Introduction: Variations in the galactic cosmic ray (GCR) intensities over the last 1 Gyr can be estimated based on the abundance of cosmogenic isotopes in meteorites, such as stable $^{39,41}$K and longlived $^{40}$K ($T_{1/2} = 1.277$ Gyr) [1-3]. Meteorites often show clustering of cosmic-ray exposure (CRE) ages, which was caused by formation of the “paired” meteoroids in a single collision with a parent body. In studying cosmic ray variations, one should remove the effect of paired meteorites. In this study, GCR flux variations were deduced using strict selection criteria [4, 5] for the analysis of the CRE age distribution of iron meteorites. The ages were taken from [1-3].

Analysis of age distribution of iron meteorites: Our analysis was based on the following fact: if the GCR flux varies periodically, but the calculation of ages for all meteorites relied on the assumption that the GCR flux was constant throughout their history, then the distribution of the measured CRE ages of iron meteorites should exhibit the corresponding periodic peaks [6]. Clustering of ages should influence the distribution of the phase (Ph) calculated for the assumed period of changes (t) in the distribution of the exposure ages (T) and, respectively, cosmic ray intensity. The phase values were calculated by the relation:

$$\text{Ph} = \frac{T}{t} - \text{int}(\frac{T}{t})$$

We analyzed the distribution of the phase for 17 values of t over a wide range of possible values; t = 100, 150, 200, …, 850, 900 Myr. The value of $\chi^2$ was calculated for every value of t. Changes of $\chi^2$ as a function of t were considered for both sets of iron meteorite exposure ages and further for model ages.

The results of the analysis of iron meteorites are shown in Fig. 1. As seen, for a period of GCR variation of 450 Myr, $\chi^2$ differs considerably from the respective average value for all meteorites (Fig. 1a) and for the corrected ages (Fig. 1b). Significant deviations of $\chi^2$ from the average values can be also observed for shorter periods (t) of ~250 (Fig. 1a) and ~150 Myr (Fig. 1b) obtained for the ages not corrected and corrected for paired meteorites, respectively. The insets in Fig. 1 show that the phase values for t = 450 Myr approximated by Gaussian curves are close to the normal distribution. The normal distribution of the phase for a certain value of t may reflect possible periodic GCR variability with this period.

Analysis of the distribution of the model set of CRE ages: Numerical modeling was used to answer the question whether the observed deviations can be

$$\chi^2 = \frac{\sum (Ph - \text{fit})^2}{\text{degree of freedom}}$$

caused by GCR intensity variations with a period of ~450 Myr and, possibly, ~150 Myr. For this purpose, we used a model set of 100 values of “true” ages randomly distributed in the range 0–1000 Ma.

Similarly, for the model set of “true” ages, we calculated the phase values (Ph) for 17 assumed periods (t) of GCR variations and calculated the $\chi^2$ values for each phase distribution. As expected, no significant deviations of the sample characteristics from the respective average values were found at a constant GCR flux over time. All $\chi^2$ values, independent of t, agree with the average value within ±1.5σ (Fig. 2a). At the same time, for all values of t there are observed relatively uniform distributions of the phase values, similar to that for t = 450 Myr shown in the inset in Fig. 2a.

The calculated $\chi^2$ values for the model set of CRE ages under the assumption of GCR variability with 150 and 450 Myr periodicities (t) are shown in Figs. 2b and 2c. These results indicate that the phase distribution is close to normal for a value of t similar to the assumed period of GCR variations. Therefore, the analysis of the distribution of phase values for the distributions of the model ages and iron meteorite ages (of the entire age population and corrected for paired meteorites)
confirms the possible GCR variations with a period of about 450 Myr.

The above results suggest the existence of the GCR flux variability with a period of ~450 Myr. The variations in the GCR flux can be explained by periodic spiral arm crossings of the solar system. The GCR variations with a period of ~150 Myr discussed in the previous studies [6, 7] appears to be less certain.

**Fig. 2.** $\chi^2$ for the distribution of the phase values $\Phi = T/t - \text{int}(T/t)$ depending on the assumed period (t) of variations in the CRE ages (T) of meteorites in the range T=0–1000 Ma. The average values are shown by the dashed line. Model set of random ages ($N=100$) (a) at a constant GCR flux and at a variable GCR flux with periodicities of (b) 150 and (c) 450 Myr. The insets show the distributions of the phase values for (a, c) $t = 450$ Myr and (b) $t = 150$ Myr. The distributions are approximated by the Gaussian curves.

The conclusion about the possible GCR variations with a period of ~450 Myr can be achieved by comparing the distributions of CRE ages of iron meteorites and the model set of ages based on the assumption of GCR variations with different periodicities. **Figure 3a** shows the initial distribution in the model set of 100 random “true” values of ages in the range 0–1000 Ma; the number of meteorites decreases with increasing age, according to the relation: $N = e^{-\tau/T}$ (I) for the average lifetime of iron meteorites in space, $\tau = 700$ Myr; (b) “measured” ages for the model set assuming variations in the GCR flux with the period $t = 150$ Myr and (c) $t = 450$ Myr. (d) The distribution of the CRE ages of iron meteorites after rejection of paired meteorites and meteorites with a complex cosmic ray exposure history ($N = 28$). Distributions (c) and (d) are approximated by the “best” Gaussian curves. The maxima are shown by arrows. The exponential curve according to Eq. (I) is shown by the dashed line.

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