IRON-60 IN THE EUCRITE PARENT BODY AND THE INITIAL $^{60}Fe/^{56}Fe$ OF THE SOLAR SYSTEM.

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Introduction: Basaltic eucrites are differentiated meteorites that crystallized rapidly. Most of them have experienced thermal metamorphism and impact brecciation. The exact timescales of all these events is still a matter of debate. There is evidence that eucrites formed 8 to 10 Myrs after the start of the solar system ([1] and references therein) and other evidence that has been used to argue for an earlier formation (e.g. [2,3]). The ^{60}Fe-^{60}Ni chronometer (half-life = 1.49±0.27 Myrs) is well suited for constraining the age of the oldest basalts of our solar system. Nickel is more siderophile and more compatible in silicate melting than iron, so that both elements strongly fractionate during core formation and mantle differentiation. The resulting Fe/Ni ratio in eucrites is extremely high. Large excesses of ^{60}Ni are therefore expected in these meteorites. A first Ni isotopes study has been conducted for two eucrites using TIMS about ten years ago [4,5]. It was shown that the ^{60}Ni excesses found in the samples result from the in situ decay of ^{60}Fe which was extant at the time the eucrites formed and crystallized. To obtain a more comprehensive picture of Ni isotopes in eucrites, we have readdressed the topic using MC-ICPMS. We here present data for whole rock samples from Bouvante and Juvinas, two non-cumulate eucrites, and for mineral separates from Juvinas.

Techniques: The bulk rock samples were not washed to avoid any possible preferential leaching and fractionation of the Fe/Ni ratio. Leaching experiments demonstrated indeed that Ni is easily removed, unlike the case for Fe. Instead small chips were picked from the innermost part of the large piece we received, in order to avoid terrestrial contamination. After acid dissolution, Ni was first separated from Fe and Zn on an anion exchange resin. The second step of the chemical procedure consisted of a liquid-liquid extraction based on the complexation of Ni with dimethylglyoxime. Finally, Ni was purified on a cation exchange resin.

The Ni isotope ratios were measured using a high resolution Nu Plasma multi-collector ICPMS (Nu 1700) with a mass resolution M/ΔM of about 2600. This allows us to resolve the $^{40}Ar^{18}O$ interference on mass 58 and $^{40}Ar^{20}Ne$ and $^{38}Ar^{22}Ne$ on mass 60. ^{57}Fe and ^{66}Zn were monitored in order to correct for the isobaric interferences on mass 58 and 64 respectively. Because of the very limited amount of nickel available for analysis, the time-resolved mode was used. Background zeroes were measured on-peak for 60 seconds and sample data were then acquired over a 90 second period as a series of 0.2s integrations. Intrumental mass fractionation was corrected according to an exponential law by normalizing the $^{62}Ni/^{58}Ni$ to 0.05338858. Results are expressed in epsilon units (1ε is the deviation of the sample in parts per 10^4 relative to the Ni terrestrial standard).

Iron and Ni concentrations were determined using a high mass resolution, double focusing sector field ICPMS. This instrument allowed us to determine both concentrations simultaneously in the same aliquot, even with the high Fe/Ni ratio of eucrites, which can reach a few million.

Results: Nickel concentrations in bulk samples span more than an order of magnitude. Nickel is heterogeneously distributed in Juvinas: it resides mainly in tiny metal grains, in ilmenite and chromite. The range of Fe concentrations, on the other hand, is extremely limited.

All samples are characterized by a ^{60}Ni excess indicating that ^{60}Fe was alive at the time of core segregation in the eucrite parent body. The $^{61}Ni/^{58}Ni$ ratios are always normal within error. Different bulk rock samples from the same meteorite have distinct isotopic compositions. Two trends can be defined for Bouvante. For each of them $^{60}Ni/^{58}Ni$ ratios are correlated with the Fe/Ni ratios. If these regression lines are interpreted as isochrons, a time interval of 5.0 Myrs can be calculated between the two events. The Ni redistribution during secondary events, due to its high mobility, is apparently limited enough to preserve these isochrons.

The two Juvinas bulk rocks, the feldspars and the two ilmenite fractions define a line whose slope corresponds to the $^{60}Fe/^{56}Fe$ ratio at the closure time of the Fe-Ni system. However, the pyroxene fraction plots below this regression line (as do the pyroxenes from Chervony Kut relative to the whole rock isochron [4]) and the chromites plot above the best-fit line. This is probably due to a redistribution of nickel by diffusion from the pyroxenes into chromites during a thermal event. The metal fraction also plots far above the isochron, indicating that metal did not form at the same time or that the system has been disturbed in this phase.

Discussion: If the regression lines are interpreted as isochrons, what event do the Ni isotopic compositions define timewise?

Mineral isochron vs. whole rock isochron. A time interval of 3.4 Myrs can be calculated between the mineral isochron determined in the present study and the whole rock isochron published by Shukolyukov and Lugmair for Juvinas [5], the mineral isochron being steeper than the whole rock isochron. In case of a shock-induced melting, the glassy mesostasis material could be re-melted or could exchange preferentially relative to silicate minerals because the former has a low melting temperature and is metastable. Bulk rock samples may well register this reheating event preferentially because of mass balance whereas separate minerals do not. Juvinas (type 5 non cumulate eucrite) is indeed characterized by recrystallisation of the mesostasis and such a resetting can explain the steeper slope of the mineral isochron compared to the whole rock isochron. In addition, Juvinas has variable metamorphic textures, suggesting multistage impact and thermal events [6]. Two different pieces of the meteorite have been analysed in the 1993 study and in the present work. It might also be that isotopically normal Ni has been introduced during the brecciation event in the samples analysed by Shukolyukov and Lugmair [5].

Crystallization age? Different bulk rock samples of a given meteorite have different isotopic compositions, which means that live ^{60}Fe was still present at the time of eucrite crystallization. Shukolyukov and Lugmair determined a whole rock isochron for the non cumulate eucrite Chervony Kut [4]. Based on the slopes of the isochrons, the Fe-Ni system closed in Juvinas (1.3±0.5) Myrs later than in Chervony Kut. This time interval is in excellent agreement with the Mn-Cr data: according to Cr isotopes, Juvinas solidified (1.10±0.95) Myrs after Chervony Kut [2]. Both chronometers then date the solidification (i.e. crystallization). Similarly, the steeper Bouvante isochron also corresponds to the crystallization of the meteorite.

Brecciation or metamorphic age? Chervony Kut, which yielded a single isochron, is relatively unbrecciated whereas Juvinas and Bouvante are brecciated. Therefore, the isochrons that have lower slopes and indicate younger ages may date brecciation. However, the ^{39}Ar-^{40}Ar ages are younger than those inferred from Fe-Ni data and support a much later brecciation event. Ar-Ar ages may also indicate the end of metamorphism. Thus, the Fe-Ni system could dates a first brecciation step or it dates metamorphism.

Pyroxenes have been extensively studied in eucrites [e.g. 7] and show chemical zoning, exsolution and inversion of pigeonite to orthopyroxene. These features can be used as indicators of the post-crystallization thermal history. The pyroxene annealing is likely a much earlier process than the impact event and the reset K-Ar ages. The best fit line going through the chromites and the pyroxene data has the same slope within error as the secondary isochron for Juvinas and Bouvante, and most likely dates a thermal metamorphic event corresponding to pyroxene annealing and redistribution of nickel, prior to brecciation.

Initial ^{60}Fe/^{56}Fe ratio of the solar system: Some short-lived radionuclides are considered as possible heat sources for planetary differentiation. Among them, ^{26}Al and ^{60}Fe are the best candidates because of their short half-lives. Meteorites contain significant amounts of iron, but the efficiency of ^{60}Fe as a heat source fully depends on its initial abundance in the solar system. Tungsten isotopes indicate that thermal metamorphism in eucrites occurred 19.4±3.2 Myrs after the start of the solar system [8]. With the hypothesis that the Hf-W and Fe-Ni systems date the same event and closed at the same time within the precision of the chronometers, the initial ^{60}Fe/^{56}Fe ratio of the solar system can be back-calculated. A value of about 4.4×10^{-6} is found. This estimate is higher than the value of 1.0×10^{-6} generally admitted at present but still falls within the range predicted by Wasserburg et al. [9] for ^{60}Fe that has been produced in a supernova explosion. This result seems to support the hypothesis of a supernova trigger at the origin of the solar system. According to the model developped by Yoshino et al. [10] an initial ^{60}Fe/^{56}Fe ratio between 2×10^{-7} and 2×10^{-6} would increase the temperature of parent bodies enough to melt rocks within the first million years of the solar system. The ratio we deduced from the eucrites data is even higher than the upper limit and therefore, ^{60}Fe was probably an important heat source for planetary differentiation.

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