PYROXENE CHONDRULES FROM OLIVINE-DEPLETED, DUST-ENRICHED SYSTEMS. D. S. Ebel[1], A. Engler[2,3], and G. Kurat[3]. [1]Dept. of Earth and Planetary Sciences, American Museum of Natural History, New York, NY 10024 (debel@amnh.org), [2]Department of Mineralogy and Petrology, University of Graz, Universitätsplatz 2, A-8010 Graz, Austria, [3]Naturhistorisches Museum, Postfach 417, A-1014 Vienna, Austria.

Introduction: The principal solid precursor components of chondrules are nebular condensates and/or presolar interstellar grains. In either case, the precursors are most likely dominated by forsterite (Mg_2SiO_4), iron-nickel metal, Ca-aluminate phases, and a C-rich component [1-5]. It is reasonable to explore the consequences of enriching a solar gas in these components, on local scales in the early nebula, in ratios which yield CI chondritic abundances of rock-forming elements, in considering the formation of meteorite components (i.e.-chondrules) [6].

Silicate liquids and FeO-bearing silicates are the main components of ferromagnesian chondrules. Neither is stable in a vapor of solar composition under nebular conditions, except at extremely high total pressure ($P^{tot} > 10^{-1}$ bar), but both are thermodynamically stable in dust-enriched systems at $10^{-6} < P^{tot} < 10^{-3}$ bar [6]. In chemical systems of solar bulk composition, and in such systems enriched in dust of CI bulk composition, Mg/Si = 1.074. In these systems, olivine, $(Mg,Fe)_2SiO_4$, always becomes the dominant thermodynamically stable condensed phase at a temperature at least 100° higher than that at which orthopyroxene, $(Mg,Fe)SiO_3$, appears, regardless of P^{tot} [6]. For example, in a cooling gas with a CI dust enrichment factor of 800x, $P^{tot} = 10^{-3}$ bar, olivine appears at 1980 K, opx at 1650 K, metal at 1790 K. At 500x enrichment, these T are 1940, 1700, and 1780 K, respectively (Fig. 1). Thus olivine-rich chondrules with unfractionated REE are to be expected, if these chondrules formed near thermodynamic equilibrium as liquid droplets, in systems enriched in unfractionated chondritic dust.
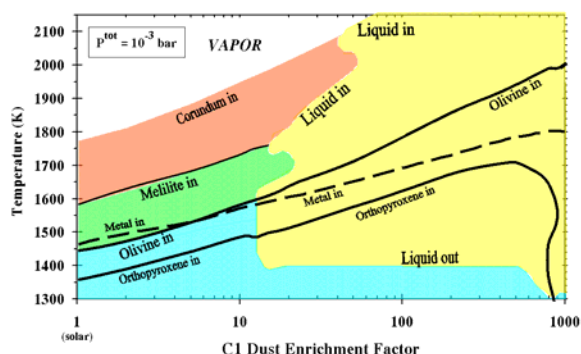

Fig 1: Stability of orthopyroxene relative to silicate liquid (yellow) and olivine, in dust-enriched systems.

Among the chondrites, the most abundant lithophile elements, Si and Mg, are significantly fraction-ated [7]. Among rapidly quenched chondrules (e.g.-barred olivine, radiating pyroxene), a wide variation in Si/Mg ratio yields enstatitic ($MgSiO_3$-rich) as well as forsteritic varieties, yet many pyroxene chondrules also have unfractionated REE patterns, in many types of chondrites [8]. These chondrules may have acquired their REE from unfractionated precursor material before becoming molten, if the REE were not fractionated by the process which fractionated Mg from Si.

In considering the formation of enstatitic chondrules, it is reasonable to explore the consequences of enriching a solar gas in differing amounts of the components forsterite, iron-nickel metal, Ca-aluminate phases, and a C-rich component [e.g.-9, 10]. Any fractionation process in which a high-temperature silicate liquid is removed should leave a residuum with fractionated REE pattern. Removal of forsterite dust, however, should increase the Si/Mg ratio without necessarily disturbing the REE abundances in the residuum.

The work reported here is a simple exercise, to determine how much olivine depletion from the dust-enriched systems of [6], would be necessary to make enstatitic pyroxene stable at a higher temperature than forsteritic olivine. Fractional condensation of solar and dust-enriched systems has been explored for the assumption of isolation of fixed percentages of all minerals as they condense [11]. Here, fractionation of the primordial dust is explored, to address the chemical conditions under which silicate liquids coexisting with Fe-bearing orthopyroxene, in the absence of co-crystallizing olivine, would be thermodynamically stable.

Technique: Starting compositions are vapor of solar composition, enriched in CI chondrite dust as in [1]. From these, a percentage of the Mg was removed as forsterite, Mg_2SiO_4, decreasing the Mg/Si ratio in the bulk composition of the chemical system, relative to the chondritic ratio. These bulk compositions were cooled from 2400 K to 1300 K, at fixed P^{tot}, in 10 K steps. The equilibrium distribution of elements between thermodynamically stable vapor, mineral, and silicate liquid phases was calculated at each step using the VAPORS computer code [1, 12].

Results: One might estimate that the depletion of olivine necessary to make enstatite appear at higher T than olivine, would be the amount of olivine which has condensed at the time enstatite appears in an undepleted, CI dust enriched system. In the undepleted system at 800x (Fig. 1), olivine appears at 1980 K.

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When enstatite becomes stable at 1650 K, 19% of Mg is in liquid, 81% in olivine. Similarly, in a 500x enriched system, enstatite is stable at 1700 K, with 21% Mg in liquid, 79% in olivine, and at 200x, stable at 1670 K, with 16% Mg in liquid, 82% in olivine, and 2% in the vapor.

Stability fields of silicates are plotted in Fig. 2, calculated at 0, 10, 20, 30, 50, 60, 70, 80 and 90 % depletion in Mg as Mg_2SiO_4, for systems initially enriched in CI dust by 800x above solar. Thus the undepleted system is shown along the left side of Fig. 2, with increasing initial depletion in Mg_2SiO_4 toward the right. The sequence of mineral stabilities is remarkably stable up to very high percentages of olivine depletion. At all olivine depletions, silicate liquid is present at high temperatures. Silicates and spinel crystallize from liquid under the conditions investigated, while at high temperatures elements continue to condense into liquid from the vapor phase. Liquids crystallize completely near 1400 K in all cases, primarily to feldspar and pyroxenes. Orthopyroxene does not crystallize at a higher temperature than olivine, unless more than about 70% of the Mg has been removed as Mg_2SiO_4, such that olivine has no stability field at all. At 800x (Fig. 2), a narrow region of enstatite (opx) stability occurs near 1800 K, but enstatite dissolves back into liquid with decreasing temperature as the remaining Si condenses from vapor into liquid. Above ~75% depletion, feldspar $Ca_2Al_2Si_2O_8$ crystallizes from liquid at progressively higher temperatures. Above ~85% depletion, cristobalite SiO_2 becomes the silicate stable at the highest temperature.
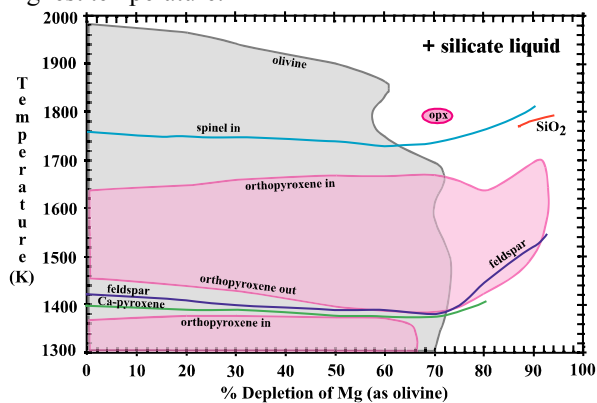

Fig 2: Stability fields of silicates at $P^{tot} = 10^{-3}$ bar, in a solar gas enriched 800x in CI dust, and depleted in Mg_2SiO_4 olivine.

The fayalite, Fe_2SiO_4, content of olivine (X_{fa}) increases slightly above that reported by [6] at all temperatures, with increasing Mg depletion. X_{fa} ranges from ~0.1 at 1800 K for all Mg depletions, to ~0.24 at 0% depletion and ~0.30 at 70% depletion at 1400 K. The ferrosilite, $FeSiO_3$, content of orthopyroxene (X_{fs})

is ~0.14 at 1600 K at all Mg depletions, only increasing slightly, with decreasing temperature, as Mg depletion increases. At lower dust enrichments, mean values at 1600 K decrease to X_{fs} ~0.09±0.01 at 500x and X_{fs} ~0.045±0.005 at 200x.

Conclusions: In all cases investigated, 200x, 500x, as well as 800x dust enrichment, enstatite does not crystallize at a higher temperature than olivine, unless more than about 70% of the Mg has been removed as Mg_2SiO_4. Mg-depletion as forsterite does not appreciably affect the FeO content of resulting crystalline silicates.

This result severely compromises any model which require orthopyroxene to form as the stable (equilibrium) silicate, in the absence of olivine, coexisting with liquid under nebular conditions. Such a model would seem to require that *all* opx-rich, ol-free rapidly quenched chondrules formed in locally olivine-depleted environments within a very narrow window of possible bulk compositions.

More generally, it is remarkable that such tremendous excursions from chondritic ratios of elements are required to significantly alter condensation systematics. We have seen this before, in the insensitivity of those systematics to variations in the C/O ratio below ~0.98 [*e.g.*-13]. In the universe of mineral assemblages, "chondritic" (*i.e.*-solar) is a deep well of thermochemical stability, a strange attractor which cosmically feeds back upon itself as generations of condensed stardust beget new generations of stars, chondritic meteorites, and planets.

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