Early Thermal Evolution of Planetesimals and its Impact on Processing and Dating of Meteoritic Material

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Meteorites: Fragments of small bodies in the solar system, the asteroids between Mars and Jupiter

- Inferred number of parent bodies is $\sim 100$
- Accretion to full-sized planet inhibited by early Jupiter
Carbonaceous chondrites
(mild thermal/aqueous metamorphism)

- Ca, Al-rich inclusions
- Chondrules
- Fine grained matrix (volatile rich)

- undifferentiated, e.g. preaccretional structures preserved
- undifferentiated, e.g. ‘cosmic’ Fe, Ni abundance

$\sim 1400-1600 \text{ K}$

$\sim 1800-2000 \text{ K}$

$< 900 \text{ K}$

Meteorite collection
Dieter Heinlein, Augsburg, Germany
Ca,Al-rich inclusions

4564.7± 0.6 Ma
(CR Acfer059; Amelin et al., 2002)

Chondrules

4567.2± 0.6 Ma
(U-Pb-Pb, CV Efremovka; Amelin et al., 2002)

Meteorite collection
Dieter Heinlein, Augsburg, Germany
Metal abundance of chondrites: Origin from primitive, undifferentiated parent bodies

Variation of oxidation state and metal abundance: Origin from compositionally different parent asteroids

Ordinary chondrites:
- H: high Fe
- L: Low Fe
- LL: Low total, low metallic Fe

Enstatite chondrites

Carbonaceous chondrites: named after main member
- CI (Ivuna)
- CM (Mighei)
- CV (Vigarano)
- CO (Ornans)

Ca, Al-rich Inclusions: refractory mineral assemblages, oldest solar system objects → 4567.2 ± 0.6 Ma (Amelin et al., 2002) → contain excess $^{26}\text{Mg}$ from decay of short-lived $^{26}\text{Al}$

Short-lived nuclides in the early solar system and their half-lives:

- $^{26}\text{Al} \rightarrow ^{26}\text{Mg}$ (0.72 Ma)
- $^{129}\text{I} \rightarrow ^{129}\text{Xe}$ (16 Ma)
- $^{182}\text{Hf} \rightarrow ^{182}\text{W}$ (9 Ma)
- $^{53}\text{Mn} \rightarrow ^{53}\text{Cr}$ (3.7 Ma)
- $^{244}\text{Pu} \rightarrow$ fission (80 Ma)
- $^{10}\text{Be} \rightarrow ^{10}\text{B}$ (1.5 Ma)
- $^{41}\text{Ca} \rightarrow ^{41}\text{K}$ (0.1 Ma)
- $^{60}\text{Fe} \rightarrow ^{60}\text{Ni}$ (1.5 Ma)

... nucleosynthesis in mass-rich stars

... or nuclear reactions due to solar irradiation ($^{10}\text{Be}$)

... injected into protoplanetary disks (solar mass)

$\rightarrow$ Radiometric dating (if homogenously distributed)

$\rightarrow$ Planetesimal heating

Trapezium (Orion nebula)
Courtesy of NASA
Formation of planetesimals and planets

→ growth from (sub)micrometer sized dust to km-sized planetesimals by hit-and-stick collisions

1 μm

Courtesy of NASA

Meteorite collection
Dieter Heinlein, Augsburg

Courtesy of NASA
Early formed asteroids: high abundance of $^{26}$Al, strongest heating effects → Differentiated meteorites: from metallic cores and silicate mantles and crusts of differentiated asteroids

Fast accretion and differentiation
→ formation of metallic cores contemporaneously with CAIs ($^{182}$Hf-$^{182}$W; Kleine et al., 2004; Schersten et al. 2004)
→ formation and cooling of basaltic crust within few Ma (Eucrites, Angrites: Pb-Pb-dating; e.g. Lugmair and Galer, 1992; Baker et al., 2005)

Trieloff & Althaus (2003) Sterne und Weltraum special 2, 83
$^{26}\text{Al}$ as planetesimal heat source: Extent of heating as a function of $^{26}\text{Al}$ content and accretion time after CAIs.

Modeling the thermal evolution of small bodies

Start with highly porous planetesimal with subsequent sintering

Implementation of porosity dependent heat conductivity of micrometer sized silicate aggregates

Krause et al. (2011) Icarus 214, 286
Modeling the thermal evolution of small bodies

Start with highly porous planetesimal with subsequent sintering

Implementation of porosity dependent heat conductivity of micrometer sized silicate aggregates

Pressure and temperature stratification → equations of hydrostatic equilibrium and energy transport

Decrease of porosity of granular material by hot pressing due to self-gravity → set of equations for sintering of powder materials


²⁶Al and ⁶⁰Fe heat sources (+long lived radioactivities) are taken into account
Modeling the thermal evolution of small bodies

Model starts with highly porous planetesimal with subsequent sintering

Decrease of porosity of granular material by hot pressing due to self-gravity

→ set of equations for sintering of powder materials


Modeling the thermal evolution of small bodies

Model starts with highly porous planetesimal with subsequent sintering

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→ set of equations for sintering of powder materials

Modeling the thermal evolution of small bodies

Exploring the parameter space:
Influence of porosity on heating of very small bodies
(instantaneous accretion)

Neumann et al. (2012) A&A 543, A141
Modeling the thermal evolution of small bodies

Exploring the parameter space:
Influence of duration of accretion
(linear accretion to D=10km, 1.44 Ma after CAIs)

Neumann et al. (2012) A&A 543, A141
Modeling the thermal evolution of small bodies

Exploring the parameter space:
Influence of accretion rate
(accretion within 1 Ma to D=10km, 1.44 Ma after CAIs)

Neumann et al. (2012) A&A 543, A141
Effect of porosity and $^{60}\text{Fe}$ heating on central temperatures of bodies of different radius formed at different times (relative to CAIs)

Modeling the thermal evolution of small bodies


$^{60}\text{Fe}/^{56}\text{Fe} = 0$

$4 \times 10^{-7}$

$16 \times 10^{-7}$

0% porosity

50% porosity
Modeling the thermal evolution of small bodies

Effect of porosity and $^{60}$Fe heating on central temperatures of bodies of different radius formed at different times (relative to CAIs)
Ordinary chondrites (H, L, LL): significant thermal metamorphism by $^{26}\text{Al}$ decay heat.
Cooling curves in a chondritic asteroid heated by $^{26}$Al decay, $r=100$ km, $^{26}$Al/$^{27}$Al=$4 \times 10^{-6}$, i.e. 2.5 Ma after Allende CAIs (analytical model after Miyamoto et al., 1981)

Closure temperature of U-Pb/Pb in phosphates: 720K
Closure temperature of K-Ar / $^{40}$Ar-$^{39}$Ar in oligoclase: 550K
= Retention temperature of $^{244}$Pu fission tracks in orthopyroxene

Retention temperature of $^{244}$Pu fission tracks in merrillite: 390K
Structure and thermal history of the H-chondrite parent asteroid revealed by thermochronometry

Göpel et al., 1994

H6 Guarena
H6 Kernouve
H6 Estacado
H5 Richardton
H5 Nadiabondi
H5 Allegan
H4 Ste. Marguerite
H4 Forest Vale

U-Pb/Pb

40Ar-39Ar / 244Pu (Opx)

244Pu (Mrl)
Thermal model of the H chondrite parent body constrained by radioisotopic ages (Henke et al. 2012a,b, 2013)

New data since 2003

Henke et al. (2013) Icarus 226, 212

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Type</th>
<th>$^{182}$Hf/$^{180}$Hf (metal-silicate)</th>
<th>$^{206}$Pb/$^{204}$Pb (pyroxene olivine)</th>
<th>$^{26}$Al/$^{27}$Al (feldspar)</th>
<th>$^{238}$U/$^{206}$Pb (phosphates)</th>
<th>$^{39}$Ar/$^{39}$Ar (feldspar)</th>
<th>Pu-fission tracks$^f$ (merrillite)</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estacado</td>
<td>H6</td>
<td>$4557.3 \pm 1.6$</td>
<td>$4561 \pm 7$</td>
<td>$4501.6 \pm 2.2$</td>
<td>$4465 \pm 5$</td>
<td>$4401 \pm 10$</td>
<td>$4402 \pm 14$</td>
<td>Ma</td>
</tr>
<tr>
<td>Guarela</td>
<td>H6</td>
<td>$4557.9 \pm 1.0$</td>
<td>$4530 \pm 1.1$</td>
<td>$4522 \pm 2.0$</td>
<td>$4469 \pm 6$</td>
<td>$4428 \pm 10$</td>
<td>$4428 \pm 10$</td>
<td>Ma</td>
</tr>
<tr>
<td>Kernouveé</td>
<td>H6</td>
<td>$4554.8 \pm 6.3$</td>
<td>$4543 \pm 27$</td>
<td>$4516 \pm 5$</td>
<td>$4471 \pm 13$</td>
<td>$4471 \pm 13$</td>
<td>$4471 \pm 13$</td>
<td>Ma</td>
</tr>
<tr>
<td>Mt. Browne</td>
<td>H5</td>
<td>$4561.6 \pm 0.8$</td>
<td>$4562 \pm 1.7$</td>
<td>$4551 \pm 0.6$</td>
<td>$4525 \pm 11$</td>
<td>$4525 \pm 11$</td>
<td>$4525 \pm 11$</td>
<td>Ma</td>
</tr>
<tr>
<td>Richardson</td>
<td>H5</td>
<td>$4558.9 \pm 2.3$</td>
<td>$4555.6 \pm 3.4$</td>
<td>$4541 \pm 11$</td>
<td>$4490 \pm 14$</td>
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<td>Ma</td>
</tr>
<tr>
<td>Allegan</td>
<td>H4</td>
<td>$4552 \pm 0.2$</td>
<td>$4560 \pm 0.7$</td>
<td>$4553 \pm 10$</td>
<td>$4543 \pm 20$</td>
<td>$4543 \pm 20$</td>
<td>$4543 \pm 20$</td>
<td>Ma</td>
</tr>
<tr>
<td>Nadiabondi</td>
<td>H4</td>
<td>$4566 \pm 0.2$</td>
<td>$4567 \pm 0.6$</td>
<td>$4562 \pm 16$</td>
<td>$4562 \pm 16$</td>
<td>$4562 \pm 16$</td>
<td>$4562 \pm 16$</td>
<td>Ma</td>
</tr>
<tr>
<td>Forest Vale</td>
<td>H4</td>
<td>$4567 \pm 0.2$</td>
<td>$4569 \pm 0.7$</td>
<td>$4554 \pm 8$</td>
<td>$4551 \pm 11$</td>
<td>$4551 \pm 11$</td>
<td>$4551 \pm 11$</td>
<td>Ma</td>
</tr>
<tr>
<td>Ste. Marguerite</td>
<td>H4</td>
<td>$4566 \pm 0.2$</td>
<td>$4568 \pm 0.7$</td>
<td>$4552 \pm 14$</td>
<td>$4550 \pm 17$</td>
<td>$4550 \pm 17$</td>
<td>$4550 \pm 17$</td>
<td>Ma</td>
</tr>
</tbody>
</table>

Notes:

$^a$ Hf-W ages are from Kleine et al. (2008) and were re-calculted relative to the $^{182}$Hf/$^{180}$Hf of the angrite D’Orbigny, which has a Pb-Pb age of $t = 4563.4 \pm 0.3$ Ma (Kleine et al., 2012). Closure temperature calculated using lattice strain models.


$^c$ Data from Zinner and Gopel (2002). Activation energy and frequency factor by Lalouette and Wasserburg (1998): $E = 274$ kJ/mol, $D_0 = 1.2 \times 10^{-6}$. Closure temperature calculated according to Dodson (1973) at 1000 K/Ma cooling rate and 2 $\mu$m feldspar grain size.

$^d$ Closure temperature by Cherniak et al. (1991), phosphate U-Pb-Pb age data by Gopel et al. (1994), and Blinova et al. (2007) for Estacado and Mt. Browne.

$^e$ Ar-Ar ages by Trieloff et al. (2003) and Schwarz et al. (2006) for Mt. Browne, recalculated for miscalibration of K decay constant (Renne et al., 2011; Schwarz et al., 2011, 2012, see text). Closure temperature by Trieloff et al. (2003) and Pelias et al. (1997).

$^f$ Calculated age at 390 K from time interval between Pu-fission track retention in merrillite at 390 K and Pu-fission track retention by pyroxene at 550 K (corresponds to Ar-Ar feldspar age at 550 K). Data by Trieloff et al. (2003), closure temperature by Pelias et al. (1997).
Thermal model of the H chondrite parent body constrained by radioisotopic ages (Henke et al. 2012a,b, 2013)

Optimum model: fitting time temperature curves defined by radioisotopic cooling ages (least square fits)

→ Variation layering depth for a specific H chondrite

→ Variation of parameter set within reasonable values

Henke et al. (2013) Icarus 226, 212

<table>
<thead>
<tr>
<th>Parameter range for the meteoritic parent bodies.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
</tr>
<tr>
<td>Formation time, $t_{\text{form}}$</td>
</tr>
<tr>
<td>Radius, $R$</td>
</tr>
<tr>
<td>$^{60}\text{Fe}/^{56}\text{Fe}$ ratio</td>
</tr>
<tr>
<td>Surface temperature, $T_{\text{srf}}$</td>
</tr>
<tr>
<td>Surface porosity, $\phi_{\text{srf}}$</td>
</tr>
<tr>
<td>Bulk heat conductivity, $K_0$</td>
</tr>
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Thermal model of the H chondrite parent body constrained by radioisotopic ages (Henke et al. 2012a,b, 2013)

Best fit:

Formation time:
2.0 Ma after CAIs

$^{60}\text{Fe}/^{56}\text{Fe} = 1.4 \times 10^{-8}$

Tang & Dauphas 2012:
$^{60}\text{Fe}/^{56}\text{Fe} = (1.08 \pm 0.21) \times 10^{-8}$

→ Negligible heating effect by $^{60}\text{Fe}$

Surface porosity 20% (Porous layer <1km)

Fit quality given by $\chi^2$

Henke et al. (2013) Icarus 226, 212
Thermal model of the H chondrite parent body constrained by radioisotopic ages (Henke et al. 2012a,b, 2013)
Thermal model of the H chondrite parent body constrained by radioisotopic ages (Henke et al. 2012a,b, 2013)

→ Duration of accretion very likely less than 1 Ma

Henke et al. (2013) Icarus 226, 212
Modeling the thermal evolution of small bodies

Melting - differentiation - core formation

Implementation of partial melting of FeNi / FeS and silicates

Melt and heat transport via advection → Flow in porous media theory, Darcy flow equation, < 50%melt

Redistribution of radiogenic heat sources:
• lithophile $^{26}$Al partitions into mantle/crust
• siderophile $^{60}$Fe partitions into core

Trieloff & Althaus (2003) Sterne und Weltraum special 2, 83
Fig. 5. The evolution of the central temperature (left panel) and the radial temperature distribution at the instance of the maximum temperature (right panel) in a body that accreted instantaneously to \(D = 35\) km at \(t_0 = 1.6\) Ma. Consideration of both the heat transport by melt and the redistribution of radioactive elements (solid line), consideration of the heat transport by melt and neglect of the redistribution of radioactive elements (dashed line), consideration of the redistribution of radioactive elements and neglect of the heat transport by melt (dot-dashed line), neglect of both the heat transport by melt and the redistribution of radioactive elements (dotted line).
Modeling the thermal evolution of small bodies

In most models an undifferentiated layer (both sintered and unsintered) remains on top. Some chondrite and achondrite classes may originate from the same parent body.

Neumann et al. (2012) A&A 543, A141
Summary and conclusions (1)

Undifferentiated / chondritic bodies:

Improvements by implementation of porosity, cold and hot pressing / sintering in model calculations

Improved sets of experimental data and analyses are available:

→ Porosity dependent heat conductivity of micrometer sized silicate aggregates

→ Radioisotopic cooling ages (Hf-W, U-Pb-Pb, Ar-Ar, PU FT)

Best fit model for H chondrite parent body found by „evolution algorithm“:

→ $^{60}\text{Fe}/^{56}\text{Fe}$ was low ($1.4 \times 10^{-8}$), $^{60}\text{Fe}$ did hardly contribute to heating

→ Surface porosity 20% (Porous layer <1 km)

→ Formation time 2.0 Ma after CAIs

→ Accretion was fast (<1 Ma)

Still controversial:

→ Role of impact heating, for some bodies onion shell structure could have been disturbed by early large impacts

→ Distribution of $^{26}\text{Al}$
Summary and conclusions (2)

Differentiated bodies:

Improvements by implementation of partial melting of FeNi / FeS and silicates, melt and heat transport via porous flow, and redistribution of radiogenic heat sources

Differentiation strongly depends on formation time and accretion process

Metal and silicate segregation processes last between 0.4 Ma and 10 Ma

In most models an undifferentiated layer (both sintered and unsintered) remains on top

→ Some chondrite and achondrite classes may originate from the same parent body