A Bayesian framework for exploring the early impact history of the asteroid belt with meteorite thermochronology

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Background

Planetary migrations in the early solar system would have caused dynamical instabilities that enhanced collisions in the nascent asteroid belt.

The mineral thermochronologic records of asteroidal meteorites may record energetic bombardment events.

Meteorite thermochronology [Mojzsis+ 2019, *ApJ*] and recent dynamical models [Ribeiro de Sousa+ 2020, *Icarus*] favor early orbital reorganizations within the first ca. 100 Ma of solar system history.

Yet, prior studies do not resolve a precise estimate of the date of the postulated migration event(s).

Approach

We aim to estimate the timescales of dynamical excitation and enhanced impactor flux in the early solar system (>4000 Ma) from the chondrite ^{40}Ar-^{39}Ar thermochronologic record with a Bayesian statistical approach.

We simulate asteroidal thermal histories and ^{40}Ar closure with an analytical conductive cooling code [after Hevey & Sanders 2006, *MaPS*] and a model that simulates reheating by impactor fluxes.

The thermochronologic code is coupled to a Markov chain Monte Carlo inversion that stochastically varies model parameters and calculates the likelihood that the distribution of chondrite ^{40}Ar-^{39}Ar ages [adapted from database of Mojzsis+ 2019] is drawn from the distribution of model-predicted ages.

Synthesis & Future Work

Asteroid thermal models with impact reheating histories better reproduce the ^{40}Ar-^{39}Ar age distribution of chondrites than unperturbed histories.

We report posterior estimates for the timing, intensity, and duration of two episodes of enhanced impactor flux in the first 200 Ma of the solar system.

Our results suggest that the primordial impactor flux was larger in magnitude and duration than a ca. 4510 Ma bombardment.

Future work will **1.** refine these preliminary estimates with a more comprehensive ^{40}Ar-^{39}Ar age database and **2.** explore the sensitivity of the system to model impactor sizes and the shape of the reheating zone.

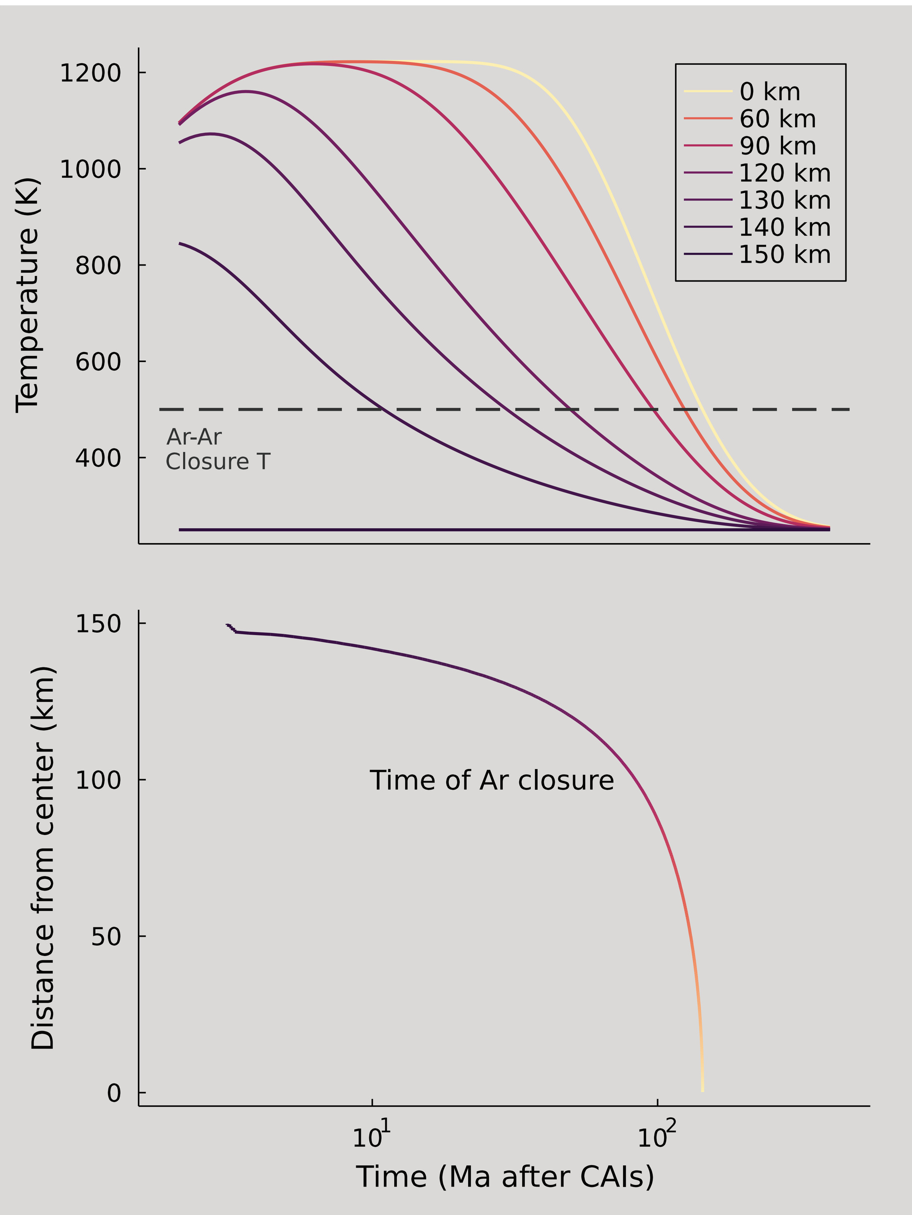
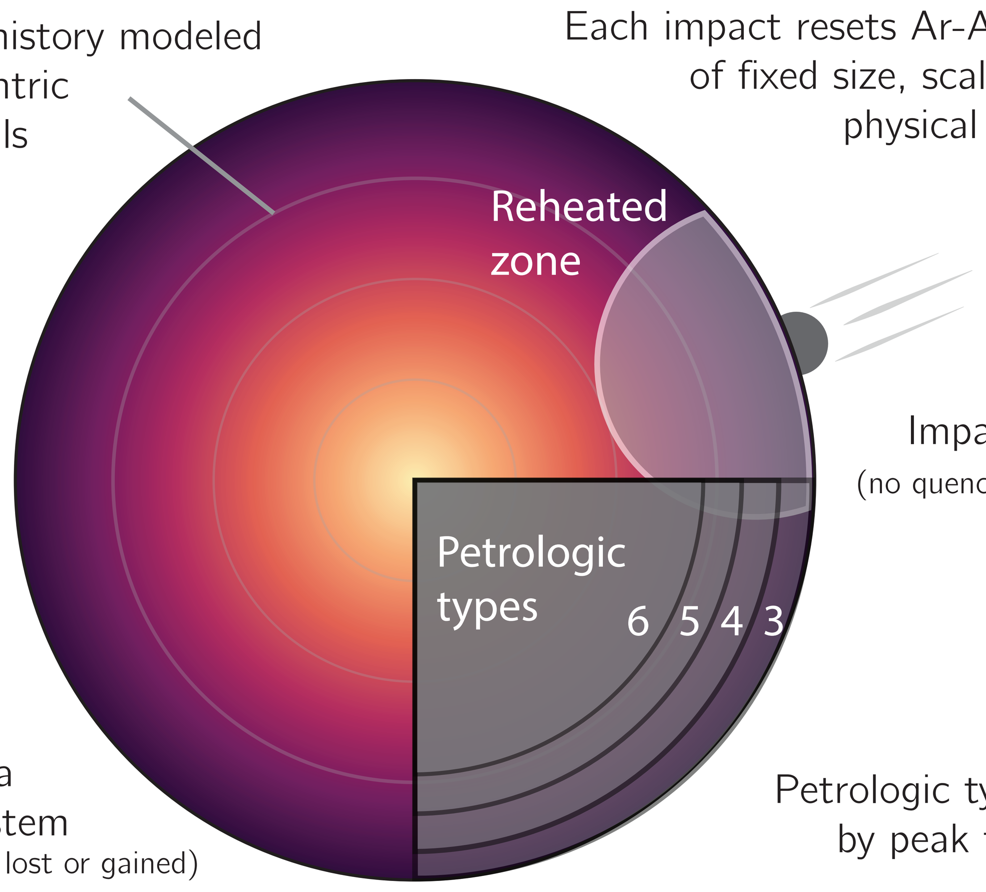
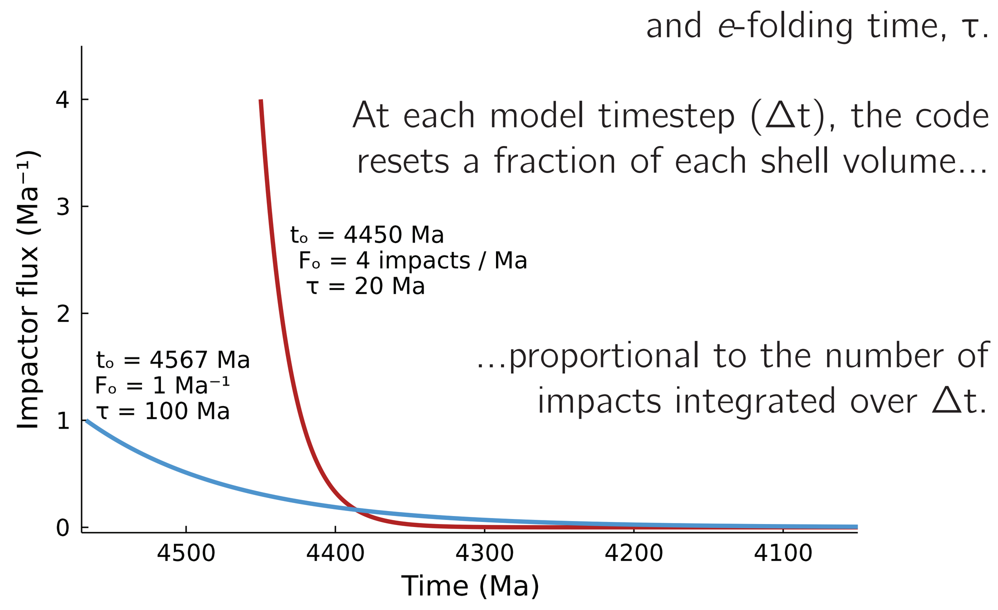


Figure 1 We can predict the thermal history and timing of Ar closure in a radiogenically heated and conductively cooled body, for a given suite of parameters (Table 1).

1. Simple thermal model and impact reheating code

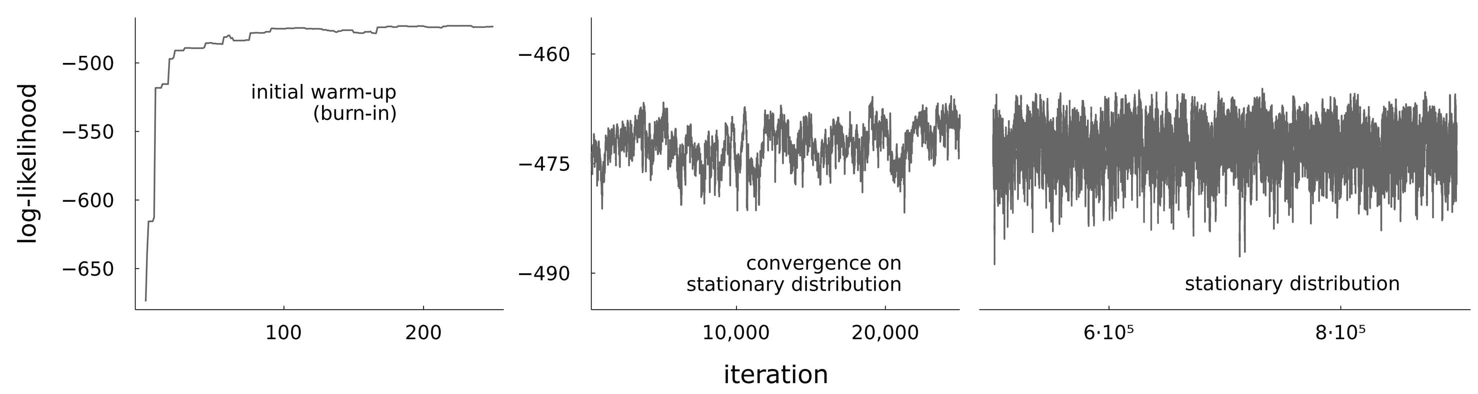




For each "reset" Δt, the reheated volume is taken proportionally from all preceding "cooling ages" within the corresponding shell.

Volumetric proportion in body reflects abundance in meteorite record, optionally weighted by proportions of petrologic types.

2. Markov chain Monte Carlo inversion



The Metropolis algorithm inversion explores the likelihood space calculated from thermochronologic model outputs and converges on distributions that estimate the posterior for each parameter.

Figure 2 Posterior estimate obtained by Bayesian inversion for an unperturbed asteroid (no impact flux).

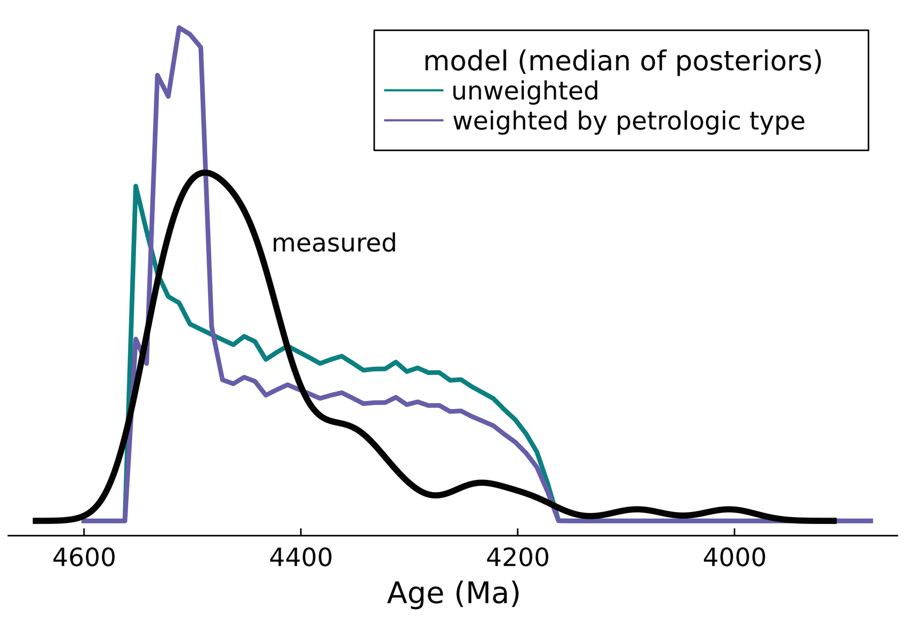
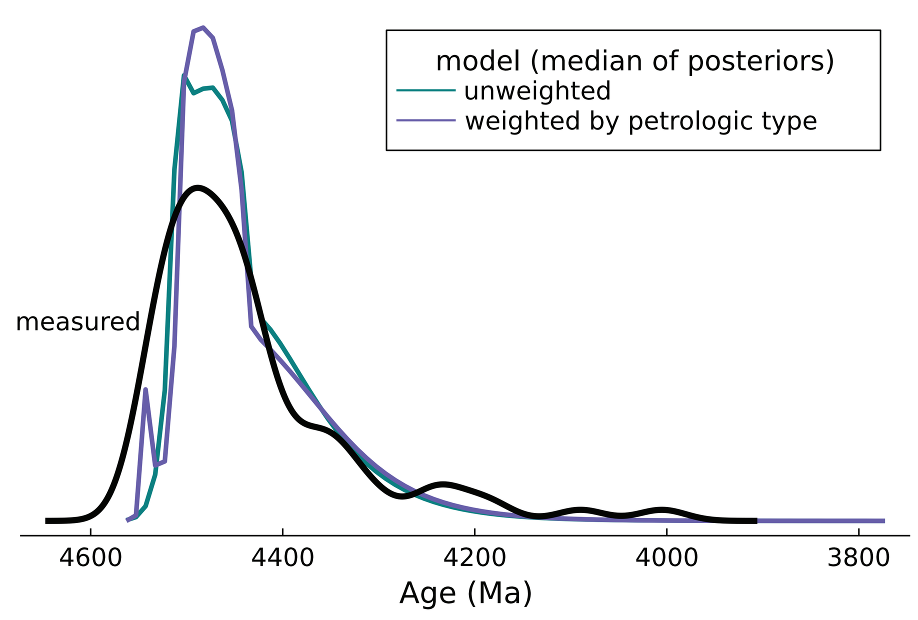


Figure 3 Posterior estimate obtained by Bayesian inversion for a history with impacts.



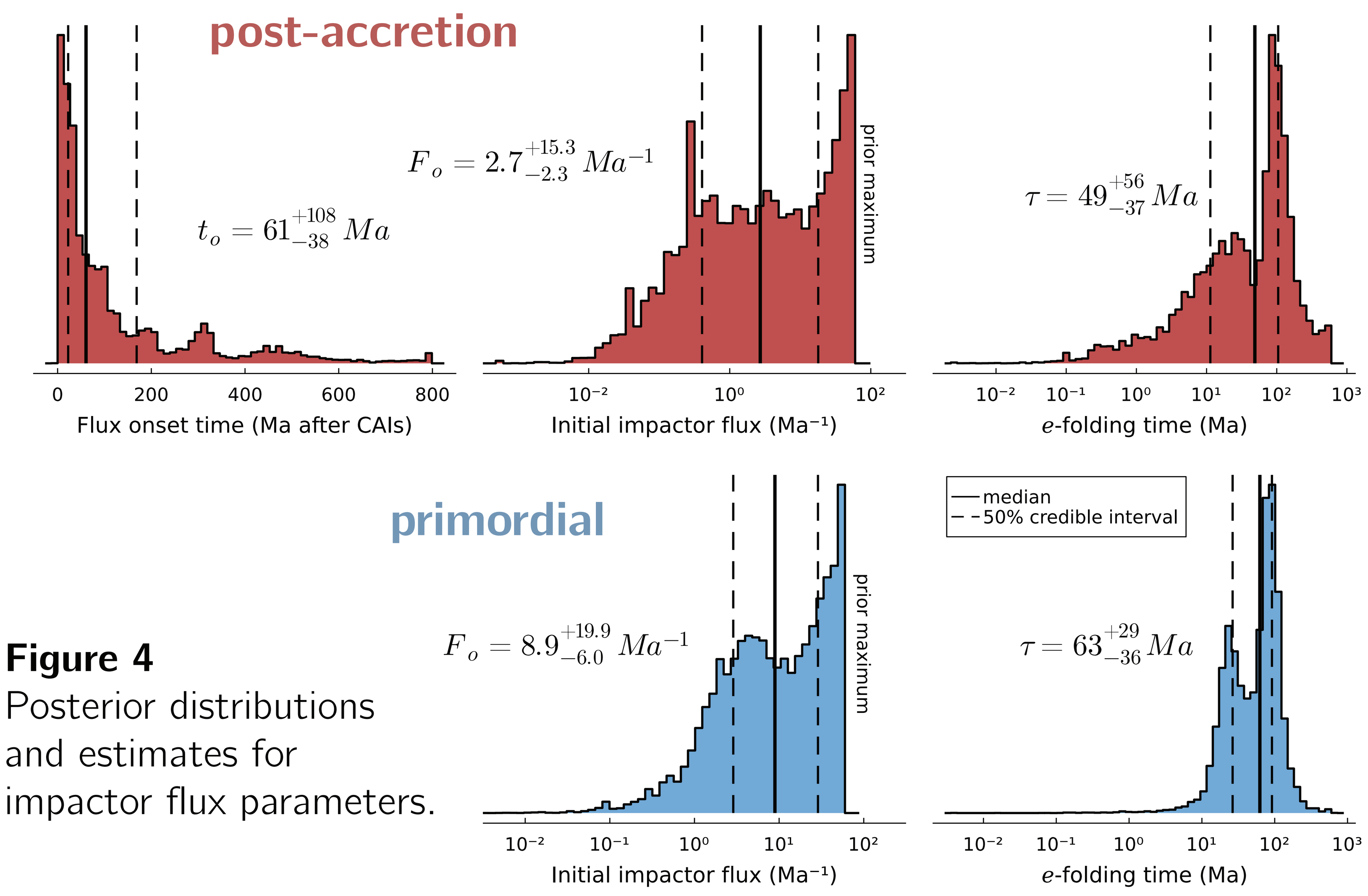
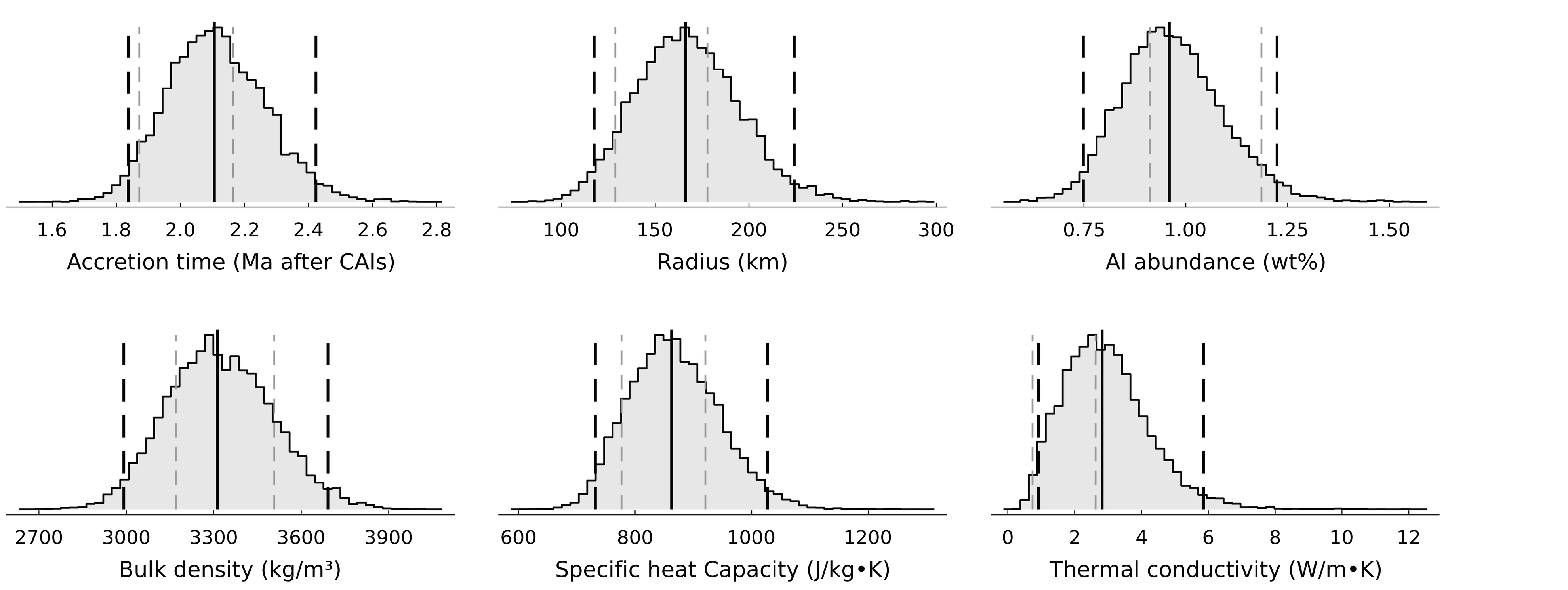


Figure 4 Posterior distributions and estimates for impactor flux parameters.

Table 1 Parameters and prior distributions used in the asteroid thermochronology and MCMC inversion models. Priors include constants as well as uniform ($\mathcal{U}[a,b]$), normal ($\mu \pm \sigma$), and lognormal distributions ($\log\mathcal{N}(\mu,\sigma^2)$ with linear-space approximations).

Parameter	Prior	Reference
Environmental/disk parameters		
Solar age (i.e. first CAIs)	4567.3 Ma	[1]
Initial $^{26}Al/^{27}Al$	$5.23 \cdot 10^{-5}$	[2]
Midplane temperature	$\log\mathcal{N}(5.35, 0.22) \sim 210$ K	[3]
Asteroid parameters		
Time of accretion	$\log\mathcal{N}(0.700, 0.005) \sim 2$ Ma after CAIs	[4–9]
Radius	$\log\mathcal{N}(11.9, 0.04) \sim 150$ km	[5–9]
Al abundance	$\log\mathcal{N}(-4.6, 0.01) \sim 1.0$ wt%	[10]
Material parameters		
Bulk density	$\log\mathcal{N}(8.11, 0.0025) \sim 3300\ kg/m^3$	[11]
Specific heat capacity	$\log\mathcal{N}(6.74, 0.09) \sim 850\ J/kg \cdot K$	[12]
Thermal diffusivity	$\log\mathcal{N}(0.33, 0.40) \sim 1.4\ W/m \cdot K$	[13–15]
Ar closure temperature	500 ± 75 K	[16, 17]
Impactor flux parameters		
Start time	$\mathcal{U}[0, t_{max}]$ (Ma after CAIs)	
primordial	0 Ma after CAIs	
Initial flux	$\mathcal{U}[0, 30]$ (Ma^{-1})	
e-folding time	$\mathcal{U}[0, 600]$ (Ma)	

[1] Connelly+, 2012, Science. [2] Jacobsen+, 2008, EPSL. [3] Woolum & Cassen, 1999, MaPS. [4] Sugiura & Fujiya, 2014, MaPS. [5] Henke+, 2013, Icarus. [6] Blackburn+, 2017, GCA. [7] Gail & Trieloff, 2019, A&A. [8] Edwards & Blackburn, 2020, Sci Adv. [9] Trieloff+, 2022, Icarus. [10] Lodders & Fegley, 1998, Planetary Scientist's Companion. [11] Flynn+, 2018, Geochemistry. [12] Wach+, 2013, Met Soc Abstract. [13] Yomogida & Matsui, 1983, JGR. [14] Opeil+, 2010, Icarus. [15] Opeil+, 2012, MaPS. [16] Turner+, 1978, LPSC Proc. [17] Bogard & Garrison, 2009, GCA.



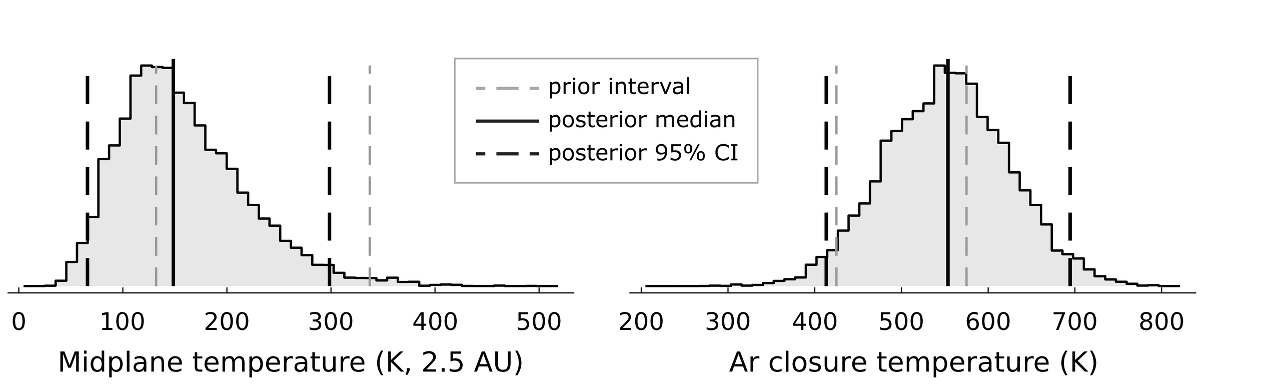


Figure 5 Posterior distributions and estimates for disk, asteroid, and material parameters.

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