Heating of planetesimals by SLRs ^{60}Fe & ^{26}Al and the effect on the water content of protoplanets

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Context

Radiogenic sources of heating in the form of short-lived radioisotopes (SLRs) have been theorised since the 1950s to play an important role in planet formation [1]. SLRs were subsequently found to be the dominant source of planetesimal heating in the early solar system [2]. Radiogenic heating also results in loss of H_2O in a nascent planetesimal through vaporisation and outgassing, which would significantly impact the liquid water content of the resultant protoplanet [3]. Whilst the SLR ^{60}Fe did not provide sufficient heating in the early solar system, increased enrichment due to supernovae in star forming regions may result in a greater impact in other systems.

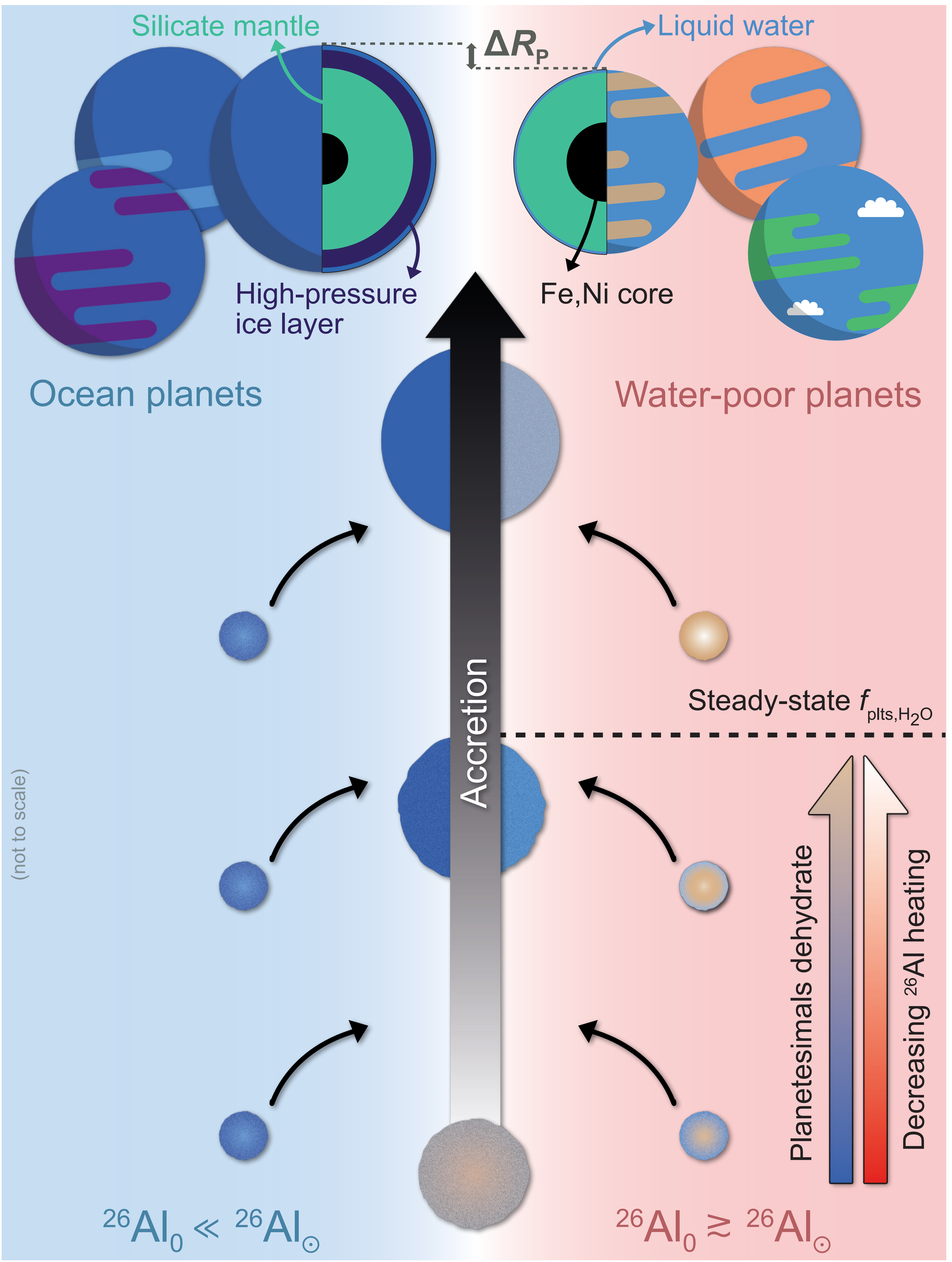

Figure 1. Planetary evolution due to desiccation [4].

Methodology

The I2ELVIS [5] hydrodynamical code was used to perform multiple simulations to determine the influence SLR enrichment has on retained water in large planetesimals. Simulations had a maximum run time of 20 Myr, and planetesimals were assumed to form 1 Myr after CAI formation. The H_2O content within the planetesimal is tracked over time, and based on whether a cells temperature has exceeded a threshold temperature of $T_{vap} = 1223\,K$. The final planetesimal H_2O abundance is then calculated from the fraction of cells that have exceeded T_{vap} ($\mathcal{H}_f = N_{wet}/N_{dry}$). Radiogenic heating is simulated through introduction of a heating rate, given by the equation:

$$Q_{SLR}(t) = f_{E,CI} Z_{SLR} \frac{N_A E_{SLR} \lambda}{m_{SLR}} e^{-\lambda t}, \quad (1)$$

where f is the elemental abundance by mass, Z is the isotopic enrichment, N_A is Avogadro's constant, E is decay energy, λ is the decay constant, m is the atomic mass, and t is the elapsed time [6]. Enrichment is normalised to early solar system levels:

$$\Lambda_{SLR} = \frac{Z_{SLR,\star}}{Z_{SLR,\odot}}, \quad (2)$$

where $Z_{SLR,\star}$ is the isotopic enrichment of the system and $Z_{SLR,\odot}$ is the early solar system enrichment.

Results – Iron Core Model

For the first model, a core of iron is surrounded by a mantle of hydrous silicates. The radius of this core relative to the planetesimal is described with variable $\Psi = r_c/r_{pl}$. Whilst this is a simple model to implement and simulate, this implies that core stratification occurs extremely quickly ($\lesssim 1$ Myr from CAI formation) [7], however in the case of significant SLR enrichment this process could be accelerated. Due to this, this model as well as an undifferentiated model are simulated.

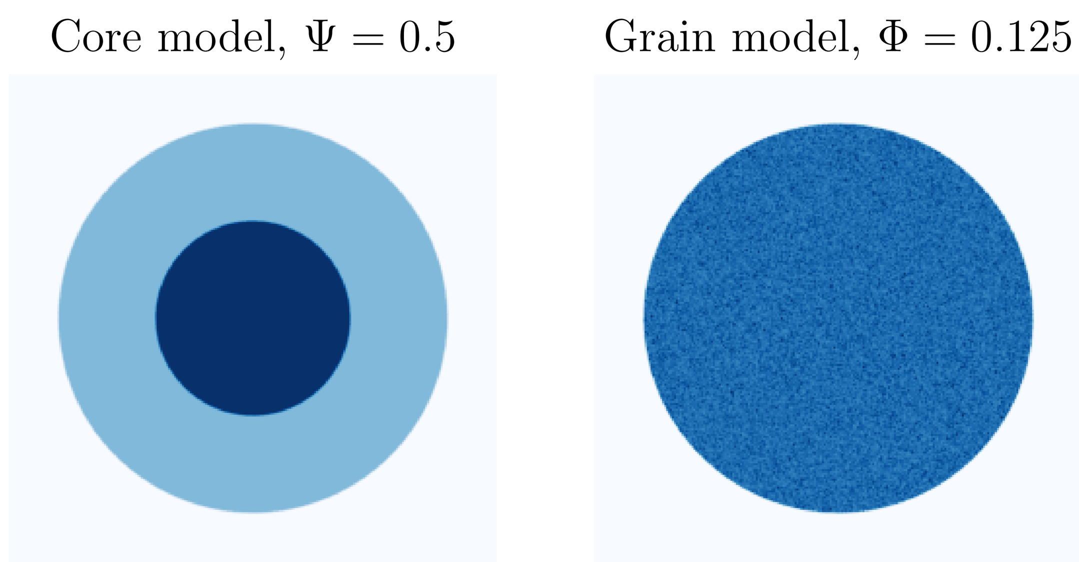

Figure 2. Comparison of core and grain composition models for similar iron volume fractions.

The parameter space exploration was of the isotopic enrichment of both ^{26}Al and ^{60}Fe for a planetesimal of radius 100 km. ^{26}Al enrichment was varied from $0 \le \Lambda_{26Al} \le 10$ and ^{60}Fe enrichment was varied over $0 \le \Lambda_{60Fe} \le 10^3$.

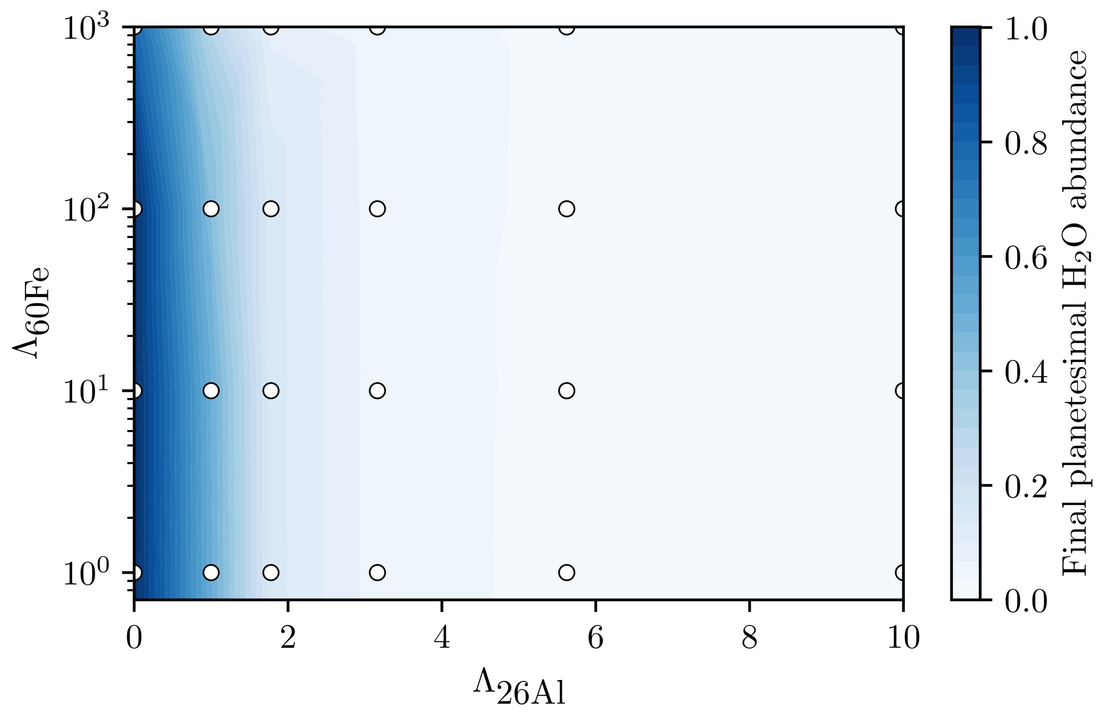

Figure 3. Remaining water fraction for simulations where $\Psi = 0.25$.

For simulations where $\Psi = 0.25$ it was found that desiccation barely occurs even at an ^{60}Fe enrichment of $\Lambda_{60Fe} = 10^3\times$, where a final water fraction of $\mathcal{H}_f = 0.796$ was found.

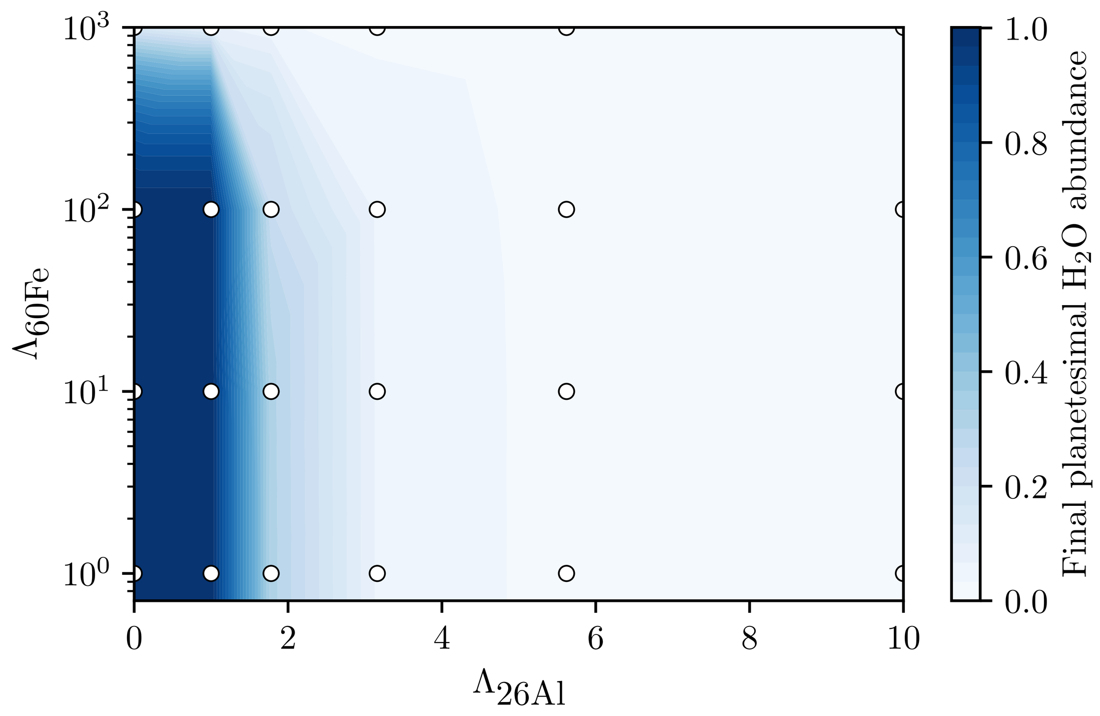

Figure 4. Remaining water fraction for simulations where $\Psi = 0.5$.

In simulations where $\Psi = 0.5$, ^{60}Fe enrichment is more influential on desiccation, but final water fraction in systems with high ^{60}Fe enrichment and ^{26}Al depletion are comparable to simulations where ^{26}Al is enriched only slightly above early solar system estimates.

Results – Iron Grain Model

The second model consists of a hydrous silicate body where iron marker "grains" are randomly interspersed. The amount of ^{60}Fe grains is varied using a fraction, Φ (N_{Fe}/N_T). The main parameters explored in this set of simulations were Φ, ^{60}Fe & ^{26}Al enrichment. Λ_{60Fe} was varied from 0 to 10^4, while Φ was varied between 0 and 0.9. Subsets were performed where $\Lambda_{26Al} = 0$, 1 & 10.

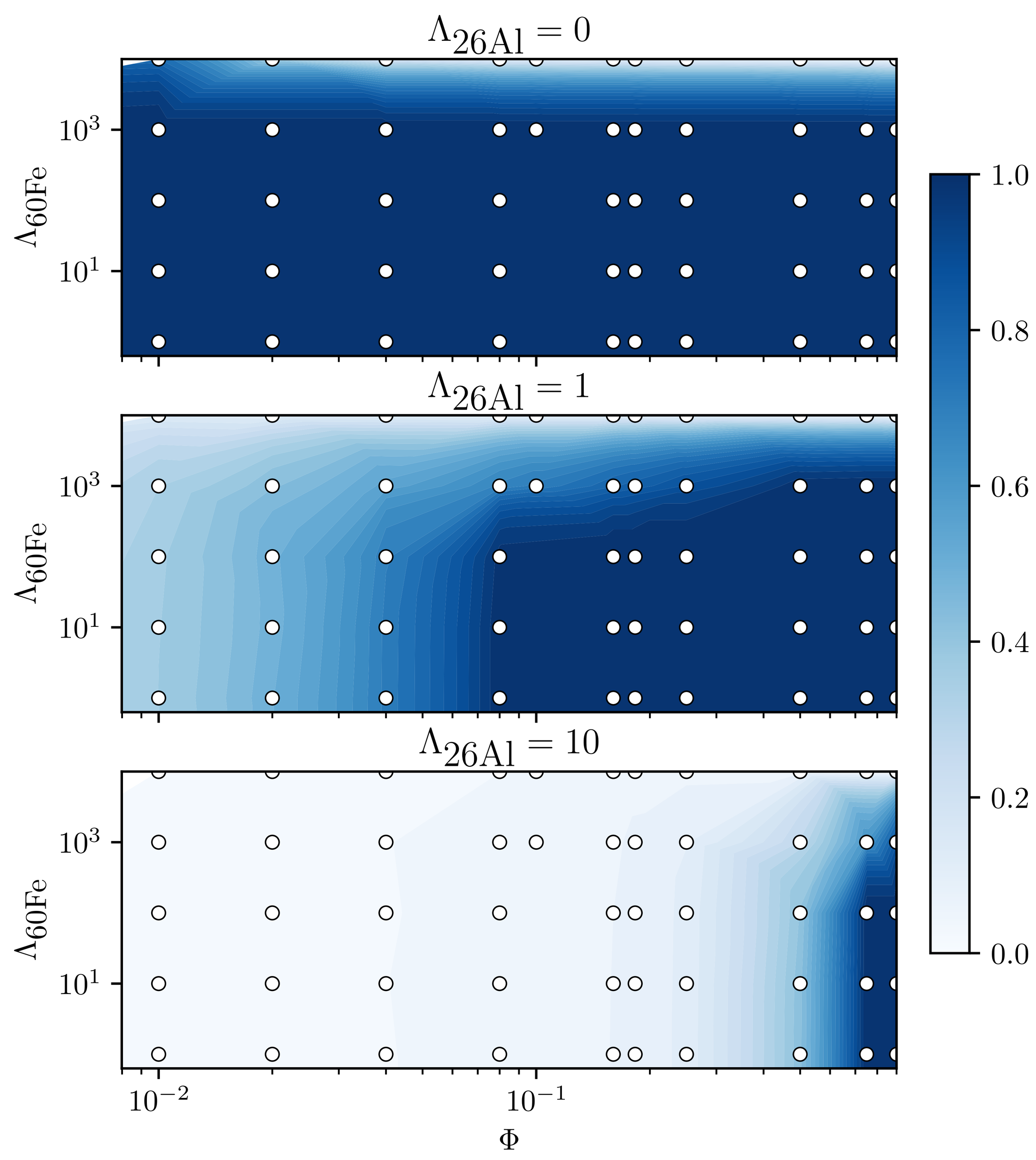

Figure 5. Remaining water fraction for simulations using the iron grain model.

Whilst a more accurate model overall, the grain model displays similar characteristics to the previous model. ^{60}Fe is still not influential except in cases of extremely high enrichment ($\Lambda_{60Fe} > 10^3$), high Φ and total ^{26}Al depletion. Even then, desiccation values are still far below what is observed with the core model. In cases of high ^{26}Al enrichment, large quantities of iron grains can actively *inhibit* desiccation, as there is less ^{26}Al to heat the planetesimal.

Discussion

From these simulations it can be determined that ^{60}Fe is a markedly less effective radiogenic heating source than ^{26}Al during the planetesimal formation stage. Whilst some desiccation can occur as a result of ^{60}Fe heating, it is significantly less drastic compared to even a slight enrichment of ^{26}Al over early solar system estimates. Additionally, for extreme ^{60}Fe enrichment the system may need to undergo extremely close or multiple supernovae encounters – which could inhibit the formation of the protoplanetary disk.

References

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