Blowing in the Wind: II. Creation and Redistribution of Refractory Inclusions in a Turbulent Protoplanetary Nebula

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Abstract: Ca-Al rich refractory mineral inclusions (CAIs) found at 1-6% mass fraction in primitive chondrites appear to be 1-3 million years older than the dominant (chondrule) components which were accreted into the same parent bodies. A prevalent concern is that it is difficult to retain CAIs for this long against gas-drag-induced radial drift into the sun. We reassess the situation in terms of a hot inner (turbulent) nebula context for CAI formation, using analytical models of nebula evolution and particle diffusion. We show that outward radial diffusion in a weakly turbulent nebula can overwhelm inward drift, and prevent significant numbers of CAI-size particles from being lost into the sun for times on the order of 10^6 years. CAIs can form early, when the inner nebula was hot, and persist in sufficient abundance to be incorporated into primitive planetesimals at a much later time. Small ($\lesssim$ 0.1 mm diameter) CAIs persist for longer times than large ($\gtrsim$ 5mm diameter ones. To obtain a quantitative match to the observed volume fractions of CAIs in chondrites, another process must be allowed for: a substantial enhancement of the inner hot nebula in silicate-forming material, which we suggest was caused by rapid inward drift of meter-sized objects. This early in nebula history, the drifting rubble would have a carbon content probably an order of magnitude larger than even the most primitive (CI) carbonaceous chondrites. Abundant carbon in the evaporating material would help keep the nebula oxygen fugacity low, plausibly solar, as inferred for the formation environment of CAIs. The associated production of a larger than canonical amount of CO_2 might also play a role in mass-independent fractionation of oxygen isotopes, leaving the gas rich in ^{16}O as inferred from CAIs and other high temperature condensates.

1 Introduction

Chondrite parent bodies are dominated by particles with a surprisingly well-defined range of physical, chemical, and petrographic properties. Fe-Mg-Si-O mineral chondrules, many of which solidified from melted precursors stable at $T < 680$K, constitute 30-80% of primitive meteorites. Most workers in the field believe that chondrules are formed by either localized or nebula scale energetic events operating on freely floating precursors of comparable mass, at some location or locations in the protoplanetary nebula (see *eg.* Grossman 1989, Grossman *et al.* 1989, Boss 1996, Connolly and Love 1999, Jones *et al.* 2000, and Desch and Connolly 2002).

A different class of mineral grains called Ca-Al-rich inclusions (CAIs), whose constituent minerals condense out of nebula gas at a much higher temperature ($T > 1500$K), make up 1-6% of primitive meteorites depending on CAI and chondrite type. Many, but not all, have