PROTRACTED CORE DIFFERENTIATION IN ASTEROIDS FROM ^{182}Hf-^{182}W SYSTEMATICS IN THE EAGLE STATION PALLASITE. N. Dauphas[1,2,3], C.N. Foley[4], M. Wadhwa[2,3], A.M. Davis[1,3], P.E. Janney[2,3], L. Qin[1,2,3], C. Göpel[5], and J.-L. Birck[5], [1]Origins Laboratory, Department of the Geophysical Sciences, and Enrico Fermi Institute, The University of Chicago, 5640 South Ellis Avenue, Chicago IL 60637, USA (dauphas@uchicago.edu), [2]Department of Geology, The Field Museum, 1400 South Lake Shore Drive, Chicago IL 60605, USA, [3]Chicago Center for Cosmochemistry, [4]Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington DC, 20015-1305 USA, [5]Laboratoire de Géochimie-Cosmochimie, Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cedex 05, France.

Introduction: Observations of remote stellar systems have reached a point where meaningful comparisons can be made between these astronomical observations, astrophysical models, and meteorite measurements. Among the parameters that can be compared are the timescales of formation of protoplanetary disks and subsequent condensation, aggregation, and differentiation of solids. With a ^{182}Hf half-life of 8.90±0.09 My [1], the ^{182}Hf-^{182}W pair is well suited to answer these questions. There are, however, some caveats to the application of short-lived nuclides to early solar system chronology. Some short-lived nuclides may have been produced by irradiation in the early solar system [2,3] or may have been injected in the disk by the explosion of a nearby supernova that may have triggered the protosolar nebula into collapse [4,5]. In either case, the extinct radionuclides may have been heterogeneously distributed in time and space, thus blurring to some extent the chronological information that can be retrieved from these nuclides. Another complication is related to the presence of nucleosynthetic anomalies that may cause the daughter nuclides to vary regardless of the abundance of the parent nuclides. We address these two issues for the ^{182}Hf-^{182}W system.

A reliable way of assessing the usefulness of an extinct radionuclide is to compare the timescale inferred from its abundance with timescales inferred from other long and short-lived nuclides. Manganese-53 has a comparatively long half-life (3.7 My) and the ^{53}Mn-^{53}Cr system has been successfully applied to a variety of objects [6]. Until now, only one anchor point, silicate differentiation on the HED parent body, was available to compare the ^{182}Hf-^{182}W and ^{53}Mn-^{53}Cr systems, because the initial ^{182}Hf/^{180}Hf and ^{53}Mn/^{55}Mn ratios at the time of the condensation of the first solids in the nebula are both uncertain. The recent finding of unradiogenic ^{182}W in the Tlacotepec iron meteorite implies an initial ratio of $1.60\pm0.25\times10^{-4}$ [7], which is significantly higher than recent estimates based on internal isochrons in ordinary chondrites and CAIs ($1.00\pm0.08\times10^{-4}$) [8]. The initial ^{53}Mn/^{55}Mn is also uncertain but may have been as high as $2.8\pm0.3\times10^{-5}$ [9] (although the best estimate of [6] for this value is lower by a factor of ~2). The first anchor comes from bulk samples of HED meteorites, which yield isochrons with slopes of $7.25\pm0.50\times10^{-5}$ for the ^{182}Hf/^{180}Hf ratio [10] and $4.7\pm0.5\times10^{-6}$ for the ^{53}Mn/^{55}Mn ratio [6]. The two decay systems define consistent time intervals between condensation of the first solids and mantle differentiation on Vesta of around 10 My (less than 5 My if the lower initial values of [6] and [8] are adopted).

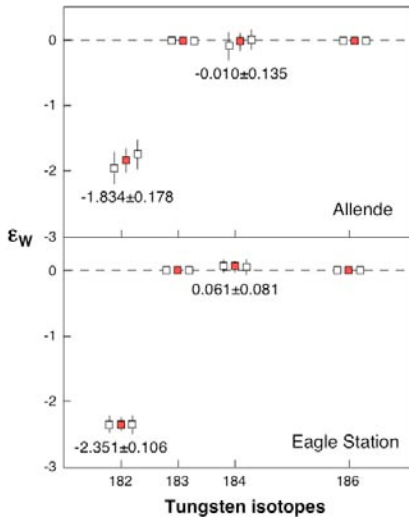

Fig.1. Tungsten isotopic compositions of Allende (CV3.2) and Eagle Station (ES-PAL), shown as squares (corrected for mass fractionation by internal normalization of the ^{183}W/^{186}W ratio). The open symbols are replicate analyses and the filled symbols are the resulting weighted averages ($1/\sigma^2$). Uncertainties are 2σ. Mass fractionation was corrected by internal normalization of the ^{183}W/^{186}W ratio.

The Eagle Station anchor: The ^{53}Mn/^{55}Mn ratio at the time of crystallization of the Eagle Station pallasite is $1.17\pm0.09\times10^{-6}$ [11], close to that measured in angrites [6]. This ratio is lower than that defined by the HED bulk samples, which requires that Eagle Station crystallized 7.4 My after silicate differentiation on the HED parent body. Determining the ^{182}Hf/^{180}Hf ratio in either angrites or Eagle Station group pallasites would therefore provide a second anchor point for ^{182}Hf-^{182}W and ^{53}Mn-^{52}Cr systematics. Based on the presence of

isotope anomalies in O [12], Cr [11], and Mo [13,14], a genetic relationship was inferred between ES-pallasites and CV carbonaceous chondrites. Eagle Station also has clear trace element evidence for mantle differentiation and is likely from the core-mantle boundary of its parent body [15]. We have therefore measured bulk Allende, the Hf/W ratio and W isotopic composition of which should be the same as that of the Eagle Station parent body. The results are shown in Fig. 1. Eagle Station is slightly less radiogenic than Allende. Assuming a two-stage metal segregation model for Eagle Station,

$$\left(\frac{^{182}\mathrm{Hf}}{^{180}\mathrm{Hf}}\right)^{0}_{\mathrm{ES}} = \left(\frac{^{182}\mathrm{W}}{^{180}\mathrm{Hf}}\right)_{\mathrm{All}} (\varepsilon_{\mathrm{All}} - \varepsilon_{\mathrm{ES}}) \times 10^{-4}$$

we calculate a ^{182}Hf/^{180}Hf ratio of 3.508±1.430×10^{-5} at the time of metal separation. Cooling and crystallization of the HED parent body occurred shortly after metal-silicate differentiation [7,10]. It is therefore reasonable to assume that ^{182}Hf and ^{53}Mn abundances record events that occurred almost simultaneously. Eagle Station does indeed fall on the ^{53}Mn/^{55}Mn-^{182}Hf/^{180}Hf evolution curve.

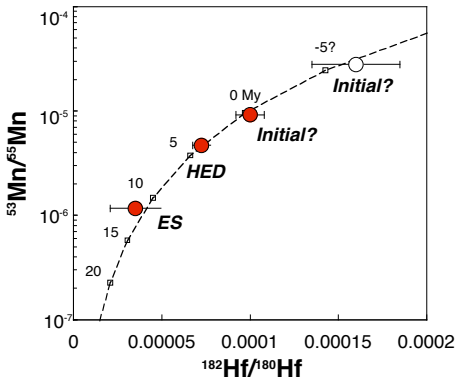

Fig.2. Comparison between ^{182}Hf-^{182}W and ^{53}Mn-^{53}Cr chronometers in Eagle Station (ES, Fig.1), the HED parent body, and the initial composition (open circle from [7,9], filled circle from [6,8]). Uncertainties are 2σ. The dashed curve is the theoretical evolution based on the half-lives of the two nuclides. See text for details. Only if the lower initial values are taken are the ^{182}Hf-^{182}W and ^{53}Mn-^{53}Cr systems consistent with ^{26}Al-^{26}Mg and U-Pb systems.

As shown in Fig. 2, for the initial ^{182}Hf/^{180}Hf and ^{53}Mn/^{55}Mn ratios of [7] and [9], the ^{182}Hf-^{182}W and ^{53}Mn-^{53}Cr systems appear to provide consistent time information, lending support to their use as chronometers. However, they are not consistent with ^{26}Al-^{26}Mg systematics ($t_{1/2}$=0.74 My), which suggest that HED silicate differentiation occurred within ~5 My of the formation of the first solids (e.g., [16]). This may be due to problems with the estimation of the initial ^{53}Mn/^{55}Mn and ^{182}Hf/^{180}Hf ratios or it may result from prolonged injection or production of fresh ^{26}Al in the protosolar nebula. If true, this would invalidate the use of this nuclide as a chronometer. However, ^{26}Al-^{26}Mg systematics seem to be consistent with ages derived from the U-Pb system [17], which would point to the initial ^{53}Mn/^{55}Mn and ^{182}Hf/^{180}Hf as the possible culprits. If the initial ^{182}Hf/^{180}Hf ratio was 1.00±0.08×10^{-4} [7], then the initial ^{53}Mn/^{55}Mn ratio must have been 1.0±0.2×10^{-5}, which turns out to be very close to the ratio measured in chondrules [9], and is similar to the initial value estimated by [6]. In that case the chronologies based on ^{53}Mn and ^{182}Hf would agree with ages derived from the U-Pb and ^{26}Al-^{26}Mg systems. Clearly more work is required to bring all extinct and extant chronometers into agreement.

At this stage, it may be more reliable to only compare the relative chronologies of differentiated asteroids. The Eagle Station pallasite has radiogenic W, corresponding to ^{182}Hf/^{180}Hf=3.508±1.430×10^{-5} at the time of core formation. The ^{182}Hf/^{180}Hf ratio at the time of core differentiation in the HED parent body is 7.8±0.7×10^{-5} [9]. This difference in the initial ratios corresponds to a difference in age of 10.3±5.4 My and demonstrates that core differentiation in asteroids proceeded over an extended period of time.

It is worthwhile to note that despite the presence of isotope anomalies in O, Cr, and Mo for Allende and Eagle Station [11-14], the tungsten stable isotopic compositions (^{184}W/^{186}W) of these two meteorites are normal within uncertainties, thus demonstrating that ^{182}W is not affected by nucleosynthetic effects in bulk meteorites.

Conclusions: The presence of radiogenic W in Eagle Station indicates that the metal in this meteorite differentiated late, possibly 10 My after Vesta. At such a late time, ^{26}Al and ^{60}Fe are unlikely to have been significant heat sources and impacts must have played a role in the metal-silicate differentiation history of some asteroids.

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