ELEMENTAL DISTRIBUTION IN METAL FROM THE CR CHONDRITES Acfer 059 AND PCA 91082.

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Introduction: CR chondrites contain abundant metal, including metal blebs rimming chondrules [1-4]. Models for CR rim metal formation include direct condensation from a solar gas [1], formation by reduction of FeO [2], or re-deposition of vapor [2-3, 5-6]. Two recent studies have built a persuasive case for the role of surface tension in concentrating the metal on CR chondrule rims [7-8]. Wasson and Rubin [4, 8] proposed that surface tension would create a sphere of liquid metal on chondrule surfaces, and that a decrease in surface tension on cooling would break the sphere into beads, such as are presently observed on the surfaces of CR chondrites. They observed that CR metal on the rims of chondrules are compositionally homogeneous in Co and Ni abundances (±10% relative variations) within a chondrule, but different from chondrule to chondrule. This homogeneity is an expected consequence of a thin film of liquid metal. There exist limited data on the distribution of other siderophiles in CR chondrule metal, including SIMS measurements of Os, Ir, Pt, and Au abundances in PCA 91082, EET 92042, and Renazzo [2], and LA-ICP-MS measurements of siderophiles in Renazzo [3, 6, 9]. The SIMS data indicate an order of magnitude or more variation in refractory element abundances within a single chondrule [2], raising the issue of why refractory elements span such a large range when Co and Ni are homogeneously distributed [8]. To enhance our understanding of the distribution of siderophile elements in CR metal, and to confirm the validity of previous SIMS data, we performed laser ablation ICP-MS measurements on two CR chondrites, Acfer 059 and PCA 91082. The Acfer 059 section was from the electron microprobe study of [4], while the PCA 91082, 15 section was from the SIMS study by [2].

Analytical methods: Laser ablation ICP-MS analyses were performed at Florida State University using a New Wave UP193 FX excimer laser ablation system coupled to a Thermo Element XR. Metal grains were analyzed using a 25 µm spot size (with some exceptions), 5 s dwell time, 20 Hz repetition rate, 100% power output (2.5 GW/cm^2, 12 J/cm^2). The crater depths were estimated at 20µm, and only one crater in a former SIMS pit penetrated through the metal. The peaks ^{51}V, ^{53}Cr, ^{57}Fe, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{69}Ga, ^{74}Ge, ^{75}As, ^{97}Mo, ^{102}Ru, ^{103}Rh, ^{106}Pd, ^{184}W, ^{185}Re, ^{192}Os, ^{193}Ir, ^{195}Pt, and ^{197}Au, were acquired in low resolution mode using the fast scanning option of the Element XR. Standards used were North Chile (Filomena) IIA iron meteorite, Hoba IVB iron meteorite, and NIST SRM 1263a steel.

Results: Results for Acfer 059 and PCA 91082 overlap and are described together below. Fig. 1a shows CI-normalized Co/Ni and Ir/Ni ratios confirming the homogeneity of CR chondrite metal in Co and Ni, with Co exhibiting less than ±10% variation. This plot also shows that Ir varies by more than two orders of magnitude relative to Ni. To establish that this is a generic feature of CR chondrite metal, Fig. 1b shows a the correlation of two refractory elements in CI-normalized ratios of Os/Ni vs. Ir/Ni. Other refractory elements (Mo, Ru, W, Re, Pt) similarly correlate well with Ir, while Rh, Pd, Au, and more volatile elements, do not correlate well with Ir.

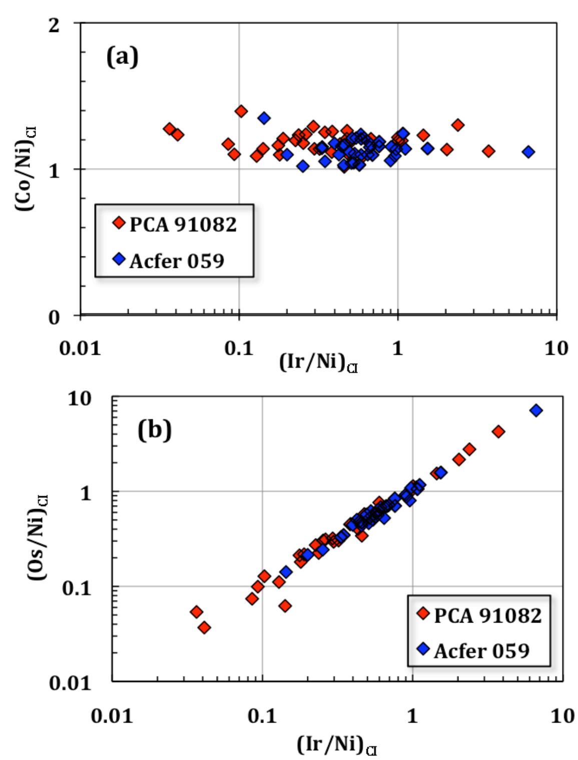

Fig. 1: (a) CI-normalized (Co/Ni) *vs*. (Ir/Ni) ratios, and **(b)** CI-normalized (Os/Ni) *vs*. (Ir/Ni) ratios, for Acfer 059 and PCA 91082 metal.

Siderophile elements of intermediate volatility, Fe, Co, Ni, and Pd, showed little variation as evident from Fig. 1a. However, the moderately volatile siderophiles Au, As, and Cu, exhibit 1-2 orders of magnitude variation in their ratios relative to Ni and mutually correlate. The abundance of Ge was very low, $(Ge/Ni)_{CI}$ 0.01-0.001, often close to its detection limit. The ubiquitous presence of V, correlated with Cr, attests to the reduced nature of CR metal. A CI- and Ni-normalized siderophile element pattern for a single chondrule, I7m, from Acfer 059, is given in Fig. 2.

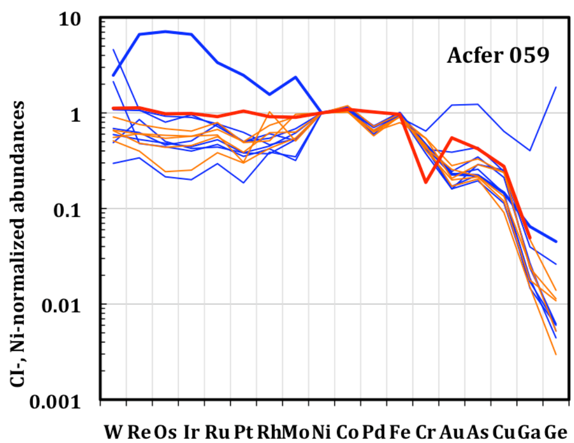

Fig. 2: Siderophile element pattern for a single chondrule, I7m from Acfer 059. Red: Bulk CR metal [5], blue: rim metal, orange: exterior or interior metal.

Comparison of SIMS and LA-ICP-MS results for PCA 91082: A total of 38 spots were analyzed on 5 chondrules and two matrix grains from PCA 91082, 15. Spots were selected near SIMS craters on PCA 91082. For example, the extremes of Ir observed in two points taken on the rim of Chondrule 1 of PCA 91082 in the present study was 0.54 ppm (0.37±0.06 ppm [2]) and 4.70 ppm (5.78±0.58 ppm [2]), with SIMS data for the craters closest to the LA-ICP-MS spots given in parentheses. The highest Ir spot was taken in the SIMS crater. Six of the nine spots taken in Chondrule 1 exhibit a ~40% range of Ir abundances: 0.76-1.13 ppm, which is more restricted than the full range observed: a factor of 9 (this study) or a factor of 18 [2]. Thus, if we allow for heterogeneity in individual metal grains, the SIMS data [2] agreed with LA-ICP-MS data.

Discussion: The presence of metal-cladding of practically all chondrules observed in random sections of CR chondrites implies that the metal must have uniformly covered the surfaces of the chondrules. The reason for metal-cladding of CR chondrules may be due to expulsion of metal from the interior [4], or by re-condensation of metal at the surface from partial volatilization during chondrule formation [2-3, 5-6]. Expulsion of metal from the interior implies that the metal should be compositionally uniform around a given chondrule [4]. For Chondrule I7m (Acfer 059) the range in Ir is a factor of 30, mainly due to a single rim spot (thick blue line in Fig. 2). Without this spot, the Acfer I7m Ir exhibits a factor of 5 variation from 0.5-2.4 ppm, with extremes represented by rim metal (Fig. 2). Thus, the remarkable homogeneity observed in Ni and Co, is not evident in refractory and volatile siderophiles. Some of the refractory element variation may be attributable to solid metal-liquid metal partitioning in the metal blebs during cooling. In Fig. 2, a single rim metal spot (thick blue line) has high abundances of compatible elements (Re, Os, Ir, Pt, Ru, etc.), with a markedly subchondritic W/Re ratio, while two other grains (thin blue lines) show complementary high W/Re ratios.

Excluding these 1-3 spots, the metal around chondrule I7m, and around chondrules in PCA 91082, is systematically depleted in refractory siderophiles relative to Fe-Co-Ni and bulk CR metal (Fig. 2). This observation is inconsistent with an origin by reduction alone, and implies recondensation of metal from a refractory-depleted vapor formed during chondrule formation [2-3, 5-6]. Bulk CR metal (Fig. 2, thick red line) does not exhibit a depletion in refractory elements [5], so that the refractory elements must be preserved within bulk CR chondrites. Metal grains with high refractory contents were reported from chondrule interiors in Renazzo [6], but were not encountered in the present study of Acfer 059 and PCA 91082 (bulk PCA 91082 is included in the study of [5]).

We infer that recondensed metal cladding CR chondrules likely formed as a liquid metal film around each chondrule that subsequently beaded due to surface tension and interfacial forces [4, 8]. Further work on the role of crystallization and the location of the complementary refractory metal is needed to understand the compositional heterogeneity of CR metal.

References:

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