

DETERMINATION OF THE PREATMOSPHERIC SIZES OF METEORITES

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1966

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Abstract

Full Text

UDC 523.51+539.17+523.165

Astronomy

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DETERMINATION OF THE PREATMO- SPHERIC SIZES OF METEORITES

(Presented by Academician A. P. Vinogradov, September 1, 1965)

The principal source of cosmic matter is meteorites. The matter of meteorites and of their parent bodies—asteroids—has changed during the time of its existence (about 4.5 billion years) to a considerably lesser degree than the matter of the Earth. Therefore meteorites constitute an extremely important source of information on the early stages in the formation of the bodies of the Solar System. In addition, they are the only source of knowledge about temporal and spatial variations of cosmic rays, since meteoritic matter accumulates the products of nuclear interactions.

One of the substantial gaps in our knowledge of meteorites is the absence of data on the preatmospheric sizes of meteoritic bodies and on the position of the specimens that fell to Earth within these bodies. It is known only that a considerable part of a meteoritic body that has entered the Earth's atmosphere is lost as a result of the ablation process.

The only method that makes it possible to determine the preatmospheric sizes of meteorites is the study of the depth distribution of the rates of formation of cosmogenic isotopes arising in nuclear interactions of cosmic rays with meteoritic matter. The basis of this method is the existence of differences in the excitation functions—the dependence of formation cross sections on particle energy, $\sigma_{A_i} = f(E_{\text{part}})$ —for different groups of products of nuclear reactions.

Fig. 1. Excitation functions of V^{49} (1), Na^{22} (2) in reactions of protons with iron nuclei

As follows from experiments on the irradiation of iron targets with protons of various energies from 0.1 to 2.5 GeV (10^{-5}), all products of nuclear reactions may

Fig. 2. Depth distribution of the formation rate $H_{\text{Na}^{22}}$ and $H_{\text{V}^{49}}$ in iron meteorites with different R

Figure 2: Fig. 2. Depth distribution of the formation rate $H_{\text{Na}^{22}}$ and $H_{\text{V}^{49}}$ in iron meteorites with different R

be divided into two groups: 1) isotopes with $\Delta A = A_{\text{target}} - A_{\text{prod}} \leq 10$; for them σ_{A_i} is constant in the indicated range of proton energies (see curve 1, Fig. 1); 2) isotopes with $\Delta A > 10$; for them a sharp increase of σ_{A_i} is observed in the region $E_p < 1$ GeV and a small change for $E_p > 1$ GeV (similar to curve 2, Fig. 1).

The rate of formation of isotopes H_{A_i} at the i -th point, determined by the quantity r_i (distance from the surface) of a meteoritic body of radius R_i , is a function of the intensities of the primary cosmic radiation and of secondary nuclear-active particles, which depend on r_i and R_i , and a function of the quantities

$$\bar{\sigma}_{A_i} = \int_{E_0}^{E_\infty} \sigma_{A_i}(E) F(E) dE / \int_{E_0}^{E_\infty} F(E) dE; \quad (1)$$

$\bar{\sigma}_{A_i}$ depend on the form of the spectrum of the nuclear-active particles and on the excitation functions of the isotopes.

In the model proposed by us ^(6,7), the quantities $H_{A_i}(r_i, R_i)$ in iron meteorites are equal to

$$H_{A_i}(r_i, R_i) = \frac{N}{A} \left[\bar{\sigma}_{A_i}^{\text{prim}} I_{\text{prim}} + \bar{\sigma}_{A_i}^{\text{sh}} I_{\text{sh}} + \bar{\sigma}_{A_i}^p I_p + \bar{\sigma}_{A_i}^\pi I_\pi + \bar{\sigma}_{A_i}^{n_1} I_{n_1} + \bar{\sigma}_{A_i}^{n_2} I_{n_2} \right], \quad (2)$$

where N is Avogadro's number; $A = 56$; I are particle intensities; $\bar{\sigma}_{A_i}$ is the mean weighted cross section for formation of isotope A_i ; the indices prim., sh., p , π , n , and n_2 refer respectively to primary cosmic radiation, shower particles ($E > 1$ GeV), fast protons, mesons and neutrons ($0.1 \text{ GeV} \leq E \leq 1 \text{ GeV}$), and slow neutrons ($0.001 \text{ GeV} \leq E \leq 0.1 \text{ GeV}$).

Fig. 2. Depth distribution of the formation rate $H_{\text{Na}^{22}}$ and $H_{\text{V}^{49}}$ in iron meteorites with different R

The role of particles of each type in the formation of the A_i -isotope is determined by the shape of the particle spectrum and by the function $\sigma_{A_i} = f(E)$. Therefore the character of the depth distribution of H_{A_i} in meteorites with different R_i is different for isotopes of the two groups indicated above. This is seen from the curves in Fig. 2, obtained by us with the following parameters: $I_0 = 0.23 \text{ particles/cm}^2 \cdot \text{sec} \cdot \text{ster} = 0.386 \text{ nucleons/cm}^2 \cdot \text{sec} \cdot \text{ster}$, according to the spectrum of primary cosmic radiation for the minimum of solar activity from 1953-1956 data ⁽⁸⁾; the change in the shape of the spectrum for different r_i

Figure 3: Dependence of $H_{V^{49}}$ on $H_{V^{49}}/H_{Na^{22}}$ for various R_i and r_i/R_i

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due to ionization losses was taken into account. The multiplicities of secondary mesons and protons were determined from their spectra obtained in exposing photographic plates in the atmosphere ⁽⁹⁾. In accordance with these data it was assumed that the spectra of secondary particles do not depend on r_i and R_i . In determining $I_p(r_i, R_i)$ and $I_\pi(r_i, R_i)$, ionization losses were taken into account. The neutron multiplicity was determined from the neutron spectrum in the atmosphere ⁽¹⁰⁾, with normalization to the value for $R = 26$ cm and $r = 13$ cm ⁽¹¹⁾. The multiplicities are: $\bar{S}_{sh} = 0.27$, $\bar{S}_p = 0.70$, $\bar{S}_\pi = 0.46$, $\bar{S}_{n_1} = 3.46$, $\bar{S}_{n_2} = 37.53$. It was assumed that the excitation functions for protons, mesons, and neutrons are identical, and that the meteoritic body had a spherical shape before entering the Earth's atmosphere.

From the course of the curves in Fig. 2 there follow substantial differences in the absolute formation rates of Na^{22} and V^{49} and in the character of their depth distribution. Most important is that the ratio $H_{V^{49}}/H_{Na^{22}}$ in general changes little at the surface of meteorites with different R_i (for example, for $R = 5$ cm it is 28, for $R = 40$ cm 25, and for $R = 200$ cm 19), whereas at the centers these changes are substantial (for $R = 5$ cm, 36.7; for $R = 40$ cm, 80; and for $R = 200$ cm, 44). With increasing R_i there is observed an increase in the values of the ratio $(H_{A_i})_{surface}/(H_{A_i})_{center}$; for example, if at $R = 5$ cm it is equal to 0.85 for V^{49} and 1.07 for Na^{22} , then at $R = 100$ cm we obtain 11.4 for V^{49} and 51 for Na^{22} .

These features of the depth distribution of H_{A_i} for isotopes with different excitation functions are manifested still more sharply in the graph

in the coordinates H_{A_i} and H_{A_1}/H_{A_2} (Fig. 3), which is a nomogram of mutually intersecting parallel lines corresponding to $R_i = \text{const}$ and $r_i/R_i = \text{const}$.

Such a nomogram makes it possible, from the activities of the corresponding isotopes in a given specimen of an iron meteorite, to determine the preatmospheric radius of the meteoritic body and the distance of the investigated sample from

Fig. 3. Dependence of $H_{V^{49}}$ on $H_{V^{49}}/H_{Na^{22}}$ for various R_i and r_i/R_i

its surface (or center). In order to exclude a possible temporal change in the intensity of cosmic rays, isotope pairs with close half-lives should be chosen. Such pairs are Na^{22} ($T = 2.58$ years) and V^{49} ($T = 330$ days) or Mn^{54} ($T = 291$ days) for recently fallen meteorites, and Be^{10} ($T = 2.5 \cdot 10^6$ years) or Al^{26} ($T =$

Table 1

Preatmospheric dimensions of the meteoritic body that fell as the Yardymly iron shower

R , cm	r/R	r , cm	$R - r$, cm	Total weight, kg	Degree of ablation, %	Source
26	0.4	10.4	15.6	550	75	Present work
39	0.6-0.4	23.4-15.6	15.6-23.4	1850	92	(13)

$= 7.4 \cdot 10^5$ years) and Mn^{53} ($T \geq 2 \cdot 10^6$ years) for meteorites that fell 5 or more years ago. From the maximum value of the activity of Na^{22} and the mean activity of V^{49} in the Arus specimen of the Yardymly iron shower⁽¹²⁾ (point in Fig. 3), we determined the preatmospheric radius and weight of the meteoritic body that gave rise to this shower (see Table 1). If the fallen body had the shape of a sphere with radius $R_{\text{after atm}} = 15.6$ cm, then its weight should have been 550 kg—a value close to the weight of the recovered specimens (150 kg). The difference between these weights is explained by the nonuniformity of the blowing-off of the molten layer from the surface of the moving body,

with cosmic velocity. The value of r for the specimen studied is 10.4 cm.

Our estimates of the dimensions and weight of the meteoritic body that fell in the form of the Yardymly iron shower differ from the data of work⁽¹³⁾, obtained on the basis of an analysis of the dependences of the ratios of the contents $\text{He}^3/\text{Ne}^{21}$ and He^3/He^4 on $H_{\text{Ar}^{38}}$ in the Arus specimen. The nomograms were constructed from data on the depth distribution of these isotopes in the Grant meteorite, whose cosmic-ray age by the $\text{Ar}^{36}/\text{Cl}^{36}$ method is 600 million years. However, in work⁽¹⁴⁾ substantial differences were found in the depth dependence of Cl^{36} and Ar^{36} , and in the values of cosmic-ray ages for different portions of the Grant meteorite, apparently due to spatial erosion, which may distort the pattern of the depth distribution of stable isotopes. Nor can one exclude the possibility of temporal variations in the intensity of cosmic rays, which would lead to different effects for stable and radioactive isotopes.

The method proposed by us is free of these uncertainties. Its accuracy is determined chiefly by the accuracy of radiometric determinations of low activities and by the correctness of the adopted assumption concerning the constancy of the spatial distribution of cosmic rays in the Solar System.

I express my gratitude to L. D. Revina, T. A. Ibraev, and T. I. Kholodkovskaya for their assistance in the work.

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Received
25 VIII 1965

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