ANALYSIS OF THE SOLAR PROTON EFFECTS IN THE STUBENBERG AND JESENICE CHONDRITES. G. K. Ustinova, Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, ustinova@dubna.net.ru

Introduction: The Stubenberg (LL6) and Jesenice (L6) chondrites fell on March 3 2016 and on April 4, 2009, respectively, their falls being photographed and their orbits being calculated exactly [1]. Both the chondrites are studied extensively, including the chemical compositions and the contents of cosmogenic radionuclides of various half-lives ($T_{½}$) [2,3]. In particular, they differ from each other mainly in the ^{59}Co content (0.056 and 0.088 weight %, respectively), from which ^{60}Co is produced. Ranges of the measured values of the ^{60}Co/^{26}Al ratios in the investigated samples of the chondrites [2.3] and calculated depth distributions of this ratio in L/LL chondrites of different sizes [4] point out to the sizes *R* and to the screening depths *d* of the samples from the surface: namely, *R* ~ 10-20 cm, *d* ~ 2-8 cm (Stubenberg) and *R* ~ 20-30 cm, *d* ~ 2-6 cm (Jesenice) [5].

The cosmogenic radionuclides in meteorites are produced by the solar cosmic rays (SCR) (mainly, protons of *E* ~ 20-500 MeV), as well as by the galactic cosmic rays (GCR) of *E* > 100 MeV. The solar protons are practically depleted at the first ~10 cm from the surface, whereas the primary GCR component and initiated cascade of the secondary particles prevail at the depths > 2 cm from the surface [4] Therefore, the solar proton effects would be conserved in both the chondrites and should be taken into account.

Solar modulation: The GCRs enter the Solar System isotropically from the surrounding cosmic space. The SCRs, in accordance with the 11-year variations of the solar activity, are emitted periodically by the sun to meet GCRs. Due to the sun rotation, the initially radial motion of SCRs is gradually twisted as an Archimedean spiral, so that at about ~ 5 AU their motion becomes the practically azimuthal one [6]. It creates hardly superable barriers to GCR penetration into the heliosphere. Thus, the solar modulation of GCRs arises, i.e. at the higher solar activity (e.g. SCR intensity) the GCR intensity is lower near the Earth.

Since 1957, the monthly measurements of GCR intensity (*E* > 100 MeV) in the stratosphere [7] allow us to analyze cosmogenic radionuclides of different $T_{½}$ in meteorites, and to derive the unique information on the character of the GCR modulation at different heliocentric distances in accordance with the sizes of the meteoritic orbits [4,8]. However, such an analysis provides the necessity to estimate and exclude contributions of the SCRs in production of the radionuclides.

Dependence on the solar activity: Unfortunately, any continuous data on the SCR intensity are absent. There is a value of 330 proton cm^{-2}s^{-1} (>20 MeV) measured for the maximum solar activity in 1956, 1959 and 1960 [9], whereas the average SCR intensity (>20 MeV) for the solar cycle, as well as for the last million years, is 31 proton cm^{-2}s^{-1} (2.46 proton cm^{-2}s^{-1}sr^{-1}), which follows from the ^{22}Na and ^{26}Al radioactivity data of the lunar sample 10017 delivered by Apollo 11 [10]. The anti-correlated interdependency of decline and rise of the GCR intensity near the Earth with the periodical increase and decrease of the SCR intensity allows us to approximate such a process with the Gauss error curve, namely, $y = 330e^{-1.051(x-1.5)^2}$, which links the maximum (330 proton cm^{-2}s^{-1}) and the average (31 proton cm^{-2}s^{-1}) intensities of the solar protons with the minimal (1.5nucleon cm^{-2}s^{-1} (0.12 nucleon cm^{-2}s^{-1}sr^{-1})) and the average (3 nucleon cm^{-2}s^{-1} (0.24 nucle.cm^{-2}s^{-1}sr^{-1})) GCR intensities near the Earth, respectively (Fig. 1).

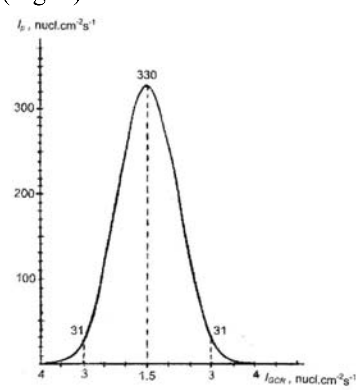

Fig.1 A function $y = 330e^{-1.051(x-1.5)^2}$ *of the solar cycle approximation. Real interrelated decreases of the GCR intensity* I_{GCR} *(from 4 down to 1.5 nucl.cm*$^{-2}$*s*$^{-1}$*) are marked on the x axis at the corresponding increases of the solar proton intensity* I_p *(from 0 up to 330 nucl.cm*$^{-2}$*s*$^{-1}$*), and further vice versa: the subsequent increases of the GCR intensity at the corresponding decreases of the solar proton intensity.*

Dependence on the radionuclide production cross sections: Considering different radionuclides, it should be taken into account that their contents depend on the cross sections of their production by nuclear-active particles of different energies on the target elements of the meteorite composition. Some difference of the production cross sections of radionuclides in L-chondrites with primary SCRs and GCRs, which are averaged in accordance with their energy spectra as ell as with the chondrite compositions [4], are presented in Table 1.

Table 1 Mean-weighted values of the cross sections (in mbarn) of some radionuclides with the solar protons (>0.02GeV) and with the GCRs (>0.2 GeV) in L- chondrites.

	^{48}V	^{51}Cr	^{46}Sc	^{54}Mn	^{22}Na	^{55}Fe	^{26}Al
P_{solar}	0.27	5.36	0.11	5.06	7.22	65.62	8.24
P_{GCR}	1.55	6.96	1.26	3.99	4.99	10.07	3.99

Dependence on heliocentric distances: In the case of production of the radionuclides of $T_{½} \geq 1$ y, it should be taken into account that the force of source (e.g., the Sun) is reduced proportionally to the distance squared. Indeed, up to 80% of the measured contents of radionuclides (at the moment of meteorite fall) are accumulated during ~ 1.5 $T_{½}$ of the radionuclides, i.e. at the average heliocentric distances r_c of meteorites corresponding to ~0.75 $T_{½}$ [4,8]. Considering the dependence *r(t)* of the heliocentric distance *r* on time *t* of the Stubenberg and Jesenice orbits before their fall to the Earth at *t*=0, one may obtain that in the Stubenberg chondrite ^{22}Na is produced at r_c = 1 AU with the average SCR and GCR intensities for the last ~ 4 y before its fall in March 2016, and ^{54}Mn is produced at r_c = 1.98 AU with the average intensities for the last ~ 450 days before its fall. Similar values for the ^{22}Na and ^{54}Mn in the Jesenice chondrites are r_c = 1.65 AU and r_c = 2.14 AU, respectively before its fall in April 2009 [5]. Thus, apart from the phase of solar activity during the chondrite fall, the decrease of the average SCR intensity proportionally to $(r_c)^2$ in the radionuclide production should be taken into account. It is clear that the short-lived radionuclides (up to ~ ^{46}Sc) are produced with the SCR intensity at 1 AU. Meanwhile, the ^{26}Al is accumulated at the average heliocentric distances r_0 of the orbits, corresponding to ¼ of the orbital period *P* of the meteorites. Hence, it is accumulated with the solar proton fluxes which were (r_0^2) times lower. The larger is the meteorite orbit - the smaller is the contribution of solar protons to the production of long-lived radionuclides to be expected.

The solar proton effects in the Stubenberg and Jesenice chondrites: Taking into account all the factors (described above), one may determine the contributions of the solar protons into the measured contents of some radionuclides of various $T_{½}$ in the Stubenberg and Jesenice chondrites. The results are presented in Table 2 in comparison with the data for the Bruderheim (L6) chondrite obtained earlier [4]. That L6-chondrite fell on March 1960 just after the maximum of the 19 solar cycle at the intensity of solar protons (*E* > 20 MeV) of 330 proton cm^{-2}s^{-1}. The aphelion of its most optimal orbit is *q'* = 4.06 AU; its average heliocentric distance is *r* ~ 3.29 AU; pre-atmospheric radius of the chondrite is *R* ~ 30-50 cm; screening depth of the samples is *d* ~ 2-10 cm.

Table 2. Contributions of the solar protons (E > 20 MeV) into production of the measured contents of the radionuclides (in dpm kg^{-1}) in the Bruderheim, Jesenice and Stubenberg chondrites.

	^{48}V	^{51}Cr	^{46}Sc	^{54}Mn	^{22}Na	^{55}Fe	^{26}Al
Brud.	6.1	122	1.5	18.1	15.2	138	0.8
Jesen	0	0	0	0	0.32	2.92	2.1
Stub.	0.09	1.85	0.02	5.4	44.4	404	2.8

Some definite regularities would be recorded, e.g., the high content of ^{55}Fe and the low one of ^{46}Sc, which is conditioned by the strong difference of their production cross sections with protons of low energy (see Table 1). Further, the short-lived radionuclides, being similar to ^{48}V, ^{51}Cr and ^{46}Sc, are practically produced just prior to the chondrite fall at ~ 1 AU, so that their contents depend on the level of solar activity for the date of fall. Despite the intensity of solar protons near the Earth being smaller by an order of magnitude as compared with their intensity at the Bruderheim irradiation, the solar proton contributions into the ^{22}Na and ^{55}Fe production in the Stubenberg chondrite are much higher, because in the Bruderheim chondrite they are produced at the average heliocentric distance of *r* ~ 3.29 AU, i.e., at the solar proton intensity being smaller proportionally to that distance squared. The quite different situation is in the case of ^{26}Al, which is produced at the average intensity of solar protons for the last million years and which does not depend anyway on the level of the solar activity over chondrite falls. In particular, the solar proton contributions in the ^{26}Al production in the chondrites, considered in Table 2, are defined only by relations of the average heliocentric distances of their orbits. In the case of the radionuclides of various half-lives, some joint action of all the factors that affected the magnitude of the solar proton contribution to their production should be taken into account.

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