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The Kunya–Urgench H5 Chondrite and its cosmophysical evidence

V.A. Alexeev, V.D. Gorin, A.I. Ivliev, L.L. Kashkarov, G.K. Ustinova

V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow

The fresh-fallen Kunya–Urgench H5 chondrite was studied in various aspects including natural and induced (X-ray and γ -ray) thermoluminescence, tracks of VH nuclei, and cosmogenic radionuclides with different half-lives. The experimental data, comparative analysis, and theoretical modelling were used to reconstruct the shock-thermal and radiation history of the chondrite, to estimate its preatmospheric size and orbit dimensions, and to characterize the radiation conditions in the heliosphere during the decline of the 22nd solar cycle.

ХОНДРИТ КУНЯ–УРГЕНЧ Н5 И ЕГО КОСМОФИЗИЧЕСКИЕ ДАННЫЕ, Алексеев В.А., Горин В.Д., Ивлиев А.И., Кашкаров Л.Л., Устинова Г.К. — Выполнены комплексные исследования естественной и наведенной (рентгеновским и гамма-излучением) термолуминесценции, треков VH-ядер и космогенных радионуклидов с разными периодами полураспада в свежесвыпавшем хондрите Куня–Ургенч Н5. Экспериментальные данные, результаты корреляционного анализа и теоретического моделирования использованы для реконструкции ударно-термической и радиационной истории этого хондрита, оценки его доатмосферных размеров и протяженности орбиты, а также для характеристики радиационных условий в гелиосфере на спаде 22-го солнечного цикла.

ХОНДРИТ КУНЯ–УРГЕНЧ Н5 ТА ЙОГО КОСМОФІЗИЧНІ ДАНІ, Алексеев В.О., Горін В.Д., Івлиєв А.І., Кашкаров Л.Л., Устинова Г.К. — Виконано комплексні дослідження природної і наведеної (рентгеновським і гамма-випромінюванням) термомінісценції, треків VH-ядер і космогенних радіонуклідів із різними періодами напіврозпаду в хондриті Куня–Ургенч Н5. Експериментальні дані, результати кореляційного аналізу і теоретичного моделювання використані для реконструкції ударної-термічної і радіаційної історії цього хондрита, оцінки його доатмосферних розмірів і протяжності орбіти, а також для характеристики радіаційних умов у геліосфері на спаді 22-го сонячного циклу.

1. INTRODUCTION

Meteorites are unique samples of the oldest matter of the solar system. Unaffected by terrestrial factors, they are the only sources of information on the major processes and conditions of formation of the matter and bodies of the solar system. A prominent place among them is held by the fresh-fallen meteorites, which come rather rapidly into research laboratories allowing registration of the contents of cosmogenic radionuclides with varying half-lives ($T_{1/2}$). The point is that the cosmogenic radionuclides are natural detectors of cosmic radiation along meteorite orbits for a period of $\sim 1.5T_{1/2}$ prior to the meteorite fall onto the Earth. Having orbits of different sizes and inclinations and falling in years of varying solar activity, the fresh-fallen meteorites are universal probes of cosmic rays in the three-dimension heliosphere [1, 2]. On the other hand, the depth distribution of radionuclides in meteorites obeys strict regularities, the knowledge of which allows one to estimate the preatmospheric sizes and orbit parameters of the meteorites [1,3]. The introduction of every new fresh-fallen meteorite into the investigation cycle is, therefore, an important and often long-expected event.

The stony meteorite (H5 chondrite) Kunya–Urgench fell on June 20, 1998, near the town of Kunya–Urgench in Turkmenistan [4], creating a crater about 6 m in diameter and ~ 4 m deep at the fall site. The total mass of the chondrite was estimated at 900–1000 kg, while the main fragment was $72 \times 81 \times 48$ cm in size and about 800 kg in weight. These data and a chondrite density of 3.32 g/cm^3 led to

the velocity of its penetration into the Earth's atmosphere of ~ 13 km/s and to a preatmospheric mass of $2-3 t$ [5]. The atmospheric trajectory reconstructed due to the eyewitness evidence allowed the estimation of falling radiant, which suggests that the meteorite overtook the Earth and met it in the ascending node after passing the perihelion. The estimates of the radiant and preatmospheric velocity suggest an orbit lying almost exactly in the ecliptic plane with a perihelion $q \sim 1$ AU and aphelion $q' \sim 3$ AU [5]. In our study, we used sample № 15 932 weighing 365 g.

2. THERMOLUMINESCENCE

Since its time of formation, the solar system matter has been affected by various evolution processes in the protoplanetary nebula, in meteorite parent bodies and at the stage of meteorites as independent cosmic bodies. Collision processes obviously played a leading role in the formation of cosmic bodies in interplanetary space, in particular, meteorites. Shock and thermal metamorphism accompanying the collisions is considered therefore to be the most fundamental process in the evolution of the primordial matter. One of the most sensitive methods for the assessment of the degree of structural changes in a substance is thermoluminescence (TL). A measurement of TL in equilibrium ordinary chondrites showed variations in the glow intensity by almost two orders of magnitude [6]. The investigation of TL in minerals affected by experimental loading in spherically converging shock waves [7] allowed the construction of a linear barometric scale for the estimation of the degree of shock influence with an error of about 3 GPa. The shock stages of a great number of ordinary chondrites were determined using the petrographic method [8, 9]. The comparative study of TL in chondrites with a petrographically identified extent of shock influence and in chondrites with unknown shock loading allows shock stage assessment in the latter without preliminary petrographic investigations. Such an approach was tried at the evaluation of the shock and thermal metamorphism of the Kunya-Urgench chondrite.

The shock stage quantification was performed using TL induced by γ and X-ray radiation. The investigation of TL induced by γ quanta demonstrated that the most sensitive shock stage indicator was the proportion of the areas below the glow curves in the low-temperature ($\sim 100-188^\circ\text{C}$) and high-temperature ($\sim 188-340^\circ\text{C}$) intervals: S_{LT}/S_{HT} . The TL and petrographic comparative examination of some chondrites shows that shock stage S1 ($< 4-5$ GPa) corresponds to $S_{LT}/S_{HT} \sim 1$; shock stage S2 ($5-10$ GPa) to $S_{LT}/S_{HT} \sim 0.9-0.8$; and shock stage S3 ($15-20$ GPa) to $S_{LT}/S_{HT} < 0.8$. The Kunya-Urgench chondrite yielded $S_{LT}/S_{HT} \sim 1.01 \pm 0.05$, which allowed us to assign it to shock stage S1, i.e. the chondrite did not experience significant collision impacts.

However, the investigation of X-ray-induced TL in equilibrium chondrites with petrographically identified shock stages revealed more sensitive indicators, including a peak height (I_p) and an area (S) under the glow curve in the temperature interval $40-350^\circ\text{C}$. These values increased as the shock pressure increased up to 10 GPa (stages S1, S2). A further increase in shock pressure up to $75-90$ GPa (stages S5, S6) resulted in a sharp decrease of these parameters by two orders of magnitude. This is illustrated in Fig. 1. A similar character of changes in S was observed at the investigation of TL in spherical calcite samples loaded by spherically converging shock waves [7]. It is reasonable to suggest that the variations in TL parameters are related to different shock histories of the chondrites studied. These data suggest that Kunya-Urgench was affected by shock loading up to 10 GPa (shock stage S2); i.e., it experienced a more significant impact than was deduced from the analysis of the results of TL induced by γ radiation.

During occurrence in orbit, natural TL is accumulated in meteorite owing mainly to cosmic ray radiation. An equilibrium level is attained relatively rapidly ($\sim 10^5$ years [6]). In most ordinary chondrites with known fall dates, it is within $20-80$ krad (at 250°C on the glow curve). Calculation of the value of the equivalent dose of natural TL in ordinary chondrites allows us to suggest that the intensity of TL is a sensitive indicator of their heating by Sun at passing the perihelion. Chondrites having orbits with the perihelion $q < 0.85$ AU must show very low levels of natural TL (< 5 krad at 250°C on the glow curve), whereas those with $q > 0.85$ AU must show wide ranges of natural TL values (> 5 krad). However, comparison of the thermal and radiation histories of meteorites solely on the basis of natural

TL is hampered by considerable variations in the sensitivity of TL accumulation in different meteorites. Thus, it appears reasonable to normalize the intensity of natural TL in each sample to its sensitivity through the measurement of the TL value per unit dose induced by a radioactive source. Using such an approach, the perihelia of 45 meteorites are estimated in [10]. Our comparative measurements of natural TL and TL induced by γ radiation were carried out for 21 chondrite samples. Some of these chondrites were studied in [10], including the Pribram chondrite with a known orbit (perihelion $q = 0.8$ AU). For the majority of chondrites q is within $\sim 1.0 - 0.8$ AU. Lower perihelia were determined only for the L5 chondrites Malakal ($q \sim 0.5 - 0.6$ AU), which is consistent with [10], and Dimmit H3.7 ($q \sim 0.6 - 0.8$ AU). For the Kunya-Urgench orbit $q \sim 1$ AU was obtained, which agrees with the q estimate from the radiant of the chondrite fall [5].

3. TRACKS

The most efficient approach to investigation of the radiation, shock, and thermal histories of meteorites is a joint study of their matter using thermoluminescence and track methods. Charged particles of cosmic rays are decelerated in crystal generating radiation damage zones near the halting point. At certain charge to energy ratios of these particles, the ionization generated by them exceeds some critical, for the given matter, value when the track can be revealed using selective chemical etching. The length of the etched track depends on the charge of the particle. For instance, VH nuclei ($23 < Z < 28$) of the iron group form tracks visible under a microscope in olivine and pyroxene grains, which are typical of ordinary chondrites. The average length of such tracks is $\sim 10 \mu\text{m}$. The VH nuclei occur both in modern galactic (GCR) and solar (SCR) cosmic rays and in radiation of the early solar system. If the meteoritic matter was not affected by the high temperatures that resulted in track annealing, radiation tracks can be revealed in the minerals and correlated with various stages of radiation meteorite history starting from the early regolith stage on the surface of a meteorite parent body [11] and even from the period of preaccretional irradiation [12]. On the other hand, since the moment of meteorite separation from its parent body, the rate of track generation depends strongly on the shielding depth of the grains: at a depth of 40 cm, the density of the VH tracks of the GCRs decreases in comparison with the surface by eight orders of magnitude [13]. Therefore, tracks are the most accurate indicators of the shielding depth of

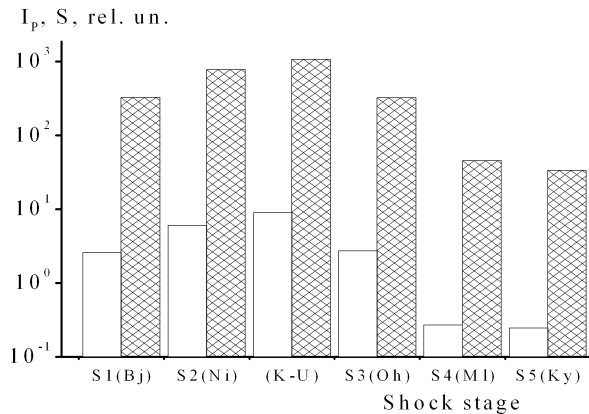


Fig. 1. The most sensitive indicators of the degree of shock metamorphism: peak height (I_p , unfilled rectangles) and area beneath the glow curve at $T \sim 40 - 350^\circ\text{C}$ (S , shaded rectangles) in chondrites with different shock histories. Digits in parentheses are the chondrites: Bj — Bjurbole; Ni — Nikol'skoe; K-U — Kunya-Urgench; Oh — Okhansk; MI — Malakal; and Ky — Kyushu.

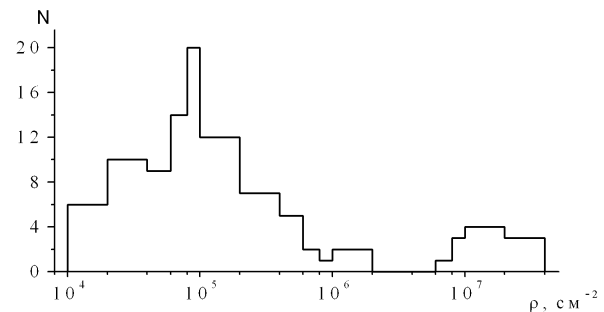


Fig. 2. Distribution of olivine grains of the Kunya-Urgench chondrite with respect to the track density (ρ) of the VH nuclei of cosmic rays. N is the number of grains studied.

samples, which can be used to estimate the preatmospheric size and the degree of ablation of meteorites at their passage through the Earth's atmosphere [14]. To recover such information on the Kunya–Urgench chondrite, track investigations were carried out, using olivine grains with an average size of 100–200 μm .

The results of measurements of the average values of track density in every grain for all samples studied (258 olivine grains) are presented on the histogram (Fig. 2). It is seen that the track density ρ varies by four orders of magnitude, and the results are consistent with those for other ordinary chondrites: olivine grains with $\rho \leq 10^6 \text{ cm}^{-2}$ contain mostly tracks formed by the VH nuclei of GCR, while grains with $\rho \geq 10^6 \text{ cm}^{-2}$ are dominated by tracks from the VH nuclei of SCR. The following feature in the distribution of olivine grains with respect to track density deserves special mentioning. Olivine grains with values within $\sim (10^4 - 10^6) \text{ cm}^{-2}$ account for 90% of all the crystals studied. These tracks show uniform distribution in the volume of each olivine grain. The exposure age of the Kunya–Urgench chondrite is $\sim 42 \text{ Ma}$ [15]. Proceeding from the regular change in track density with age, preatmospheric size of chondrites [16], and screening of the samples, the shielding depth of the fragments was determined at $18 \pm 3 \text{ cm}$.

About 10% of the olivine grains yield higher values of track density, from $\sim 6.5 \cdot 10^6$ to $\sim 1 \cdot 10^8 \text{ cm}^{-2}$. In most cases, these grains show uneven distribution of track density in the volume, which is manifested either in very high ρ values in the near-surface parts of the grain or in the presence of a track density gradient at the transition from the surface toward the interior zones of the grain. The existence of grains with track density gradients suggests the presence of matter in Kunya–Urgench that was affected by SCR radiation (or low-energy VH nuclei of another origin) at early preaccretion and (or) regolith stages of formation of the chondrite parent body. The survival of tracks of such an early origin in olivine grains indicates that the material of the meteorite was never heated up to $\sim 700^\circ\text{C}$ during its subsequent history even for a few minutes. Important is the consistency of this inference with the low shock stage of Kunya–Urgench according to the TL results and its old gas retention age, 4.0–4.5 Ga [15]. The latter characteristic suggests the absence of significant diffusion losses of inert gases since the moment of formation of the material of the Kunya–Urgench chondrite.

4. RADIONUCLIDES

Depending on the moment of sample delivery to a research laboratory, radionuclides with various $T_{1/2}$ can be measured in meteorites, from ^{22}Na ($T_{1/2} = 15 \text{ h}$) to ^{40}K ($T_{1/2} = 1.48 \cdot 10^9 \text{ years}$). It is evident that the cosmogenic radionuclides in meteorites with high radiation ages encompass a wide time interval and, consequently, are witnesses of many events in the history of the solar system. Therefore, the cosmogenic radionuclides allow us to trace both the radiation history of meteorites and the regularities in change of the heliospheric processes within the past $\sim 1.5T_{1/2}$ of the radionuclides before the fall of meteorites onto the Earth. The methods of applying the radionuclide contents in extraterrestrial matter (meteoritic and lunar) to study of the distribution and variations of cosmic radiation in the solar system, as well as to the cosmic body investigation are described in [1–3, 17, etc.]. In order to evaluate the individual radiation histories of chondrites and radiation conditions in the modern heliosphere, we carried out experiments, lasting many years, on the measurement of radionuclide contents in fresh-fallen chondrites using a non-destructive low-level counting [18].

In the Kunya–Urgench chondrite the following contents of cosmogenic radionuclides were measured (in dpm/kg): $^{46}\text{Sc} - 24 \pm 5$, $^{54}\text{Mn} - 210 \pm 30$, $^{22}\text{Na} - 88 \pm 9$, $^{60}\text{Co} - 42 \pm 7$, $^{26}\text{Al} - 72 \pm 7$, and $^{40}\text{K} - 1420 \pm 140$. On the basis of a previously developed analytical method [1], modelling of radionuclide production rates was carried out for the Kunya–Urgench chondrites using the results of the stratospheric measurements [19] of GCR intensity in the periods $\sim 1.5T_{1/2}$ of radionuclides before the fall of these chondrites onto the Earth. The analysis of experimental data and results of theoretical modelling allowed us to estimate the preatmospheric size and ablation of the Kunya–Urgench chondrite, size of its orbit, and the spatial distribution of GCRs in the heliosphere at the decline of the 22nd solar cycle.

The most sensitive indicator of the preatmospheric size of a chondrite is ^{60}Co , which is formed by thermal and resonance neutrons via the reaction $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ and accumulates in chondrite within ~ 8

years before the fall [1, 3, 17]. The generation of ^{60}Co is evidently proportional to the Co content, which is highly variable in ordinary chondrites (in wt %): 0.03–0.11; 0.04–0.08; and 0.03–0.07 in H, L and LL chondrites, respectively [20]. In order to estimate the influence of this factor, the ^{60}Co production rate was modeled for Co contents of 0.04 and 0.08 wt %. The ^{60}Co depth distribution in spherical H chondrites of radius $R \sim 10–100$ cm are shown in Fig. 3. The results of modelling suggest that at the Co content of 0.04 wt %, the measured activity of ^{60}Co of 42 ± 7 dpm/kg (solid cross and left ordinate) in the Kunya–Urgench sample (shielding depth of $d = 18 \pm 3$ cm, determined above from the track density of VH nuclei) corresponds to the preatmospheric radius of the Kunya–Urgench chondrite $R = 47_{-5}^{+8}$ cm. If the average Co content in H chondrites is $\geq 0.08\%$ (dashed cross and right ordinate), the calculated preatmospheric radius of Kunya–Urgench is smaller than the effective radius corresponding to its fall weight. This can result from the strong deviation of the Kunya–Urgench chondrite from the spherical shape, because neutron leakage and, consequently, ^{60}Co content at a certain depth depend on the body shape. Taking into account the linear dimensions of the largest fragment of the Kunya–Urgench chondrite, screening depth of the sample and ^{60}Co dependence on deviation of the chondrite from the spherical shape, the effective radius might be estimated in the range $R \sim 42–54$ cm [21]. Since the density of the Kunya–Urgench chondrite is 3.32 g/cm 3 [5], its average preatmospheric mass was $M_0 \sim 1.5$ t (maximum, ~ 2.2 t), and the degree of ablation, $< 30\%$ (maximum, $\sim 50\%$). The low degree of chondrite ablation and its fall mainly as a large fragment (0.9 t from a total collected mass of ~ 1.1 t) suggest a relatively low velocity of chondrite at the entrance into the Earth’s atmosphere: 13 km/s.

The orbit (its aphelion, q') of the Kunya–Urgench chondrite was estimated using “isotopic” approach [1,3], based on the content of ^{26}Al . The activities of ^{26}Al in chondrites with known orbits (Pribram, Lost City, and Innisfree) show that, within ~ 1 Ma, the average gradient of GCR intensity along meteorite orbits was about 20–30%/AU; i.e., chondrites with larger orbits are significantly enriched in ^{26}Al . This

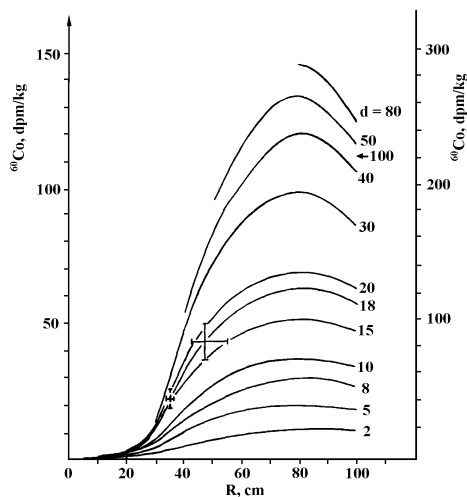


Fig. 3. Distribution of ^{60}Co at varying shielding depths d as a function of radius R (crosses are measured ^{60}Co content, 42 ± 7 dpm/kg at a depth of $d = 18 \pm 3$ cm determined from tracks; the left axes and solid cross refer to the modeling at the Co content of H chondrites of 0.04 wt %; and the right axes and dashed cross refer to it at Co content of 0.08 wt %).

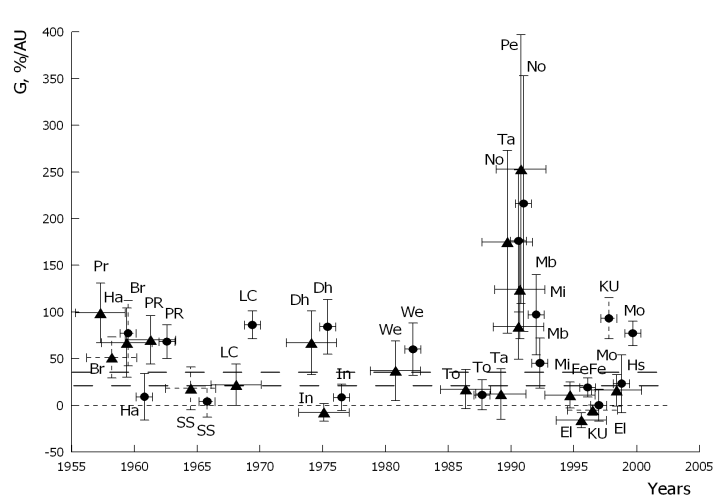


Fig. 4. Distribution and variation of the GCR radial gradients (G_r) with rigidity $R > 0.5$ GV in 1954–2000 along the orbits of the following chondrites: Pr – Pribram; Br – Bruderheim; Ha – Harleion; PR – Peace River; SS – Sen-Severin; LC – Lost Cily; Dh – Dhajala; In – Innisfree; We – Wethersfield; To – Torino; Ta – Tahara; No – Noblesville; Pe – Peekskill; Mb – Mbale; Mi – Mihonoseki; El – El Hammami; Fe – Fermo; KU – Kunya–Urgench; Hs – Hassilabyade; Mo – Moravka. Points with dashed error bars are gradient values in the ecliptic plane. The horizontal dashed lines show average values of radial gradients in one million years.

regularity can be phenomenologically described as a function of q' , which allows estimation of the aphelia of meteorites from their ^{26}Al contents. Application of this method to the Kunya–Urgench chondrite shows that the measured ^{26}Al activity, 72 ± 7 dpm/kg in a sample with a shielding depth of $d = 18 \pm 3$ cm in a body with a radius of $\sim 42 - 54$ cm, corresponds to an orbit with $q' \sim 3.5 - 4.0$ AU. Within increasing errors in the determination of such high q' values, this is consistent with the value $q' \sim 3$ AU obtained from the radiant of the Kunya–Urgench fall at a preatmospheric velocity of ~ 13 km/s [5].

5. GCR MODULATION ALONG METEORITE ORBITS

It can be stated that radiation conditions in the solar system are controlled by solar activity, because, in active Sun years, severe barriers are formed on GCR paths by the magnetic heterogeneities of the solar wind, which reduce and modulate the GCR intensity in the heliosphere. This results in GCR periodic variations in antiphase with the 11-year sunspot cycle. Our long-lasting investigations of radionuclides in fresh-fallen chondrites led us to the conclusion that the character of the GCR modulation was controlled mainly by processes within meteoritic orbits, i.e., at 2–4 AU from the Sun [1, 2, 22].

Indeed, Fig. 4 shows a series of similar data on the radial GCR gradients in the heliosphere during four cycles of solar activity, which were obtained in our comprehensive studies of fresh-fallen chondrites (investigations of track density and radionuclide contents, modelling of their depth distribution, estimates of preatmospheric sizes, sample shielding, and orbit dimensions). The meteorite monitoring of radiation conditions suggests that the value of the GCR gradient at heliocentric distances of $\sim 1.5 - 4.0$ AU depends strongly on the phase of a solar cycle, changing from small and even negative values in years of minimum solar activity (1965, 1976, 1987, and 1998) up to 80–100%/AU in years of maximum activity (1957–1958, 1969–1970, 1981–1982, and 1990–1991). In particular, the negative GCR gradients at the decline of the 22nd solar cycle, which were obtained from ^{22}Na content in the Kunya–Urgench chondrite, are consistent with the gradients near the minimum of previous solar cycles, which were derived from data on the Sen–Severin (1965–1966), Innisfree (1973–1976), Torino, and Tahara (1984–1991) chondrites [1, 22], as well as with the results of direct measurements in interplanetary space [23]. These results suggest a decrease in the GCR modulation in the years of calm Sun.

It should be noted that each gradient value in Fig. 4 corresponds to particular spatial and temporal coordinates (see [22]). Moreover, many of these values refer to certain heliosphere latitudes rather than to the ecliptic (up to 16° N and 23° S). This provides an insight into the distribution and variations in radiation conditions in the three-dimension heliosphere. It is evident that, since the processing of data on the radioactivity of all the chondrites was carried out by a single method, despite the high absolute errors of particular gradient values, their variations in time reflect real regularities. It is important also that the investigation of long-lived cosmogenic radionuclides provides evidence on the average values of GCR intensity and gradient over large time scales. This smoothed out the influence of short-term and fortuitous fluctuations of the magnetic field in the heliosphere and enabled us to reveal the most general regularities. For instance, it was found that average values of the GCR gradient during modern solar cycles ($\sim 20 - 30\%$ per AU) coincided with the average gradient during the past million years (Fig. 4), which was estimated from ^{26}Al contents in chondrites with known orbits. This suggests a constancy of the mechanism of solar modulation for at least one million years.

6. CONCLUSION

The importance of a combined approach to study of such valuable matter as meteorites should be specially emphasized. Information obtained from the measurement of the particular properties of the matter or parameters of the meteorites appears to be in demand in the investigation of completely different aspects. This paper does not touch on all the necessary and possible work that could have been done by researchers in various fields. Precisely because of the understanding of the “randomness” of opportunities for studying extraterrestrial matter, it has now become an established tradition to create large consortiums including many research teams for detailed studies of fresh-fallen meteorites (e.g. Lost City, Jilin, Peekskill, etc.).

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