FOURTEEN POINTS – A WILSONIAN APPROACH TO CHONDRULE FORMATION: EVIDENCE FOR MULTIPLE MELTING OF CHONDRULES.

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Introduction: To end the verbal skirmishing involving chondrule formation, we need to examine a plethora of petrographic, mineralogic, geochemical and experimental constraints. We can also look to history. Nearly a century ago, U.S. President Woodrow Wilson offered Fourteen Points as a statement of principles to aid peace negotiations and end World War I. Offered here is a new set of Fourteen Points addressing contemporary chondrule clashes.

Constraints: There is strong evidence that most chondrules were melted multiple times: (1) Many chondrules include relict grains derived from disrupted chondrules [1,2]. (2) Some porphyritic chondrules contain olivine shards (with acute internal angles) that differ in shape from grains that crystallize from melts [3]. (3) In some PO chondrules, the central Fa contents differ significantly between large and small olivine grains (e.g., Fa_{47} vs. Fa_{26}); these sets of grains could not have crystallized from the same melt at the same time [3]. (4) Dynamic crystallization experiments show that porphyritic textures were produced only in runs with precursor nuclei ≥40 µm [4]; in natural systems, such coarse nuclei were likely derived from pre-existing chondrules. (5) In many Type-II PO chondrules, overgrowths on relict olivines differ in FeO from relicts [3], indicating that the late-stage melt had a different composition than the preceding melt. (6) In many Type-II PP and POP chondrules, there are low-Ca pyroxene grains with overgrowth layers that exhibit compositional zoning, interpreted as having resulted from repeated heating episodes that mainly melted mesostasis [5]. (7) Some Type-II PO chondrules contain chromite grains trapped within a late-added layer at the outer margins of large olivine phenocrysts [3]. (8) In Type-II PO chondrules, there are relict grains and overgrowths in FeO-rich olivine phenocrysts revealed by P X-ray maps [6] or by their distinct Mn/Fe ratios [7]. (9) Cathodoluminescence reveals the presence of low-FeO relict olivine grains in Type-I chondrules [8,9]. (10) Proportionately very large relict phenocrysts constitute up to 90 vol.% of some host chondrules and are unlikely to have formed from their surrounding melt [10]. (11) Many chondrules possess igneous rims formed by melting fine-grained porous dust aggregates around the chondrule [11-13]. (12) Enveloping compound chondrules commonly consist of primary chondrules encircled by secondary spherical shells formed during later melting events [14]. (13) Microchondrules occur within fine-grained chondrule rims; in many cases, these seem to have formed by partly melting low-Ca pyroxene phenocrysts at the chondrule margins [15]. (14) Nonspherical Type-I chondrules (particularly in CO chondrites) appear to have formed by minor remelting of pre-existing chondrule fragments [16].

Multiple Melting and Rapid Cooling: If chondrules were partly melted and rapidly cooled several times, there would be less melting and evaporation of critical nuclei in chondrule melts (thereby facilitating the development of common porphyritic textures), less destruction of relict grains, less volatile loss, and a lower likelihood of K-isotopic fractionation. Rapid cooling is indicated by several features: (a) Isotropic glass. Some nonporphyritic chondrules contain up to 99 vol.% glass [17]. (b) Quench crystallites of Ca-pyroxene in the mesostasis of many porphyritic chondrules. (c) Low-Ca clinopyroxene phenocrysts exhibiting polysynthetic twinning parallel to (001) in many Type-I chondrules [18]. Smyth [19] found that twinned low-Ca clinopyroxene forms from protoenstatite in a quench lasting no more than a few seconds; otherwise, appreciable orthoenstatite would form. Weinbruch and Müller [20] estimated the absence of orthoenstatite lamellae in clinopyroxene requires cooling rates on the order of 10,000 K hr^{-1} at ~1270 K. Even faster cooling probably occurred at higher temperatures. (d) Large variations in the $^{11}B/^{10}B$ ratios within some CV and OC chondrules [21,22]. Rubin [23] reported that experiments by M. Chaussidon had shown significant equilibration of B isotopes held at 1888 K for 180 s and nearly complete homogenization in 900 s.

Moral Imperative: Whereas Wilson proposed a league of nations to resolve political disputes, there already exists an international organization – the Meteoritical Society – that sponsors meetings in which scientific disputes can be aired. If we are to resolve the chondrule conundrum, we cannot be separated in interest or divided in purpose. We must stand together until the end.

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