VARIATION IN PARTICLE FLUXES AND SHORT-LIVED COSMOGENIC NUCLIDE PRODUCTION RATES DURING SOLAR CYCLE.

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Introduction: Processes in the Sun and solar activity notably affects processes in heliosphere that lead to the changes in solar magnetic field. Solar activity can be described be the solar modulation parameter Φ, which is equivalent to the energy loss per heliocentric distance of a particle entering the solar system. Changes in solar activity influence intensity of GCR particle flux in solar system and therefore the differential primary particle spectra depend on the solar modulation parameter Φ [MeV]. Modulation parameter Φ shows spatial and temporal variations [1]. Some of the solar variations are cyclic and lead to some measurable effects as for example eleven-year Schwabe cycle and the 22-year solar magnetic polarity cycle (other cycles are less pronounced). Variation in solar activity can induce only negligible effects on production of long-lived cosmogenic radionuclides as ^{26}Al (T1/2 = 7.17x10^5 y), ^{53}Mn (3.74x10^6 y), ^{10}Be (1.36x10^6 y). This is due to the fact that activities measured in meteorites correspond to saturation values and represent long term average values that can be obtained by irradiation of meteoroids by long term average GCR flux, represented in our case, with the modulation parameter Φ = 550 MeV [2]. Long-lived radionuclides require millions of years of irradiation by GCR to reach their saturation and therefore cycles average out. One can expect much pronounced variations in production rates caused by primary flux intensity variation during solar cycle, if short-lived radionuclides with half-lives ranging from days to a few years are investigated. Aim of this work is to develop formulae for calculation of production rates of radionuclides with short half-life, taking into account temporal variation in primary cosmic ray intensity.

Calculational Model: The numerical simulation of interactions of primary and secondary cosmic-ray particles was done with the LAHET Code System (LCS) [3] which uses MCNP [4] for transport of low energy neutrons. The investigated objects were spheres with various radii that were divided into spherical layers. We used the spectrum of the galactic-cosmic-ray particles corresponding to solar modulation parameter Φ = 250-1400. This range of modulation parameters is covering variation in solar activity in a recent few decades.The statistical errors of the LCS calculated fluxes were ~3–5%. The production rates of nuclides were calculated by integrating over energy the product of these fluxes and cross sections for the nuclear reactions making the investigated nuclide. For cross sections of spallogenic products, we relied on the values evaluated by us and tested by earlier calculations [5]. In the next step we developed the formula that takes into account contribution to production rate of short-lived radionuclides from instantenous production rate that is strongly dependent on actual solar activity.

Discussion and conclusions: The calculation model for short-lived radionuclides described in this paper allowed us to reconstruct production rates and activities of cosmogenic radionuclides for recent meteorite falls Košice and Chelyabinsk. Production rate of cosmogenic radionuclide is immediately respond to changes in GCR, as it is directly dependent on the source of irradiation, while activity of radionuclide integrates those changes over time (Fig. 4-5.). As one can see from figures 4-5., variations in activity of particular radionuclide (in this case between solar maximum and minimum) are dependent on its half-life. Radionuclides with longer half-lives ~ few years undergo lower variation. Variation can be quantified using equation (1); for particular radionuclides it gives ~ 14 % for 60Co (5.27 y), ~ 26 % for 22Na (2.6 y). Radionuclide with shorter half-lives ~ tens or few hundred days are influenced much more by actual solar activity and therefore very strong variation in their activity can be seen. Using the same approach as in previous cases it can be estimated as ~ 50 % for 54Mn (312.3 d), ~ 55 % for 57Co (271.8 d), ~ 70 % for 58Co (70.86 d).The dependence of calculated activities for short-lived radionuclides is function of their half-lives. The shape of corresponding curve is somehow smoother and the position of local extreme is slightly shifted with increasing half-life. Those effects are due to aggregation and decay of radionuclides through the longer period of time. This means that activity of radionuclides with longer half-lives are less sensitive to the instantaneous changes in GCR flux and their response to change is weaker and slightly delayed. Activity of radionuclides with half-life much longer than 11yr solar cycle average out changes in solar activity and therefore experimentally measured radioactivity is equal to the production rate of given radionuclide corresponding to the long-term average GCR spectrum. Solar modulation strongly influences particles with lower energies and this influence lose strength with increasing energy. Therefore variation in activity of a radionuclide is also naturally higher near surface, where many lower energetic primary particles contribute to the production (but they are not able to penetrate deeply into body of meteoroid), and decreases with depth .Obtained results clarify behavior of short-lived nuclides through the solar cycle and have direct impact on their application e.g. to the determination of preatmospheric size of a meteoroid that is commonly estimated from activity of ^{60}Co (60Co is the one of the most sensitive depth indicators), Its activity is usually calculated either from averaged GCR flux or using a very rough approximation of the solar activity influence on production rates. Precisely calculated activities of short-lived radionuclides can become useful tool for accurate estimation of depth of a particular sample in meteoroid body and it can provide very helpful information about characteristics of investigated meteorite as well.

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