Hf-W CHRONOMETRY AND THE TIMING OF THE GIANT MOON-FORMING IMPACT ON EARTH.

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Introduction: The last major event in Earth's formation is thought to have been the collision with a Mars-sized differentiated impactor, resulting in the formation of the Earth-Moon system (EMS). The recent discussion of the timing of this event centers on the extent of equilibration of the Hf-W system during this event. While Hf-W equilibration was very effective in small planetesimals [1], its efficiency at the late giant impact stages of planetary accretion is debated [1-4] and remains a source of disagreement in interpretation of ^{182}Hf-^{182}W chronometry. The key to resolving this disagreement is to obtain experimental data on the scale of physical and chemical mixing and equilibration of metal and silicate in the post-giant impact Earth. Because the extreme conditions that prevailed in the Earth during and shortly after the giant Moon-forming impact [5] are inaccessible for conventional techniques, we use the results of high power laser shock-induced melting of metal-silicate targets at high pressures (100's GPa) and temperatures (10^4's K).

Evaluation of the late Moon formation model: Since planetary accretion is a stochastic process, the last giant impact does not necessarily have to occur on an exponentially decreasing accretion rate curve; it could happen either before or after. It has recently been argued that the Moon formed late at about 70-110 Myr [6]. Because the W isotopic compositions of the modern Earth's mantle ($\varepsilon_{W(CHUR)}$ (t_f) = 1.9) and the bulk impactor ($\varepsilon_{W(CHUR)}$ = 0 by definition) are well known, the recently suggested formation of the Moon by a late impact ~ 70-110 Myr after the Solar System formation places rather tight constraints on the W isotopic composition and the accretion time of the silicate proto-Earth, if the mass ratio of the impactor to the total system is known. Simulations of the Moon-forming impact [5] require the mass fraction of the impactor to be ~0.13 of the final Earth-Moon system in order to match its astronomical characteristics. Neglecting the small mass of the Moon, the mass ratio of the pre-impact mantle to the current mantle is 0.87. For this ratio the isotopic composition of the pre-impact Earth's mantle of $\varepsilon_{W(CHUR)}$ (t_i) = 11.6 was calculated from the equation 76 of [1] using the Hf-W fractionation factor $f^{Hf/W}$ = 12 [1]. The time t_i when the pre-impact Earth's mantle reaches the $\varepsilon_{W(CHUR)}$ value of 11.6 can be calculated from the equation 14 of [1] for the two-stage model of core-mantle differentiation. For the mean life of ^{182}Hf, τ_{182Hf} = 13 Myr, $(^{182}Hf/^{180}Hf)_{T_o} = 10^{-4}$, $q_W = 1.55x10^4$, and $f^{Hf/W}$ = 12 the pre-impact Earth's two-stage model age is 6.1 Myr. At this stage the mass of pre-impact proto-Earth is 87% the modern Earth. Then the mean Earth (63.2 % by mass) accretion time of 2 Myr (prior to the giant impact) after the Solar System formation is determined from Figure 12 of [1] and in this case ~90% of Earth accreted in the first 6 Myr of the Solar System.

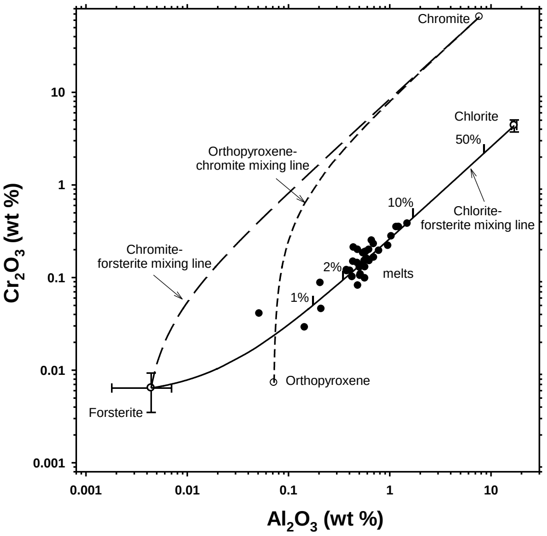

Fig. 1. The two-component mixing curves between minerals demonstrate that the Cr and Al in the melts are primarily derived from chlorite.

Experiments: The experimental setup and results are described in details in [7-10]. Targets were fabricated by pressing mixtures of Ni-free Fe metal crystals (20-50 μm) and powdered ALM-2 dunite (5-300 μm) into disk-shaped pellets of 6.35 mm in diameter and ~2 mm thick. The dunite contains >90% forsterite grains, chlorite grains (a few to < 10 percent), and < 1% of orthopyroxene and chromite. Each target was shocked by a single ~0.4 ns pulse of 527 nm laser radiation focused to ~1 mm spot. The laser shot created a plasma cloud above the target surface and an ablation region of a high density melt at the plasma-target interface that eventually produced a "crater". BSE images of cratered target fragments show rough crater surfaces with the host metal and forsterite grains (below the crater surfaces) being bound together by thin films or pockets of silicate melt containing varying amounts of dispersed metal beads. No traces of melt were found on the crater surfaces. We conclude that the melt was injected into porous space, grain boundaries, and cracks and crevasses in forsterite grains likely at the maximum ablation depth when close to peak pressures and high temperatures existed at the front surface. Silicate melt is enriched in Al_2O_3, Cr_2O_3, and FeO compared to the host forsterite [9]. The high and relatively uniform contents of Al_2O_3 and Cr_2O_3 in the silicate melt require a high degree of target homogenization since the bulk of the target material is essentially free of Cr and Al. The mixing relationships (Fig. 1) suggest that the homogenization occurred in the ablation melt layer by incorporating Al_2O_3 and Cr_2O_3 from the few relatively large (100-300 μm) grains of Al-rich chlorite that are present in the target material.

Experimental conditions: In the ZBL-16 experiment the isothermal speed of sound in the plasma region (U_T) is ~81 km/s (calculated from the laser intensity of $I = 2.8\ TW/cm^2 = 4\rho_{crit}(U_T)^3$ and the critical density [10] ($\rho_{crit} = 1.33x10^{-2}\ g/cm^3$). In the ablation region the peak shock pressure is estimated [10] to be ~ 276 GPa at a temperature of ~21,000 K. The target central crater depth is 470 μm and the estimated ablation depth [10] (d) is 250 μm. The linear scale of homogenization is the diameter of the crater (~1 mm). The estimated diffusion length scale (1 to 5 μm) is a factor of 200 to 1000 smaller than the observed mixing length scale of ~ 1 mm. Thus, the efficient mixing observed in our experiments requires a mechanism other than diffusion.

Richtmyer-Meshkov (RM) instabilities and mixing in the experimental melts: It is known that a high pressure shock wave drives fluids of different densities at different rates, creating turbulent mixing interfaces due to RM instabilities. Laser irradiation induces a shock wave propagating through the target and produces RM instabilities in high power laser ablation experiments [11]. It provides the seed of the Rayleigh-Taylor (RT) instability that develops during the acceleration phase of implosion. The RM instability scale (L) for a shock wave driven process in dense (molten) liquids is obtained from the following simple relationship: $L = An\tau U_{implosion}$, where A = ~0.4 is the Atwood number, τ is the laser pulse length (0.39 ns), n is the duration of the shock process in multiples of τ. The implosion velocity ($U_{implosion}$) that drives turbulent mixing can be calculated from an estimate of the relative amount of ablation (high P, T melting) and the isothermal speed of sound in the plasma (U_T) by the equation: $U_{implosion} = -2U_T \ln x$ where $x = m(t)/m_o$, m(t) is the remaining mass at time t, and m_o is the initial mass. Substituting $U_{implosion}$ yields $L = -2An\tau U_T \ln x$. Here n ~10 for the RM because it demands a shock process that will not persist much longer than the high pressure plasma pulse. While $x = m(t)/m_o$ for our experiments cannot be precisely determined, it is estimated to be ~0.10 (>90% ablation and <10 % injected into the target) which yields a value of L ~ 582 μm for the ZBL-16 experiment. This is very similar to the required equilibration length scale of ~0.5 mm (radius of crater) and much larger than the estimated diffusion length scale (~1 to 5 μm). We conclude that the observed Cr and Al mixing in the silicate melt is consistent with being produced by the RM instability caused by the implosion shock.

RM mixing in the impactor and proto-Earth: The turbulent mixing induced by the RM instabilities in our experiments has important implications to the mixing during the final stages of Earth's accretion. In this case the implosion velocity for a planetary collision can be calculated from the speed of the impactor ($U_{Impactor}$ ~10 km/s) in a way similar to our single pulse laser ablation experiment, yielding the RM length scale for the planet collision: $L_{Planet} = -2A_{Planet} \times \tau_{Planet} \times U_{Impactor} \times \ln x_{Planet}$. We use A_{Planet} ~0.4 and a conservative value for the amount of the melt produced in the impact zone that is initially ejected from the Earth of $x_{Planet} = 0.5$, based on the simulation by [5]. Thus, we obtain RM mixing length-scales of 2200, 6400 and 17000 km for the times of 0.11, 0.32 and 0.86 hours, respectively. Therefore, if the collision can maintain the high P and T at the interface, then the turbulence induced by shock wave will effectively mix the interior of the impactor in less than 1 hour.

Conclusions: Our new experimental results provide strong support for ^{182}Hf-^{182}W dating of core-mantle differentiation by using the standard global magma ocean model that yields a mean time of core formation of 11 Myr and EMS formation ~32 Myr after the Solar System formation [1]. In contrast, a late formation of the Moon [6] would require an extremely fast accretion of the Earth prior to the EMS formation. We are currently left with two end member options: (i) the formation of the EMS at ~ 32 Myr or (ii) formation of 90 % of the Earth in the first 6 Myr followed by a very late (~ 100 Myr) formation of the Moon.

References:

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