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Invited review

Do lunar and meteoritic archives record temporal variations in the composition of solar wind noble gases and nitrogen? A reassessment in the light of Genesis data

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ABSTRACT

Since about half a century samples from the lunar and asteroidal regoliths been used to derive information about elemental and isotopic composition and other properties of the present and past solar wind, predominantly for the noble gases and nitrogen. Secular changes of several important compositional parameters in the solar wind were proposed, as was a likely secular decrease of the solar wind flux. In 2004 NASA's Genesis mission returned samples which had been exposed to the solar wind for almost 2.5 years. Their analyses resulted in an unprecendented accuracy for the isotopic and elemental composition of several elements in the solar wind, including noble gases, O and N. The Genesis data therefore also allow to re-evaluate the lunar and meteorite data, which is done here. In particular, claims for long-term changes of solar wind composition are reviewed.

Outermost grain layers from relatively recently irradiated lunar regolith samples conserve the true isotopic ratios of implanted solar wind species. This conclusion had been made before Genesis based on the agreement of He and Ne isotopic data measured in the aluminum foils exposed to the solar wind on the Moon during the Apollo missions with data obtained in the first gas release fractions of stepwise in-vacuo etch experiments. Genesis data allowed to strengthen this conclusion and to extend it to all five noble gases. Minor variations in the isotopic compositions of implanted solar noble gases between relatively recently irradiated samples (<100 Ma) and samples irradiated billions of years ago are very likely the result of isotopic fractionation processes that happened after trapping of the gases rather than indicative of true secular changes in the solar wind composition. This is particularly important for the $^{3}He/^{4}He$ ratio, whose constancy over billions of years indicates that hardly any ^{3}He produced as transient product of the pp-chains has been mixed from the solar interior into its outer convective zone. The He isotopic composition measured in the present-day solar wind therefore is identical to the $(D+^{3}He)/^{4}He$ ratio at the start of the suns's main sequence phase and hence can be used to determine the protosolar D/H ratio.

Genesis settled the long-standing controversy on the isotopic composition of nitrogen in lunar regolith samples. The $^{15}N/^{14}N$ ratio in the solar wind as measured by Genesis is lower than in any lunar sample. This proves that nitrogen in regolith samples is dominated by non-solar sources. A postulated secular increase of $^{15}N/^{14}N$ by some 30% over the past few Ga is not tenable any longer. Genesis also provided accurate data on the isotopic composition of oxygen in the solar wind, invaluable for cosmochemisty. These data superseded but essentially confirmed one value – and disproved a second one – derived from lunar regolith samples shortly prior to Genesis.

Genesis also confirmed prior conclusions that lunar regolith samples essentially conserve the true elemental ratios of the heavy noble gases in the solar wind (Ar/Kr, Kr/Xe). Several secular changes of elemental abundances of noble gases in the solar wind had been proposed based on lunar and meteoritic data. I argue here that lunar data – in concert with Genesis – provide convincing evidence only for a long-term decrease of the Kr/Xe ratio by almost a factor of two over the past several Ga. It appears that the enhancement of abundances of elements with a low first ionisation potential in the solar wind (FIP effect) changed with time.

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Finally, Genesis allows a somewhat improved comparison of the present-day flux of solar wind Kr and Xe with the total amount of heavy solar wind noble gases in the lunar regolith. It remains unclear whether the past solar wind flux has been several times higher on average than it is today.

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1. Introduction

Solar history is recorded in a variety of archives, covering times scales from years to billions of years. Many of these archives record solar activity, e. g. solar wind or solar energetic particle fluxes or the solar magnetic field. Examples are solar flare tracks (radiation damages induced by heavy – Fe group and heavier – energetic particles of solar origin) in samples from the lunar or asteroidal regoliths (e.g., Crozaz, 1980), radionuclides produced by solar energetic particles in the lunar regolith (Reedy, 1980), or radionuclides such as ^{10}Be in ice cores, whose concentration reflects – among other parameters – the modulation of the Galactic Cosmic Ray (GCR) flux by the sun's magnetic field (e.g., Beer et al., 2013). Noble gases produced by high energy spallation reactions in specific phases in some meteorites in excess of what is straightforwardly explainable by the meteoroid's recent exposure to GCR particles have also been interpreted as evidence for a very high solar particle flux emitted by the early sun (e.g., Woolum and Hohenberg, 1993), but this issue is controversial (Roth et al., 2011). Another solar particle flux proxy will be discussed in this contribution, namely the amount of Kr or Xe from the solar wind stored in the lunar regolith. However, this paper deals mostly with the question of whether the elemental or isotopic *composition* of the solar corpuscular radiation as recorded in suitable archives may have changed.

The lunar regolith – and to a lesser extent samples from asteroidal regoliths in the form of "solar gas-rich" meteorites – have been used to infer the composition of solar wind species since almost 50 years. Such work has largely concentrated on noble gases and nitrogen, though other studies dealt with H (Epstein and Taylor, 1972), Li (Chaussidon and Robert, 1999), C (Becker 1980; Hashizume et al., 2004), O (Ireland et al., 2006; Hashizume and Chaussidon, 2005), Cr (Kitts et al., 2003) and some radionuclides (Nishiizumi and Caffee 2001; Lal et al., 2007). In addition, densities of solar flare tracks in lunar soil grains have been studied with the goal to infer the temporal evolution of fluxes, energy spectra and composition of heavy solar energetic particles (Zinner, 1980; Zook, 1980; Crozaz, 1980) though sometimes with controversial results. Likely the most important achievement of Genesis has been to provide reliable and accurate data on the isotopic composition of oxygen in the solar wind (McKeegan et al., 2011) and hence to resolve the controversy between Hashizume and Chaussidon (2005) and Ireland et al. (2006) as is discussed elsewhere (McKeegan et al., 2011).

The unique value of the lunar regolith to study possible long-term changes in the composition of solar wind noble gases and nitrogen, and hence the sun's outer convective zone, has been recognized with the first samples brought back by the Apollo astronauts. Several compositional changes have been postulated over the years (Table 1). Eberhardt et al. (1972) and Geiss (1973) noted that the $^3He/^4He$ ratio of solar wind trapped in lunar regolith samples several billion years ago was lower than in samples irradiated relatively recently by lunar standards, i.e., perhaps in the last 100 Ma. This seemed to indicate an increase of the abundance of the rare He isotope on the order of 10 percent per billion years. Possible small differences in the isotopic composition of neon and argon between ancient and more recent solar wind have occasionally also been proposed, as will be discussed below. Apart from helium, by far the largest change in isotopic composition has been proposed for nitrogen, however. Kerridge (1975), Becker and Clayton (1977) and Thiemens and Clayton (1980) showed that the $^{15}N/^{14}N$ ratio of nitrogen trapped in lunar regolith samples was higher by some 30% in relatively recently irradiated samples than in samples exposed at the lunar surface presumably several Ga ago. The "classical" picture (Kerridge, 1993) to explain this variation for a long time was a secular change in the isotopic composition of N in the solar wind, although this view was controversial (e.g., Wieler et al., 1999; Bochsler, Geiss and Bochsler, 1991).

Also several elemental ratios of solar wind noble gases trapped in lunar samples presumably at different times in the past were reported to vary (Table 1). Some workers attributed this variability to true secular variations in solar wind composition (e.g., Kerridge et al., 1991 and other references in Table 1), whereas others (e.g., Bogard et al., 1973) argued that the variability was mainly or exclusively caused by fractionation during or after implantation. These fractionation effects would then hamper recognizing potential true variations in solar wind composition.

The workers involved in these discussions have always been aware of the basic problems when attempting to deduce the true composition – elemental and isotopic – of the impinging solar wind and/or potential long-term compositional variations, viz. how can