A PLETHORA OF PARTIALLY MELTED ASTEROIDS?

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A number of recent quantitative mineralogical interpretations of S-type asteroids have identified compositions consistent with partially differentiated assemblages [e.g., 1-5]. However, partially differentiated meteorites (often designated as "primitive achondrites") constitute only a tiny fraction of the meteorite falls represented in terrestrial collections (~0.2% [6]). These two results would seem to be contradictory and would appear to raise serious questions concerning the validity of the asteroid spectral interpretations.

Several factors must be considered when assessing the significance of this apparent discrepancy. The first is the general disconnect between meteorite fall frequency and the relative abundances of corresponding assemblages among main belt asteroids. If one considers the diversity of meteorite types (as opposed to the fall frequency for particular types) it is evident that most (~80%) of the meteorite parent bodies represented in our meteorite collection underwent strong heating and at least partial melting and differentiation [7]. Parent body location with respect to main belt "escape hatches" (the 3:1, 5:2 and ν_6 resonances in particular) appears to be the primary factor controlling the fall frequency of meteorites. Thus the fall abundance of meteorites cannot provide a robust check on the plausibility of asteroid spectral interpretations.

Actually this apparently contradictory relationship is expected due to the processes that occur during the heating of small planetary bodies. The early transient asteroid and meteorite parent body heat sources were – by definition - finite since the bodies were not vaporized. This may seem obvious, but it has significant implications for the relative abundances of differentiated, partially differentiated, and undifferentiated assemblages among the asteroids. With a finite heat source, there is a limit to the peak temperature that can be attained within the parent body. If this peak temperature is elevated but below the point where the first melt appears (eutectic melt ~970°C for FeNi-FeS and ~1075°C for chondritic silicates [e.g., 8-10]), the parent body assemblage will only be metamorphosed and not melted. If the peak temperature is above the melting point of all the constituent mineral phases, the body will experience complete melting, magmatic differentiation and fractional crystallization. The temperature of complete melting will vary (~1500-1800°C) depending on the phase composition of the initial assemblage. The final melting temperature will also depend upon whether the melt phase is retained in or removed from the melt region.

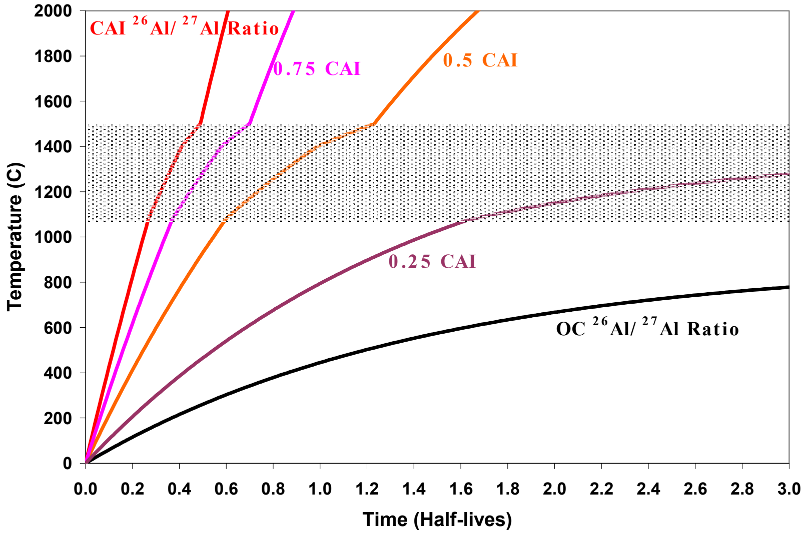
Silicate partial melt assemblages are formed in the temperature interval between the onset of silicate partial melting and the completion of silicate melting. If a parent body was heated at a constant rate and its thermophysical properties were not temperature dependent, the fraction of its heating period spent in the "partial melting" interval would simply be proportional to width of the interval between the onset and completion of melting divided by the peak temperature attained.

However, the assumption of constant thermophysical properties is clearly invalid. The temperature change of a material as a function of the heat input is designated as the "specific heat" of the material. For typical mafic mineral assemblages similar to chondrites, the specific heat is ~1400 J Kg^{-1} $°C^{-1}$ (~0.33 cal gm^{-1} $°C^{-1}$). Specific heat of basaltic magma (eutectic melt of chondritic assemblages) is ~1000 J Kg^{-1} $°C^{-1}$. Thus as the melt fraction increases, the rate of temperature rise should increase for a constant energy input.

This simple calculation ignores a critical factor, the heat of fusion. Energy is absorbed during the phase transition from a solid to a liquid (e.g., during the melting process) without raising the temperature. The heat of fusion for a mafic mineral assemblage is ~500,000 J Kg^{-1} [11]. Thus once melting begins, a large portion of the energy input is absorbed by the phase transition, and the rate of temperature rise slows dramatically, significantly extending the time spent in the partial melting interval.

The figure below shows the results of a simple model for asteroid heating which incorporates specific heat and heat of fusion. The stippled region indicates the approximate range of partial melting. The different curves represent the effects of different initial $^{26}Al/^{27}Al$ ratios [12] (100%, 75%, 50% & 25% of CAI & Ordinary Chondritic) and assumes a typical chondritic Al abundance of 1.2% (wgt.). The horizontal (time) axis is in units of the half-life of ^{26}Al. The model does not include heat conduction and heat loss which would slow the rate of temperature increase (flatten the slopes of the curves), lower the peak temperatures and extend the time spent in the partial melting regime. In that respect, the model generally provides a lower limit on the time spent in the partial melting interval.

Even for the more strongly heated parent bodies ($^{26}Al/^{27}Al$ = 50% - 100% of CAI), ~20-25% of the heating time up to 2000°C is spent in the partial melting interval. For the $^{26}Al/^{27}Al$ = 25% of CAI, the object attains partial melting but does not get to full melting. For the ordinary chondrite case, the object does



not attain even partial melting. The model does not incorporate the effects of accretion during heating [e.g., 13, 14] which is expected to be minor in most cases.

The various CAI curves correspond to parent bodies formed at or after the formation time of the CAI inclusions in chondrites. The 50% and 25% curves would correspond to parent bodies formed 1 and 2 half-lives of ^{26}Al after CAI formation. This model – as over-simplified as it is – would indicate that most meteorite parent bodies (the 80% which are partially or fully differentiated) formed within two ^{26}Al half-lives of the CAIs (~1.4-1.5 Myr), and well before the parent bodies of the ordinary and carbonaceous chondrites.

Thus it is plausible many asteroid and meteorite parent bodies will have spent a significant portion of their heating history in the partial melting temperature interval. This is consistent with the relatively high frequency of partially melted asteroids indicated by quantitative analysis of asteroid spectra. But there is still a problem – the reciprocal of that stated earlier - with the meteorite statistics; particularly why isn't there more diversity among the partially differentiated assemblages in our meteorite collections, even if represented only by single specimens. As noted previously, it is now clear that meteorite fall statistics are controlled primarily by the locations of their parent bodies. At least 135 parent bodies are represented in the meteorite collections [7], but ~75% of all meteorites falling during the past several hundred thousand years derive from just three favorably parent bodies. One of these (6 Hebe) has already been identified [15]. In the present epoch (the past few million years) it would appear that only one of the partially differentiated asteroids (the lodranite-acapulcoite parent body) has been near a favorable location. The high abundance of parent bodies sampled by only one or a few iron meteorites strongly suggests that the short collisional lifetimes of stones severely limit their ability to traverse significant distances to an escape hatch. So even though main belt asteroids derived from partially melted parent bodies are relatively abundant, the "luck of the draw" apparently hasn't resulted in such a body being in a favorable location recently.

Thus there is no contradiction between the plethora of partial differentiated asteroids indicated by spectral studies and the rarity of similar assemblages in our meteorite collections. The identification of a partially asteroid in a location favorable for meteorite delivery would constitute a contradiction, but to date no such objects have been identified in our small sample.

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