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On the Character of the Solar Flare Activity over a Long-Time Scale

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A modeling of the ionic charge states of the solar noble gases in the lunar samples of different antiquity, taking into account the differences of isotopic and elemental composition of the SW and SEP components of the noble gases, is presented. The ionic charge states of Ne, Ar, Kr and Xe in the lunar samples of the cosmic ray exposure age of ~100 Ma turned out to be Q = 8, 14, 18-19 and 18, respectively, and those in the lunar samples of ~ 1 Ga turned out to be Q = 8, 16, 21-23 and 23, respectively. That testifies to rather an impulsive character of the solar flare activity ~1 Ga ago, in comparison with the gradual solar flare activity, on the average, during the last ~100 Ma. Besides, the energy spectrum of the solar protons was, apparently, more rigid in the past: the power law spectrum index ~2.5 vs. 3.0 of their average contemporary spectrum.

1. Introduction

The noble gases in the lunar ilmenites [1,2] are analyzed with respect to the charge states of their ions in the solar wind (SW) and with respect to the shock wave acceleration of the solar energetic particles (SEP, 1-50 MeV/n). The SW and SEP, being two distinguishable components of the solar corpuscular emanation, provide the direct clue to the processes in the corona and the chromosphere [3]. Indeed, the chromosphere and the lowest layers of the corona are the likely regions of the atom-ion separation, depending on the first ionization potential (FIP) of the elements; the charge states of the ions are eventually formed in equilibrium with the local temperature and density of electrons, and they remain unaltered in further processes.. Both the components are distinguished by their isotopic and elemental abundances. SEP, associated with the solar flares, are considered to be shock wave accelerated before injection from the corona and/or during propagation in the heliosphere. This leads to the SEP fractionation in proportion to A/Z or $(A/Z)^2$ (to A/Q or $(A/Q)^2$, where Q is the ionic charge, if the ionization is incomplete) [4]. In the case of i and j isotopes of the same element the fractionation is proportional to A^i/A^j or $(A^i/A^j)^2$, i.e. to the common mass-fractionation.

2. Lunar ilmenites

The SEP fractionation is strongly variable from event to event, so that its long-time average values provided with implanted noble gases in meteorites and lunar samples are of paramount importance. The closed system stepped etching (CSSE) data [1,2] in the lunar ilmenites: soil 71501 (I71) with exposure age ~100 Ma and breccia 79035 (I79) with that of ~1 Ga, are especially valuable. The solar noble gases, released by CSSE from the initial I71(1) and I79(3-4) steps of etching, turned out to be unfractionated SW noble gases, and those from the deep I71(13) and I79(16-17) steps were noticeably heavier, like the SEP noble gases (see rows 3 and 6 in Table 1a,b). In Figure.1 the polynomial approximation curves demonstrate visually that Ne, Ar, Kr and Xe become heavier with increasing the depth of etching. On the other hand, the effects of higher diffusion losses of lighter gases were recorded in the element ratios of He, Ne and Ar during the first etching steps. One may see, for instance, in Figure. 2 that $^{20}Ne/^{36}Ar$ ratio grows with increasing the etching depth in both the I71 and I79 samples. Indeed, our corrections of the ratios, in accordance with the self-diffusion coefficients [5] from Table 2, equalize the SWI71 compositions with those in the SW [6] and in the solar system [7] (see rows 2 and 4 of Table 1a). Such an equalizing is not entirely reached in I79 breccia (see rows

2 and 4 of Table 1b) that will be discussed below. Meanwhile, the effect of the near surface diffusion is not observed at all in the case of heavy gases in I71, as well as in I79 ilmenites (see Fig.2). Taking into account the mass-fractionation only, the authors of [1, 2] get the "paradox" that ratios of light gases ($^{4}He/^{36}Ar$ and $^{20}Ne/^{36}Ar$) grow with the depth, whereas the $^{84}Kr/^{132}Xe$ ratio remains essentially constant. It is easy to see

Table 1a. Modelling the noble gas ratios of the SW and SEP components in the lunar ilmenites *I*71 (parameter $K_{I71} = (A^i/Q^i_{I71})^2/(A^j/Q^j_{I71})^2$, where *i* and *j* denote isotopes; *A* – mass number; *Q* – ion charge)

1	Composition	$^{20}Ne/^{22}Ne$	$^{36}Ar/^{38}Ar$	$^{20}Ne/^{36}Ar$	$^{36}Ar/^{84}Kr$	$^{82}Kr/^{84}Kr$	$^{130}Xe/^{132}Xe$	$^{84}Kr/^{132}Xe$
2	Solar system [7]	13.68	5.31	37.65	3307	0.2004	0.1653	20.73
3	SW: *I*71 $_{(1)}$ [1,2]	13.81	5.46	13.91	2043	0.2037	0.1659	12.46
4	$SW_{I71}=I71_{(1)}\cdot D^i_0/D^j_0$	13.81	5.46	40.3	3984	0.2037	0.1659	20.77
5	SEP: $SW_{I71}\cdot K_{I71}$	11.41	4.90	38.09	1348	0.2052*	0.1609	7.55
6	SEP: *I*71 $_{(13)}$ [1,2]	11.21	4.68	38.64	1308	0.2079	0.1586	7.97

* - at Q_{I71}=18-19 for ^{82}Kr and Q_{I71}=19 for ^{84}Kr.

Table 1b. Modelling the noble gas ratios of the SW and SEP components in the lunar ilmenites *I*79 (parameter $K_{I79} = (A^i/Q^i_{I79})^2/(A^j/Q^j_{I79})^2$, where *i* and *j* denote isotopes; *A* – mass number; *Q* – ion charge)

1	Composition	$^{20}Ne/^{22}Ne$	$^{36}Ar/^{38}Ar$	$^{20}Ne/^{36}Ar$	$^{36}Ar/^{84}Kr$	$^{82}Kr/^{84}Kr$	$^{130}Xe/^{132}Xe$	$^{84}Kr/^{132}Xe$
2	Solar system [7]	13.68	5.31	37.65	3307	0.2004	0.1653	20.73
3	SW: *I*79 $_{(3-4)}$ [1,2]	13.47	5.43	10.67	2160	0.2119	0.1761	4.64
4	$SW_{I79}=I79_{(3-4)}\cdot D^i_0/D^j_0$	13.47	5.43	30.91	4212	0.2119	0.1761	7.74
5	SEP: $SW_{I79}\cdot K_{I79}$	11.13	4.87	38.16	1598	0.2315*	0.1708	3.13
6	SEP: $I79_{(16-17)}$ [1,2]	11.12	4.72	37.51	1547	0.2306	0.1635	3.53

* - at Q_{I79}=21-22 for ^{82}Kr and Q_{I79}=23 for ^{84}Kr.

that this paradox is easily resolved from the point of view of the noble gas fractionation due to the shock wave acceleration. Let us notice that *A/Z*=2 for both the isotopes of each pair of the light noble gases, so that their relative abundances have not to be changed during SEP acceleration, but have to remain the same as in SW (if ionization was complete). With heavy gases, *A/Z*=2.33 for ^{84}Kr and *A/Z*= 2.44 for ^{132}Xe, so that their relative abundances have to vary during SEP acceleration (their ratio should decrease with the depth, but it is masked by the higher losses of lighter Kr near the surface). It is more likely, however, that ionization in the chromosphere is not complete, e.g., in the contemporary SW the average charge states of Ne, Ar, Kr and Xe ions are Q_{SW}= 8,9,12 and 14, respectively, corresponding to the ionization potential range of ~200-400 eV [8]. Our modelling leads to the average charge states for ~100 Ma (*QI71*) and for ~1 Ga (*QI79)* listed in Table 2. Indeed, using these charges and SEP fractionation in shock waves in proportion to $(A/Q)^2$ (see parameters K_{I71} and K_{I79}), one can convert the diffusion-corrected $SW_{I71(1)}$ and $SW_{I79(3-4)}$ data for the initial etching steps (rows 4 in Tables 1a,b) to the corresponding SEP relations, which fit closely the measured ratios of isotopes and elements in the deep $I71_{(13)}$ and $I79_{(16-17)}$ fractions (rows 5,6 in Table 1a,b). Notice that the same approach has been used to the isotopic as well as to the elemental ratios. The best fit for Kr (marked by *) is observed under the different charge states of its isotopes, namely, 18-19 in the similar proportion for ^{82}Kr and 19 for ^{84}Kr in *I*71, and 21-22 in the similar proportion for ^{82}Kr and 23 for ^{84}Kr in *I*79. The obtained charge states in Table 2 are rather higher than those for the modern SW [8], the average charge states for ~1 Ga being rather higher than those for ~100 Ma.

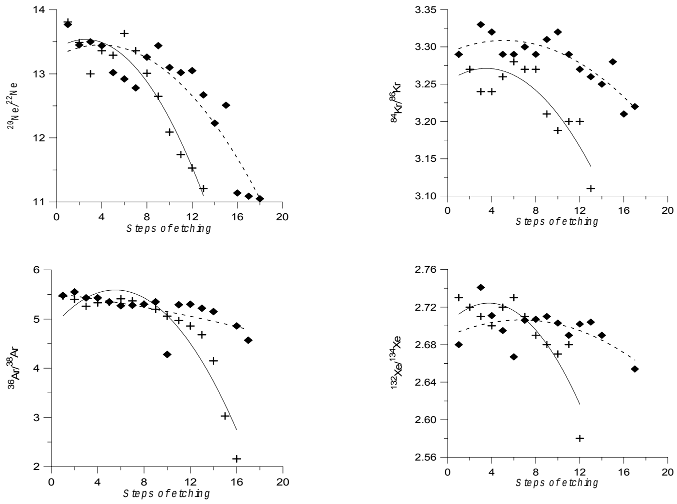

Figure 1. Dependence of the noble gas isotopic ratios on the etching steps of samples of the lunar ilmenites (crosses – lunar soil I71, diamonds – regolith breccia I79 (according to data of [1,2]); polynomial approximation: solid curves are for I71; point curves are for I79)

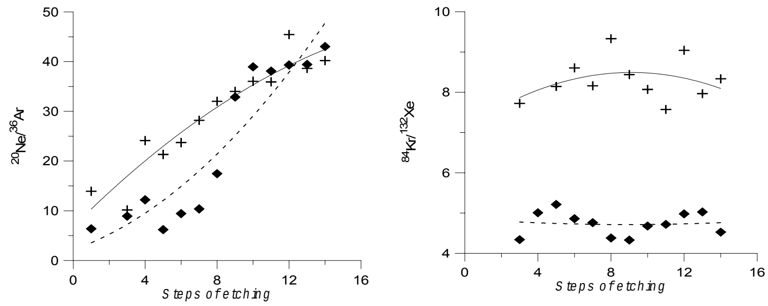

Figure 2. Dependence of the noble gas elemental ratios on the etching steps of samples of the lunar ilmenites (notations are the same as in Figure.1)

2. Discussion

The ion charge states of the majority of elements in the contemporary SEP components of the gradually developing flare events correspond to the ionizations in the conditions of the thermal equilibrium at the typical coronal temperature of $2 \cdot 10^6$ K (e.g., $Q_{Fe} \sim 10$ for iron ions) [9]. However, in more rigid impulsive SEP events, enriched with ^{3}He and heavy ions, a higher mean charge state $Q_{Fe} \sim 20$ was found, suggesting an origin in hotter, ~10^7 K flare plasma [10]. Thus, the higher ionic charge states of the SEP noble gases for ~1Ga than for the last ~100Ma may testify to rather impulsive than gradual character of the solar activity events in the past over that time scale.

As well seen in Figure.2, the heavy gas data in *I*79 lie about twice as lower as in *I*71. It may be caused by insufficient correction for cosmogenic components in [1,2]. Such a correction for all the gases, except for Xe, was made separately for each etching step in *I*71 and *I*79, in accordance with the measured cosmogenic gas contents in the deeper etching steps. In the case of Xe, because of high contamination of the atmospheric Xe, a phenomenological cosmogenic composition of Xe is used for cosmogenic corrections in *I*71, as well as in *I*79. Meanwhile, the results obtained above allow us to suppose that the energy spectrum of the solar

Table 2. Self-diffusion coefficients D_0 [5] of the noble gases and the charge states Q of their ions: Q_{SW} - in the modern SW [8]; Q_{I71} and Q_{I79} - in the SW, averaged for ~100 Ma and ~1 Ga, respectively [this work]; * - a range of the ionization potential is indicated in the parentheses [5].

Parameter	Ne	Ar	Kr	Xe
D_0, cm^2/s	0.452	0.156	0.08	0.048
Z	10	18	36	54
Q_{SW} (200-400 eV)*	8	9	12	14
Q_{I71} (700-800 eV)*	8	14	18-19	18
Q_{I79} (900-1000 eV)*	8	16	21-23	23

protons was more rigid ~1Ga ago, which would be strongly change the cosmogenic isotope relations. Increasing rigidity of the energy spectrum of initial protons intensifies yields of all the cosmogenic nuclides, but the gain is various for different ones, so that the isotopic relations change [11]. Indeed, if γ decreases from 3 (the average contemporary spectrum of the solar protons) to 2.5 (the more rigid spectrum, e.g. the galactic cosmic ray spectrum), the $^{84}Kr/^{86}Kr$ ratio decreases from 62 to 57, and the $^{132}Xe/^{134}Xe$ ratio decreases from 39 to 36 only, whereas the $^{84}Kr/^{132}Xe$ ratio decreases from 285 to 148, i.e., approximately twice. It is just the overestimation of the cosmogenic contribution to $^{84}Kr/^{132}Xe$ ratio in the ancient ilmenites I79 might lead to such low ratios of the trapped components of these noble gases in Figure.2.

It is clear, that no diffusion mechanism could be responsible for the observed difference of the elemental ratios of the heavy gases in the lunar ilmenites of different antiquity because such an effect would be displayed to an even greater degree in the case of light gases. However, the decrease in $^{84}Kr/^{132}Xe$ ratios could be conditioned with additive admixtures of Xe from fission of some transuranic elements, first of all, ^{238}U and ^{244}Pu. They are present in various quantity, mainly, in lunar crystalline rocks, and they are absent in lunar soils formed after decay of those elements [12]. They are also typical for lunar breccias, in which Xe could be implanted by shock from earlier accumulated reservoirs of the fission Xe in the lunar rocks [13]. Probable existence of the fission Xe admixtures in the ilmenites of I79 breccia leads to decrease of the estimated values of the ion charge states, so that the Q_{I79} values presented in Table 2 should be considered as their upper limits only.

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