larger Ceres did not.

As this is the first coupled study involving two separate theoretical subdisciplines, it is important to delineate in some detail the broad assumptions underlying the synthesis.

**Anchoring of Timescales for the Accretion and Thermal Codes**

We assume that at CAI formation, the abundance of $^{26}$Al was canonical ($^{26}$Al/$^{27}$Al was $5 \times 10^{-5}$). However, this does not mean that the condensation of chondritic material was completed at that time. Thus, this material could have been available for the accretion of larger bodies. If a time interval exists between the formation of CAIs and chondrules, as has been suggested (e.g., Amelin and Krot 2002), then accretion cannot proceed until chondrule formation takes place. Time zero for the multizone accretion code corresponds to a time when 0.5 km radius bodies exist in the terrestrial planet region (such that the total mass equals 5 Earth masses with a surface density proportional to $-1.5$ times the heliocentric distance). Thus, to reconcile the timescales for the thermal code and the accretion code, it is necessary to take into account the time required to form km-sized bodies from $\mu$m-sized bodies. As explained previously, this encompasses the first and least understood stage of the accretion process, where growth takes place primarily by coagulation and sticking, and is dependent upon factors like the Brownian motion, turbulence, differential settling towards the midplane, and differential radial migration. This stage acts as a limiting factor for the onset of planetesimal accretion—the duration of this stage is uncertain. But, once particles reach cm size, km-sized bodies need to form within $10^5$ yr to prevent them from spiraling inwards into the sun. $T[\text{init}]$ is the time between CAI formation and formation of km-sized bodies and includes the time difference between CAI and chondrule formation, as well as the time interval between chondrule formation and the formation of km-sized bodies. The period of accretion (as shown in Fig. 6), actually continues from CAI formation (or the formation of $\mu$m-sized bodies) to the end of accretion. But, in our model, we have divided this period into 2 intervals: $T[\text{init}]$ and $T[\text{dur}]$. Thus, as defined in our model, $T[\text{dur}]$ is not actually the duration of accretion but is the time required to form the final asteroid from a km-sized nucleus. As mentioned previously, the value of $T[\text{init}]$ and $T[\text{dur}]$ are treated as free parameters and are adjusted in order to match the peak temperature of Hebe.

**Temperature of the Accreting Body**

We assume that the temperature of an accreting body is equal to the ambient temperature of the nebula. To test this assumption, we carried out the following exercise. As seen in Fig. 2, the accretion code produces a size distribution among asteroid-sized bodies that is a good approximation of a power law. Collisional evolution in this size range is, therefore, self-similar—the slope of the distribution is such that the median mass impacting an accreting asteroid-sized body during most of its growth is smaller by about 6 size bins, or a factor of 64 in mass. This is illustrated in Fig. 7a, which shows the median
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size of bodies accreting to Hebe at various stages of accretion. Using this observation, we tracked the growth and thermal histories of the planetesimals accreting to Hebe, and the thermal history of Hebe at the same time for case 1. The temperature profile (as a function of distance from the center) of Hebe at various times during the accretion process is evaluated (Figs. 7b–d). Simultaneously, the temperature-depth profile of the median body is plotted on the same figure (Figs. 7b–d). For the largest body accreting to Hebe (radius = 25 km), the peak temperature is ~20 K above ambient temperature. The peak temperature of Hebe at this time is found to be far higher (~700 K above the nebular temperature). This is an upper limit to the heat content of accret ing bodies, since planetesimals could shatter in the process of accreting to the larger body and be deposited near the surface, which will cause extensive heat loss. Bodies larger than the median body would carry a greater heat content, thereby skewing the approximation, as with the extreme case of two spheres of radius ~73 km (or with half the final volume of Hebe) colliding with Hebe. Given the low stochastic possibility of 2 large bodies coming together to form Hebe at the end of accretion, the approximation of accreting mass at the ambient temperature is fairly robust.

Assumption of Initial and Ambient Temperatures

Various approaches to determine the ambient temperature of the solar nebula exist: hydrodynamic models (e.g., Boss 1995), models of equilibrium condensation (e.g., Grossman 1972), and models motivated by recent observations of T-Tauri stars (Woolum and Cassen 1999). Nebular models trace the evolution of temperature over time and heliocentric distance. Unfortunately, it is not possible to anchor timescales of nebular models to CAI formation, which, consequently, rules out a correlation with meteorite geochronology. Moreover, temperatures derived from various nebular models define a large range of values, from 1000 K (Cameron and Pine 1973) to 160 K (Hayashi et al. 1985) at 3 AU. Most of the difference in model temperatures stems from differences in the mass and accretion rate of the nebula. This precludes an accurate constraint on initial temperatures or the decay of initial temperatures with time. Our value of 292 K at the location of Hebe (2.4–2.5 AU) is consistent with all three approaches for determining nebular temperatures. This does not necessarily mean that nebular temperatures and their variation with time and heliocentric distance do not have any perceptible effect on planetesimal thermal history.

In the context of the present study, a variation in nebular temperature will cause variation in the relative timing of events (in the thermal model), leaving the pattern of heating and cooling almost unchanged. A difference in nebular temperature (which equates to a difference in initial temperature of the asteroid) changes the amount of live $^{26}$Al required to maintain the peak temperature of Hebe at 1223 K. This change is implemented in the thermal model by
adjusting the value of $T_{\text{init}}$. Thus, if the initial temperature is 200 K (instead of 292 K), the peak temperature of the asteroid needs to be increased by 1023 K instead of 931 K from the base temperature (assuming a peak temperature of 1223 K for Hebe). This means that additional live $^{26}$Al is required, which can be adjusted by lowering the value of $T_{\text{init}}$. Therefore, thermal model outputs that are measured relative to CAI formation (like closure ages) need to be offset by the same amount in which the value of $T_{\text{init}}$ changed. A change in the nebular temperature affects a change in the rate of heat loss from the surface through radiation, so this should change cooling rates and closure ages. However, the cooling history of an asteroid is determined primarily by the interior peak temperature and thermal diffusivity. Thus, the effect of a change in initial temperature is secondary.

Broad ranges for permissible nebular temperatures exist at the location of Hebe. If temperatures are <160 K, ice should accrete at the location of Hebe. Thus, 160 K is the lower limit of temperature since we do not find evidence of significant water in ordinary chondrites. On the other hand, the higher the initial temperature, the greater the need for the nebula to remain hot for a longer period. For example, in the present case, the best match for ordinary chondrites is obtained for $T_{\text{init}} = 2.7$ Myr with an initial temperature of 292 K. This means that the temperature at the location of Hebe 2.0 Myr after the formation of the first solids (CAIs) is 292 K. As explained above, if the initial temperature was 600 K, $T_{\text{init}}$ would need to be readjusted to higher values, which would require the nebula to be at 600 K at the location of Hebe >2.0 Myr after CAI formation. This can be crosschecked with nebular models that address the rate of nebular cooling.

**RESULTS**

Peak temperature in instantaneous accretion models must occur, by definition, after accretion is complete. However, in cases 1, 2, and 3, the peak temperature is attained in the center of the asteroid during accretion (Figs. 1 and 5) due to the long
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In cases 4–6, the peak temperature is attained after accretion is complete (Figs. 1 and 5), since \(^{26}\text{Al}\) is still potent after accretion. The peak temperature in instantaneous accretion is attained later than the incremental accretion used in any test case (Fig. 5). Instantaneous accretion models underestimate the time at which peak temperature is realized, with \(T_{[\text{dur}]}\) determining the magnitude of the error.

In the thermal models of chondrite parent bodies which involve instantaneous accretion (Miyamoto et al. 1981; Bennett and McSween 1995; Akridge et al. 1998), the time at which peak temperature is realized decreases progressively from the center of the body outward (Fig. 8). The entire asteroid undergoes heating from the outset, so surficial layers not surprisingly attain peak temperatures earlier than interior layers (given that peak temperatures for surficial layers are lower than peak temperatures for interior layers). However, in incremental accretion models, this simple relationship may differ because the center (which accreted earlier) undergoes a longer heating period than that which occurs at the surface—the magnitude of the deviation being proportional to \(T_{[\text{dur}]}\). Thus, for a \(T_{[\text{dur}]}\) of 0.3 Myr (case 6), we observe a relationship similar to an instantaneous accretion model (Fig. 8). However, when \(T_{[\text{dur}]}\) is increased, this relationship changes until the opposite relationship is observed in case 1 where \(T_{[\text{dur}]} = 6.6\) Myr (e.g., the time at which peak temperature is realized decreases from the surface to the center [Fig. 8]). Thus, the nature of asteroid heating is strongly dependent on the timescale of the accretion process.

Incremental accretion exerts a profound effect on the volume proportions of material that undergo different degrees of metamorphism (Figs. 1 and 9). Instantaneous accretion models overestimate the proportion of highly metamorphosed material relative to unmetamorphosed chondrites. However, neither instantaneous nor incremental accretion models are able to match the observed relative abundances of petrologic types in H chondrites collections. Of the 357 classified H chondrites, H3, H4, H5, and H6 constitute 3%, 24%, 49%, and 24% respectively, as plotted in Fig. 9 (Motylewski 1978). Similarly, fall statistics show that types 4 and 5 together account for 65% of H chondrite falls (Koblitz 1997).

The inclusion of incremental accretion causes variations in terms of the ages of Pb isotope closure and the rates of metallographic cooling, as determined from the thermal model. Figs. 10a and 10b show model closure ages and cooling rates (calculated at 727 K and 750 K, respectively). Variations in closure ages and cooling rates reflect an interplay of three factors: \(T_{[\text{dur}]}\), the thickness of the region of metamorphism for the relevant petrologic type, and the proximity of this region to the asteroid surface. The instantaneous accretion model produces a larger range for closure ages and cooling rates. In addition, Fig. 10b shows that the instantaneous accretion model overestimates cooling rates for lower petrologic types (types 4 and 5) in comparison to incremental accretion models.

Neither of these runs include a regolith, which are known to affect asteroid thermal history due to low conductivity (Wood 1979; Akridge et al. 1998). To include this effect, we recalculated our models by adding a regolith at the end of accretion (Figs. 10c, 10d, and 11) (Fountain and West 1970). An attempt was made to match the Pb isotopic closure ages (Gopel et al. 1994) and metallographic cooling rates (Scott and Rajan 1981) measured in H chondrites with thermal model closure ages (with and without a regolith, [Figs. 10a

Fig. 8. The times (after CAI formation) at which peak temperature is attained at various distances from the asteroidal center for 6 Hebe.

Fig. 9. Volume proportions of petrologic types obtained in cases 1–6 compared with results for an instantaneous accretion model for 6 Hebe, and H chondrite fall statistics. 
and 10c]) and cooling rates (with and without a regolith [Figs. 10b and 10d]) for Hebe. We focused on H6 chondrites which, because of their protracted cooling histories, may provide the most accurate constraints on cooling history. For runs with a regolith, a match for the closure ages and cooling rates was obtained between case 3 (where $T_{\text{init}}$ = 1.8 Myr, $T_{\text{dur}}$ = 3.3 Myr) and case 4 (where $T_{\text{init}}$ = 2.2 Myr, $T_{\text{dur}}$ = 2.2 Myr) (Figs. 10c–d). Four additional runs of the code were made between $T_{\text{init}}$ = 1.8 and 2.2 Myr with the following pairs of values for $T_{\text{init}}$ and $T_{\text{dur}}$ in Myr: (1.8, 3.3), (1.9, 3.0), (2.0, 2.7), and (2.1, 2.5). Matches of H6 metallographic cooling rates were obtained for values of $T_{\text{init}}$ between 1.7–2.2 Myr, while matches for the Pb isotope closure ages of H6 were obtained for $T_{\text{init}}$ values between 2.0–2.2 Myr. Theoretical studies of the solar nebula place $T_{\text{init}}$ between 0.1 and 2 Myr (Weidenschilling et al. 1997; Woolum and Cassen 1999; Kortenkamp and Wetherill 2000). Our thermal model places $T_{\text{init}}$ at the upper end of this bracket. Studies in the Mg diffusion of anorthites in CAI support a $T_{\text{init}}$ value of ~2 Myr (LaTourrette and Wasserburg 1998). Using the multizone accretion code, preliminary results of the thermal model of Vesta indicate that to match the Hf-W (Quitte et al. 2000) and the Mn-Cr (Birck 1999) ages of HED meteorite, a $T_{\text{init}}$ of 2 Myr is necessary (Ghosh et al. 2000).

## DISCUSSION

### Obtaining a Match of Cooling Rates for Types 4, 5, and 6

A satisfactory match is not obtained for Pb closure ages and metallographic cooling rates of H4 and H5 chondrites...
Tilton (1985) or the ages of H4–H6 measured by Gopel et al. However, Hanan and Tilton (1985) deduced an age of ~80 Myr for Sharps (H3)—older than the age of 57.4 Myr reported by Hanan and Tilton (1985) or the ages of H4–H6 measured by Gopel et al. (1994). Lastly, Gopel et al. (1994) note the absence of a clear correlation between observed U-Pb ages and the corresponding Ar-Ar, Rb-Sr, and I-Xe chronologies. Distinguishing whether a particular cooling rate measurement indicates parent body cooling or the effect of shock has been one of the vexing problems in meteorite petrology. In summary, the meteoritic evidence is far from decisive and possibly accounts for the lack of a mismatch between the thermal model and the meteoritic closure ages for types 4–6.

Multiple H chondrite Parent Bodies?

A scenario of multiple parent bodies might be a better fit for the observed data of cooling rates and closure ages. Consider bodies less than the size of Hebe that accrete with the same Tdur and Tinit in the same local region of the nebula (such that they inherit an identical oxygen isotope signature). As radius decreases, the peak temperature attained in the planetesimal will decrease. In other words, as the radius of the body decreases, the peak temperature at the center of the planetesimal corresponds to type 5, type 4, and type 3 metamorphism, respectively. For ease of discussion, let us classify the hypothetical H chondrite parent bodies based on the peak temperature realized in the interior. Thus, if the peak temperature corresponds to H6 metamorphism, we refer to it as the H6 parent body. Planetesimals with peak temperature corresponding to type 6 (H6 bodies) will have materials of types 3–6, H5 bodies will have materials of types 3–5, and so on. Thus, an H3 chondrite could form in any of the following bodies: H6, H5, H4, and H3; and an H4 chondrite could form in an H6, H5, H4 body, and so on. However, an H4 chondrite on an H4 parent body will have faster cooling rates and shorter closure ages than an H4 chondrite from an H6 parent body. Thus, the existence of multiple bodies produces a greater range of cooling rates and closure ages for types 4 and 5, as the present meteorite data seem to indicate. Interestingly, the concept of multiple parent bodies does away with the requirement of a direct correlation between petrographic type and cooling rate. However, until additional parent bodies for H chondrites are located, this hypothesis cannot be tested.

Effect of Regolith on Thermal History

The density of asteroidal material at various stages of evolution has been vigorously debated. Does the asteroid grow as a fluffy ball of dust (Wood 1979) or does it grow as a lithified body? If the former is true, what is the threshold temperature at which the dust is sintered into rock? If the surface does not realize the sintering temperature, does it remain unsintered or is there a process that ensures lithification? Assuming that the surface lithifies, what is the rate of regolith formation due to continued impacts? At the present level of understanding, we cannot arrive at unambiguous answers to these questions.

Is the Meteoritic Evidence Decisive?

If a larger number of measurements of Pb ages were available, a more regular clustering of ages for the various petrologic types could be obtained. The total number (5) of measurements of Pb ages for types 4–6 used for the comparison may not be statistically accurate. Also, as Gopel et al. (1994) point out, the U-Pb system was possibly disturbed during the first 200 Myr, in which case the ages record a partial resetting event (the exact time of which cannot be determined). It is also possible that type 4 chondrites experienced temperatures lower than the closure temperature of the U-Pb system, implying that the U-Pb closure might not be related to the cooling history. Tera and Carlson (1999) raise the possibility of terrestrial Pb contamination, recent U-Pb mobility, and multiple stages of evolution, and contend that the single stage calculations of Gopel et al. (1994) do not have temporal significance. In an onion shell model, type 3 unequilibrated material should produce the oldest age, older than that measured for H4–H6. However, Hanan and Tilton (1985) deduced an age of ~80 Myr for Sharps (H3)—older than the age of 57.4 Myr reported for Guarena (H6) by Gopel et al. (1994). This may indicate an inconsistency in either the H3 ages measured by Hanan and Tilton (1985) or the ages of H4–H6 measured by Gopel et al. (1994). Lastly, Gopel et al. (1994) note the absence of a clear correlation between observed U-Pb ages and the corresponding Ar-Ar, Rb-Sr, and I-Xe chronologies. Distinguishing whether a particular cooling rate measurement indicates parent body cooling or the effect of shock has been one of the vexing problems in meteorite petrology. In summary, the meteoritic evidence is far from decisive and possibly accounts for the lack of a mismatch between the thermal model and the meteoritic closure ages for types 4–6.

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In the context of the present study, the thermal evolution of the body is influenced by the thermal diffusivity of the asteroid (in turn, affected by density) at various stages of evolution. Unconsolidated material, regardless of its mode of formation as accreted dust or later-formed regolith, has low thermal diffusivity and can significantly affect asteroidal cooling. We must clarify that the amount of regolith generated in the first ~100 Myr is of importance in the thermal context; regolith generated in the intervening 4400 Myr until the present day has no bearing on asteroidal thermal history (since the asteroid has already attained geochemical closure).

In the present study, we have attempted to address briefly the influence of regolith on the thermal history of Hebe. We have used three types of models as summarized in Fig. 11: a) the entire asteroid is composed of unconsolidated material; b) regolith is added after accretion (and regolith thickness stays constant until cooling); and c) regolith thickness increases with body size during accretion and remains constant after accretion. The first category of models (a) does not produce peak temperatures (1223 K) on Hebe for $T[\text{dur}] < 10$ Myr, which is not acceptable from the perspective of accretion models. In the second category of models (b), we systematically decreased regolith thickness from 3 km to 120 m with no significant change in thermal model output. This might mean that the flow of heat from the interior to the surface can be disrupted by a thin layer of regolith, and increasing the thickness of the layer does not produce any noticeable effect. At the same time, decreasing the regolith thickness to zero (or the runs with no regolith) produces significant differences in output. Due to restrictions of numerical stability, we could not decrease the thickness of the regolith <120 m. Probably, between 0–120 m lies a transition thickness that determines whether the regolith will influence cooling history. In (c), we increased the thickness of the regolith linearly with accretion such that the ratio of thickness versus the size of Hebe remained constant. Adding a regolith at the start of accretion produces nearly identical results compared to runs where a regolith is added after accretion for cases 4–6. This is because the duration of accretion is relatively small in these cases compared to cases 1–3. For cases 1–3, a match of peak temperatures was not obtained for $T[\text{dur}] < 10$ Myr.

### Effect of Impact Heating

The case against impact heating as a cause of global (as opposed to local) metamorphism in asteroids stems from the fundamental equation for conversion of gravitational potential energy into kinetic energy of impact, as discussed by Melosh (1990). The heat released in a target body per unit mass of an impactor is:

$$E = h(V_{\text{esc}}^2 + V_{\text{rel}}^2)/2 = h(GM/R + V_{\text{rel}}^2/2)$$

(1)

where $G$ is the gravitational constant; $M$ and $R$ are the mass

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**Fig. 11.** Schematic diagram of the 3 types of models that were used to explore the effect if: a) the entire asteroid is composed of unconsolidated material (the thickness of the “regolith” equals the asteroidal radius); b) regolith is added after accretion (and regolith thickness stays constant until cooling); and c) regolith thickness increases with body size during accretion and stays constant after accretion.
and radius of the target body; \( V_{esc} \) is the escape velocity from its surface; and \( V_{rel} \) is the relative velocity “at infinity,” i.e., outside the gravitational influence of the target. The fraction of energy assimilated as heat is \( h \) (the remainder is radiated away from the ejecta). During accretion, gravitational perturbations typically produce random velocity of the order of the escape velocity of the median-mass body in the swarm (Wetherill and Stewart 1993), so the two terms will be comparable. For a body the size of Hebe, \( V_{esc} \approx 100 \) m/s, and \( E \) is of order \( 10^4 \) J/kg. This leads to an increase in temperature of a few tens of degrees K during accretion if \( h = 1 \). The actual value would be less, since heat deposited near the surface may be lost by radiation faster than it can diffuse into the interior (but may be buried by later-accreted material). As accretion produces larger bodies, i.e., “runaway” embryos, \( V_{rel} \) will increase, and the second term comes to dominate the impact energy. In that case, \( V_{esc} \) is proportional to the radius of the median-mass body; if that is, say, 1000 km, then \( E \) is increased by a factor of 100. This would imply a temperature increase due to impact heating of ~1000 degrees—enough to melt the impactor. However, it also would imply impacts of about 10 times Hebe’s escape velocity. Under such conditions, we would expect most ejecta to be lost, carrying off much of the impact energy. Thus, \( h \) would be small. Indeed, Hebe would probably experience net loss of mass in such impacts, so accretion would effectively be halted. In summary, impact heating on asteroid-sized bodies can produce only local, not global, thermal metamorphism, and only during erosion rather than accretion.

CONCLUSIONS

We show that the assumption of incremental accretion in asteroid thermal models that use \(?Al as a heat source, produces significant differences in model output compared to instantaneous accretion models. In contrast to results from instantaneous accretion models, an asteroid can reach its peak temperature during accretion. The times at which different depth zones within the asteroid attain peak metamorphic temperatures may, in certain cases, increase from the center to the surface, while 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 on the times at which accretion initiates and ends, the thermal history of Hebe varies.

This study shows for the first time that the process of accretion can affect thermal history, enabling comparisons between a parameter set of an accretion code (and the underlying assumptions about the initial conditions in the accretion code) toward measurable properties in meteorites. The solution can be argued to be far from unique. This is no different from the overall problem of terrestrial planet and asteroid belt formation. Theoretical studies define forward models that need to be uniquely inverted to fit experimental or observational data (where the number of variables in the system and the uncertainty in initial conditions far exceed the number of observations). Until a better understanding of the forward problems and a greater number of observations are available, “requests for the luxury of uniqueness are premature” (Wetherill 1980). Inclusion of additional complexity in thermal modeling makes the problem multivariate. On the other hand, simpler thermal history calculations (though capable of more pointed determinations) do not accurately represent asteroidal thermal evolution unless it can be shown that the complexity ignored in modeling has no bearing on thermal history.

There are 2 reasons to argue that the present coupled accretion-thermal model presents a solution better constrained than previous thermal codes. First, as pointed out by Podosek and Cassen (1994), various approaches produce solutions that are at odds with each other. The present coupled code requires the solution to satisfy constraints from both disciplines, as well as constraints from meteorite chronology. Second, the coupled model, with the same accretion/thermal scenario, should be able to reproduce the thermal histories of 4 Vesta as well as the overall structure of the asteroid belt. For example, if the best match for Hebe is obtained for \( T[^{init}] = 2.0 \text{ Myr} \), it should be possible to match the thermal history of Vesta with the same value of \( T[^{init}] \) (together with the same accretion and thermal parameters) or reevaluate the value of \( T[^{init}] \) so that a satisfactory match is obtained in the case of Hebe and Vesta.

Acknowledgments—We thank Robert Coker and Paul Benoit for insightful comments, and the Joint Institute of Computational Science at the University of Tennessee and the NASA HPC/ESS Program for computer time. This work was supported by NASA grants NAG5–11567 to Harry Y. McSween under the Origins of Solar Systems Program, NAGW–4219 to S. J. Weidenschilling under the Planetary Geology and Geophysics Program, and a CITR (Center for Information Technology Research) Challenge Grant from the UT to A. Ghosh.

Editorial Handling—Dr. Patrick Cassen

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