THE TIMING OF CORE FORMATION IN PROTOPLANETS REVISITED: NEW EVIDENCE FROM A COMBINED TUNGSTEN – NOBLE GAS ISOTOPE STUDY ON MAGMATIC IRON METEORITES

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Introduction: Previous Hf-W studies suggested many magmatic iron meteorites to have formed coeval with, or even earlier than Ca-Al-rich inclusions (CAI) [e.g. 1-4]. Cosmic-ray-induced W isotope variations [5], however, may at least in part account for the apparent antiquity of these ages [1-4,6-7]. Determining accurate Hf-W ages for iron meteorites thus requires the quantification of cosmic-ray-induced effects on W isotopes. Previous studies used published exposure ages and ³He contents to correct the measured W isotope compositions of iron meteorites [e.g. 4,6]. However, even after such corrections, some iron meteorites still have $^{182}$W/$^{184}$W ratios that are less radiogenic than the initial W isotope composition of CAI, most probably reflecting an insufficient correction for cosmic-ray induced W isotope shifts. Consequently, there is yet no reliable method for correcting cosmic-ray effects on W isotopes, such that the exact timing of core formation in protoplanets remains inadequately constrained.

Approach: Cosmic-ray produced noble gas abundances allow the identification of iron meteorite samples with limited or lacking cosmic-ray induced W isotope variations. Very low noble gas concentrations in a particular sample could either point to relatively short time of exposure (few Myr), or alternatively, effective shielding from (high-energy) nuclear reactions, e.g. because the sample was deeply buried inside a large, meter-sized iron meteoroid [e.g. 8].

While cosmogenic noble gases are produced through interaction with high-energy protons and neutrons, W isotope compositions are modified by thermal and epithermal secondary neutrons whose fluxes have maxima at higher shielding depths than the depth interval at which the production of cosmogenic noble gases is highest [5,6,9]. Hence, cosmogenic noble gas data strictly only provide an indirect measure of the production rate of thermal neutrons [6,9]. Future work will therefore focus on the complementary application of a direct neutron dose monitor. In this study we used published noble gas data [10] to identify iron meteorite samples with negligible cosmic-ray effects, i.e. those samples that are most suitable for obtaining reliable core formation ages. We report W isotope data and noble gas concentrations for these iron meteorite specimens and use these data to obtain new constraints on the timing of core formation in protoplanets.

Analytical methods: After careful cleaning and leaching, the selected iron meteorite specimens were dissolved in 6 M HCl-0.06 M HF. Tungsten was separated from the matrix using a modified anion exchange chemistry after [1]. Tungsten isotope compositions were measured using a Nu Plasma MC-ICPMS at ETH Zürich following previously published procedures [1,3]. Measured $^{182}$W/$^{184}$W ratios are reported as $\varepsilon$-unit (i.e. parts per 10 000) deviations relative to a terrestrial W standard that was analyzed bracketing the sample analyses. Reported are mean $\varepsilon^{182}$W values of multiple solution replicates ($n=5$-11) at an external reproducibility (95% conf.) of $\pm0.2$ $\varepsilon$-units.

Noble gas abundances in samples collected adjacent to the specimens used for W isotope analyses were determined at the University of Bern. Analytical methods follow those outlined in [11]. As a result of the low noble gas contents - some analyses were not resolved from blank levels - relative errors are highly variable.

Results: As expected, most cosmogenic noble gas contents in the analyzed samples were found to be at the lowest end of the range previously observed in iron meteorites [10]. $^3$He abundances range from 0 to 133, $^{21}$Ne from 0 to 2.61, and $^{38}$Ar from 0.002 to 14.5 [in $10^{-8}$ cm$^3$STP/g]. The majority of the samples have noble gas contents close to the lower limit of the above-mentioned range. The abundances of different noble gas isotopes ($^3$He, $^{38}$Ar, $^{21}$Ne) are well correlated (Fig. 1), demonstrating that our analyses are accurate. Tungsten isotope compositions of the same iron meteorite samples are displayed in Fig. 2. Most of our samples have $\varepsilon^{182}$W values ranging from -3.3 to -3.2, indistinguishable from the CAI initial of -3.28±0.12 [7]. An important observation from Fig. 2 is that one IIAB specimen having the highest noble gas abundances has

![Fig. 1: Cosmogenic $^{21}$Ne versus $^{38}$Ar for magmatic irons investigated for this study. One sample (IIAB) with the highest noble gas contents is not shown, but its noble gas concentrations also plot on the (extrapolated) correlation line.](image-url)
\( \varepsilon^{182}W \) significantly lower than the initial W isotope composition of CAI. Another IVA sample with relatively high noble gas contents also has \( \varepsilon^{182}W \) distinctly lower than the other samples. One iron (UNG) shows a resolved positive anomaly relative to the CAI initial.

### Discussion:
Iron meteorites with the lowest cosmogenic noble gas contents have \( \varepsilon^{182}W \) indistinguishable from the CAI initial, while two samples with higher noble gas contents have \( \varepsilon^{182}W \) lower than the CAI initial. The latter two samples likely experienced \( ^{182}W \) burnout resulting from cosmic-ray-induced neutron capture reactions. Our combined noble gas and W isotope data thus for the first time unequivocally demonstrate \( \varepsilon^{182}W \) values lower than the CAI initial to have been caused by the interaction with cosmic rays.

The weighted mean \( \varepsilon^{182}W \) of those iron meteorites whose W isotope budgets likely remained unaltered by cosmic-rays of \( \varepsilon^{182}W = -3.25 \pm 0.05 \) (95% conf.; \( n = 7 \)) is identical to the initial W isotope composition of CAI (\( \varepsilon^{182}W = -3.28 \pm 0.12 \) [7]), but \( \sim 0.1-0.4 \) \( \varepsilon \)-units higher than \( \varepsilon^{182}W \) values for magmatic irons that were corrected for cosmic-ray induced W isotope effects using their exposure ages and \( ^{3}He \) contents [4,6]. Our results thus emphasize that such correction procedures do not fully account for cosmic-ray induced shifts in W isotopes. Consequently, the chronology of core formation based on such corrected W isotope data is systematically biased towards older ages (Fig. 3).

Our W isotope results differ in two important aspects from previous Hf-W studies on magmatic irons. First, the calculated (weighted) mean \( \varepsilon^{182}W \) of \( -3.25 \pm 0.05 \) for weakly irradiated iron meteorite specimens obtained in this study translates to an average core formation age of 0.3±1.2 Myr after CAI formation. Unlike the mostly negative ages obtained in previous studies (Fig. 3), the model age obtained here is positive, suggesting cosmic-ray induced effects in our sample suite to be minor to absent. The model age of 0.3±1.2 Myr is \( \sim 1-3 \) Myr younger than previously published ages and is the currently most precise and accurate estimate for the timing of metal segregation in protoplanets. Second, previous studies - after correcting for cosmic-ray induced effects - report W isotope variations among magmatic irons that correspond to a \( \sim 4 \) Myr time interval of metal segregation (Fig. 3).

In contrast, we find no resolvable W isotope differences among the investigated irons with low cosmogenic noble gas abundances. Our results thus indicate that the parent bodies of these irons segregated their cores within 0.5 Myr of each other, i.e., over a much shorter interval than previously suggested.

### Conclusions:
Our combined W isotope – noble gas study demonstrates the difficulty in using exposure ages to correct for cosmic-ray induced shifts in W isotopes. Only samples with relatively short time of exposure or effective shielding from nuclear reactions are suitable for establishing a precise Hf-W chronology of metal segregation in iron meteorite parent bodies. Using noble gases we identified a suite of iron meteorite specimens whose W isotope budgets likely remained unaltered by cosmic rays. The Hf-W systematics of these samples indicate that metal segregation in iron meteorite parent bodies occurred at 0.3±1.2 Myr after CAI formation and that the different parent bodies of the investigated iron meteorites segregated their cores within 0.5 Myr of each other.

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### References: