

ON A NEW MODEL FOR THE GENERATION OF CHONDRITES. Herbert A. Zook,
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There seems little doubt that an important source of energy acted to melt much solid matter at or near the time of origin of our solar system. The very early solidification ages measured for most meteorites (1) indicate, in addition, that this source was of a transient nature. It was early recognized (2) that a short-lived radioactive species such as ^{26}Al could be responsible. Evidence that important amounts of ^{26}Al did exist and was decaying at this time has since been put forward by Lee et al. (3) although it has been alternatively argued (4,5) that remnants of extinct radionuclides could also be preserved in the solar system as unmelted presolar grains.

Fish et al. (2) argued that large planetary bodies, if once molten, would not cool fast enough to give the observed early retention of the rare gas decay products of certain radioactive parent nuclides. They suggested instead that the meteorite parent bodies had a radius of less than 250 km. Wood (6) found through detailed modelling that, with the early ^{26}Al abundance suggested by Lee et al. (3), bodies as small as 20 km in radius could be in a largely molten state a few million years after solar system initiation. Such small bodies, Wood suggested, would not only cool fast enough to give the observed rare gas closure ages but would also explain the apparent lack of stresses on olivine minerals in pallasites.

Obviously, if one can argue for the early existence of a few largely molten planetoids with dimensions of kilometers or tens of kilometers, one can quite as easily argue for very large numbers of such planetoids. The very high early lunar cratering rate certainly suggests a correspondingly high flux of impacting planetoids.

The prospect of great numbers of small, partly molten, bodies orbiting about the early sun also gives rise to the prospect of a very high collision rate between these objects. Indeed, gravitational perturbations by the still-growing protoplanets are probably very important in putting many planetoids onto collision trajectories at an early time. When collisions between objects not too dissimilar in size occur, the resulting "splash ejecta" will create large numbers of molten (or semi-molten) droplets, as well as fragmental material from the exterior portions of the colliding objects. The now isolated droplets will then rapidly solidify (or be "quenched") to become protochondrules. Then - perhaps with the aid of the remaining nebular gas - they again re-accrete into, and are buried inside of, solid small planetary bodies presently represented by some asteroids. By this time, most of the ^{26}Al is presumed to have decayed away, so that remelting does not occur. Enough later heating, including heating from long-lived radioactivity, is presumed to have occurred to have caused various amounts and kinds of metamorphism. Nickel-iron kamacite-taenite growth may have occurred during this later period. Later impact fragmentation then gave rise to the meteorites now held in terrestrial collections.

Not only will chondrules be generated, but other chondrite features may also rather naturally follow from this model. We can imagine that the initial precursor planetoids are composed of some type of carbonaceous material; the type and composition may vary from planetoid to planetoid. At an early stage of heating (assumed to occur from ^{26}Al decay) one can imagine that hydrated H_2O will be released. Under a sufficient overburden, this water may be in liquid form. If hot, it will react with sulphides in the matrix and form sulphuric acid. As the central region of the planetoid becomes still hotter, the carbon in the carbonaceous material will reduce much of the iron and other siderophiles to their metallic state and form CO and CO_2 . As these pass through the water already generated, some carbonic acid will be formed. As

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this hot acidic solution attempts to escape the interior of the planetoid it will leach the surrounding minerals. When this mineral-rich solution cools upon passing through cracks in the cooler crust, carbonates, sulfates and other minerals will precipitate. These veined deposits and alterations may be exactly those observed by Kerridge and Bunch (7) in C1 and C2 carbonaceous chondrites. Thus it is imagined that carbonaceous chondrites originate from the exterior portions of the original planetoids.

If the planetoid is large enough, interior temperatures will rise high enough to first sinter the material and later melt the low temperature melting silicate fractions of the matrix. We can imagine this as a kind of "slush" with liquids intimately intermixed with solids. Because of the low gravitational forces involved, gravitational separation of phases may not initially be effective due to the residual strength of the slush. Finally, central temperatures may rise high enough to create a sufficient fractional volume of liquid so that the denser solids will settle out to the core (2).

It seems likely that impacts should not only give rise to liquid droplets and to fragmental debris from the planetoid exteriors but should also give rise to "slush droplets," that is droplets which contain solids that were never melted. One candidate chondrule type that was initially investigated as possibly arising from such a slush were the porphyritic olivine chondrules. The equant olivine crystals might grow during the planetoid heating period. However it appears that the intergranular matrix in these chondrules never represented a melt that was in equilibrium with the olivine crystals (8,9). Reid and Fredrickson (10) long ago suggested that carbon may be reducing and removing iron preferentially from the intergranular melt; other explanations have also been put forward more recently (8,9). However it may be that we should look to other chondrule types for evidence of slush droplets.

A first requirement for any model involving chondrule formation is that it should be physically reasonable - or at least not violate well understood physical laws. One requirement concerns the energy input necessary to form the chondrule surfaces. According to Dave Walker (personal comm.) silicate surface tensions are in the neighborhood of 350 dynes/cm. With this value, the surface energy per unit mass (in ergs/g) to form droplet chondrules of radius r (in cm) is given by $300/r$, where it was assumed that the material density was 3.5 g/cm^3 . For droplet chondrules one millimeter in diameter, the required energy is 6000 erg/g. This is roughly equivalent to the kinetic energy per gram of an object traveling at one meter per second. In other words an almost negligible fraction of the impacting kinetic energy will be used to create typical chondrules for impact velocities in the km/s range. Although not directly comparable, it is interesting to note that about 10^7 erg/g of kinetic energy of impact is required to catastrophically disrupt rocks (11).

The present collision lifetimes of asteroids of 10 km radius in the asteroid belt is about 10^9 years (12). A factor of a thousand more objects in similar orbits would lower this lifetime to 10^6 years. This is compatible with ^{26}Al heating times. As less than one earth mass of material would thus be required - assuming an asteroidal size distribution - to create this number of planetoids, no objection seems in order here.

Lack of space prevents presenting here a review of problems with earlier theories of chondrite formation. Wood and McSween (13) and Kerridge and Kieffer (14) have covered some problems not covered by others already cited. The model put forward here has not yet been investigated in enough detail to know if it fits all the observational constraints. Given an early high spatial density of partly molten planetoids, however, the consequences put forward here do not seem unreasonable.

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