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Refractory Inclusions and Chondrules: Insights into a Protoplanetary Disk and Planet Formation

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Abstract. Presented is a general review of the importance of refractory inclusions and chondrules, issues surrounding their origin, and the questions and hypotheses that are investigated within the following section and elsewhere in this volume.

1. General Introduction

In 1963, John Wood suggested "…evidence is strong that some chondrules cooled very quickly, probably through the range of 1500 – 1000 K in a matter of minutes…". It took approximately 25 years of investigations to quantify the petrography of chondrules and combine these data with the experimental reproduction of chondrules to test his hypothesis. The same can be stated for calcium-aluminum-rich inclusions (CAIs), although their importance was not understood in 1963. As is reviewed in the following chapters, Wood was essentially correct.

2. Refractory Inclusions and Chondrules: What are They?

2.1. Overview

Numerous reviews concerning the petrographic, geochemical, and isotopic compositions, and the constraints that these properties place on the origin of refractory inclusions [CAIs and amoeboid olivine aggregates (AOAs)] and chondrules have been published in recent years (Jones & Scott 1996; Hewins 1997; Brearley & Jones 1998; Jones et al. 2000; Rubin 2000; Connolly & Desch 2004; Krot et al. 2004; MacPherson 2004; Zanda 2004). Within this volume, specifically the chapters following this summary, the advances that have been made in our understanding of CAIs, chondrules, and their formation since the 1996 publication of *Chondrules and the Protoplanetary Disk* are concisely reviewed. Taken individually, they are reviews of specific areas in the study of refractory inclusions, chondrules, and the constraints that these objects place on disk evolution. Then, by considering all the chapters together, the big picture of the nature of these objects, their formation, and properties of a protoplanetary disk are brought to light.

2.2. Defining Refractory Inclusions and Chondrules

Figure 1 is a schematic representation of the terminology for and relationships between refractory inclusions and chondrules. The point of the illustration is to provide a basic framework for understanding the compositional diversity of these objects and the issues surrounding both their existence and their formation. Because of the diversity of these objects it is not easy to simply and clearly state a definition of refractory inclusions or chondrules. Petrographically, the identification of these objects is almost always obvious and most researchers observing a thin section of a chondrite would at least be able to distinguish refractory inclusions from chondrules (Figs. 2-4).

MacPherson, Wark, & Armstrong (1988), MacPherson (2004), and Krot et al. (2004) reviewed the definition and classification of refractory inclusions. It is important to note that the term CAI is often used synonymously with refractory inclusion, although to be technically correct CAIs are a subset of refractory inclusions. As a very simple working definition, refractory inclusions are defined as rocks that may or may not be igneous and that contain minerals dominated by phases having a high vaporization temperature, the primary minerals being rich in Al and Ca, ranging in size from submillimeter to several centimeters. In some of these objects, the composition matches closely to the first solids predicted to condense from a gas of solar or enhanced solar composition.

Chondrules, which are always igneous (although the degree of melting can be debated) are silicate-dominated crystallized melt spheres often composed of olivine ($(Fe,Mg)_2SiO_4$), pyroxene ($(Fe,Mg)SiO_3$), anorthite ($CaAl_2Si_2O_8$), and other phases such as glasses, sulfides, Fe, Ni-metals, chromites ($(Fe,Mg)(Cr,Al)_2O_4$), and many other minor components. Chondrules are submillimeter in size and can be found as fragments with clearly defined arcs or as broken pieces. Both the composition and sizes of refractory inclusions and chondrules vary among chondrite classes and often chondrite groups, but they are, to date, only observed within chondrites (with the exception of CI). Most recently, Connolly & Desch (2004) reviewed the classification of chondrules. Unless good future arguments are presented to the contrary, refractory inclusions and chondrules are only found within chondrites and thus only those objects from chondrites should be considered refractory inclusions or chondrules. In the following chapters, more details on the characteristics of refractory inclusions and chondrules will be presented that should clear any confusion or doubts as to their nature.

3. Pertaining to the Nature and Origins of Refractory Inclusions and Chondrules

3.1. Why Investigate these Rocks?

The answer to this question is simple – because they are rocks and rocks tell a story. It is the job of geology and related fields to understand rock formation. It is perfectly legitimate to study one CAI at a level of detail that is almost unheard of in terrestrial geology. Such information then provides powerful constraints on the precursors, thermal histories, and post-formation alteration of these rocks. In addition, the presence of refractory in-

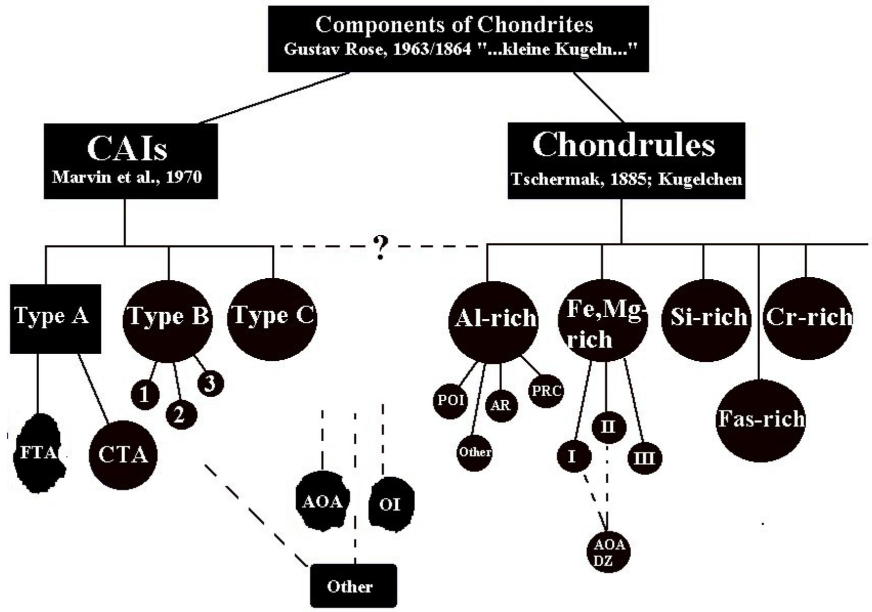

Figure 1. Schematic of the various types of refractory inclusions and chondrules found in chondrites. Chondrites were given their name in 1863 by Rose who also termed the inclusions he saw within them "kleine Kugeln". Tschermak (1885) termed the klein Kugeln as Kugelchen which was later somehow translated into English as chondrules (Connolly & Desch 2004). The term calcium-aluminum-rich inclusion was coined by Marvin et al. (1970). All those objects that are definitively igneous rocks are shown as black circles. Objects where it is not clear if they are igneous or if not all of their compositional types are igneous are represented in various non-round shapes. Solid lines represent a clear compositional relationship between objects. Dashed lines indicate that the verdict is still out as to a compositional relationship. Type A CAIs are classified into Fluffy Type A (FTA) and Compact Type A (CTA). Type B CAIs are sub-divided into B1, B2, and B3. Al-rich chondrules are subdivided into many different types including plagioclase-olivine inclusions (POI), anorthite-rich (AR) and plagioclase-rich chondrules (PRC). Fe, Mg-rich chondrules are subdivided into types I, II, and III based on their compositions. The acronym AOA appears in two places; under Fe, Mg-rich chondrules, AOA means agglomeratic-olivine aggregates and as a blue-colored object AOA means amoeboid-olivine aggregate. DZ = dark zoned chondrule. OI = olivine inclusion. The right side of the chondrule section is not terminated because there are numerous other, rare chondrule types such as those from CH chondrites. I have included as many nomenclature data as possible, even in areas where similar kinds of materials have been termed differently by different authors. The aspiration of this approach is that it can clear confusion in the nomenclature that the non-specialist may experience.

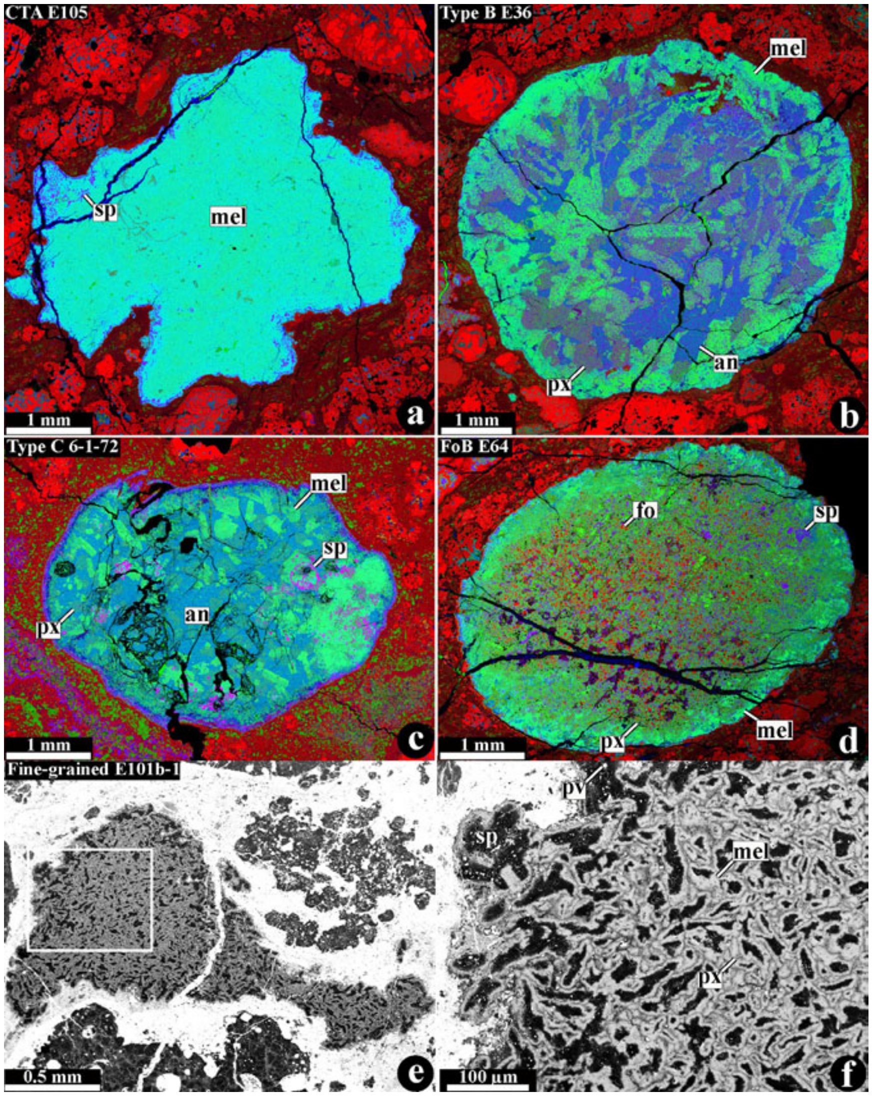

Figure 2. Combined X-ray elemental images (a-d; red = Mg, green = Ca, and blue = Al) and backscattered electron images (e, f) of different types of CAIs: (a) compact Type A (CTA), (b) Type B, (c) Type C, (d) forsterite-bearing Type B, and (e, f) fine-grained spinel-rich. Region outlined in (e) is shown in detail in (f). The Type C CAI is from the CV chondrite Allende; others are from the CV chondrite Efremovka. All CAIs, except the fine-grained inclusion, have igneous textures, indicating crystallization from melt; the fine-grained CAI appears to have formed by aggregation of gas-solid condensates. an = anorthite ($CaAl_2Si_2O_8$); fo = forsterite (Mg_2SiO_4); mel = melilite (solid solution of åkermanite ($Ca_2MgSi_2O_7$) and gehlenite ($Ca_2Al_2SiO_7$); pv = perovskite ($CaTiO_3$); px = Al,Ti-diopside; sp = spinel ($MgAl_2O_4$). Courtesy of A. Krot.

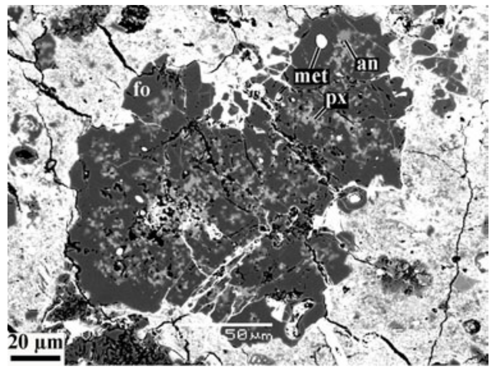

Figure 3. Backscattered electron image of an amoeboid olivine aggregate from the ungrouped carbonaceous chondrite, Acfer 094. an = anorthite; fo = forsterite; met = Fe, Ni metal; px = Al-diopside. Courtesy of A. Krot.

clusions and chondrules provides an important opportunity within science to gain insight into the material present and the processes that occurred within a protoplanetary disk. Observational astronomy cannot yet provide views into stellar disks. Thus, to investigate the origins of these objects is to place constraints on the evolution of rock-forming materials within the disk (why are CAIs and chondrules compositionally so different?), on transient heating events (what melted these objects?), on early asteroid processes (what happened to them after accretion?) – the list is vast and impressive. Finally, we do not have any rocks on Earth that are as old as chondrites and their components. Therefore, by investigating these rocks, constraints on the materials that made terrestrial planets and potentially aspects of forming such planets are determined.

3.2. Critical Issues to Evaluate in the Origins of Refractory Inclusions and Chondrules

Listed below are some of the most important issues that are explored in this section of the proceedings and are provided as a blueprint for the focus of future research.

Molten spheres: As is illustrated by Figure 1, most CAIs and chondrules, both in the types or compositional diversity of objects and their absolute numbers, are igneous rocks. From astronomical or astrophysical hypotheses concerning the origin of a solar system CAIs and chondrules would not be predicted to exist if they did not exist. The formation of planetary bodies within the inner solar system, from the approach used in astronomy or astrophysics, does not require that CAIs and chondrules be made before planets. However, from the approach applied by meteoritics, it is a common assumption that CAIs and chondrules are pre-planetary. Therefore, some unknown mechanism or mechanisms probably processed at least 10^{24} g of CAI and chondrule materials (Connolly & Desch 2004). This fact presents many questions. What was the mechanism? Why and how did the mechanism(s) operate? How many mechanisms existed? When within the life of the disk did the mechanism start to process materials? How long did the mechanism(s) last? Why did it or they stop? What, if any, relationship existed between the mechanism(s)

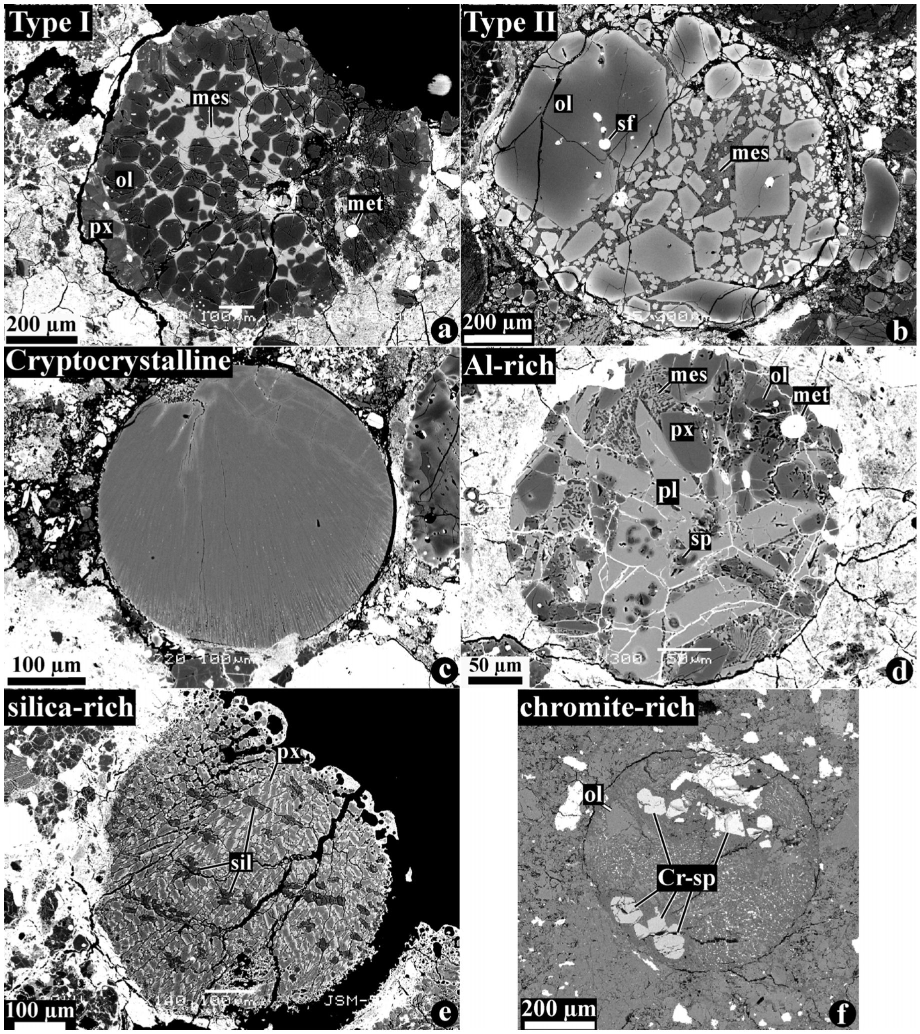

Figure 4. Backscattered electron images of various chondrule types. a - Magnesium-rich (Type I) chondrule composed of forsteritic olivine (ol), low-Ca pyroxene (px), glassy mesostasis (mes), and Fe, Ni metal (met). b - Ferrous-rich (Type II) chondrule composed ferrous olivine (ol), microcrystalline mesostasis (mes), and troilite (sf). c - Cryptocrystalline chondrule. d - Aluminum-rich chondrule composed of anorthitic plagioclase (pl), forsteritic olivine (ol), low-Ca pyroxene (px), Fe, Ni metal (met), and spinel (sp). e - Silica-rich chondrule largely composed of low-Ca pyroxene (px) and silica (sil). f - Chromite-rich chondrule largely composed of chromium-spinel (Cr-sp), olivine (ol). Courtesty of A. Krot.

and terrestrial planet formation? MacPherson et al., Hewins et al., and Russell et al. explore many of these issues within this volume.

Thermal Histories of CAIs and chondrules: Although 20 years of research has provided many powerful constraints on the thermal history of CAIs and chondrules, Hewins et al. and Jones, Grossman, & Rubin (this volume) discuss many questions that remain unsolved or are without unique solutions. Such issues include: What was the environmental condition experienced by CAIs and chondrules before they were melted? What was the post-formation, pre-accreationary environment like? What was the thermal history of CAIs and chondrules after they were melted but before they were accreted? What was the time duration between melting, alteration, and re-melting for igneous CAIs? How many times were individual objects melted and re-heated? What are the differences in the environmental conditions during melting, such as the abundance of particles, between CAIs and chondrules? Why did igneous CAIs experience Rayleigh fractionation but chondrules did not? Is lack of evidence for Rayleigh fractionation in chondrules representative of higher partial pressures of elements and/or higher total pressure during melting than experienced by CAIs? Is it related to the abundance of particles present before and during melting? What was the physical and chemical nature of CAI and chondrule precursors? Is the redox state of CAIs and chondrules reflecting precursors, thermal processing, or both? Finally, what controlled the distribution of CAIs within chondrites?

Composition of CAIs and chondrules: Within Figure 1, a dashed line is used to connect CAIs and chondrules. The implication of the dashed line is that the compositional relationship between the two groups of objects is unknown, if any exists. To speculate, it is possible that CAIs, or at least their precursors, being the most refractory, formed first and chondrule precursors formed at a later time. Several lines of evidence support this hypothesis, but none of them are definitive. CAIs appear to be slightly older than chondrules, which we can use as a reasonable working hypothesis. This suggests that the compositions of objects being processed into crystallized melt droplets evolved over time from highly refractory to less so. However, another hypothesis that cannot be entirely ruled out is that the composition of CAIs and chondrules are co-genetic representing different areas within the protoplanetary disk and that in time their ages will be found to be similar if not identical. The major questions that need to be explored and answered are: What is the compositional relationship between CAIs and chondrules? Is there any compositional relationship? Why does such a diversity of compositions exist? Does a relationship exist between the composition of CAIs and chondrules to the mechanism(s) that produced them? Is there a relationship between the variations in the composition of these objects, the mechanism that produced these variations, and the different bulk compositions of the inner planets? MacPherson et al. (this volume) and Russell et al. (this volume) explore aspects of this important issue.

The oxygen isotope story: As a general observation, CAIs are more ^{16}O-rich than chondrules. As discussed by Kawamoto & Yurimoto and by Lyons & Young (this volume), many hypotheses to explain the difference are explored ranging from mixing of materials to photochemical reactions. It appears at the writing of this chapter that the oxygen record points to a simple conclusion – CAIs and chondrules, or at least their precursors, formed in environments that were vastly different. It is important to remember that the oxygen data do not necessarily support a hypothesis that the mechanism that melted igneous CAIs and chondrules was different. Indeed, it could have been the same mechanism but the time at which the material was processed was different. If the mechanism was similar to the X-wind hypothesis (Shu et al. 1996), then it is possible that material was evolving from refractory to less so within the disk and radially transported to the X-point or a similar area. Similarly, rock-forming materials may have been evolving in the disk due to thermal processes by nebular shocks, perhaps combined with radial transport. Again, although speculation, these issues cannot yet be dismissed and are explored to various degrees in this volume.

Formation ages of CAIs and chondrules: A major issue is constraining the epoch of melting and processing of CAIs and chondrules within the disk. As is shown in Figure 5,

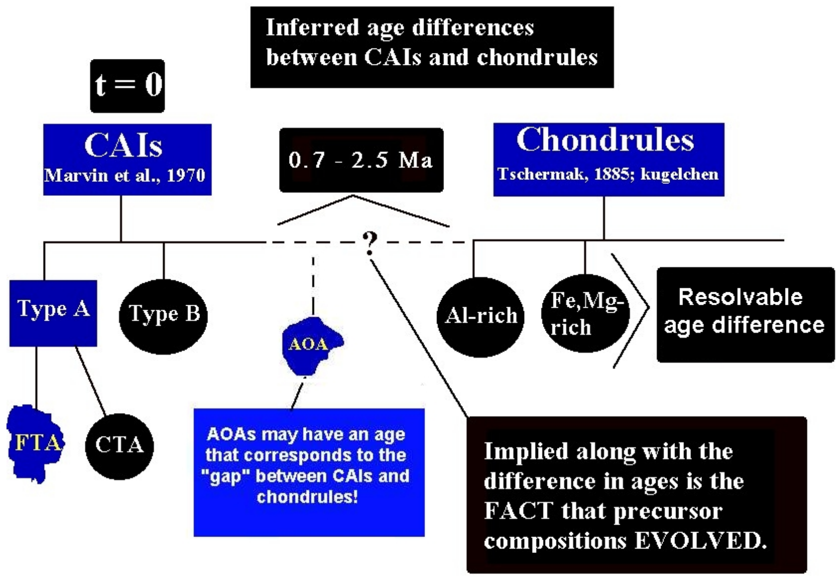

Figure 5. Modified version of Figure 1 showing the age difference between CAIs and chondrules. AOA may have ages that fall in the "gap" between CAIs and chondrules. It appears from recent research that it may be possible to resolve a relative age difference between the different types of Fe, Mg-rich chondrules; MgO-rich chondrules being older than FeO-rich chondrules. Regardless of whether an age gap exists between CAIs and chondrules, it is very clear that the material being processed into igneous spheres evolved over a million years from refractory to less so.

the data are interpreted to suggest that the melting of the two sets of objects was separated by at least 0.7 and up to 2.5 million years. The overall processing of chondrules may have lasted as long as 5 million years and the vast majority of them may have originated after formation of CAIs with a canonical $^{26}Al/^{27}Al$ ratio of 5×10^{-5} (Kita et al., this volume). Although discussed in more detail in section 4 of this volume, it is nonetheless pertinent to the perspective of this section. If this "time gap" for the formation of CAIs and chondrules continues to stand the rigors of the scientific method over the course of the next decade, then some important implications must be understood and investigated. First, regardless of the name of the objects, it appears that material being processed into spheres or at least experiencing some degree of melting in the nebula evolved over time from refractory to less so. This is an important point to continue to emphasize. Although the data are still very preliminary, Krot et al. (2004) point out some AOAs have a relative age of 0.3 to 0.5 million years after CAI formation. That lands them smack in the middle of the "time gap" between CAI and chondrule formation. If these data hold upon study of more AOAs, it would appear that there is no time gap, but rather a continuum of processing and what is recorded is the evolution of planet-forming materials over time. If the data support a gap in the future, then serious consideration is warranted to hypotheses such as CAI and chondrules were melted by different mechanisms. Second, can a difference in the formation ages of Fe, Mg-rich chondrules be determined with confidence? Research is suggesting that such a difference may exist (Tachibana et al. 2003 and references therein), but the verdict is far from delivered. If true, however, then at a more subtle level the evolution of primitive planetary materials over time is revealed.

The Beryllium Story: The discovery of ^{10}Be in CAIs and subsequent claims of ^{7}Be can be interpreted to suggest that at least some of the precursors of CAIs experienced irradiation from solar energetic particles before melting (Goswami et al., this volume). These data and this particular interpretation are used as support that the objects melted in an X-wind model or at least some model for the formation of these objects that involved the early active Sun (Gounelle et al. 2001). However, more than one hypothesis for the presence of ^{10}Be exists and it cannot be viewed convincingly as a smoking gun for solar irradiation (Desch, Connolly, & Srinivasan 2004). Several questions are raised by the data and interpretations: Do all CAIs and other refractory inclusions contain ^{10}Be? Do chondrules contain ^{10}Be? Where was it produced and what can be inferred from its presence? If CAIs or their precursors were irradiated by energetic particles from the Sun, what are the implications of such a conclusion?

4. Concluding Remarks

Towards the end of John Wood's keynote address at the conference, he presented what can be considered to be a highly provocative concept. To paraphrase, he suggested that CAIs may have formed early during the life of the disk as free-floating objects whereas chondrules are the product of collisions or some other physical process that involved planetesimals. Such an idea, forming these objects by two different mechanisms and one of them involving planetesimals, is not currently in favor with many meteorite researchers. However, John Wood has an interesting point. First, the production of chondrules (or potentially CAIs) as the result of collisional events has not been quantitatively ruled out---however unpopular an idea it may be. Second, and perhaps more important, John Wood's statement points out an overlooked issue within meteoritics. No clear link has been made between refractory inclusions, chondrules, and the formation of inner planets. Such a concept is one of the basic foundation assumptions of meteoritics. Exploring such links needs to be the focus of future research. If chondrules (and potentially CAIs) are discovered to be the by-product of planet formation rather than a critical component or foundation step in their formation, our view of the internal processes of a protoplanetary disk and the importance of chondrules (and potentially CAIs) as recorders of nebular processes will be changed to a level that will change the field.

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