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Solar wind neon in Earth´s interior and constraints on terrestrial planet formation

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One of the most fundamental perceptions of planet formation theory - already realized by Laplace and Kant, and confirmed by modern astronomical observations [1] - is that the origin of planets is associated with protoplanetary disks. The lifetime of these disks around young stars sets important constraints on the time scale of accretion. While disk lifetimes as monitored by the infrared excess of fine dust are 3 – 6 Ma (50%, 0% disk abundance; [2]) direct measurements of the gas lifetime are more difficult. Dispersal of the gas in inner parts of accretion disks seems similarly fast [3], while in the outer disks cold gas may survive a few tens of Ma [4].

Most studies suggest that formation of asteroid-sized planetesimals in the early solar system occurred within a few Ma [e.g. 5-8], indicating that the building blocks of terrestrial planets were already present when the disk was dissipated. However, it is not yet clear, if full-sized terrestrial planets accreted within the presence of disk gas or not. While for the outer gas or ice giant planets rapid accretion and attraction of disk gas as major constituent is mandatory [e.g. 9], the terrestrial planets obviously needed significantly longer time for complete accretion, as indicated by Hf-W ages of core formation of 10 Ma for Mars and 33 Ma for Earth [10].

The question if terrestrial planets accreted with the presence of gas [11] or after disk dissipation [12] can be answered using neon isotopes [13-21], particularly utilizing advances in high precision neon isotope measurements in recent years [17-21]. Neon in the Earth´s mantle has a solar-type isotopic composition [14, 17-21]. If the Earth accreted to its full size before disk dissipation [11], it would have attracted a dense (about 100 bar) solar-type protoatmosphere, and solar helium and neon could have been dissolved into an early magma ocean [13,16], and neon would have the isotopic composition of solar gas with $^{20}Ne/^{22}Ne=13.8+-0.1$ [14,15]. Contrary, if the Earth´s precursor planetesimals were small upon loss of the disk gas, the only way to acquire solar neon is implantation as solar wind ions, with an isotopic composition found in meteorites exposed to the solar wind ("Ne-B" with $^{20}Ne/^{22}Ne=12.5+-0.2$ [22]). Trieloff et al. [17,18] first recognized that solar neon in terrestrial mantle reservoirs (Hawaii, Iceland, Réunion, MORB-mantle) has Ne-B composition, which was first challenged and afterwards confirmed by Ballentine et al. [23, 19]. Indeed, there is increasingly compelling evidence that the whole terrestrial mantle contains Ne-B as fundamental component, e.g. for mantle reservoirs involved in generating the late Cenozoic mafic alkaline volcanism in Europe [20], and Réunion island [21]. Suggestions [19], that the lower mantle contains some portions still dominated by solar gas acquired in early accretionary epochs (e.g. based on data from the fossil Kola mantle plume with $^{20}Ne/^{22}Ne=13.0+-0.2$) are not compelling regarding the uncertainties, and imply circumstantial preservation of lower mantle reservoirs that only marginally exchange with other mantle reservoirs during highly energetic processes like core formation, mantle differentiation, or the moon forming impact.

The occurrence of solar wind implanted neon (and helium) in planetary interiors tightly constrains accretion scenarios in the inner solar system, as appropriate irradiation conditions must have existed. I discuss several possible irradiation scenarios: 1) irradiation before disk gas dispersal, due to planetesimal orbits with high inclinations (possibly triggered by gravitational disturbations of Jupiter) 2) late accretion of fine, irradiated dust, e.g. after the moon forming impact 3) Disk gas dissipation 3-4 Ma after CAIs in the inner solar system [2,3]. Distinguishing these scenarios could be performed by considering early irradiated meteorites. Early irradiation histories had been suggested for carbonaceous chondrites [24]. The amount of solar wind implanted neon increases in the sequence CI-CM-CV–Earth [18] that also is a sequence of decreasing abundances of moderately volatile elements [25]. This probably links early T-Tauri activity of our sun and volatile depletion in the inner early solar system.

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