Thermal Models of Iron Meteorite Evolution and Comparison with Pd-Ag Volatile-Loss Constraints.

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Summary: We model the thermal history of a suddenly-exposed planetesimal core in order to reconcile metallographic cooling rate data [1] with recent results [2] that constrain the time of mantle stripping and subsequent core quenching. We find good fits to both with a roughly 40 km iron body which is entirely molten when it is first exposed.

Introduction: Yang et. al. [1] measured metallographic cooling rates of IVB meteorites and showed they were broadly consistent with a ∼65 km body which was solid and hot upon exposure.

Kleine et. al. [2] show that the Pd-Ag chronology of a IVB meteorite is consistent with it originally evolving with a higher Ag content than it currently displays. This can be explained by an event that reduced the IVB parent body's volatile content, which we assume to be the catastrophic disruption event. The data suggest a time (8-14 Myr after CAI formation) of volatile loss and a timescale (≤2 Myr) for the now-exposed core to cool.

Our thermal models (Figure 1) indicate that it is essentially impossible for the IVB parent body to have had its core crystallize prior to exposure unless the stripping event was extremely late (100s of Myr after CAI), inconsistent both with the results from [2] and the period during which the early solar system was most violent [3]. We model the evolution of a IVB parent body with an initially liquid core, and show that it is consistent with the results from both [1] and [2]. Figure 2 shows a cartoon of our suggested history of the body (cf. [1]).

Thermal Models: Our model for the body prior to stripping assumes an initially differentiated, isothermal planetesimal [4]. The mantle cools conductively, and the core is isothermal until it crystallizes. The size and initial temperature of the body are varied, two examples of which are shown in Figure 1. These models show that even for unphysically conservative cases, the core should still have been liquid when it was exposed.

After the mantle is stripped, we model the planetesimal as crystallizing from the outside in, in line with [1]. The growing solid crust is taken to be conductive, with any liquid held isothermal (Figure 3). We find good agreement between this numerical model and a published analytical solution [5]. We extract the cooling rates along the 800 K isotherm to compare to [1]. This is adapted from the code used in [6].

Results: We find that the data in [1] are consistent with an initially liquid body approximately 40 km in radius. In addition, a body of this size will quench to the Pd-Ag closure temperature within the 2 Myr required by [2]. Thus both the thermal and volatile loss data are consistent with this model (Figure 4).

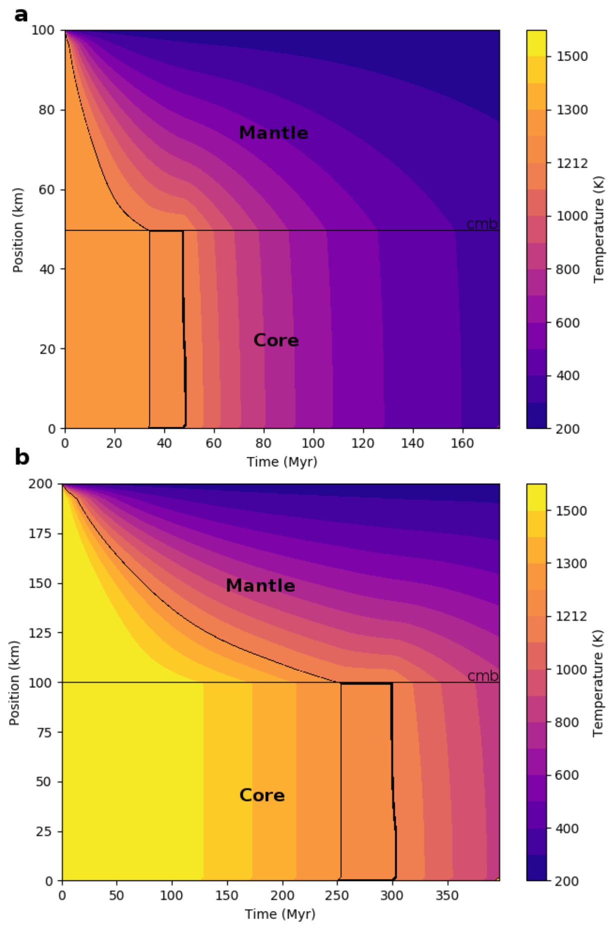

Figure 1: Conductive thermal history for a differentiated asteroid prior to breakup. (**a**) shows a very conservative situation, with a 100 km radius body and an initial temperature of 1300 K. (**b**) is a more realistic situation, with a 200 km radius body and a 1600 K initial temperature. The black contour is the assumed melting point of iron (not a sensitive parameter), and the box shows the period of core crystallization.

References: [1] Yang J., et. al. (2010) *GCA*, 74, 4493-4506. [2] Kleine T., et. al. (2018) *this meeting*. [3] Chambers J. (2006) *Meteorites and the Early Solar System*, 487-497. [4] Tarduno J. A., et. al. (2012) *Science*, 338, 939-942. [5] Riley D. (1974) *IJHMT*, 17, 1507-1517. [6] Nimmo F. & Spencer J. R. (2015) *Icarus*, 246, 2-10.

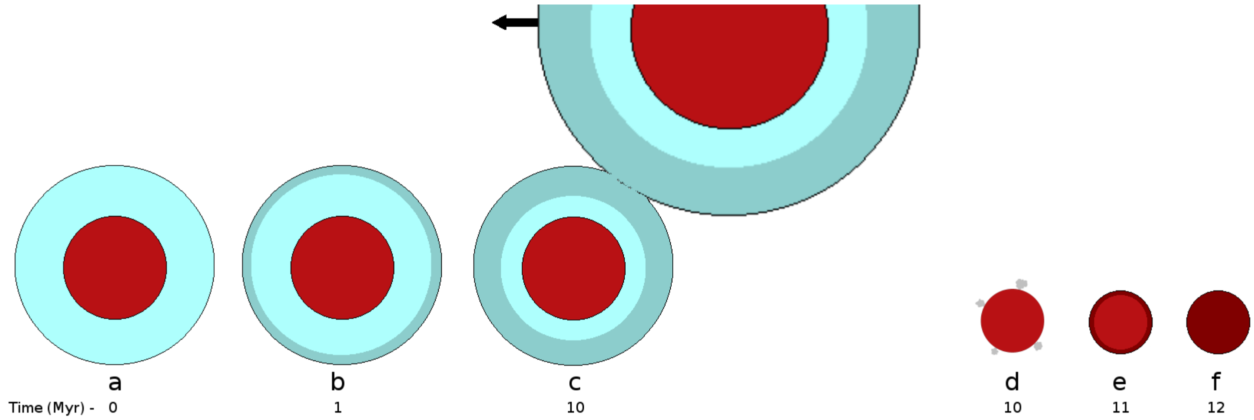

Figure 2: Cartoon in the same vein as Figure 11 in [1]. Timescale at the bottom is very approximate and model dependent. (**a**) and (**b**) show the body prior to breakup (darker blue illustrates cooling, not necessarily a phase change). (**c**) is the collision which exposes the (liquid) core. (**d**) is the situation immediately after exposure: a residual metallic body which is suddenly depressurized (with volatiles exiting). (**e**) and (**f**) show the subsequent top-down crystallization of this metallic body (darker red is the solid).

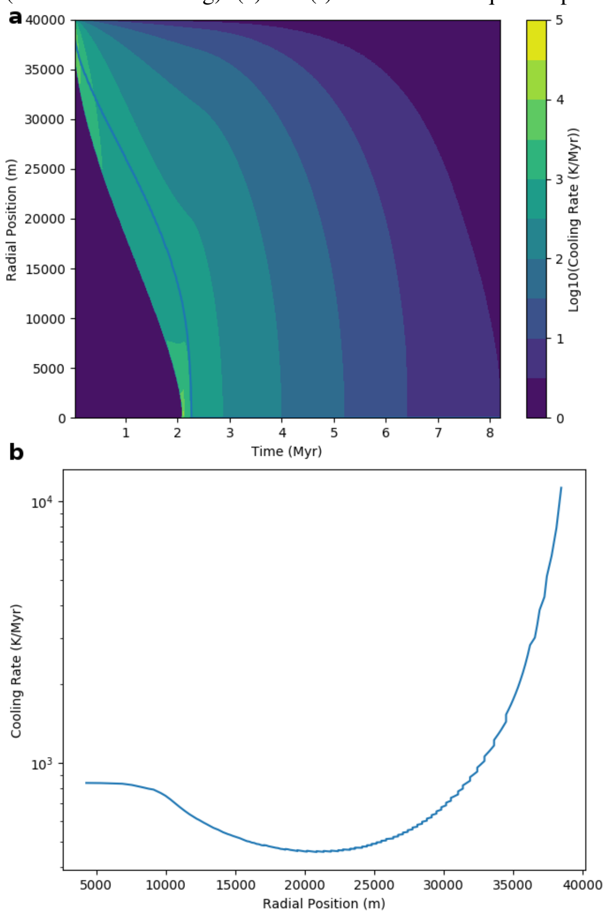

Figure 3: Cooling rate history of a 40 km core following exposure. Contours in (**a**) show cooling rate, with the purple region on the left indicating the remaining melt. The blue line to the right of the crystallization front is the 800 K isotherm. (**b**) is the cooling rate on the 800 K isotherm, and is broadly consistent with Figure 13 from [1] (although the accelerated cooling near the center is noteworthy).

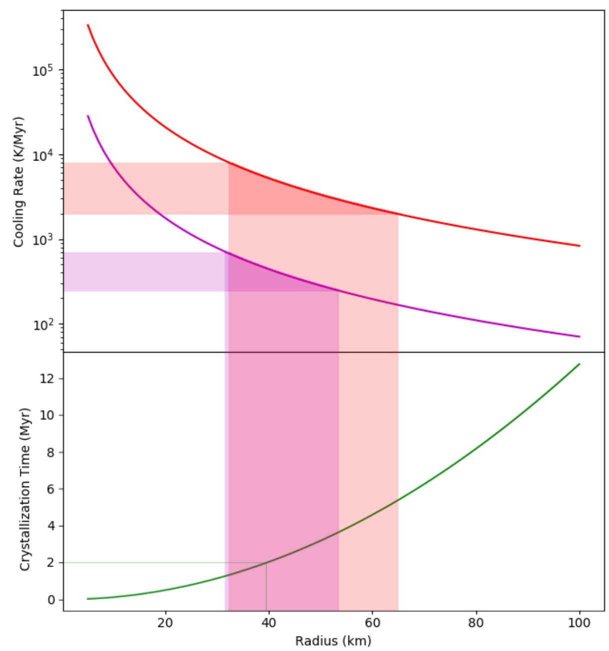

Figure 4: Constraints on IVB parent body size. The orange (top) curve is the fastest cooling rate found in a metallic body of a particular size. The purple (middle) curve is the slowest cooling rate in a body. These curves must bracket the metallographic cooling rates found in [1], indicated by the colored boxes extending from the left (thickness indicates error bars). The green (bottom) curve is the time after mantle stripping to quench the body to the Pd-Ag closure temperature. This must not exceed the time limit inferred by [2], which is marked by the faint green line extending from 2 Myr at the left. However, this curve has many sources of uncertainty, compounded by uncertainty in the Pd-Ag measurements, that make it only a check on the cooling rate constraints instead of a strong constraint itself. It should be assumed to have a fairly wide (up to a factor of a few) uncertainty.