Possible thermal evolutionary pathways of irregular shaped small asteroids and planetesimals

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MS received 27 July 2021; revised 20 October 2021; accepted 11 November 2021

Two distinct thermal evolutionary pathways of irregular-shaped small planetesimals in the early solar system have been studied. We have taken a case study of two S-type asteroids: (243) Ida and (951) Gaspra, on the basis of their precise physical dimensions accessed by the Philip Stooke small body 3-D shape models of the NASA Planetary Data System. The 3-D shape models for the two asteroids are based on the Galileo spacecraft fly-by mission. Based on our novel thermal evolutionary code for the precise shape of the asteroids, we found that the small planetary bodies that accreted within the initial 2–3 million years (Myr) experienced sintering, whereas the bodies formed afterwards were left unconsolidated, e.g., as a rubble pile. The former set of bodies could have formed by direct aggregation of nebula dust, or by the accretion of sub km-sized planetary bodies. Whereas, the majority of the rubble pile type small planetary bodies accreted later by the assemblage of the fragmented debris of the initially existing planetesimals. These bodies cooled over tens of millions of years. The generations of small planetesimals formed over time in the early solar system evolved from an ensemble of compact consolidated bodies to rubble pile bodies due to collision-induced fragmentation and re-accretion.

Keywords. Planetesimals; radioactive heating; sintering; thermal models; thermal metamorphism; Galileo spacecraft.

1. Introduction

The formation of the planetesimals in the early solar system started with the agglomeration of colliding dust grains in the solar nebula (Birnstiel et al. 2016; Weidenschilling 2019). The gravitational collapse of an initially rotating pre-solar molecular cloud had earlier resulted in the formation of the protosun at the center around 4.56 billion years ago (Bouvier and Wadhwa 2010), surrounded by an accretion disc of gas and dust that is generally referred as the solar nebula. The commencement of the formation of the planetesimals initiated with the growth of large dust accumulates due to collisional-induced sticking of the fine dust particles through van der Waals interaction, at least within the inner accretion disk where ice condensation did not occur in a predominant manner (Birnstiel et al. 2016). The coagulation of dust grains resulted in the fractal growth of large accumulates with substantial porosity. The motion of the fine dust particles was initially coupled with the gas dynamics. The solar nebula gas dynamics, determined by radial gas inflow and gravitational fall towards the mid-plane of the disc along with turbulent currents, was mostly determining the motion of small dust grains in the early stages. Due to the growth in the size of dust particles, the motion got decoupled as the larger particles started following Keplerian motion around the protosun.
The Keplerian motion was initially hampered by the viscous drag of the nebula gas. The growing particles eventually settled down towards the mid-plane and spiraled inwards within the accretion disk. The collisions experienced by planetesimals, assisted by gravity, eventually resulted in the formation of the planets. Some of these earliest formed planetesimals survived as asteroids and trans-Neptunian objects (TNOs) by escaping accretion in any major planetary body, e.g., a planet or a satellite. These survived planetesimals provide significant information regarding the physico-chemical processes operating in the solar nebula and the earliest accreted small planetary bodies.

The planetesimals and the parent bodies of asteroids experienced a wide range of planetary processes in the early solar system (e.g., Dodd 1981; Huss et al. 2006; Rudraswami et al. 2008). Depending upon their initial composition, especially, the ice to dust ratio, and the accretion timescales, the planetary processes range from thermal metamorphism, aqueous alteration to partial and extensive melting and planetary scale differentiation. While the impact-induced heating became a prominent heat source for the thermal processing of large planetary bodies, like the terrestrial planets, Moon, etc., the thermal processing of the majority of the planetesimals and asteroid parent bodies was brought about by the radiogenic decay energy of $^{26}\text{Al}$ that is known to be present in the early solar system at a canonical initial level of $5 \times 10^{-5}$ for $^{26}\text{Al}/^{27}\text{Al}$, as deciphered from the early condensed first solar system objects, Ca–Al-rich inclusion (CAIs) (MacPherson et al. 1995).

In order to understand the nature of the early thermal processing of the planetesimals, several thermal models based for the radiogenic heating have been proposed (Miyamoto et al. 1981; Bennett and McSween 1996; Sahijpal 1997; Ghosh and McSween 1998; Merk et al. 2002; Hevey and Sanders 2006; Gupta and Sahijpal 2010; Harrison and Grimm 2010; Henke et al. 2012a, b, 2016; Šránek et al. 2012; Monnereau et al. 2013; Golabek et al. 2014; Neumann et al. 2014, 2018; Gail et al. 2015; Bhatia and Sahijpal 2017a, b; Sahijpal and Goyal 2018). All these models deal with the thermal evolution of spherical planetary bodies that are assumed to have acquired quasi-hydrostatic equilibrium. However, some of the planetesimals and parent bodies of asteroids have not achieved equilibrium due to their small sizes and low gravity. Sahijpal (2021) recently developed 3-D (three-dimensional) thermal models for the irregular-shaped objects by assuming ellipsoidal-shaped small objects of any arbitrary shape. The spacecraft deduced 3-D shape and size models of small asteroids, TNOs and small satellites can be directly fed in our numerical code to deduce their thermal evolution.

We have used the dataset, ‘EAR-A-5-DDR-STOOKE-SHAPE-MODELS-V2.0’ of the NASA Planetary Data System (PDS3) (Seidelmann et al. 2002; Archinal et al. 2011). This dataset contains Philip Stooke small body 3-D shape models that are based on the optical photographs obtained from the NEAR, Galileo, Giotto, Vega 1, Vega 2 and Voyager missions. On the basis of the International Astronomical Union (IAU) recommendations for the Cartographic coordinates, the recommended 3-D shape models for the asteroid’s surface is divided into longitudinal ($0^\circ$–$360^\circ$) and latitudinal ($-90^\circ$ to $90^\circ$) angular grid, with an angular gap of $5^\circ$ each, at specified radial distances of the surface from the body center.

The data in the case of the asteroids (243) Ida and (951) Gaspra are based on the Galileo spacecraft fly-by mission (D’Amario et al. 1992; Chapman 1996). The Galileo mission made the first-ever close observation of an asteroid, (951) Gaspra on 29th October, 1991, at a closest approach of $\sim 1600$ km (Belton et al. 1992). On 28th August, 1993, the spacecraft performed a fly-by at a distance of $\sim 2400$ km from the asteroid (243) Ida. It discovered its moon Dactyl. Ida has been classified as an S-type asteroid on the basis of its reflectance spectra (Sullivan et al. 1996; Wilson et al. 1999). It could have a density of $3.48–3.64$ g cm$^{-3}$ with a porosity of 11–42%. It has been suggested that Ida could be a fragment of a large partially differentiated asteroid, with a size of 120 km diameter (Greenberg et al. 1996).

We performed numerical simulations of the thermal evolution by considering two distinct S-type asteroids with shape and size comparable to (243) Ida and (951) Gaspra as a case study, without actually probing into the real origin of the two asteroids in their parent bodies. We are more focused towards the development of the numerical technique that can be used for a wide-range ensemble of small planetary bodies of different shapes and sizes. Our major goal is to understand the consequence of complete or partial consolidation of an initially accreted porous planetesimal on the long-term thermal evolution of the body. The details of the numerical technique are mentioned in...
section 2 (methodology) along with the description of the various simulation parameters. The results obtained from the two sets of thermal models, viz., the sets with and without thermal sintering (consolidation) of the initially accreted porous planetesimals are discussed in section 3. The major conclusions drawn from the work are finally summarized in section 4.

2. Methodology

The thermal models of the radiogenic heating of planetesimals and asteroids are based on the 3-D heat conduction partial differential equation (1) that involves a radioactive decay heat source, $^{26}$Al, with a decay energy of 3.16 MeV (see, Sahijpal et al. 2007). The radiogenic heating due to the long-lived radionuclides, $^{40}$K, $^{235}$U, $^{238}$U, and $^{232}$Th, along with impact-induced energy released during the accretion of planetary bodies influence the thermal evolution of large bodies (>1000 km) over a timescale of one billion years (Bhatia and Sahijpal 2017b). These scenarios are not relevant here as we are addressing the thermal evolution of small bodies. There is a possibility of induction heating of the planetesimals and asteroids as these bodies move around the protosun through the ionized and magnetic solar wind (Menzel and Roberge 2013). However, corresponding to the heliocentric distances and the thermal evolution timescale associated with asteroid, the proposed induction heating can become comparable with $^{26}$Al radiogenic heating only with extremely high value of electrical conductivity of asteroids and high solar wind velocities. The high electrical conductivity is not possible for chondrites. The majority of the scenarios with moderate values of the parameters yield substantially low induction heating (Menzel and Roberge 2013) that can be ignored compared to radiogenic heating. Hence, we confine our present work to the short-lived nuclide radiogenic heating. The temperature $T \equiv T(x, y, z, t)$ in equation (1) is estimated on the basis of the radioactive heat generation and conduction within planetesimal and asteroid. $Q (\sim 2.2 \times 10^{-7}$ W kg$^{-1}$) is the initial heat production rate of the radioactive, $^{26}$Al, defined at the onset time of the formation of the Ca–Al-rich inclusions with a canonical value of $5 \times 10^{-5}$ for $^{26}$Al/$^{27}$Al. Here, we have assumed an H-chondrite value of 1.22% for the stable $^{27}$Al isotope (Saslawsk 1933; Dodd 1981; Yomogida and Matsui 1983; Lodders 2020). The role of the radiogenic $^{60}$Fe as a potent heat source has been a debatable issue. An initial $^{60}$Fe/$^{56}$Fe value of $\sim 10^{-6}$, earlier estimated by Mostefaoui et al. (2005) suggested an initial heat production rate of $\sim 2.2 \times 10^{-7}$ W kg$^{-1}$ for an undifferentiated planetary body (Sahijpal et al. 2007). The initial $^{60}$Fe/$^{56}$Fe has been subsequently revised to a much lower value of $\sim 10^{-8}$ (e.g., Tang and Dauphas 2014), thus reducing the effective role of the radionuclide in planetary heating. Since, the majority of the debate regarding the initial abundance of $^{60}$Fe is skewed in favour of the lower abundance, the majority of the recent works dealing with thermal modelling ignore the thermal contribution due to $^{60}$Fe. $\kappa$ and $c$, in equation (1), are the temperature-dependent thermal diffusivity and specific heat, respectively. Equation (1) is sufficient enough to handle thermal metamorphism. The consolidation (sintering) of asteroids with an initial high porosity is incorporated appropriately by altering the spatial dimensions along with the variations in the thermal diffusivity.

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T + \frac{Q}{c} e^{-\lambda t}.$$ (1)

The basic theoretical and numerical formulation adopted for solving the partial differential equation by using finite difference method is based on the recent numerical approach (Sahijpal 2021). We solve the 3-D partial differential equation by converting it into finite difference equation (FDM) in 3-D (Lapidus and Pinder 1982). We choose spatial ($\Delta x$, $\Delta y$, $\Delta z$) and temporal ($\Delta t$) grid elements in the FDM. In order to mathematically realize the exact shape and size of the asteroids on the basis of the space-craft deduced shape models, we develop a logic shape generator function that defines the physical dimension of the asteroids in the Cartesian coordinate system. This function defines the physical existence of the asteroid in a binary manner, with the unity and zero values implying the existence and non-existence, respectively.

2.1 Logic shape generator function

The heat conduction partial differential equation (1) is solved in Cartesian coordinates. We generate a hypothetical cuboid of adequate dimensions $[2a \times 2b \times 2c]$ so that it can accommodate the size of the initially unconsolidated, instantaneously accreted asteroid in all three dimensions. The
cuboid as well as the unconsolidated asteroid are assumed to be centered at the coordinates \((a, b, c)\), with the origin of the Cartesian coordinate system at \((x, y, z) = (0, 0, 0)\), that represents one of the vertices of the cuboid. The initially accreted unconsolidated asteroid is assumed to be 1.2 times larger than the consolidated asteroid for which we have taken the shape model deduced by the fly-by mission. The distances in our present work are measured with respect to the origin of the coordinate system. All the spatial grid Cartesian coordinates within the cuboid are initially converted into spherical polar coordinates \((r, \theta, \varphi)\) with respect to the center \((a, b, c)\) of the cuboid. Here, \(\theta\) ranges over \(0^\circ–360^\circ\), and \(\varphi\) varies over \(0^\circ–180^\circ\), and defines the azimuthal and polar angles, respectively. This facilitates a direct comparison between the Spatial Grid array, \(\text{SG}\{r, \theta, \varphi\}\), within the hypothetical cuboid in which the asteroid 3-D shape has to be mathematically embedded, with the actual shape models deciphered from the spacecraft. As mentioned earlier, the 3-D shape models for the two asteroids are presented in spherical polar coordinates by dividing the asteroid’s surface into longitudinal \((0^\circ–360^\circ)\) and latitudinal \(\left(–90^\circ\text{ to } 90^\circ\right)\) angular grids, at an equal interval of 5° each, with specified radial distances of the surface from the body center (Seidelmann et al. 2002; Archinal et al. 2011). The data is in ASCII format, with three columns containing surface grid longitude, latitude and radial distance of the surface from the body center. In order to implement these shape-size models into our numerical code, we initially transform the latitudinal \(\left(–90^\circ\text{ to } 90^\circ\right)\) angular coordinates to \((180^\circ–0^\circ)\) coordinate system, and create an Asteroid-Surface Grid array, \(\text{ASG}\{r_s, \theta, \varphi\}\). Here, ‘\(r_s\)’ represents the distance of the unconsolidated asteroid’s surface from the center \((a, b, c)\) at particular azimuthal and polar angles.

The shape model of the asteroid is mathematically embedded into the hypothetical spatial grid cuboid \([2a \times 2b \times 2c]\) by making a comparison of the radial distance, ‘\(r\)’ at every spatial grid from the center \((a, b, c)\) within the cuboid as defined by \(\text{SG}\{r, \theta, \varphi\}\) with ‘\(r_s\)’ as determined by \(\text{ASG}\{r_s, \theta, \varphi\}\).

We use linear interpolation over the nearest neighboring \(\varphi\) angular grids for a specific value of \(\theta\), wherever the \(r_s\) value is not available. A logic shape generator function is constructed in the Cartesian coordinate system to define the 3-D physical shape and size of the asteroid by equation (2). Here, the value of unity for \(G(x, y, z)\) represents the physical existence of asteroid. A value of zero represents asteroid’s exterior region. It could also be mathematically possible to model the initial voids or porosities within the unconsolidated asteroid by zeros. Subsequent to consolidation, as these voids are removed, the logic shape generator function can take unity values in these places. We have not attempted such a possible procedure here due to its complexity.

\[
G(x, y, z) = \begin{cases} 
1, & \forall r \leq r_s, \quad r \in \text{SG}\{r, \theta, \varphi\}, \quad r_s \in \text{ASG}\{r_s, \theta, \varphi\} \\
0, & \forall r > r_s.
\end{cases}
\]

2.2 3D-FDM

The heat conduction partial difference equation (1) is solved using finite difference method. Two distinct numerical approaches for the 3-D finite difference method have been recently developed for non-spherical bodies (Sahijpal 2021). There is one explicit 3D-FDM method based on the direct conversion of the PDE into central difference equations involving the three spatial dimensions. The second approach involves semi-implicit Crank–Nicholson technique by using fractional-step method (FSM). Even though, the second approach is more efficient in terms of saving computational time, we have adopted the explicit 3D-FDM approach in the present work due to its numerical simplicity. We can numerically perform three orders of magnitude variations in thermal diffusivity during the consolidation (sintering) of the small bodies using the explicit approach in a much simpler manner. Equation (1) can be converted into a series of finite difference (equation 3) across the entire physical extent of the asteroid by using an explicit central difference approximation. Here, the \(n+1\)th and \(n\)th thermal states are defined at two consecutive time-steps that are separated by a time \(\Delta t\). The three consecutive spatial grids, \(i–1, i, i + 1\), are separated by a spatial gap of \(\Delta x\) along the \(x\)-axis. Identically, the three consecutive spatial
grids, \(j - 1, j, j + 1\), are separated by a spatial gap of \(\Delta y\) along the \(y\)-axis, and the three consecutive spatial grids, \(k - 1, k, k + 1\), are separated by a spatial gap of \(\Delta z\) along the \(z\)-axis.

\[
\frac{T_{i,j,k}^{n+1} - T_{i,j,k}^n}{\Delta t} \simeq \kappa \left[ \frac{T_{i-1,j,k}^n - 2T_{i,j,k}^n + T_{i+1,j,k}^n}{\Delta x^2} + \frac{T_{i,j-1,k}^n - 2T_{i,j,k}^n + T_{i,j+1,k}^n}{\Delta y^2} \right]
+ \frac{Q}{c} e^{-\lambda t},
\]

(3)

\[
\frac{\kappa \Delta t}{\Delta x^2} = R_x; \quad \frac{\kappa \Delta t}{\Delta y^2} = R_y; \quad \frac{\kappa \Delta t}{\Delta z^2} = R_z.
\]

(4)

The dimensionless normalized thermal diffusivities are defined for the three dimensions by equation (4). With an assumption of \(\Delta x = \Delta y = \Delta z\), in all the performed simulations, the dimensionless normalized thermal diffusivity becomes identical in all directions. \(R_x = R_y = R_z = R\).

\[
T_{i,j,k}^{n+1} \simeq R \left( T_{i-1,j,k}^n + T_{i,j-1,k}^n + T_{i,j+1,k}^n \right)
+ (1 - 6R) T_{i,j,k}^n
+ R \left( T_{i+1,j,k}^n + T_{i,j+1,k}^n + T_{i,j,k+1}^n \right)
+ \frac{Q}{c} \Delta t e^{-\lambda t}.
\]

(5)

Thus, the temperature at any \(n + 1\)th time-step can be deduced on the basis of temperature at the \(n\)th time-step for any spatial grid point using equation (5).

2.3 Numerical implementation of sintering

Due to the fractal nature of the growth of large dust aggregates from fine dust in the solar nebula, the growth of the planetesimals resulted in substantial amount of porosity in the small planetary bodies. The random collisions experienced by the large rocky bodies during the accretion of planetesimals resulted in porosity as high as 50% (Hevey and Sanders 2006; Sahijpal et al. 2007; Henke et al. 2012a, b, 2016; Šránek et al. 2012; Gail et al. 2015). These un-sintered (unconsolidated) planetary bodies have extremely low thermal diffusivity due to the presence of large number of voids that can transfer heat only by radiative heat transfer. Majority of these bodies are thus able to retain the radioactive decay heat, thereby, resulting in rapid heating. However, subsequent to the sintering (consolidation) experienced at high temperature \(\sim 700\) K, the planetesimals experience compaction and loss of porosity. This result in an increase in thermal diffusivity, hence a rapid cooling of the bodies. Some of the earlier works have indicated that there is an almost three orders of magnitude increase in the thermal diffusivity on account of compaction (Hevey and Sanders 2006; Sahijpal et al. 2007; Henke et al. 2012a; Gail et al. 2015). In the case of small bodies, the compaction occurs due to heating around 650–700 K. However, on the basis of the observations of the vanishing pore space between the petrologic type 4 and type 5 H chondrites, the complete sintering might have occurred at higher temperature of \(\sim 970\) K (McSween et al. 1988; Slater-Reynolds and McSween 2005). The C-type asteroids experienced substantially lesser amount of post-accretion sintering compared to S-type asteroids probably on account of lesser extent of radiogenic heating and higher volatile content. Apart from the possibility of their formation as extremely small bodies, the carbonaceous chondrites might have evolved in the crustal regions of larger parent bodies that suffered extensive thermal processing in their interiors on account of radiogenic heating (e.g., Sahijpal and Gupta 2011). The crustal regions were probably excavated by collisions, and got separated from the main bodies. The C-type asteroids could have thus retained high porosity on account of less heating and comparatively low hydrostatic pressure even in a larger body.

We implemented the temperature dependence of thermal diffusivity for the unconsolidated as well as consolidated asteroid by following equation (6) for two distinct temperature regimes. A constant thermal diffusivity of the unconsolidated asteroid at temperature \(< 670\) K was assumed to be \(6.4 \times 10^{-6}\) m\(^2\) s\(^{-1}\). The unconsolidated body was assumed to have uniform density with uniform
distribution of voids. Using a three-parameter Sigmoidal function, the thermal diffusivity was varied from this low value to higher values for a consolidated body at temperature $\geq 700$ K (Yomogida and Matsui 1983) over the temperature range of 670–700 K. This approach is distinct compared to the numerical approach adopted by Henke et al. (2012a). In spite of the differences, the essential change in the thermal diffusivity on account of compaction brings a rapid change in the heat conduction rate of the asteroid around 700 K by three orders of magnitude. The Sigmoidal function helps in a gradual thermal transition across three orders of magnitude variation (Sahijpal et al. 2007). Subsequent to the consolidation of the asteroid, the temperature dependence of the thermal diffusivity was adopted from the work by Yomogida and Matsui (1983).

$$\kappa(T) = 6.4 \times 10^{-6} + \frac{0.06762}{1 + e^{-\left(\frac{T_{i,j,k,t} - 700}{10}\right)}}$$

\begin{align*}
&\forall \ T_{i,j,k,t} < 700 \text{ K} \\
&= A + \frac{B}{T_{i,j,k,t}} \quad \forall \ T_{i,j,k,t} \geq 700 \text{ K},
\end{align*}

where $A = 4.5 \times 10^{-7} \text{ m}^2 \text{s}^{-1}$ and $B = 1.32 \times 10^{-4} \text{ m}^2 \text{K}^{-1} \text{s}^{-1}$ (Yomogida and Matsui 1983).

The rise in the thermal diffusivity on account of consolidation is because of the compaction of the asteroid due to the loss in porosity ($\Phi$). We assumed a compaction of the unconsolidated body from the initial to the final state by a factor of 1.2 along the three Cartesian coordinates in an identical manner, irrespective of the distinct shape. This corresponds to a net porosity loss ($\Delta \Phi$) of $\sim 42\%$. For every 10 K rise in the temperature of a specific spatial grid in the asteroid from 670 to 700 K, the linear dimensions across the three Cartesian coordinates within a spatial grid were systematically reduced in three steps by a factor of $\sim 1.06$ each on account of porosity loss. This corresponds to a gradual volume loss of the porous space from an initially assumed value of $\sim 42\%$ to the finally assumed value of $\sim 0\%$, with the two intermediate porosity steps of $\sim 31\%$ and $\sim 18\%$. This accounts for a net porosity change ($\Delta \Phi$) of $\sim 11\%$, $\sim 13\%$ and $\sim 18\%$, respectively, in three sequential steps. We assume that the sintering occurs throughout the planetary body without any absence of regolith layer. The existence of regolith layer can substantially reduce the heat losses from the body as the thickness of the insulating regolith layer controls the overall heat losses from the surface.

The size reduction on account of compaction by a factor of 1.2 in the three orthogonal dimensions was performed by assuming that the rigidity of the entire body is not compromised. The shape of a basic spatial cube, defined by $\Delta x \times \Delta y \times \Delta z$, was retained along with its association with the neighbouring cubes to maintain the integrity of the orthogonal spatial grid array. In actual practice, we could not visualize any mathematical procedure that could achieve this compaction in a gradual manner. It is much more complex to perform gradual compaction in 3-D compared to the 1-D compaction as performed in the earlier works (e.g., Sahijpal et al. 2007). It is not simply possible to perform compaction of 3-D body without compromising the cubic structure of the unit spatial cell and the spatial grid array. However, since the compaction occurs in a very small temperature regime of 670–700 K, within a short duration of $\sim 0.01$ Myr, from an initially low thermal diffusivity to moderate thermal diffusivity, we can assume a rapid re-sizing of the orthogonal spatial grid from a pre-sintered to post-sintered state, at least in the scenarios with the onset time of planesimal accretion ($T_{\text{onset}}$) considered in the present work.

### 2.4 Numerical simulation parameters

The solutions (equation 5) of the finite difference equation are obtained by assuming a consolidated spatial grid interval, ‘$\Delta x$’ (=$\Delta y = \Delta z$) of 0.1 km and a temporal grid interval, ‘$\Delta t$’ of $5 \times 10^{-5}$–5 $\times 10^{-4}$ Myr in the simulations. The temperature dependence of the specific heat, ‘$c$’, in equation (1) was adopted from the earlier works (Yomogida and Matsui 1983; Sahijpal et al. 2007). It ranges from a value of 564–826 $\text{J kg}^{-1} \text{K}^{-1}$ over the relevant temperature range of 200–1200 K according to equation (7) in the present work. A uniform density of 3560 kg m$^{-3}$ is assumed for the post-sintered asteroid. This amounts to a pre-sintered density of 1495 kg m$^{-3}$ for the asteroid with an initial porosity of 42%. This value is in the range of the hydrated C-type asteroids.
A constant temperature of 200 K was assumed across the entire unsintered asteroid at the time of accretion. An identical constant surface temperature was also maintained throughout the entire thermal evolution of the asteroid. We have assumed an initial canonical $^{26}\text{Al}/^{27}\text{Al}$ value of $5 \times 10^{-5}$ at the time of condensation of the earliest formed Ca–Al-rich inclusions (MaPherson et al. 1995). The instant accretion of the planetesimal (asteroid) was assumed to occur at a time, $T_{\text{onset}}$, subsequent to the condensation of the Ca–Al-rich inclusions with the canonical value. The onset time of the planetesimal accretion is the most critical parameter that determines its thermal evolution (e.g., Sahijpal 2021). It should be noted that the formation and reprocessing of the CAIs in the nebula could have continued subsequent to the formation of the early CAIs with the canonical value of $^{26}\text{Al}/^{27}\text{Al}$. The $T_{\text{onset}}$ time marks the epoch for the condensation of CAIs with the canonical value. The CAIs and chondrules formed and reprocessed later would have lower than the canonical value of $^{26}\text{Al}/^{27}\text{Al}$ on account of $^{26}\text{Al}$ decay. In the present work, we have simulated two

\[
c(T_{i,j,k,t}) = 280 + 553 \times (1 - e^{-0.0036 \times T_{i,j,k,t}}).
\]  

Figure 1. Temperature (K) contours of (951) Gaspra alike asteroid with $T_{\text{onset}} = 1.5$ Myr. Temperature contours for the three planes, XY, XZ and YZ through the center of the body at four distinct times corresponding to the 3D models with $\Delta t = 5 \times 10^{-5}$ and $\Delta x = \Delta y = \Delta z = 0.1$ km. Sintering commences around 0.25 Myr.
scenarios corresponding to the $T_{\text{onset}}$ of 1.5 Myr and 3.5 Myr. In the first case, the asteroid experiences complete sintering, whereas, in the second scenario, the planetesimal remains as an unconsolidated body even after the thermal evolution. The cooling rates of the planetary bodies in these two scenarios are significantly different. The transition between the two scenarios occurs around $T_{\text{onset}} \sim 3$ Myr. It should be mentioned here that the initial 2–3 Myr epoch after the formation of the CAIs with the canonical value of $^{26}\text{Al} / ^{27}\text{Al}$ remains uncertain in terms of formation and reprocessing of CAIs and chondrules in the solar nebula, and their multiphase nebula assemblages. In order to avoid large-scale melting and differentiation of chondrites on account of $^{26}\text{Al}$ decay, the formation of chondrites could have definitely occurred after the initial 1.5–2 Myr (Sahijpal et al. 2007). Thus, the initial 2–3 Myr of the initial solar system was mostly associated with the nebula events related with the formation and reprocessing of CAIs and chondrules. There is also a possibility that the CAIs and chondrules were stored either in the crustal regions of large planetesimals (see, Sahijpal and Gupta 2011), or extremely small sub-km sized planetesimals that could not have heated up substantially to melt or severe thermal processing of these bodies against radioactive heating. The accretion of the collisional debris of these bodies could have led to the final assemblage of these chondrites. The entire inventories of CAIs and chondrules that have been preserved in the chondrites would thus represent only a fraction of the survived earliest formed CAIs and chondrules against the thermally harsh nebula and planetary processes.

3. Results and discussion

Based on the 3-D shape models inferred for the asteroids (243) Ida and (951) Gaspra by the Galileo fly-by mission, we have attempted to develop the early thermal evolution of irregular-shaped small asteroids having the shortest side physical dimensions of $\leq 20$ km. The major emphasis is to establish the numerical techniques to understand the thermal evolution of small irregular-shaped planetary bodies, e.g., asteroids, TNOs and small satellites, rather than focusing our objective specifically on the two asteroids. However, the model can be used for any shape and size, except that in the case of large satellites and planets, as mentioned earlier, the heating due to the long-lived nuclides, along with impact-induced heating during accretion, have to be considered over longer timescales (e.g., Bhatia and Sahijpal 2017b). These specific asteroids could have been a part of large planetary bodies that got fragmented subsequent to their
thermal evolution (Greenberg et al. 1996). Among the 12 small planetary bodies for which the NASA Planetary Data System (PDS3) has provided the detailed shapes, three bodies are asteroids, namely, (243) Ida, (951) Gaspra and (253) Mathilde. (253) Mathilde is a C-type asteroid. The shape of the asteroid can be approximated as an ellipsoidal for which the thermal model has been presented by Sahijpal (2021).

We deduced two distinct thermal evolutionary scenarios for the asteroid identical in shape and size with (951) Gaspra. These scenarios correspond to an accretion time, $T_{\text{onset}}$, of 1.5 Myr (figures 1–3) and 3.5 Myr (figures 4 and 5). As mentioned earlier, the CAIs and chondrules associated with chondrites were either preserved in the crustal regions of large planetesimals, or extremely small sub-km sized planetesimals prior to the assumed onset time of the accretion in their final planetary bodies. The isothermal contours corresponding to these two scenarios at four distinct time-steps are presented in figures 1 and 4 for the three orthogonal dimensions, whereas, the thermal profiles at specific time intervals are plotted in figures 2 and 5, respectively. The two scenarios exhibit distinct evolutionary trends. The consolidation of the body occurs in the scenario corresponding to $T_{\text{onset}}$ of 1.5 Myr as a result of which the asteroid cools down rapidly due to three orders of magnitude enhancement in the thermal diffusivity subsequent

Figure 3. Temperature (K) contours along the eight XY planes of a (951) Gaspra alike asteroid at 0.3 Myr subsequent to accretion at $T_{\text{onset}} = 1.5$ Myr. These eight planes are orthogonal to Z-axis at a distance of $-4, -3, -2, -1, 1, 2, 3$ and $4$ km with respect to the center of the Z-axis.
to the sintering. In the second scenario corresponding to the $T_{\text{onset}}$ of 3.5 Myr, due to the delayed accretion, the radiogenic heating due to $^{26}$Al is not substantial enough to heat the body to achieve complete consolidation. Hence, the thermal diffusivity of the body stays low. As a result, the body subsequently experiences slow cooling over a time-scale of tens of million years (figures 4 and 5).

The cooling rate becomes comparable to large planetary bodies (>100 km) (Sahijpal 2021). It is possible that even in the absence of ‘hot’ pressing around 700 K, there could be ‘cold’ pressing of porous unconsolidated asteroid (see, Henke et al. 2012a) on account of gravitational settling. It should be mentioned that the thermal processing of the planetesimals and asteroids formed with $T_{\text{onset}}$ >3 Myr would be almost identical irrespective of their size (>20 km) as the potent heat source, $^{26}$Al would have decayed substantially during this time. The radiogenic heating due to the long-lived nuclides, $^{40}$K, $^{235}$U, $^{238}$U, and $^{232}$Th along with impact-induced energy released during accretion does influence the thermal evolution of large bodies (>1000 km) over a timescale of one billion years (Bhatia and Sahijpal 2017b).

The thermal sintering in (951) Gaspra alike asteroid corresponding to $T_{\text{onset}}$ of 1.5 Myr (figures 1–3) occurs around 0.24–0.25 Myr

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Figure 4. Temperature (K) contours of (951) Gaspra alike asteroid with $T_{\text{onset}} = 3.5$ Myr. Temperature contours for the three planes, XY, XZ and YZ through the center of the body at four distinct time corresponding to the 3D models with $\Delta t = 5 \times 10^{-4}$ and $\Delta x = \Delta y = \Delta z = 0.1$ km. Sintering does not occur in this scenario.
subsequent to its instantaneous accretion. Identical compaction of the body in all the three dimensions is marked in the thermal profiles (figure 2) with respect to the origin of the coordinate system. A reduction in the assumed $T_{\text{onset}}$ will result in the melting and possibly differentiation of the body (Sahijpal et al. 2007). The isothermal contours present the compaction in 3-D with respect to the body center (figure 1). These contours take the shape of the asteroid's planes. The size of the asteroid reduces considerably due to compaction.

We started the simulation with an initially large unconsolidated body so as to explain the present final size of the asteroid. The sharp spikes in the shape of the modelled asteroid surface along the XY planes (figure 1), prominent in the unconsolidated body isotherms, are due to the limitations in our linear interpolation over the nearest neighbouring $\varphi$ angular grids for a specific value of $\theta$, while defining the shape of the model for simulation (equation 2). Subsequent to the sintering, the body achieved a maximum temperature of $\sim 770$ K around 0.3 Myr after the onset of accretion. The isothermal contours along eight distinct XY planes that are orthogonal to Z-axis are graphically presented in figure 3 corresponding to this time interval. In the assumed absence of regolith with low thermal diffusivity, the temperature of the post-sintered body drops rapidly to $<300$ K within 2 Myr (figures 1 and 2). The rapid cooling occurs along the shorter Y- and Z-axis.

The pre-sintered thermal evolution of the (253) Ida alike asteroid with $T_{\text{onset}}$ of 1.5 Myr (figures 6 and 7) is almost identical to that of (951) Gaspra alike asteroid with an identical accretion timescale. The size of the asteroid does not matter in determining the thermal evolution as long as the thermal diffusivity is extremely small during the unsintered stage. The complete consolidation of the (253) Ida alike asteroid occurs around 0.25 Myr after accretion (figure 7). Subsequently, the asteroid acquired high temperature comparable to even the melting point of metallic iron. It cooled down slowly over $\sim 5$ Myr compared to the (951) Gaspra model (figure 2). The shortest Z-axis provides the fastest cooling path.

On the basis of the two distinct thermal evolutionary pathways deduced for the small planetary bodies, we could broadly divide the time regime for the accretion of small planetesimals in the early solar system if we assume a uniform distribution of $^{26}$Al in the accreting region of the chondrites. We are making this assumption at least in the chondrite forming region of the solar nebula. The canonical value of $^{26}$Al/$^{27}$Al measured in the vast majority of CAIs (MacPherson et al. 1995) substantiates this assumption. The two-time regimes can be broadly demarcated by 2–3 Myr in the early solar system depending upon the initial composition of the body. The small planetary bodies accreted during the initial 2–3 Myr experienced thermal sintering, and hence subsequently cooled rapidly. These bodies could have formed either by the direct accretion of solar nebula dust (Weidenschilling 2019) or by aggregation of
fragmented debris of the initially formed planetesimals. The planetesimals (asteroids) formed after the initial 2–3 Myr were mostly the result of accretion of the fragmented debris of the initially existing planetesimals. The accretion of these bodies through direct solar nebula dust seems to be less likely due to their delayed formation. These bodies experienced very slow cooling over tens of million years and could have survived as rubble piles.

In case $^{26}$Al was not uniformly distributed in the chondrite forming region of the nebula, the various chondrites could have accreted with distinct abundances of the potent heat source, $^{26}$Al. In this scenario, it could be possible to hypothesize that all the chondrites formed almost initially in the nebula with distinct values of initial $^{26}$Al/$^{27}$Al. Thus, the various models developed here across the distinct temporal ($T_{\text{onset}}$) scale of chondrite accretion could instead be hypothesized as chondrites forming simultaneously with spatial nebula heterogeneity in $^{26}$Al/$^{27}$Al. This would result in the total loss of the temporal context of the nebula processes associated with the formation of CAIs, chondrules and chondrites. However, the temporal context of the thermal evolution of planetesimals and asteroids subsequent to their accretion will not be affected. However, as mentioned earlier, the canonical value of $^{26}$Al/$^{27}$Al measured in majority of CAIs does not support the heterogeneity of $^{26}$Al at least in the chondrite forming region of the nebula.

In general, the formation of the small irregular-shaped planetesimals (with the shortest side physical dimension $\leq$20 km), through the accretion of solar nebula dust, initiated during the early phases of the solar system. These initially formed bodies experienced thermal sintering and rapid cooling. Some of the earliest formed bodies ($\sim$20 km), with an accretion time-scale $<$1 Myr, could have experienced widespread melting and planetary-scale differentiation. The frequent collisions experienced by the planetesimals could have produced fragmentation debris. This debris from several parent bodies accreted further to form the successive generations of small planetesimals. The thermal-induced sintering could have occurred in these successive generations of small bodies during the initial 2–3 Myr. However,
the small planetesimals, if any, formed in the subsequent generations were left unsintered as rubble pile assemblages.

4. Conclusions

We present a numerical technique for understanding the thermal evolution of small irregular-shaped planetesimals, with the shortest side physical dimension \( \leq 20 \text{ km} \). The 3-D shape models deduced for (243) Ida and (951) Gaspra from the Galileo fly-by missions were mathematically modelled to understand the thermal evolution of planetesimals and asteroid with identical dimensions. We could achieve the state transition of the initially unconsolidated planetary body to a final sintered body by numerically modelling the thermal sintering in a parametric form. Two distinct thermal evolutionary pathways were deduced for the sample asteroids. The scenario with an early accretion of planetesimal within the initial 2–3 Myr results in complete thermal sintering of the small bodies, whereas, the bodies formed afterwards were left un-sintered. In general, during the repeated cycles of the formation and collision-induced fragmentation of several generations of small planetesimals, the solar system evolved from an initial ensemble of compact small objects to an ensemble of rubble piles.

Acknowledgement

We are extremely grateful to the two reviewers for their comments and suggestions that led to significant improvement of the manuscript.

Author statement

S Sahijpal developed the numerical technique for mathematically modelling the thermal evolution of the small irregular shape asteroids and planetesimals. He wrote the manuscript.

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