PRISTINE AND PROCESSED METAL IN CR CHONDRITES: CONDENSATION IN THE SOLAR NEBULA AND PARTIAL REEQUILIBRATION DURING CHONDRULE FORMATION. T. W. Schoenbeck, H. Palme, *University of Cologne, Zuelpicher Str. 49b, 50674 Koeln, Germany (thorbjoern.schoenbeck@uni-koeln.de).*

Introduction CR chondrites are carbonaceous chondrites with comparatively high contents of FeNi metal coexisting with a heavily altered phyllosilicate-rich matrix and thus indicating extreme disequilibrium. Metal can be found in three environments: (a) within chondrules as large, rounded grains, (b) on chondrule rims and (c) as large metal grains within the fine-grained matrix [1, 2, 3]. Some authors believe that trace elements in metal grains of CR chondrules reflect equilibration with silicates during chondrule formation [4, 5] and/or were established by reduction [5, 6]. Alternatively, the trace element composition of CR metals could reflect nebular condensation. Evidence for condensed metal grains in CH- and CB-meteorites was recently provided by [7, 8]. In order to distinguish between these two possibilities we analyzed about 60 different metal grains in the CR chondrite Acfer 209 where metal is rather pristine and unaffected by weathering processes [9].

Methods All metal grains were analyzed with a JEOL JXA 8900 RL electron microprobe. To obtain improved detection limits as well as higher precision, both the electron probe current and the counting times were dramatically increased compared to regular microprobe techniques. We used a probe current of $2 - 5$ μA and counting times up to 300 seconds for light trace elements (Si, P). The precision and accuracy of all analyses were cross-checked by repeated measurements of calibration standards and external reference samples. For calibration purposes we used synthetic steel standards for Fe, Ni, Cr and Si, a natural apatite for P and a meteorite standard (San Martin hexahedrite) for Fe, Ni and Co. The resulting detection limits were $70 - 100$ ppm for all trace elements with a precision better than 5 % relative standard deviation.

Results We have analyzed chondrule, chondrule rim and matrix metals in three different thin sections of Acfer 209 (CR chondrite). A summary of the results is given in Table 1. The Fe and Ni contents of the metals are variable, with chondrule core metal having generally higher Ni concentrations than rim metals or matrix metals. Large variations in trace element contents were found between grains as well as within single grains. Matrix metal grains are compositionally more uniform than chondrule and chondrule rim metals (Table 1 and Figure 1). The most variable trace element in all metals is Si, with abundances ranging from below 50 ppm to 1.1 wt.%. The largest Si variations are found in chondrule metals. Metals from a single chondrule may vary between 100 and 2000 ppm [10]. Other trace components in metals are more uniform. For example, Cr contents of chondrule metals vary only between 1140 ppm and 3200 ppm. The most uniformly distributed element is P with variations from 1900 to 3100 ppm. There are no correlations among Si and Cr or P concentrations in the metal grains.

Variations in Fe and Ni of metal grains may result from the dissolution of Ni-rich phases (e.g. early metal condensates

Table 1: Composition of metal in Acfer 209

	Fe	Ni	Co	Cr	P	Si
	wt.%	wt.%	ppm	ppm	ppm	ppm
CR metal (chondrule & matrix) 400 analyses						
Average	92.65	6.99	2830	3140	3240	450
%RSD	2.6	32.1	24.8	43.2	53.1	240
Min	84.91	3.74	2070	400	970	$\leq$50
Max	96.25	13.51	4960	15000	9650	10900
CR metal (single chondrule) 32 analyses						
Average	93.65	6.10	2700	1300	2800	300
%RSD	1.7	19.9	7.3	52.3	29.1	150.7
Min	89.53	4.24	2300	400	150	$\leq$50
Max	95.11	8.58	3300	2800	4600	2500
Si in condensed metal (Fe, Co, Ni fully condensed)						
Pressure		Temp [K]		max Si ppm		
10^{-3} bar		1400		6500		
10^{-4} bar		1350		1690		
10^{-5} bar		1250		255		
10^{-6} bar		1190		50		

or Schreibersite) in Ni-poor metal. Matrix metal grains have generally smaller variations in all elements including Fe and Ni and exhibit the lowest Ni concentrations.

Discussion Simplified calculations were made to predict the amount of Si in metal either by condensation in the solar nebula or by metal-silicate equilibrium during chondrule formation. The procedures are similar to those of [11]. For metal silicate partitioning we used experimentally determined partition coefficients [12, 13, 14]. Activity coefficient data for Si in metal were taken from [15]

Condensation: The Si concentration of condensed metal grains depends on the SiO_2-bearing minerals that are present during metal condensation in the solar nebula [11, 16]. The condensation sequence of metal and silicates is pressure dependent [17]. At low total pressures, forsterite and enstatite condense prior to metal, removing effectively all Si species from the nebular gas and leading to low Si content in metal [18]. At high pressures metal condenses before forsterite, which leads to high Si concentrations in metal. Si contents of condensed metals are given in Table 1.

Metal-silicate equilibrium: The Si concentration of a metal grain in equilibrium with a silicate chondrule melt depends on the temperature as well as the oxygen fugacity and can be calculated according to:

$$2\,Fe^{Metal} + SiO_2^{Silicate} = Si^{Metal} + 2\,FeO^{Silicate}$$
$$\log X(Si) = \log K - 2 \log a(FeO) + \log a(SiO_2) - \log \gamma^{Si}$$

Table 2 gives typical Si concentrations in metal for different temperatures and different oxygen fugacities.

From trace element abundances alone it is impossible to

Table 2: Si in metal resulting from metal-silicate equilibrium

Temp	log p(O_2)	Si in metal	FeO in silicate melt
1300 K	IW -6	3500 ppm	1800 ppm
1600 K	IW -6.4	78800 ppm	1260 ppm
1300 K	IW -2.5	30 ppm	2.2 wt.%
1600 K	IW -2.8	3600 ppm	1.5 wt.%

distinguish between condensed metals and metal from metal-silicate-equilibrium.

The oxygen fugacity during metal/silicate equilibration in chondrules can be calculated from the FeO content of chondrule silicates. The Cr distribution between metal and silicate calculated from this fO_2 is roughly consistent with the observed Cr distribution between chondrule metal and silicate. However, condensation could produce similar Cr concentrations in metal. The observed amount of Si in chondrule metal is too low for metal-silicate equilibration. At 1600 K and 1.5 wt.% FeO in silicate one would expect 3600 ppm Si (Table 2). Most chondrule metals have less than 500 ppm Si. In addition, if metal-silicate equilibrium is the only process documented in chondrule metal, one should assume strong positive correlations between the oxidizable trace elements Cr, Si and P. However, these correlations are not observed. Hence other processes must have taken place.

The typical Si concentration of some matrix metals of about 200 ppm is in good agreement with an origin by condensation in the solar nebula at 10^{-5} bar. The large variability of Si in chondrule metal would require large variations of the total pressure in the nebula during condensation. This is unlikely and not predicted by astrophysical nebula models.

In summary, the large variability of Si in CR metal is neither explained by condensation models nor by metal-silicate equilibrium. The following observation may provide a clue.

The sequence of compositional variability mentioned above corresponds to the sequence of diffusion coefficients [19], as shown in Table 3. The large difference between the diffusion lengths of Si and P explains the observed homogeneity of P in the metals in contrast to their heterogeneity in Si.

Summary Based on these observations we propose the following model: (a) Metal and silicates condensed from the solar nebula leading to Si concentrations of about 200 ppm. Condensed metal grains were exposed to high temperatures during chondrule formation. Because of the short duration of chondrule formation, timescales were not sufficient for a complete redistribution of all trace elements; in particular Si with its low diffusion coefficient in metal (Table 3) was only

Table 3: Diffusion parameters in Fe metal

	D [$m^2 s^{-1}$] at 1500 K	Diffusion length after 4 hours	Variability in CR metal
P	$116 \cdot 10^{-18}$	258.6 μm	29.1 %
Cr	$7.54 \cdot 10^{-18}$	65.5 μm	52.3 %
Si	$2.42 \cdot 10^{-18}$	37.3 μm	150 %

partly equilibrated. This explains the large variations of Si in chondrule metals. The heterogeneity of Si in these metals was preserved due to its small diffusion length compared to the other trace elements. In contrast, the relatively homogeneous distribution of Si in even large matrix metal grains suggests that these matrix metals were excluded from metal-silicate equilibrium. This proves the pristine nature of some matrix metal grains. Because of faster diffusion, P and Cr were more effectively redistributed between metal and silicate during chondrule formation, although significant variations still exist (Fig. 1). The narrow range of P concentrations in matrix metal compared to chondrule metal (Fig. 1) supports a primary condensation origin of many matrix metals. Clearly, not all metals in Acfer 209 were processed in chondrules.

Figure 1: Distribution of Cr and P in CR metal
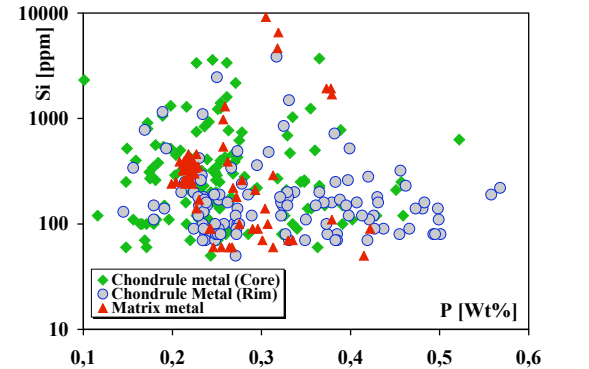
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