ACFER 182 GIVES NEW CLUES TO CHONDRULE FORMATION.

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Introduction: Acfer 182 is a member of the CH carbonaceous chondrite group characterized by small chondrules (~90 µm) and Ca-Al-rich inclusions (CAIs) [e.g., 1-2]. The parallel decrease in moderately volatile element abundances with condensation temperatures, of metal and silicates, suggest a similar condensation history [3]. The chondritic Co/Ni ratios shown by metal grains suggest that they experience a low degree of metamorphism, and was interpreted as a clue to its nebular formation [e.g., 4-5]. The presence of metal with compositional zoning signals fractional condensation from a cooling gas [6]. Therefore, it is widely accepted that the observed properties of the CH chondrites are the result of nebular condensation processes [1, 7-8]. Here, I report the study of Mg-rich cryptocrystalline (CC) and ferreous radiating pyroxene (RP) chondrules as a contribution to better constrain chondrule formation processes.

Results: Acfer 182 (PTS from M6013, NHM, Viena) is very rich in perfectly round Mg-rich CC and ferrous RP chondrules with apparent diameters varying from 45 to 140 µm. From the 25 studied chondrules, 21 have CC textures with low FeO contents (~ 0.3-3.2 wt%) and 4 have RP texture with high FeO contents (~ 15.5-19 wt%). All chondrules have low contents of refractory lithophile elements (Ca, Al) with a continuous range of concentrations varying from ~1xCI to <0.01xCI; show depletion in Mn, Na and Fe and are characterized by a Ca/Al ratio around chondritic values (Ca/Al: 1.2) (Fig. 1). All chondrules have a hypersthene-olivine normative composition.

Two of these chondrules (VIIIa and XIVc) have metallic Fe-Ni globules, as follow: 1) Acfer XIVc is a fine-grained radiating pyroxene chondrule (60 µm in apparent diameter) with a subhedral metal grain (~ 15 µm, Fig. 2A) composed of kamacite (Ni: 12 wt%, Fe: 87 wt%) and taenite (Ni; 44 wt%, Fe: 55wt%). Attach to the metal grain is a very small SFe (Fig. 2B). 2) Chondrule VIIIa is a fine-grained radiating pyroxene chondrule (100 µm in apparent diameter) with small (up to 5 µm) euhedral (cubic) to round metallic globules (Fig. 2 C-D). The metal show high content of Ni (21.5 – 26 wt%) and Co (0.62 – 0.88 wt%). The silicate material of both chondrules have a hypersthene-olivine normative composition. Nine chondrules (7 CC and 2 RP) have been studied by SIMs. They show highly variable contents in REE with normalized abundances varying from 0.02 to 2 x CI (Fig. 3-4). Based on their REE patterns, chondrules are divided in two types:

A) F-REE (Fractioned-REE): having variable La/Lu ratios with positive Eu and Ce anomalies. Some of these objects show in addition an Yb positive anomaly (Fig. 3).

B) U-REE (Unfractioanted-REE): having REE normalized abundances varying from 0.2 to 1.3 x CI. Only two objects (Acfer X and XIVa) show a slight positive Ce anomaly with chondrule Acfer X showing in addition, a clear positive Yb anomaly (Fig. 4).

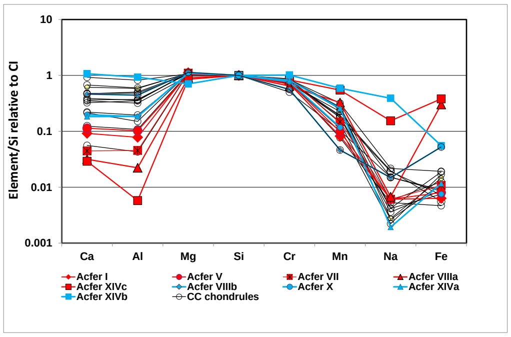

Figure 1: Bulk concentrations of major and minor lithophile elements in studied chondrules.

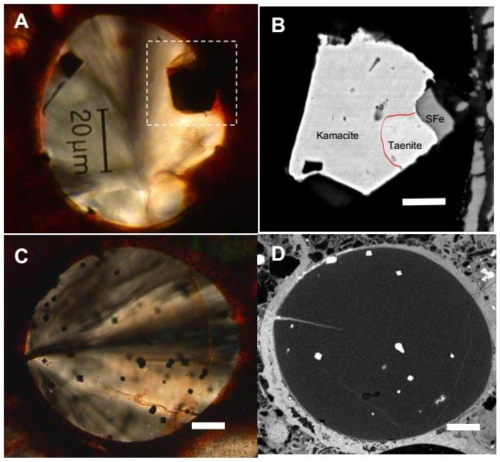

Figure 2: A) Transmitted light image of the RP chondrule Acfer XIVc. B) Detail of the metal grain (scale bar: 4 µm). C-D) Transmitted light and SEM images respectively, of the RP chondrule VIIIa. Scale bar: 20 µm.

Discussion: Ni-rich metal grains present in VIIIa and XIVc are not common in CH and CR chondrites characterized by containing up to 22 wt% Ni, except few metal grains in chondrule cores in Yamato-8449 having exsolution taenite lamellae up to 4 micrometers in width [5, 9]. Cobalt and Ni from the studied metal fall below the cosmic Co/Ni ratio, similar to what has been reported in FeNi grains of other CH chondrites [9]. The metal grain in chondrule XIVc show Co and Ni concentration that fall within the range of those found in the core of chondrules in the CR chondrites Renazzo and Al Rais [5] and plot on the condensation path of metal condensing from a gas with dust/gas ratio of 200 x CI at $P_{tot} = 1x10^{-4}$ bar [9].

Both, F-REE and U-REE chondrules show similar fractionation patterns for the very refractory elements Zr, Y, Sc and Nb. However, they differ in their normalized abundances being the U-REE chondrules one or two orders of magnitude richer in Zr, Y and Sc (from 0.1 to 1 x CI) as compared to the F-REE (0.01 to 0.1 x CI). All studied objects show high contents of Nb. The chondritic Ca/Al ratio of the studied chondrules with a positive Yb-La correlation around CI values, points towards their formation by gas/liquid condensation. As CAIs seems to have been present in the same reservoir were chondrules formed [e.g., 10-12], their early condensation depleted the reservoir in most of the refractory trace elements. Formation of F-REE chondrules from such a gas, might have taken place at temperatures low enough to allow Eu and Yb (and Nb) condensation. As for the moderately volatile and volatile elements (Sr, Ba, V, Cr, Mn and Rb) all F-REE chondrules exhibit a similar pattern; with increasing Sr and Ba abundances; around chondritic contents for V and Cr, and decreasing abundances of the volatiles elements Mn and Rb. Conversely, the U-REE chondrules show variable abundances of Sr, Ba, Mn and Rb but chondritic V and Cr contents. The fact that V, Mn and Cr abundances in F-REE and U-REE chondrules are similar to those of bulk Acfer 182 (Fig. 3-4), suggest that addition of both elements must have occur at relatively low temperatures during and after the chondrule forming process. The chondritic abundances of V and Cr indicate that such addition took place in equilibrium with the chondritic reservoir. However, the variable abundances of the very volatile Rb in CC and RP chondrules (Fig. 3-4) indicate the existence of exchange reactions with the chondritic reservoir during cooling. The efficiency of these reactions must have been variable as shown by the strong fractionation displayed by the volatile lithophile Rb. Such exchange reaction, taking place during chondrule formation, is not restrict to CC and RP chondrules in Acfer 182 but was previously detected in non-porphyritic chondrules form unequilibrated ordinary chondrites [13], in equilibrated Rumuruti and ordinary chondrites [14] and in chondrules and micro-objects in some CM2, CR2 and C3 chondrites [15]. Therefore, the variable abundances of moderately volatile and volatile elements (e.g., V, Cr, Mn, Rb) during or after chondrule formation do not necessarily require isolation of chondrules from the hot nebular gas before condensation of these elements [16]. But requires a process related to the variable efficiency under which the exchange reactions took place during cooling of the chondritic reservoir. Consequently, one would expect to find all intermediate REE patterns to be present in Acfer 182 chondrules (e.g., U-REE and F-REE chondrules) as they condense at decreasing temperatures, yielding large variations in their trace element contents (Fig. 3-4). The final abundance pattern for each individual chondrule will depend on how all these processes got to completion.

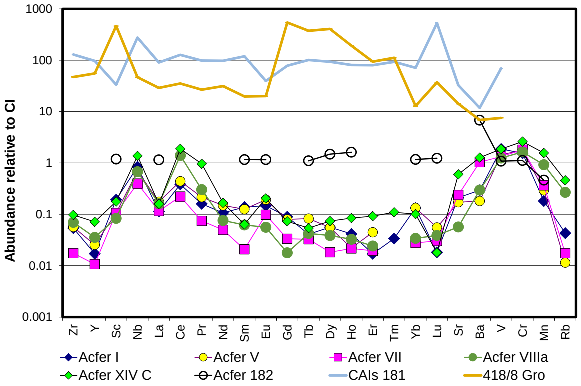

Figure 3: CI-normalized trace element abundances of F-REE chondrules. Bulk Acfer 182 [1], CAIs 181 and grossite 418/8 [2] are given for comparison.

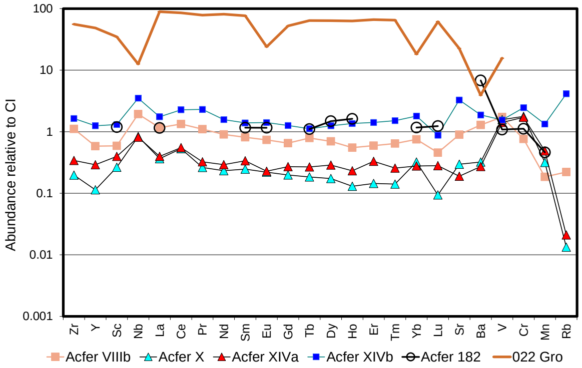

Figure 4: CI-normalized trace element abundances of U-REE chondrules. Bulk Acfer 182 [1] and grossite 022 [2] are given for comparison.

References: [1] Bischoff A. et al. (1993) *GCA* **57**, 2631-2648; [2] H.W. Weber et al. (1995) *GCA* **59**, 803-823; [3] Palme and Spettel (1992) *Meteoritics*, **27**, 272-273; [4] Grossman and Olsen (1974) *GCA* **38**, 173-187; [5] Weisberg M. et al. (1988) *EPSL*, **91**, 19-32; [6] Meibon et al. (1999) *JGR*, **104**, 22053–22059; [7] Weisberg M. et al. (1995) *Proc. NIPR Sym. Antarct. Met.* **8**, 11-32. [8] Scott E. R. D.(1988) *EPSL* **91**, 1-18; [9] Krot A. et al. (2000) *MAPS* **35**, 1249-1258 ; [10] Krot A. et al. (2009) *GCA* 4963–4997; [10] Bonal L. et al. (2010) *GCA* 2500–2522;]12] Krot A. et al. (2002) *MAPS* **37**, 1451-1490 ; [13] Engler A. et al., (2007) *Icarus*, 248-286 ; [14] Varela M.E. et al. (2012) *MAPS*, **47**, 1537–1557; [15] Engler A. et al. (2003) *MAPS*, **38** #5157; [16] Russell S. et al. (2000) *MAPS* **53** (Suppl.) A139.