COSMOGENIC RADIONUCLIDES IN CHONDRITES WITH KNOWN ORBITS: IMPLICATIONS FOR COSMIC-RAY GRADIENTS IN THE HELIOSPHERE.

P. P. Povinec[1], V. A. Alexeev[2], M. Laubenstein[3] and G. K. Ustinova[2], [1]Dept. of Nuclear Physics and Biophysics, Comenius University, 84248 Bratislava, Slovakia (pavel.povinec@uniba.sk), [2]V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, 119991 Moscow, Russian Federation, [3]INFN Laboratori Nazionali del Gran Sasso, INFN, 67100 Assergi (AQ), Italy.

Introduction: Cosmogenic radionuclides with half-lives from days to millions of years, produced in nuclear reactions of galactic cosmic rays (GCR) with meteorites, have been providing valuable information on variations of GCR on large time (~1 My) and space (2-4 AU) scales, which are typical ranges of meteorite orbits [1, 2]. A special group of meteorites are those photographed before they fall on the earth, so parameters of their orbits could be calculated [3]. Recently we investigated two such meteorites, namely the Košice chondrite (fall on 28 February 2010 in Slovakia) [4], and the Chelyabinsk chondrite (fall on 15 February 2013 in Russia) [5]. Thanks to recent developments in accelerator mass spectrometry [6] and HPGe gamma-spectrometry, operating often underground [7], we have at hand high-sensitive techniques which can analyze short and long-lived cosmogenic radionuclides even in milligram samples at very low concentrations. The aim of the present work has been to elucidate GCR gradients in the solar system during different stages of Sun activity using cosmogenic radionuclides found in meteorites. Three cosmogenic radionuclides, ^{54}Mn ($T_{1/2}$ = 312 d), ^{22}Na ($T_{1/2}$ = 2.6 y) and ^{26}Al ($T_{1/2}$ = 0.717 My), were used for detail studies of their production rates in Košice and Chelyabinsk chondrites as well as in other 5 chondrites with known orbits which fallen in 1959-2000.

Calculations of cosmogenic radionuclide production rates: During time equal to ~1.5 $T_{1/2}$ before the meteorite fall on the Earth, about 80% of the activity of a cosmogenic radionuclide is accumulating in the meteorite body. Solving the Kepler equations for a meteorite movement on its orbit, it is possible to allocate a part of the orbit at which the average content of each radionuclide was accumulated before the meteorite fall. For example, the long-lived ^{26}Al was accumulated during ~1 My by an average GCR intensity at an average heliocentric distance of the meteoroid orbit. The simulations of cosmic-ray initiated nuclear reactions in meteorites (having different sizes, compositions, cosmic-ray exposure ages and average heliocentric distances) were carried out by a cascade-evaporation model [1, 8, 9] using stratospheric balloon measurements of GCR intensity [10].

GCR gradients: The calculated GCR gradient using measured and simulated radionuclide data in chondrites predict low gradients (0-10 %/AU) for solar minima (1957-2013), similarly as it has been observed on satellites. Large GCR gradients, (50-100) %/AU, were observed during solar maxima, with exceptional cases in 1992 and 2012 with gradients of (200±50) %/AU. The average GCR gradient estimated for typical solar cycles (based on ^{22}Na data) was 20 ± 10 %/AU, similar to the average gradient (based on ^{26}Al data) observed over the last million years (20–30 %/AU), which indicates a constancy of the mechanism of solar modulation of GCR, at least for the last ~1 My. The gradient minima were regularly followed by gradient maxima in agreement with the solar activity records. The short-term maxima in GCR gradients (as manifested by ^{54}Mn and ^{22}Na data), which occurred especially in 1992 and in 2012, anti-correlated with GCR deep minima observed in neutron monitor data (http://cosmicrays.oulu.fi) and in stratospheric balloon measurements [10], demonstrating low radionuclide production rates at 1 AU, but high production rates at the meteorite orbits, conditioned by high GCR intensity at larger heliocentric distances. The GCR gradients estimated over a long-time scale at different heliocentric distances provide possibility of forecasting radiation situation in the interplanetary space, which is important for prospective cosmic man-flights. Early delivery of fresh-fallen meteorites to laboratories to catch the short-lived radionuclides, at least ^{54}Mn and ^{22}Na for the successive radionuclide studies, is pre-requisite for future investigations using meteorites as probes of GCR.

Acknowledgement: Support provided by the Slovak Science and Grant Agency VEGA (project no. 1/0891/17) is highly appreciated.

References: [1] Lavrukhina A.K. and Ustinova G.K. (1990) *Meteorites as probes of cosmic ray variations.* Nauka. 262p. (in Russian). [2] Alexeev V.A. et al. (2015) *Advances in Space Research* 56:766-771. [3] Borovička J. et al. (2015) *Arxiv.org*/pdf/1502.03307. [4] Povinec P. P. et al. (2015) *Meteoritics and Planetary Science* 50:880-892. [5] Povinec P. P. et al. (2015) *Meteoritics and Planetary Science* 50:273-286. [6] Povinec P. P. (2018) *Journal of Radioanalytical and Nuclear Chemistry* Doi.org/10.1007/s10967-018-5787-3. [7] Laubenstein M. (2017) *International Journal of Modern Physics* A 32:1743002. [8] Ustinova G. K. (1995) *Nuclear Geophysics* 9:273-281. [9] Alexeev V.A. and Ustinova G.K. (2006) *Geochemistry International* 44:423–438. [10] Bazilevskaya G. A. et al. (2014) Phys. Conf. arXiv: 1411.7534v.1.