EARLY PLANETESIMALS AS RESERVOIRS FOR CHONDRULE MATERIALS. I. S. Sanders. Department of Geology, Trinity College, Dublin, Ireland. e-mail: isanders@tcd.ie

Introduction: Tungsten-182 deficit dating of iron meteorites [1] shows that their parent bodies had already accreted and melted within less than about 0.5 Myr of the start of the solar system, defined by the formation of calcium-aluminium-rich inclusions (CAIs) in CV and other chondrites. On the other hand, dating of chondrules by the Al-Mg, Pb-Pb and Hf-W methods [2-4] consistently shows that these enigmatic objects were not made until between 1.5 and 2.5 Myr after CAIs. Thus the chronological evidence is in direct conflict with the widely held and popular view that chondritic parent bodies accreted first, and it paves the way to a better understanding of the earliest history of the protoplanetary disk.

In the new emerging scenario ^{26}Al holds the key. It now seems probable that $^{26}Al/^{27}Al$ in the inner solar system was everywhere close to 5×10^{-5}, the so-called canonical value, at the time when CAIs appeared [5,6]. This level of radioactivity translates to 6.5 kJ of radiogenic heat per gram of dry primitive dust, which is roughly four times the amount of energy needed to heat the insulated interior of an initially cold planetesimal to its liquidus temperature.

The implications are simple. Those planetesimals that melted, i.e. the parent bodies of differentiated meteorites, must have accreted within just two half lives of ^{26}Al, roughly 1.5 Myr, after the formation of CAIs. Those that did not melt, i.e. the chondrite parent bodies, must have accreted more than 1.5 Myr after CAIs. In this light, the 1.5 to 2.5 Myr clustering of chondrule ages is probably not a discrete epoch of chondrule formation; instead it seems likely that chondrules were produced continuously in the disk from the time of CAI formation, but nearly all those that were made before 1.5 Myr failed to survive because the planetesimals to which they accreted underwent substantial to total internal melting [3].

Chondrule formation: While chondrules have ages that are consistent with the declining ^{26}Al in primitive dust, their formation mechanism remains an unsolved puzzle. Most papers on chondrules are prefaced with the assumption that they began as clumps of dust and were converted to melt droplets by rapid heating in the nebula. The source of the heating is presumed to be linked with the enormous flux of energy associated with in-fall and disk accretion; the passage of shock waves through nebular gas is currently fashionable, but other mechanisms such as huge solar flares and nebular lightning have also been considered. This dust-ball scenario became well established some thirty years ago. At that time, compelling arguments [7] seemed to rule out any involvement of planetary bodies in chondrule production so, by default, chondrules were deemed to have been made in a nebular setting. This conclusion was reinforced by the then prevailing notion that chondrules must have pre-dated accretion of the first crop of planetesimals.

However, we now know that chondrules were born into a disk in which planetesimals were common. Indeed, fragments of annealed olivine-rich rock, presumed to be shattered bits of planetesimal, were recently recognized inside chondrules [8]. Clearly, early-formed planetesimals were somehow being disrupted and their debris was being recycled back into the disk. Chondrules made from this debris were, in their turn, re-accreted to make younger generations of planetesimals.

Despite the growing evidence for the contemporaneous disruption of planetesimals and the making of chondrules, the two processes are generally presumed to be unrelated, and the conventional view that chondrules began as dust clumps remains largely unchallenged.

Some problems with melting dust-clumps: The level of Na in chondrule olivines and the lack of fractionation of light isotopes from chondrules suggest clouds of closely-spaced droplets so large and dense that the droplets (and precursor dust clumps) would have been gravitationally bound and collapsing to create a new planetesimal [9, 10]. It is hard to conceive of how dust could have become sufficiently concentrated on such a scale. Moreover, the heating process must have been unbelievably powerful to melt the inferred mass of dust in one event, and its timing must have been highly fortuitous to operate just as the dust clumps were moving together under gravity. Finally, if chondrules were made on this scale, it is difficult to imagine how unheated matrix materials became incorporated between them.

Planetesimal disruption and chondrule formation: When chondrules were being made, about 2 Myr after CAIs, the population of planetesimals must have included many that were almost totally molten [11]. Collisions, and even close encounters, involving these drifting magma spheres would have led to truly enormous splashes and the production of chondrule droplets in very large numbers [12-14]. Without rehearsing the many published arguments supporting this hypothesis, it should be clear that ‘splashing’ can probably resolve all the major difficulties mentioned in the preceding paragraph – the enormous size of the cloud, the difficulty of heating it externally, the close proximity of the droplets (at least in the early stages of plume expansion), and the admixture, later, of cold matrix.

Other observations: Within the past few years several new observations seem to favour, or are at least consistent with, a central role for planetesimals in chondrule production.

Type I and type II chondrules. If chondrules come from disrupted molten planetesimals, then why do they fall into two distinct categories, FeO-poor (type I) and FeO-rich (type II)? Could the planetesimals themselves have been of FeO-poor and FeO-rich kinds? I believe this was perhaps the case. Trace elements in iron meteorites suggest that early-formed planetesimals were not only highly reduced, but were also very refractory. Such planetesimals possibly accreted from partially condensed material in the hot inner nebula, in the region of the terrestrial planets [15]. On melting and splashing they would have released type-I chondrules. Early refractory planetesimals have also been inferred, incidentally, from the carbonaceous chondrite whole rock Mn-Cr isochron [16].

Type II chondrules present their own problems for conventional thinking, because hydrogen gas in the nebula created a reducing environment in which FeO-free silicates coexisted with iron metal [17]. Evidently H_2O is required to make the environment suitably oxidising for type II chondrules. [17] invoke impacts with hydrated or ice-bearing planetesimals to deliver water into a local, post-impact nebular setting where FeO-bearing chondrules would be stable. A simpler way of achieving the same end would presumably have been the accretion of ice into the original planetesimal, prior to its melting and disruptive splashing. Such ice-bearing planetesimals likely may have accreted further from the sun, and later, than the hot, refractory planetesimals, and it is interesting to note that type I chondrules statistically are older than type II chondrules [2].

Planetesimal collisions, and their timing. Several kinds of meteorite testify to large-scale impacts between planetesimals. Examples include the mesosiderites, the IAB and the IIE silicate-bearing irons, the Shallowater aubrite, the IVA irons, and the CB chondrites. Hitherto, only the last of these have been implicated in chondrule formation, but the timing of the impact [18] and the nature of the chondrules are both unusual. However, the giant impact inferred from the IVA group of iron meteorites [19] evidently took place about 2 Myr after CAIs [20], just at the time when chondrules were made. It undoubtedly led to a truly enormous supply of type I chondrules.

Chondrule reservoirs. A problem with making chondrules from dust clumps is the diversity of chondrite groups, each with its distinctive oxygen isotope proportions and chondrule textures [21]. It seems that the 'feeding zone' from which each parent body accreted was a separate reservoir of dust and chondrules in the nebula. This suggests that chondrite parent bodies accreted rapidly following chondrule formation, before the reservoirs were homogenized by processes such as turbulence and radial mixing.

The same diversity of chondrite groups might more easily have been achieved if the local reservoirs were actually planetesimals, particularly if the chondrule spray following disruption had a brief residence time in the nebula.

References: [1] Burkhardt C. et al. (2008) GCA 72, 6177-6197. [2] Kita N. K. and Ushikubo T. (2010) Workshop on chondrules, New York. 8005.pdf. [3] Connelly J. N. et al. (2008) ApJ 675, L121-L124. [4] Kleine T. et al. (2008) EPSL 270, 106–118. [5] Thrane K. et al. (2006) ApJ 646:L159–L162 [6] Villeneuve J. et al. (2009) Science 325, 985-988. [7] Taylor G. J. et al. (1983) Chondrules and their origins. LPI. 262-278. [8] Libourel G. and Krot A. N. (2007) EPSL 254, 1–8. [9] Alexander C. M. O'D. et al. (2008) Science 320, 1617-1619. [10] Cuzzi J. N. and Alexander C. M. O'D. (2006) Nature 441, 483-485. [11] Hevey P. J. and Sanders I. S. (2006) MAPS 41, 95-106. [12] Zook H. A. (1981) LPI 12, 1242-1244. [13] Lugmair G. W. and Shukolyukov A. (2001) MAPS 36, 1017-1026. [14] Sanders I. S. and Taylor G. J. (2005) *Chondrites and the Protoplanetary Disk,* ASP Conference Series 341, 915-932. [15] Bland P. A. and Ciesla F. J. (2010) LPSC 41, 1817.pdf. [16] Scott E. R. D. and Sanders I. S. (2009) GCA 73, 5137–5149. [17] Fedkin A. V. and Grossman L. (2010) LPSC 41, 1448.pdf. [18] Krot A.N. et al. (2005) Nature 436, 989-992. [19] Yang J. et al. (2007) Nature 446, 888-891. [20] Blichert-Toft et al. (2010) EPSL 296, 469–480. [21] Jones R. H. (2010) Workshop on chondrules, New York. 8003.pdf.