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Geochemistry International, Vol. 39, No. 11, 2001, pp. 1043–1055. Translated from Geokhimiya, No. 11, 2001, pp. 1139–1151.

Combined Study of Thermoluminescence, Tracks, and Radionuclides in the Recently Fallen Kunya-Urgench Chondrite

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Received March 21, 2001

Abstract—The recently fallen Kunya-Urgench H5 chondrite was studied in various aspects including natural and induced (X-ray and gamma-ray) thermoluminescence, tracks of VH nuclei, and cosmogenic radionuclides with different half-lives. The experimental data, comparative analysis, and theoretical modeling were used to reconstruct the shock–thermal and radiation history of the chondrite, estimate its preatmospheric size and orbit dimensions, and characterize the radiation conditions in the heliosphere at the decline of the 22nd solar cycle. The results suggest that Kunya-Urgench belongs to shock stage S2, and that its material experienced only weak shock–thermal loading (shock pressure below 10 GPa and temperature <700°C). In a spherical model, the preatmospheric radius of the chondrite is R = 42–54 cm; shielding depth of the sample, 18 ± 3 cm; preatmospheric weight, ~1.5–2.2 t; and degree of ablation, ~30–50%. However, a significant departure from the spherical form is possible for the chondrite. The Kunya-Urgench orbit is similar to that of the Pribram chondrite: aphelion q' ~ 4 AU, perihelion q ~ 1 AU, and average heliocentric distance from the Earth of about 3.3 AU. The average integral gradient of galactic cosmic rays along the Kunya-Urgench orbit in the years of the minimum of the 22nd solar cycle was –5.3 ± 5.4% per astronomic unit (for a range of spectrum rigidity R > 0.5 GV). This estimate is in agreement with gradient values in the minimum phases of previous solar cycles determined from data on the St.-Severin, Innisfree, Torino, and Tahara chondrites and results of direct measurements in interplanetary space. This suggests a decrease in the modulation of galactic cosmic rays during quiet Sun years.

INTRODUCTION

Meteorites are unique samples of the oldest matter of the solar system. Unaffected by terrestrial factors, they are in fact 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 those known as recently fallen meteorites, i.e., meteorites with known fall dates, which come rather rapidly into research laboratories allowing registration of the contents of cosmogenic radionuclides with varying half-lives ($T_{1/2}$). In fact, cosmogenic radionuclides are natural detectors of cosmic radiation along meteorite orbits for a period of about ~$1.5T_{1/2}$ prior to the meteorite fall onto the Earth. Having orbits of different sizes and inclinations and falling in years of varying solar activity, recently fallen meteorites are universal probes of cosmic rays in the three-dimension heliosphere [1, 2]. On the other hand, the depth distribution of isotopes generated by cosmic rays in meteorites obeys strict regularities. The knowledge of these regularities allows one to use the measured contents of cosmogenic radioactive and stable isotopes for the estimation of the preatmospheric sizes and orbit parameters of the meteorites [1, 3–5]. The introduction of every new recently 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 [6], 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 × 81 × 48 cm in size and about 800 kg in weight. These data and a chondrite density of 3.32 g/cm^3 yielded an estimate of the velocity of chondrite penetration into the Earth's atmosphere of ~13 km/s and a preatmospheric mass of ~2–3 t [7]. The atmospheric trajectory reconstructed on the basis of 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 ~ 1 AU and aphelion q' ~ 3 AU [7]. In our study, we used sample no. 15 932 weighing 365 g.

THERMOLUMINESCENCE

Since its time of formation, the solar system matter has been affected by various evolution processes both

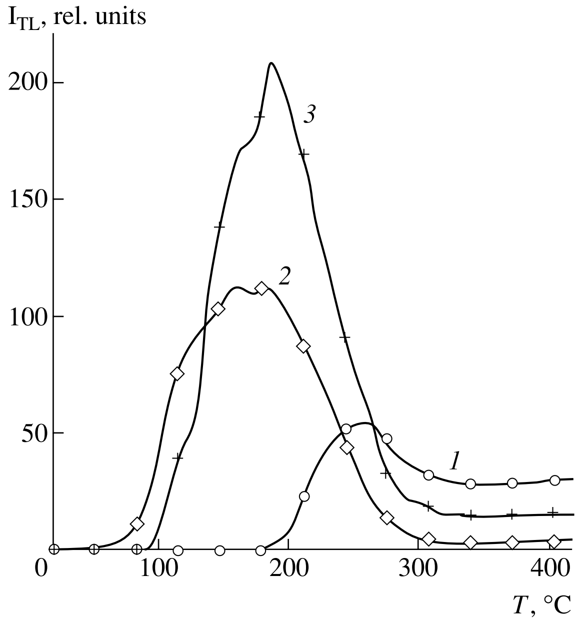

Fig. 1. Glow curves of the Kunya-Urgench chondrite obtained at the registration of natural TL (*1*) and TL induced by X-ray (*2*) and gamma radiation (*3*). I_{TL} is the intensity of TL in relative units and T is the sample temperature.

in the protoplanetary nebula or meteorite parent bodies and at the stage of meteorite occurrence as independent cosmic bodies. Collision processes obviously played a leading role in the formation of cosmic bodies in interplanetary space, in particular (and in the first place) meteorites. Shock and thermal metamorphism accompanying the collisions is considered therefore to be the most fundamental process in the evolution of the primordial matter. The experimental study of this process is undoubtedly of crucial importance, especially with respect to the search for quantitative criteria in the estimation of the effects of shock and thermal metamorphism. 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 [8]. The main TL phosphor in these meteorites is feldspar, which occurs in all H, L, and LL chondrites in approximately equal amounts and shows a uniform composition (Ab_{74}, An_{20}, and Or_6) [9]. The investigation of TL in minerals affected by experimental loading in spherically converging shock waves [10–12] demonstrated that TL characteristics were highly sensitive to changes in the crystal lattice. This 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 [13, 14]. 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.

Experimental Method

The investigation of the TL was carried out with bulk samples of the chondrite. Fragments, 0.7–1.0 g in weight, were split off the samples and carefully crushed in a jasper mortar under alcohol. The magnetic fraction of the powdered sample was separated by means of a hand-held magnet. The nonmagnetic fraction of each chondrite was used to prepare four 2-mg charges by quartation. All charges were loaded into caps, 6 mm in diameter, manufactured from nickel foil. A uniform distribution of the matter was achieved by adding a drop of acetone. Natural and X-ray and gamma-ray induced TL was registered by a modernized device. An interface constructed on the basis of the L154 board allowed us to register on a computer the photomultiplier (FEU-93) current and sample temperature. The sensitivity of the registration was 1°C. Coupling the device with a computer increased sensitivity in the measurements and the precision of glow curves. During TL registration, glow curves were displayed on the computer monitor and saved using a special program in a file as a numerical dependency of the photomultiplier current on sample temperature. In addition to the registration of glow curves, the program performed some preliminary calculation procedures: determination of the maximum TL glow and the respective temperature (position of the maximum of the TL peak); estimation of the half-height width of a glow peak; calculation of the glow intensity for two prescribed temperature intervals (areas below the glow curve); subtraction of the background glow of the Nichrome plate that was used as a heater (in our study, the TL radiation of chondrites was higher by more than two orders of magnitude than the background value, and such a correction was not necessary); and the storage of calculated results in a file. The measurements of TL demonstrated that the position of a peak on the glow curve is reproducible at an error of less than ±1°C.

Results of TL Measurements

Figure 1 shows the glow curves of the Kunya-Urgench chondrite obtained at the registration of natural TL (curve *1*) and TL induced by X-ray (curve *2*) and γ radiation (curve *3*) from a ^{137}Cs source. The shapes of all curves are typical of ordinary chondrites. The glow intensity of natural TL (I_{TL}) accumulated by the meteorite in cosmic space is characterized by a glow peak at a temperature of 260°C. The maximum intensity of TL accumulated after sample irradiation by X-rays is registered at a temperature of about 170°C and that after irradiation by γ-quanta from the ^{137}Cs source, at a temperature of about 190°C. The difference in the shapes of the glow curves induced by X-ray and γ radiation results from the different energy diapasons of the radiation spectra. The low energy of the X-ray radiation (E_x = 55 keV) provides the most effective activation of low-temperature TL centers, and the resulting glow curve parameters differ from those induced by higher energy γ quanta (E_γ = 661 keV).

Shock Stage

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 (~100–188°C) and high-temperature (~188–340°C) intervals: S_{LT}/S_{HT}. The general S_{LT}/S_{HT} sequence of the chondrites studied (Dhajala H3-4, Elenovka L5, Saratov L4, Nikol'skoe L4, and Okhansk H4) is in agreement with the petrographic examination of these chondrites. Shock stage S1 (<4–5 GPa) corresponds to S_{LT}/S_{HT} ~ 1; shock stage S2 (5–10 GPa) to S_{LT}/S_{HT} ~ 0.9–0.8; and shock stage S3 (15–20 GPa) to $S_{LT}/S_{HT} < 0.8$. The Kunya-Urgench H5 chondrite yielded S_{LT}/S_{HT} ~ 1.01 ± 0.05, which allowed us to assign it to shock stage S1 suggesting that the chondrite did not experience significant collision impacts [15].

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°C. An increase in these values was recorded 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. 2. A similar character of changes in S was observed at the investigation of TL in spherical calcite samples loaded by spherically converging shock waves [12]. It is reasonable to suggest that the variations in TL parameters (Fig. 2) 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.

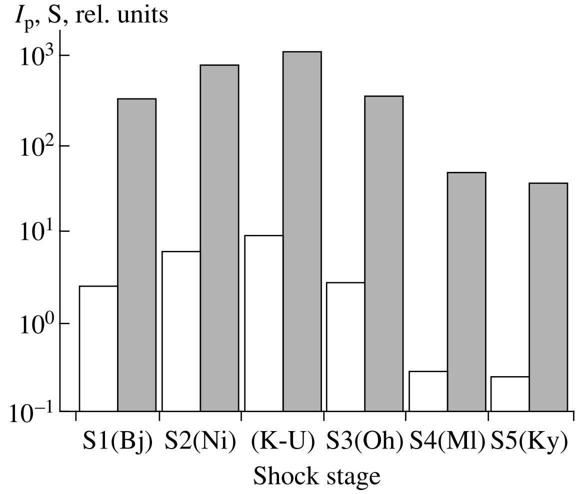

Fig. 2. The most sensitive indicators of the degree of shock metamorphism: peak height (I_p, unfilled squares) and area beneath the glow curve in the temperature interval 40–350°C (S, shaded squares) in chondrites with different shock histories. Digits in parentheses are abbreviations of meteorite names: Bj—Bjurbole, Ni—Nikol'skoe, K-U—Kunya-Urgench, Oh—Okhansk, Ml—Malakal, and Ky—Kyushu.

Perihelion of the Orbit

During occurrence in orbit, natural TL is accumulated in meteorite owing mainly to cosmic ray radiation. An equilibrium level is attained relatively rapidly (~10^5 years [8]). In most ordinary chondrites with known fall dates, it is within 20–80 krad (at 250°C on the glow curve) [16–18]. 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 degree of heating by Sun at passing the perihelion. In fact, the lower the perihelion, the higher the heating and the lower the equilibrium TL. 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) with a considerable scatter related to the variations in the rate of dose accumulation (at a varying degree of screening and albedo) [16]. 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. The ratio known as equivalent dose (ED) is determined for each temperature value of the glow curve using the formula

$$ED = D(TL_{nat}/TL_{ind}),$$

where TL_{nat} and TL_{ind} are the natural and induced TL, respectively, and D is the dose of laboratory radiation (rad). Using such an approach, Melcher [19] estimated the perihelia of 45 meteorites. However, investigations suggest that it is more reasonable to calculate ED for two temperature intervals on the glow curves; ED_{LT} at 100–240°C and ED_{HT} at 240–340°C. This allows us to reduce the error of ED estimate to ≤10% and estimate more accurately the perihelion value.

Comparative measurements of natural TL and TL induced by γ radiation and calculations of ED_{LT} and ED_{HT} using a special program were carried out for 21 chondrite samples. Some of these chondrites were studied in [19], including the Pribram chondrite with a known orbit. The ED values of Pribram correspond to its perihelion (q = 0.8 AU) and coincide with the results of ED measurements reported in [19]. For the majority of chondrites, including Bjurbole L/LL4, Chainpur LL3.4, Dalgety Downs L4, Dhajala H3.8, Gorlovka H3.7, Grady H3.7, Elenovka L5, Khohar L3.6, Kunashak L6, Kunya-Urgench H5, Kyushu L6, Mezö Madaras L3.7, Nikol'skoe L4/5, Okhansk H4, Pervomaiskii Poselok L6, Pultusk H5, Rakity L3.6, and Saratov L4, the perihelia of orbits (q) are within ~1.0–0.8 AU. Lower perihelia were determined only for the L5 chondrites Malakal (q ~ 0.5–0.6 AU), which is consistent with [19], and Dimmit H3.7 (q ~ 0.6–0.8 AU). A value of q ~ 1 AU was obtained for the Kunya-Urgench orbit, which agrees with the perihelion estimate from the radiant of the chondrite fall [7].

TRACKS

The most efficient approach to the investigation of the radiation, shock, and thermal histories of meteorites is a combined investigation 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 segment 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, which are typical of ordinary chondrites. The average length of such tracks is ~10 μm [20]. The VH nuclei occur both in modern galactic (GCR) and solar (SCR) cosmic rays and in the radiation of the early stage of solar system formation. If the meteoritic material was not affected by the high temperatures that resulted in track disappearance (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 [21] and even from the period of preaccretional irradiational [22, 23]. On the other hand, since the moment of meteorite separation from its parent body, the rate of track generation at the irradiation of the surface shows a strong dependency on the shielding depth of the crystal: at a depth of 40 cm, the density of the tracks of VH nuclei of the GCR decreases in comparison with the surface by eight orders of magnitude [24]. Because of this, tracks are most accurate indicators of the depth of sample occurrence, which can be used to estimate the preatmospheric size and the degree of ablation of meteorites at their passage through the Earth's atmosphere [25]. In order to recover such valuable information on the Kunya-Urgench chondrite, track investigations were carried out.

Material under Investigation

Track characteristics were determined in olivine grains with an average size of 100–200 μm. About 100 grains were separated from a charge of about 2 g obtained from the sample studied (no. 15 932). In addition, about 200 olivine grains were studied from 15 various fragments (several millimeters in size each) representing two other individual fragments of the meteorite, ~1 g in weight each. One of the main purposes of the track study was an attempt of revealing a possible difference in the track density (uniform in any crystal) related to VH nuclei of GCR: in olivine grains occurring in different fragments and, consequently, at different depths relative to the preatmospheric surface of the meteorite.

Study Method

Silicate mineral grains were hand-picked using a binocular microscope, mounted in epoxy tablets, polished, and treated in a boiling solution of the WN type [26] designed for selective identification of tracks in olivine. The assessment of the efficiency of track etching and final control of the process of natural track identification in all mineral grains studied were performed through the registration of artificially induced fission tracks from a ^{252}Cf source. The method allowed us to measure (1) the uniform track density (ρ), that is the number of tracks per one square centimeter of the surface of the inner section of every microscopic crystal; (2) the track density gradient from the rim of the external surface toward the center of the crystal with a spatial resolution of about 10 μm; (3) the track density in a thin near-surface layer of crystals; (4) the track length starting from 1–2 μm; and (5) the spatial orientation of tracks within the volume of each grain.

Results and Discussion

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. 3). It is clear that ρ varies by four orders of magnitude, and the results obtained for the Kunya-Urgench chondrite are in general consistent with observations in other ordinary chondrites [27]. In these chondrites, olivine grains with $\rho \leq 10^6$ cm^{-2} contain mostly tracks formed by the VH nuclei of GCR, while grains with $\rho \geq 10^6$ cm^{-2} are dominated by tracks from the VH nuclei of SCR. It should be noted that we did not identify any substantial (higher than measurement errors) difference between the average values of GCR track density in olivine grains from the three Kunya-Urgench fragments under study. This could result from either the rather great shielding depths of these fragments or the relatively small distance between the fragments.

The following feature in the distribution of olivine grains with respect to track density deserves special mentioning. Olivine grains with ρ values within ~(10^4–10^6) cm^{-2} (median, $\rho_{med} = 6.7 \times 10^4$ cm^{-2}) account for 90% of all the crystals studied. These tracks show uniform distribution in the volume of each olivine grain. The available noble gas data for the Kunya-Urgench chondrite [28] suggest that the radiation age of the meteorite is ~42 Ma. Proceeding from the regular change in track density with age, preatmospheric size of chondrites [29], and shielding depths of the samples, the shielding depth of the fragments was determined at 18 ± 3 cm from the estimated median of track density and the radiation age of the Kunya-Urgench chondrite.

About 10% of the olivine grains yield higher values of track density, from ~6.5×10^6 to ~1×10^8 cm^{-2}. In most cases, these crystals 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 crystal or in the presence of a track density gradient at the transition from the surface toward the interior zones of the crystal. The existence of crystals 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 [22]) 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 ~700°C during its subsequent history even for a few minutes. This estimate of the extent and character of heating set strict constrains on the value of the shock and thermal influence on the matter of this meteorite. 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 [28]. 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.

RADIONUCLIDES

Depending on the moment of sample delivery to a research laboratory, radionuclides with various $T_{1/2}$ values can be measured in meteorites, from ^{24}Na ($T_{1/2}$ = 15 h) to ^{40}K ($T_{1/2} = 1.48 \times 10^9$ years). It is evident that the cosmogenic radionuclides registered 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. Most frequently, the following radionuclides can be analyzed: ^{46}Sc ($T_{1/2}$ = 84.2 days), ^{54}Mn ($T_{1/2}$ = 312 days), ^{22}Na ($T_{1/2}$ = 2.6 years), ^{60}Co ($T_{1/2}$ = 5.26 years), ^{26}Al ($T_{1/2} = 0.74 \times 10^6$ years), and ^{53}Mn ($T_{1/2} = 3.7 \times 10^6$ years). They allow us to trace both the radiation history of meteorites and the regularities in processes changes in the heliosphere within the past ~1.5 $T_{1/2}$ of the radionuclides before the fall of meteorites onto the Earth in a time scale of ~10 Ma.

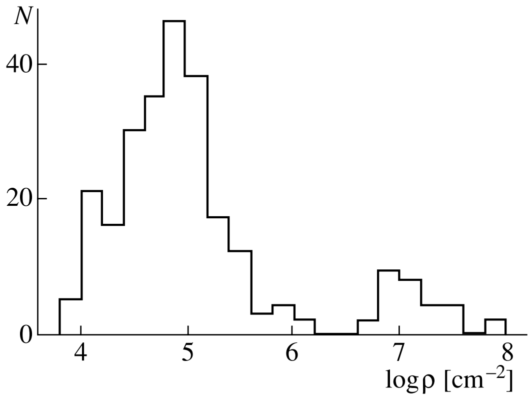

Fig. 3. Distribution of olivine crystals of the Kunya-Urgench chondrite with respect to the track density (ρ) of the VH nuclei of cosmic rays. *N* is the number of crystals studied.

The methods consisting in applying the radionuclide contents in extraterrestrial matter (meteoritic and lunar) to the investigation of the distribution and variations of cosmic radiation in the solar system are discussed in [1, 2, 30, etc.], and cosmic body investigation methods using radionuclide data are described in [1, 3–5, 31, 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 recently fallen chondrites using a low-level gamma-spectrometer complex without sample decomposition [32]. In this study, in addition to the results of radionuclide analysis in the Kunya-Urgench chondrite, data from the concurrent studies of the recently fallen chondrites Peekskill H6 (fall of October 9, 1992, sample no. 15 821, 59 g) and Hammadah du Draa H5-6 (fall of 1995, sample no. 15 892, 312 g) are presented.

Experimental Method

A sample was loaded into a cylindrical Plexiglas container and placed between two low-noise spectrometer detectors with NaI (Tl) crystals 12.0 cm in diameter and 10.2 cm in height. The crystals were installed in the axial channel of a cylindrical plastic scintillator (50 cm in diameter and 65 cm long), which was used as a plastic phosphor anticoincidence shield. During measurements, detectors were installed into the inner hollow of the protective chamber manufactured from steel plates. The thickness of the plate packet on the side and bottom walls was 30 cm, and on the top, 40 cm. In the side walls and upper part of the chamber, a layer of paraffin (75%) and boric acid (25%) mixture was loaded: 10 cm thick in the sides and 15 cm thick in the upper part. Analysis of the signals from both detectors was

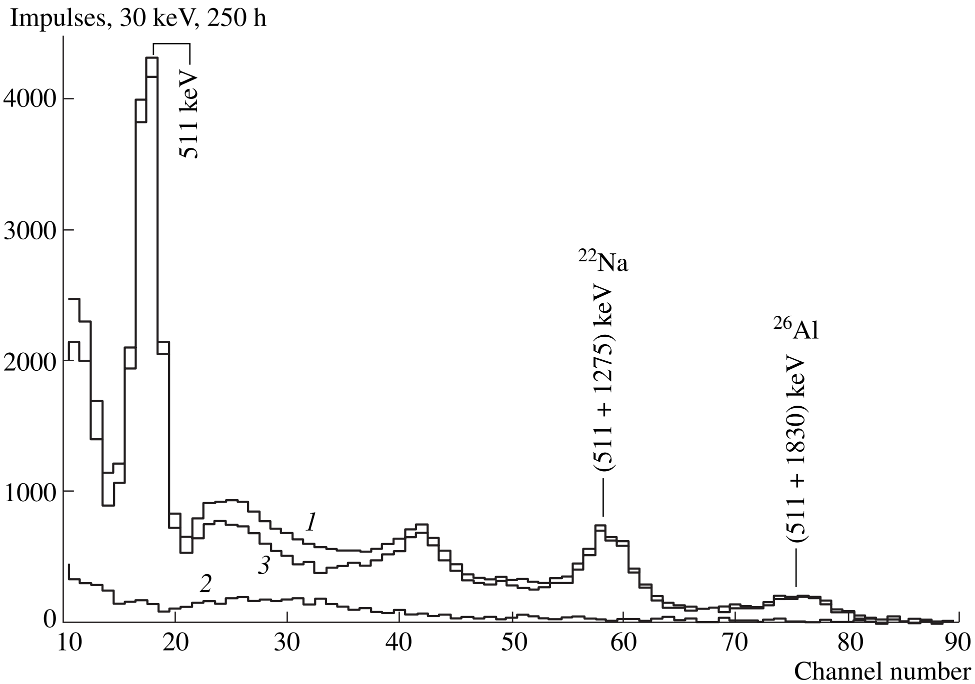

Fig. 4. A spectrum of gamma–gamma coincidence at the measurement of cosmogenic radionuclides ^{22}Na and ^{26}Al in the Kunya-Urgench chondrite: (*1*) activity spectrum recorded for 250 h without background subtraction; (*2*) background spectrum; and (*3*) resulting spectrum of the Kunya-Urgench chondrite after background subtraction.

carried out simultaneously by two spectrometers. In one of them, which was designed for the selective analysis of isotopes decaying with the emission of single gamma quanta (^{54}Mn, ^{40}K, etc.), the signals of both detectors before input into a multichannel pulse analyzer were linearly mixed, and a special electronic device prevented the passage of coincident signals, i.e., the resulting gamma spectrum was efficiently "cleaned" from the contributions of isotopes decaying with positron (^{22}Na, ^{26}Al, etc.) or cascade gamma–quantum (^{46}Sc, ^{60}Co, etc.) emission. Another spectrometer (gamma–gamma coincidence) performed a highly sensitive and selective analysis of either ^{22}Na and ^{26}Al or ^{46}Sc and ^{60}Co, depending on the setting of two supplementary differential discriminators. The background measurement was carried out with an inactive model prepared from a mixture of powdered iron with magnesium oxide similar to the meteorite sample in geometry and weight. The spectrometers were calibrated using similar active models with known activity values of ^{54}Mn, ^{40}K, ^{22}Na, ^{26}Al, ^{46}Sc, and ^{60}Co. The measurements of a sample and background were carried out in turn in 25-h cycles. Figure 4 shows a spectrum of gamma–gamma coincidence obtained at the measurement (during 250 h) of ^{22}Na and ^{26}Al in the Kunya-Urgench chondrite (histogram 1), background spectrum (histogram 2), and resulting spectrum after background subtraction (histogram 3). It is obvious that, in spite of the low ^{22}Na and ^{26}Al activities in the sample, the counting rate of the sample in characteristic photopeaks is much higher than the background. This is an advantage of the method of gamma–gamma coincidence over the methods of single-crystal gamma spectrometry, when such an effect for similar samples is only a few percent, and gamma spectrometry with Ge(Li) detectors, which show very poor registration effectiveness. The obtained values of the activity of cosmogenic isotopes were recalculated relative to the fall time of chondrites. The resulting uncertainties include both the statistical counting errors and calibration errors.

Results of Activity Measurements

The natural Th contents were estimated from the activity of the decay product, ^{208}Tl in the chondrites Kunya-Urgench, Peekskill, and Hammadah du Draa at 54 ± 6, 38 ± 5, and 100 ± 50 (ppb), respectively. These values are consistent with the average Th content of H chondrites (42×10^{-3} ppm). The content of cosmogenic ^{26}Al was 72 ± 7, 66 ± 4, and 67 ± 7 decay/(min kg), respectively, which is higher that the average ^{26}Al content of H chondrites (55 ± 1 decay/(min kg)). This suggests that theses chondrites over at least the past one million of years either had more extended orbits (aphelion, $q' \sim$ 3–4 AU) than the average for chondrites ($q' \leq$ 2.5 AU) and were irradiated by more intense (less modulated) GCR flows or the samples occurred at the optimum depth for the development of a nuclear cascade of active particles, at $d \sim$ 20–30 cm in bodies with the preatmospheric radius $R \sim$ 20–40 cm [1–5], which will be discussed in more detail below. The activity of cosmogenic ^{22}Na in the Kunya-Urgench and Hammadah du Draa was 88 ± 9 and 98 ± 13 decay/(min kg), respectively. In the Kunya-Urgench chondrite, we measured also contents of ^{46}Sc = 24 ± 5, ^{60}Co = 42 ± 7, and ^{40}K = 1420 ± 140 decay/(min kg).

On the basis of a previously developed analytical method [1], modeling of radionuclide formation rates was carried out for the Kunya-Urgench and Peekskill chondrites using the results of the stratospheric measurements [33–35] of GCR intensity in the periods ~1.5 $T_{1/2}$ of radionuclides before the fall of these chondrites onto the Earth. The analysis of experimental data and results of theoretical modeling allowed us to estimate the preatmospheric size and ablation of the Kunya-Urgench chondrite, size of its orbit, and the spatial distribution of GCR in the heliosphere at the decline of the 22nd solar cycle.

Preatmospheric Size and Ablation

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}Co(n, γ)^{60}Co and accumulates in chondrite up to a measurable (at the moment of the fall) level within ~8 years before the fall [1, 3, 5, 31]. The generation of ^{60}Co is evidently proportional to the Co content, which is highly variable in ordinary chondrites. Figure 5 shows the ranges of Co distribution in the chondrites of various chemical groups: 0.03–0.11 wt % in H chondrites, 0.04–0.08 wt % in L chondrites, and 0.03–0.07 wt % in LL chondrites [36–38, etc.]. It should be noted that Co variations in H chondrites overlap possible Co variations in ordinary chondrite in general, and Co may vary in a single chondrite (e.g., data for the Dhajala chondrite, Fig. 5 [37, 38]). In order to estimate the influence of this factor on the final conclusions, the rate of ^{60}Co formation was modeled for Co contents of 0.04 and 0.08 wt %, which involve a rather wide range of possible variations of this element. The results of the modeling of the depth distribution of ^{60}Co for a spherical model of H chondrite of radius R from ~10–100 cm are shown in Figs. 6a and 6b, whose left axes refer to a Co content of 0.04 wt %, and the right axes, 0.08 wt %.

The results of modeling suggest that, at a Co content of 0.04 wt %, the measured activity of ^{60}Co of 42 ± 7 decay/min kg (solid crosses and left axes in Figs. 6a, 6b) in the Kunya-Urgench sample (shielding depth of d = 18 ± 3 cm determined above from the track density of VH nuclei) corresponds to the preatmospheric radius of the Kunya-Urgench chondrite $R = 47^{+8}_{-5}$ cm. If the average Co content in H chondrites is ≥0.08% (dashed crosses and right axes in Figs. 6a, 6b), 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

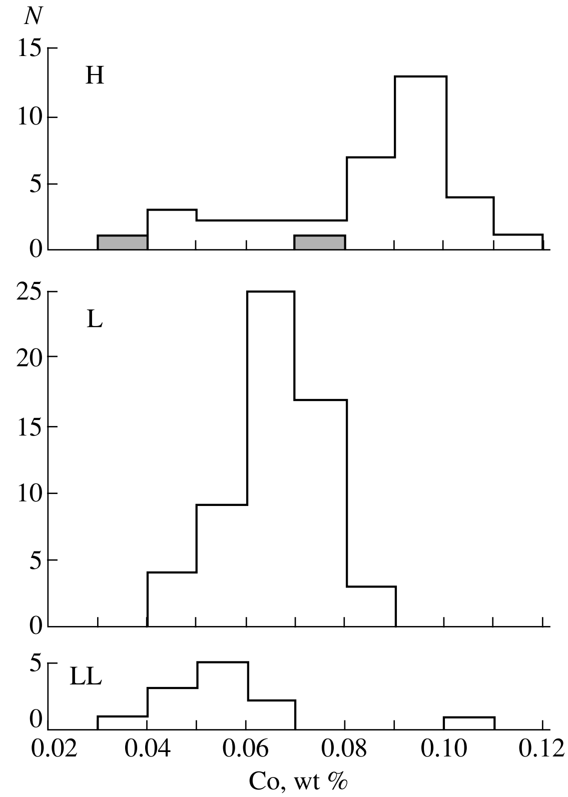

Fig. 5. Distribution of Co in ordinary chondrites of various chemical groups after [36–38]. Shaded areas show variation in Co content in the Dhajala H chondrite.

Kunya-Urgench chondrite from the spherical shape, because neutron leakage and, consequently, ^{60}Co content at a certain depth depend on the body shape [39, 40]. The linear dimensions of the largest fragment of the Kunya-Urgench chondrite are 81 × 72 × 48 cm [6]. They correspond to the general statistical regularity of the proportion of linear axes as $a : b : c$ ~ 2 : 2 : 1, which was derived from results of an investigation of the shapes of 930 Antarctic Yamato meteorites collected in 1973–1975 [41] and the experimental investigation of concrete fragments destroyed by high-velocity impacts [42, 43]. It is reasonable to suggest that the preatmospheric shape of the Kunya-Urgench chondrite corresponded to this regularity. This allows us to estimate and account for the possible ^{60}Co loss due to the departure of the chondrite from the spherical shape. Then, proceeding from the total activity level of ^{60}Co, we can estimate the effective radius in an equivalent spherical model. Taking into account the aforementioned errors in the measured ^{60}Co contents and depth of sample occurrence, it lies in the range R ~ 42–54 cm. Since the density of the Kunya-Urgench chondrite is 3.32 g/cm^3 [7], its average preatmospheric mass was M_0 ~ 1.5 t (maximum, ~2.2 t), and the degree of ablation, ≤30% (maximum, ~50%). Identical estimates (M_0 ~ 1.5 t and ablation ≤30%) were obtained for the Kunya-Urgench

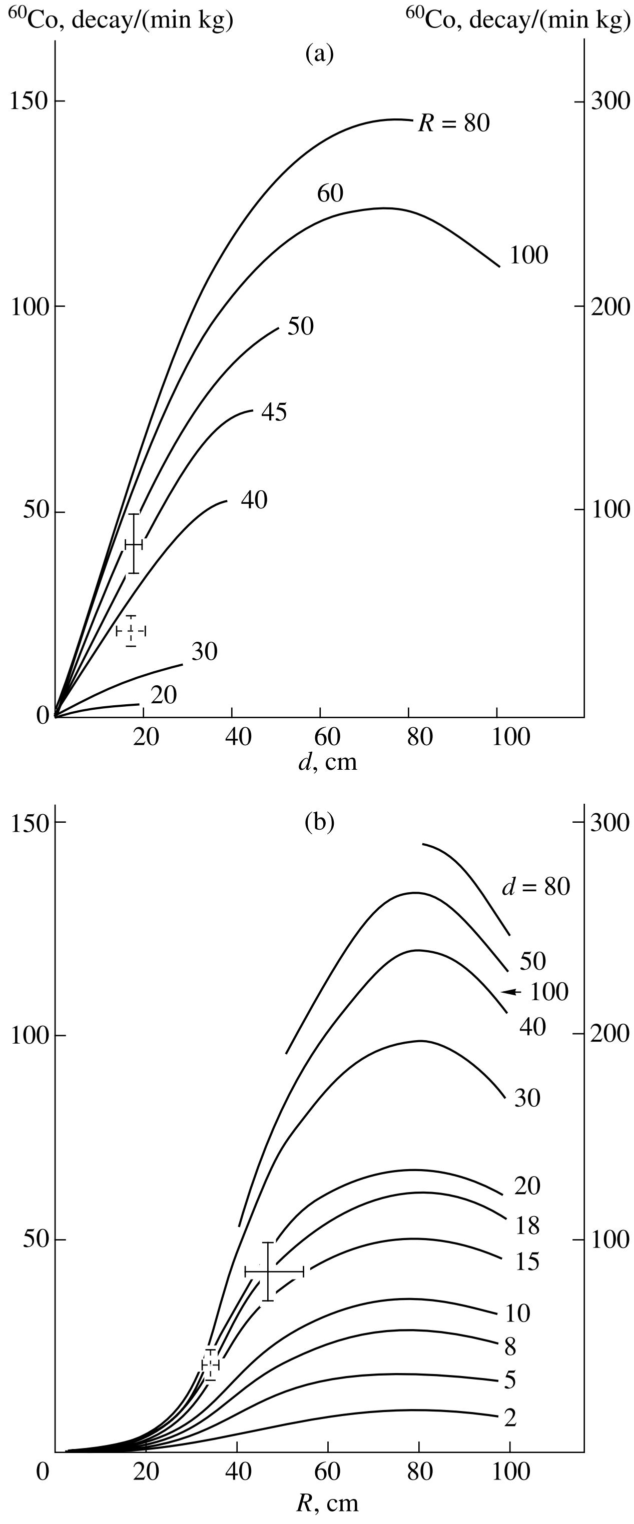

Fig. 6. Modeling of ^{60}Co formation in spherical chondrites with the radius R ~ 10–100 cm: (a) ^{60}Co distribution in chondrites of varying radii as a function of shielding depth, d; and (b) ^{60}Co distribution at varying shielding depths d as a function of radius R (crosses are measured ^{60}Co content, 42 ± 7 decay/(min kg) at a depth of d = 18 ± 3 cm determined from tracks; the left axes and solid crosses refer to the modeling at a Co abundance of H chondrites of 0.04 wt %; and the right axes and dashed crosses, 0.08 wt %).

chondrite using the phenomenological formula of the weight loss of a large meteorite entering the Earth's atmosphere at supersonic velocities [44, 45]:

$$M_f = M_0 \exp\{-\bar{\sigma}(v_0^2 - v_f^2)/2\},$$

where M_0 and M_f are the preatmospheric and fall masses of the chondrite; v_0 is the heliocentric velocity; v_f is the velocity of ablation termination (3–7 km/s); and $\bar{\sigma}$ ~ 0.02–0.03 s^2/km^2 is the average parameter of ablation according to data for the Pribram, Lost City, and Innisfree chondrites. The value v_0 ~ 7 km/s was used for Kunya-Urgench according to [7].

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 [46]. It is reasonable to expect the preservation of the near-surface (~2 cm) samples of the Kunya-Urgench chondrite, which feature effects of irradiation by solar cosmic rays. In order to collect more reliable and detailed information, it is necessary to measure the tracks, ^{60}Co and ^{26}Al in other Kunya-Urgench samples (in the ideal case, drill cores).

Size of the Orbit

The orbit (position of its aphelion, q') of the Kunya-Urgench chondrite was estimated using a previously developed [1, 4, 5, 46] "isotopic" approach 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% per AU; i.e., chondrites with larger orbits are significantly enriched in ^{26}Al. This regularity can be phenomenologically described as a function of aphelion, q'. This allows estimation of the aphelia of meteorite orbits from their ^{26}Al contents.

The fall of a new meteorite with known orbit parameters, Peekskill H6 [47], provided an opportunity for an additional evaluation of the validity of such an approach. As was mentioned above, ^{26}Al content of 66 ± 4 decay/(min kg) was measured in sample no. 15 821. Its shielding depth was determined from an investigation of the tracks of GCR VH nuclei. Among about 200 olivine grains (30–100 μm), 33 grains were suitable for this purpose. On the total area of observation of these grains, S = 1.46 × 10^{-3} cm^2, 34 tracks were recorded, which yielded a value of the track density of ρ = (2.33 ± 0.40) × 10^4 cm^{-2}. According to estimates [48], at the radiation age of the Peekskill chondrite (32 Ma), its preatmospheric radius is $R \geq$ 40 cm. According to the measured track density in the sample studied, the shielding depth could be d = 23 ± 1 cm at R = 50 cm and d = 21 ± 1 cm at R = 1000 cm. Using the average chemical composition of H chondrites, the calculations by the isotopic method lead to the conclusion

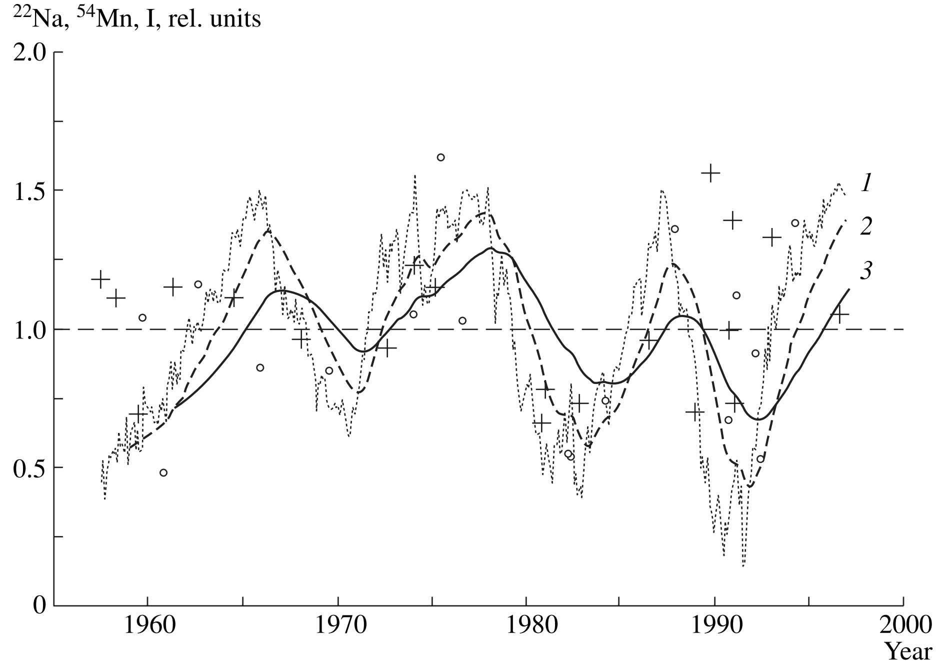

Fig. 7. Possible relative variation in the activity of ^{54}Mn (curve *2*) and ^{22}Na (curve *3*) at their formation at 1 AU by GCR with the rigidity $R > 0.5$ GV. The relative modulation of GCR (curve *1*) in solar cycles 19–22 was obtained from stratospheric measurements [33–35]. Curve *1* was normalized to an average value of GCR intensity 0.2354 particles cm^{-2} s^{-1} ster^{-1}; the experimental data for ^{54}Mn (circles) and ^{22}Na (crosses) activities in 20 chondrites that fell between 1959 and 1998 (Table 2 in [1] for the period before 1977 and [49, 52–59]) are normalized to average values of ~87 and ~84 decay/(min kg), respectively.

that the measured level of saturated ^{26}Al activity at a depth of ~23 cm could be accumulated in the Peekskill chondrite at preatmospheric radii of ~30 and ~50 cm if the aphelion of its orbit was $q' = 2.14 \pm 0.42$ and $q' = 2.59 \pm 1.24$ AU, respectively. This is consistent within errors with a measured value of $q' = 2.10 \pm 0.05$ AU [47]. A similar analysis was previously applied to the Innisfree chondrite with known orbit parameters [1] and demonstrated that consideration of the particular chemical composition of the chondrite greatly improved agreement. It should be mentioned, however, that uncertainty in the method increases strongly with increasing absolute value of the aphelion.

Application of this method to the Kunya-Urgench chondrite shows that the measured ^{26}Al activity, 72 ± 7 decay/(min kg) in a sample with a shielding depth of $d = 18 \pm 3$ cm in a body with a radius of ~42–54 cm, corresponds to an orbit with an aphelion $q' \sim 3.5$–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 [7].

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 periodic variations in GCR in antiphase with the 11-year sunspot cycle. This process was comprehensively studied near the Earth owing to the continuous registration of GCR intensity by a land-based network of neutron monitors, stratospheric measurements by means of probes and, in recent years, by measurement devices on board satellites. However, the mechanism of solar modulation remains disputable, because of the lack of necessary continuous information on the character of the modulation at greater helio-centric distances. In particular, the size of the modulation area and its boundary have not been determined. Episodic spacecraft flights are still unable to provide such valuable information in full volume. Our long-lasting investigations of radionuclides in freshly fallen chondrites led us to the conclusion that the character of the GCR modulation was controlled to a large extent by processes within meteoritic orbits, i.e., 2–4 AU from the Sun [1, 2, 30, 50]. Indeed, Fig. 7 shows GCR variations according to data of stratospheric measurements (curve *1*) and predicted variations in ^{54}Mn (curve *2*) and ^{22}Na (curve *3*) activities calculated assuming that these radionuclides were generated in chondrites at a GCR intensity similar to that observed near the Earth. Figure 7 also shows the relative contents of these radionuclides in the chondrites that fell between 1959 and 1998. It is seen that the respective points are poorly

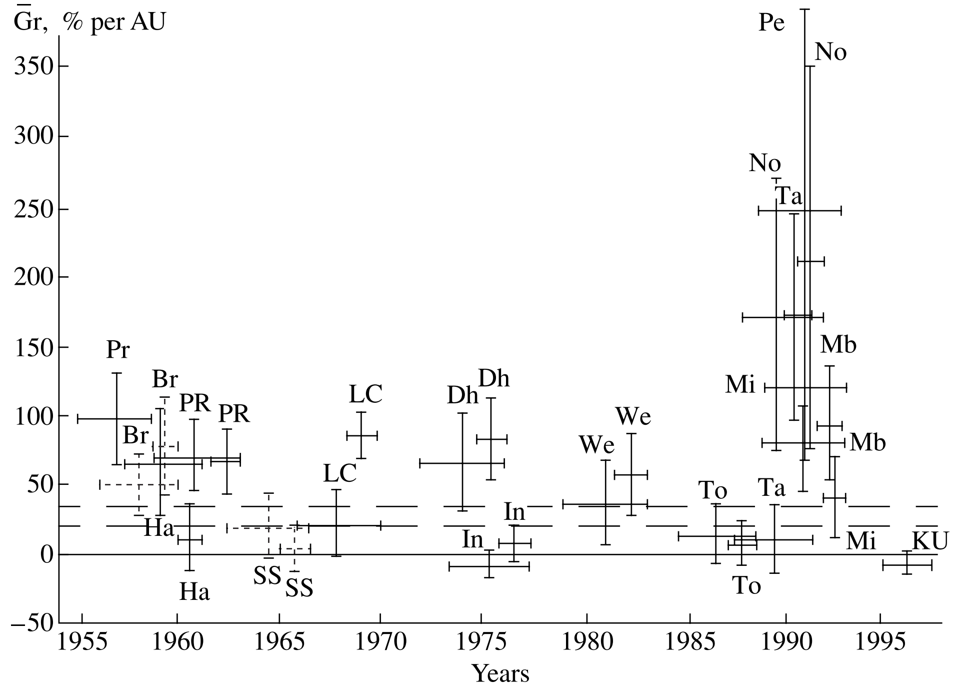

Fig. 8. Distribution and variation in the radial gradients ($\bar{G}_r$) of GCR with rigidity $R > 0.5$ GV in 1954–1998 along the orbits of the following chondrites: Pr—Pribram (VI.55–V.59, $\bar{r}$ = 3.3 AU); Br—Bruderheim (IV.56–III.60, $\bar{r}$ = 3.29 AU and I.59–III.60, $\bar{r}$ = 2.53 AU); Ha—Harleton (VI.57–V.61, $\bar{r}$ = 1.57 AU and III.60–V.61, $\bar{r}$ = 1.57 AU); PR—Peace River (IV.59–III.63, $\bar{r}$ = 1.68 AU and I.62–III.63, $\bar{r}$ = 1.99 AU); SS—Senint Severin (VII.62–VI.66, $\bar{r}$ = 1.60 AU and IV.65–VI.66, $\bar{r}$ = 1.60 AU); LC—Lost City (II.66–I.70, $\bar{r}$ = 1.81 AU and XI.68–I.70, $\bar{r}$ = 1.81 AU); Dh—Dhajala (II.72–I.76, $\bar{r}$ = 1.61 AU and XI.74–I.76, $\bar{r}$ = 1.73 AU); In—Innisfree (III.73–II.77, $\bar{r}$ = 2.25 AU and XII.75–II.77, $\bar{r}$ = 2.13 AU); We—Wethersfield (XII.78–XI.82, $\bar{r}$ = 1.94 AU and IX.81–XI.82, $\bar{r}$ = 2.13 AU); To—Torino (VI.84–V.88, $\bar{r}$ = 1.78 AU and III.87–V.88, $\bar{r}$ = 2.00 AU); Ta—Tahara (VI.87–III.91, $\bar{r}$ = 1.60 AU and I.90–III.91, $\bar{r}$ = 1.83 AU); No—Noblesville (IX.87–VIII.91, $\bar{r}$ = 1.60 AU and VI.90–VIII.91, $\bar{r}$ = 1.83 AU); Pe—Peekskill (XI.88–X.92, $\bar{r}$ = 1.72 AU); Mb—Mbale (IX.88–VIII.92, $\bar{r}$ = 2.04 AU and VI.91–VIII.92, $\bar{r}$ = 2.08 AU); Mi—Mihonoseki (I,89–XII.92. $\bar{r}$ = 1.62 AU and X.91–XII.92, $\bar{r}$ = 1.87 AU); KU—Kunya-Urgench (VIII.94–VI.98, $\bar{r}$ = 3.33 AU). 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.

consistent with curves *2* and *3*, and that the biggest deviations (higher than calculated values) are in years corresponding to the highest solar activity (lowest GCR intensity). This suggests a higher GCR intensity along meteorite orbits, i.e., significant GCR gradients in years of maximum solar activity, at least at distances of 2–4 AU where the aphelia of the majority of chondrites are situated. The rightmost point is that of ^{22}Na in the Kunya-Urgench chondrite. It practically coincides with the calculated curve, suggesting low or even negative gradients of GCR in the minimum solar activity phase of the 22nd solar cycle.

Indeed, a measured ^{22}Na content of 88 ± 9 decay/(min kg) was accumulated at the Kunya-Urgench orbit at an average heliocentric distance of ~3.3 AU during IX 1994–VI 1998. At average intensity of galactic cosmic rays near the Earth, 0.33 cm^{-2} s^{-1} $ster^{-1}$ in this period, this indicates (according to modeling [1, 2]) that the average integral GCR gradient was $-5.3 \pm 5.4\%$ per AU ($R > 0.5$ GV). Figure 8 shows a series of similar data on the distribution and changes in the radial GCR gradients in the heliosphere during four cycles of solar activity, which were in our comprehensive studies of recently fallen chondrites (investigations of track density and radionuclide contents, modeling 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 ~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% per AU in years of maximum activity (1957–1958, 1969–1970, 1981–1982, and 1990–1991). In particular, the negative values of GCR gradient at the decline of the 22nd solar cycle obtained from ^{22}Na concentrations in the Kunya-Urgench chondrite are consistent with gradient values near the minimum of previous solar cycles, which were derived from data on the

St. Severin (1965–1966), Innisfree (1973–1976), Torino, and Tahara (1984–1991) chondrites [1, 50] and the results of direct measurements in interplanetary space [51]. These results suggest a decrease in the modulation of GCR in quiet Sun years.

It should be noted that each gradient value in Fig. 8 corresponds to particular spatial and temporal coordinates (see figure caption). 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 chondrites studied was carried 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 isotopes provide evidence on the average values of GCR intensity and gradient over large time spans. 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 (~20–30% per AU) coincided with the average gradient during the past million years (Fig. 8), 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.

The results of the analysis of information obtained from meteorites on the characteristics of the distribution and variations in the intensity of GCR in the tree-dimension heliosphere during four solar cycles were described in detail in other works [1, 2, 30, 50, etc.]. The investigation of the Kunya-Urgench chondrite is but an important sequential step in gaining such information. It should be pointed out that it is necessary to continue the investigation of recently fallen chondrites in the present time, because this is dictated by the change of the secular solar cycle, which is probably taking place now [60]. Thus, the same electromagnetic and radiation conditions in the heliosphere will be repeated only within a century.

CONCLUSION

The importance of a combined approach to such valuable material as meteorites should be specially emphasized. Information obtained from the measurement of the particular properties of the material 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 recently fallen meteorites (e.g., Lost City, Jilin, Peekskill, etc.).

ACKNOWLEDGMENTS

We are grateful to G.V. Kalinina, N.S. Kuyunko, V.I. Mednikov, and T.V. Shilova for their assistance during this study. Special thanks to B.S. Shmel'kov and S.V. Masterkov for the development of an interface and a software program for the thermoluminescence device. The study was financially supported by the Russian Foundation for Basic Research, project no. 98-05-64018.

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