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IRRADIATION OF DUST IN MOLECULAR CLOUDS. II. DOSES PRODUCED BY COSMIC RAYS

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The fluxes of cosmic rays inside typical molecular clouds are calculated. Protons and a-particles with energies of $1\ MeVd \le Å \le 10\ GeV$ penetrate deeply enough to produce irradiation doses in the ice mantle of dust particles on the order of 0.1-1 eV/amu over the 10-50 million year lifetime of clouds with and without star formation regions. The possible use of these results for interpreting laboratory experiments on the irradiation of ice mixtures of the type $H_2O:CH_3OH:NH_3:CO$ is discussed. Complex organic radiolysis products may play an important role in the prebiological evolution of the dust component of molecular clouds.
Keywords: *molecular clouds: cosmic rays: ices: radiation doses*

1. Introduction

Ultraviolet (UV) radiation capable of ionizing hydrogen cannot penetrate into the interiors of dense interstellar clouds, as it is absorbed at the outer boundary by atomic and molecular hydrogen. Radiation in the range $912Å < \lambda < 2067Å$, which plays an important photochemical role, can penetrate quite deeply [1] but cannot be involved with the H_3^+ ion, which is formed during ionization of H_2 with an ionization potential of 15.43 eV. The only ionization source in the interior of a molecular cloud is cosmic rays. With energies of 1 MeV and above, they have sufficient penetrating power to irradiate denser layers in the interior of clouds. Particles with energies of several GeV or more are able to penetrate the densest central regions of clouds. Cosmic rays, consisting mainly of protons (~85-90%) and α-particles (~10-15%), interact with hydrogen via the following scheme, where an incident ion with energy E ionizes a hydrogen molecule (atom):

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$$p(E) + H_2 \rightarrow H_2^+ + e^- + p(E'), \quad (1)$$

with subsequent formation of H_3^+ ions,

$$H_2^+ + H_2 \rightarrow H_3^+ + H. \quad (2)$$

This, in turn, initiates a chain of ion-molecular reactions with essentially all the components of the gaseous phase (X) of the cloud (except He, O_2, and N):

$$H_3^+ + X \rightarrow HX^+ + H_2, \quad (3)$$

which lead, for example, to the formation of simple hydrides (water, ammonia, methane). Reactions on the surfaces of dust particles (solid phase) begin to play a role when ice mantles, consisting initially of frozen volatile compounds protected from external UV radiation, are present [1,2]. It is known that, for this, it is necessary to have an observed absorption $A_V > A_0$, with

$$N = 1.9 \cdot 10^{21} (A_V - A_0), \quad (4)$$

where N is the number of atoms (molecules) of hydrogen along the line of sight (in cm^{-2}), A_V is the absorption (in stellar magnitudes), and A_0 is the threshold absorption at which ices begin to appear [1,2]. Thus, the radiation field in the cloud limits the amount of ices but, at the same time, is necessary for their photochemical conversion. The interior regions of a cloud, shielded from UV radiation, are irradiated by cosmic ray particles, as confirmed by direct observation of IR absorption lines of H_3^+ [3]. In fact, the ion density $n(H_3^+)$ in a cloud is directly related to the rate ζ of ionization of hydrogen by cosmic rays, the flux of which can be estimated theoretically if $n(H_3^+)$ is known.

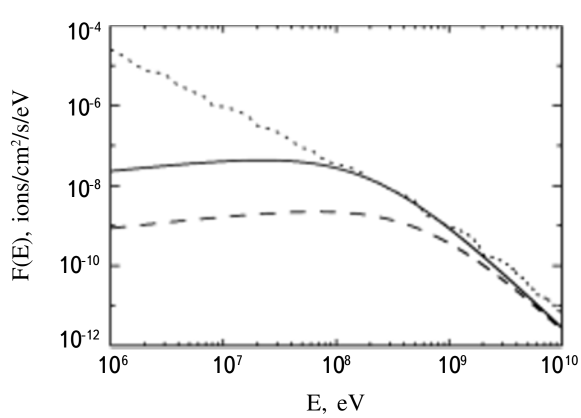

Fig. 1. Differential spectra of galactic cosmic rays [12,13] for E_0 = 200 MeV (smooth curve) and E_0 = 600 MeV (dashed curve). The dotted curve corresponds to the distribution of Ref. 14.

In modern physical and chemical models of molecular clouds, ζ is specified parametrically, assuming it is constant inside the cloud. This is true for particles with energies of a few GeV and above, but not in the MeV-GeV range, where the maximum cosmic ray flux occurs, especially in the densest regions of clouds with densities above 10^3 cm^{-3}. (See Fig. 1.) Thus, correct interpretation of the lines of H_3^+ in the spectra of molecular clouds, as well as quantitative calculations of the irradiation of ices, requires knowledge of the distribution of the soft cosmic ray component (MeV-GeV) along the cloud radius as a function of the cloud parameters. While this problem has been solved, in principle, for the hard component (GeV-TeV and above) inside dense regions of clouds [4], it has still not been studied numerically in the case of the soft component [5], although it is used for interpreting observations of H_3^+ and in calculating the irradiation dose for ices.

In order to be able to estimate the degree of radiation-chemical conversion of the corresponding products, it is necessary to know the irradiation dose (amount of absorbed energy) of the chemical compounds owing to photons and high-energy particles as functions of the absorption in the cloud. Calculating the radiation fluxes inside a cloud with a known external source for a specified (stationary one-dimensional and static) model is not especially difficult [1]. The possibility in principle of irradiating the ice mantles of dust particles in outer regions of molecular clouds that are sufficiently cold and protected from hard external radiation, but which are still reached by UV radiation in the range $912Å < \lambda < 2067Å$, has been examined in Ref. 1. It turns out that these two boundaries do not coincide in two cases, and the distance between them may be substantial. First, if a star lies at a fairly close distance (depending on its type and luminosity) from a molecular cloud, e.g., no more than 0.3 pc, for a luminosity on the order of ten times that of the sun for a type A star, regions out to $A_V \leq 50$ are irradiated. The second case is when the interstellar radiation field itself is capable of providing the required dose at distances on the order of $\Delta A_V \leq 5$ from the boundary where ices form. In both cases, we are dealing with excesses above the experimental threshold dose of 1.4 eV/amu accumulated over the corresponding cloud lifetime. Recent experiments on the UV irradiation of mixtures of the type $H_2O:CH_3OH:NH_3:CO$ in proportions of 100:50:1:1 [1] revealed the formation of extremely complex organic compounds containing up to 22 carbon atoms with an accumulated threshold dose of 1.4 eV/amu. This sort of mixture is regarded as a good analog of the ice coatings on interstellar dust [2,6,7]. On the other hand, no quantitative data exist on cosmic ray irradiation doses in molecular clouds and, especially, the radial dependences of these doses [5].

In the meantime, the available laboratory data on irradiation by energetic particles can be characterized briefly as follows: radiation-chemical conversion is observed for irradiation by ion fluxes (*E*~1 MeV) with $U = F \cdot t \sim 10^{13} - 10^{16}$ particles/cm^2 [8-11], which corresponds to irradiation times *t*~0.1-100 million years for the cosmic ray fluxes [12-14] outside clouds. (See Fig. 1.) The integrated flux *F* is evaluated in the next section of this paper. Both pure ices and mixtures were irradiated. In particular, proton bombardment of an $H_2O:C_2H_2$ ice mixture at doses of 5-25 eV/18 amu (0.28-1.4 eV/amu) leads to the formation of vinyl alcohol $CH_2 = CH(OH)$, with saturation setting in by a dose of 0.22 eV/amu [9]. Inside molecular clouds, beyond the boundaries for ice formation, the fluxes are more than an order of magnitude below those in the intercloud medium and are not everywhere capable of providing the doses necessary for formation of complex organic substances. The observational and experimental data confirming the dominant role of irradiation in the formation of complex organic substances in the ice mantles of dust particles have been reviewed elsewhere [6,7]. This paper, as an extension of the earlier work [1], is devoted to calculating the irradiation dose to ices inside molecular clouds by cosmic rays. The irradiation doses produced by radiation fields with photon energies of 6-13.6 are discussed there [1].

2. Cosmic ray fluxes inside clouds

Molecular clouds are interstellar gas-dust clouds and complexes of clouds with densities, sizes, and temperatures in the ranges n~10^2-10^4 cm^{-3}, L~1-30 pc, and T~10-100 K, respectively, and predominant H_2 in the dense segments [6]. Depending on the presence or absence of a star-formation source (sources), molecular clouds are regarded as static or dynamic, with characteristic lifetimes of 50 and 10 million years, respectively [1]. In the latter case, this implies the presence of star formation regions, which, in turn, differ as to the masses of the stars that are formed. In so-called giant molecular clouds a central densification-nucleus with n~10^7 cm^{-3} and L~0.1 pc can exist, along with densifications having $n \geq 10^5$ cm^{-3} and $L \leq 0.0001-0.1$ pc. Clouds associated with star-formation centers also contain young stars with different luminosities [2,6,7]. The dust content does not exceed 1% of the cloud mass. The dust particles, themselves, have silicate or graphite nuclei with sizes d~0.01-0.1 mm and ice mantles with sizes up to several times 0.1 mm containing mainly H_2O, CH_3OH, NH_3, CO, CH_4, and a few other compounds [2].

According to observations and model data, the intensities of galactic cosmic rays follow a power law dependence on the particle energies $1 MeVd \leq E \leq 10 GeV$,

$$I(E) = \frac{CE^{0.3}}{(E + E_0)^3} \frac{\text{particles}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot (\text{Mev/nucl.})}, \tag{5}$$

where $C = 9.42 \cdot 10^4$ is a normalization coefficient and the parameter $E_0 \leq 940$ MeV is chosen for best agreement with the observations [12,13]. A value E_0=300± 100 MeV gives the best fit for observations of protons and α-particles, while the intensities of C and O nuclei in the 10-100 MeV range are consistent with smaller values of E_0. The uncertainty in E_0 affects the soft component (1 MeV-10 GeV) of most importance for the present problem, so that in the following, fluxes [13] with values of E_0 = 200 MeV are used, along with fluxes determined [14] on the basis of recent direct measurements and model calculations of the energy distribution of protons in the neighborhood of the sun, extrapolated to the region outside the heliosphere. The two differential flux spectra $F(E) = \pi \cdot I(E)$ of the galactic cosmic rays with isotropic intensities $I(E)$ are shown in Fig. 1. Here the fluxes for energies of 1-100 MeV [13] are an order or two of magnitude smaller than the values given in Ref. 14, but coincide with it at high energies if the value for the parameter E_0 in Eq. (5) is chosen to E_0 = 200 MeV as given above. This difference can be characterized quantitatively, as usual, by the ratio of the integrated fluxes $F = \int F(E)dE$ (in particles/cm^2/s) and the irradiances $\Phi = \int F(E)EdE$ (in eV/cm^2/s), which are given by $F_C / F_W = 6$ and $\Phi_C / \Phi_W = 1.5$ within this range. (The subscripts C and W refer to the data from Refs. 14 and 13, respectively.) The reason for the difference in the distributions [13,14] is unclear, but appears to be related to a difference in the calibration procedures used for interpreting the data [12,14]. In this paper, both distributions are used in the calculations. Regarding them as

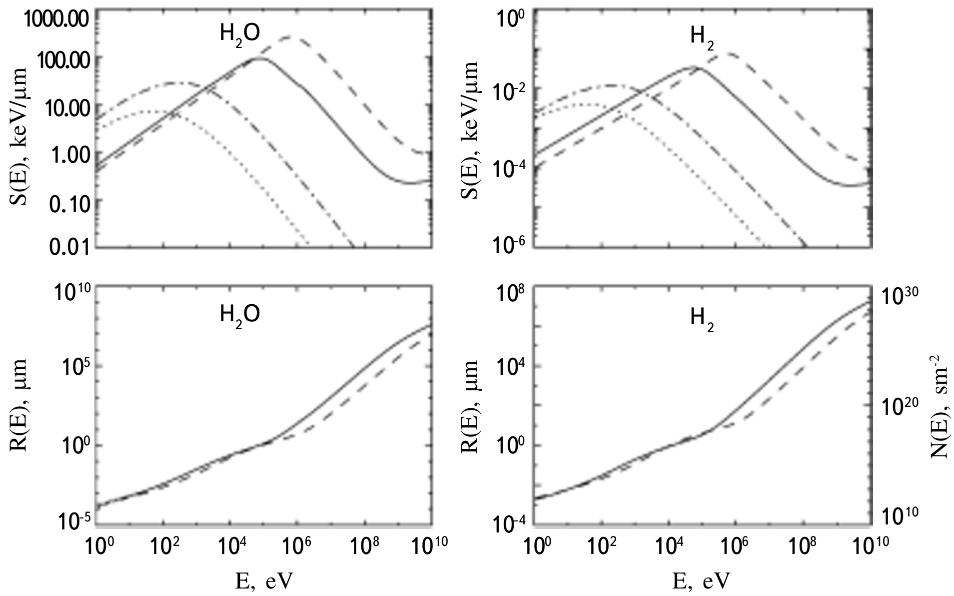

Fig. 2. Stopping power of H_2O (ice) and H_2 (gas) with irradiation by protons and α-particles calculated using the SRIM program. Top: electron stopping power for protons (smooth curves) and α-particles (dashed curves) and the nuclear stopping power for protons (dotted curves) and α-particles (dot-dashed curves). Bottom: mean free paths of protons (smooth curves) and α-particles (dashed curves) in water ice (left) and hydrogen gas (right). The means free paths in the gas at the laboratory density are scaled to the average density of a standard molecular cloud (see text).

characteristic in the neighborhoods of interstellar clouds, we shall consider only the contribution from protons (~90 %), while neglecting α-particles (~10%), as well as heavier nuclei and high-energy electrons, which amount to no more than 0.1% and ~1%, respectively [15]. We take the α-particle contribution into account approximately and directly when estimating the irradiation dose for the ices.

3. Energy losses by ions interacting with a medium

As they pass through the material, the particles lose energies of 1 MeV-10 GeV, mainly through ionization and excitation of the atoms and molecules in the medium. The theory of the interaction is well known [16-18] and here we only discuss the derivation of the needed quantities. A force S (usually measured in keV/mm) acts on a particle, causing specific energy loss per unit path length according to the Bethe-Bloch formula

$$S = -\frac{dE}{dx} = n \cdot f(E), \qquad (6)$$

where E is the energy of a particle moving in the x direction in a medium with density n. The analytic form of the function $f(E)$ is known, but this is not important here since we give results of calculations using the program SRIM

[17] that are somewhat more accurate than the Bethe-Bloch formula. Since the stopping power (slowing-down ability) of the material depends strongly on its density, it is convenient to express the energy losses in terms of the mass stopping power S_M corresponding to the specific energy losses in a layer of absorbing material containing 1 g/cm^2 of material with density ρ,

$$S_M = \frac{1}{\rho} S = -\frac{1}{\rho}\frac{dE}{dx}. \tag{7}$$

Nuclear (S_N) and electron (S_e) stopping powers are distinguished: in the first case a particle loses energy through collisions with the nuclei of target atoms and deviates strongly from its original direction and in the second, it interacts with the electrons of the atoms, leading to ionization with a negligible change in its direction of flight. At the energies of interest to us (≥ 1 MeV), electron slowing-down dominates. (See Fig. 2.) We note, also, that for particle energies greater than a few 100 MeV and, especially, beginning with $E > 1$ GeV, the contribution of nuclear reactions and relativistic radiative corrections (bremsstrahlung and Cerenkov radiation) to the energy loss becomes comparable to the ionization losses, but in the problem of calculating the irradiation doses of interest to us here, these corrections can be neglected since the cosmic ray fluxes in this energy range are several orders of magnitude smaller (Fig. 1), so that its contribution to the irradiation is correspondingly smaller.

The irradiation dose per unit time and per amu, D_r (in units of eV/s/amu) for a given substance can be calculated using Eq. (8) assuming, for simplicity, that the direction of the cosmic ray flux $F(E)$ is perpendicular to a target with stopping power $S(E)$:

$$n_t \cdot D_r = \frac{1}{M}\int_{E_1}^{E_2} S(E)F(E)dE, \tag{8}$$

where n_t is the density of target atoms (cm^{-3}), M is the molecular weight, E_1=1 MeV, and E_2=2 MeV. The contribution to the irradiance $D_r(E)$ by particles with energies in different subbands ($\leq E$) can also be estimated:

$$n_t \cdot D_r(E) = \int_{E_1}^{E} S(E')F(E')dE' \tag{9}$$

The ionization rate ζ (in s^{-1}) mentioned in the *Introduction* can be calculated using the formula

$$\zeta = \int_{E_1}^{E_2} \sigma(E)F(E)dE, \tag{10}$$

where $\sigma(E)$ is the cross section for ionization of molecular hydrogen (cm^2) (see Eq. (14), below). The irradiation dose over time interval t for a constant cosmic ray flux is obviously equal (in eV/amu) to

$$D = D_r \cdot t. \tag{11}$$

For chemical compounds and mixtures, the irradiation dose can be calculated using the Bragg rule [18],

$$D = \frac{\sum D_i k_i M_i}{\sum k_i M_i}, \tag{12}$$

where M_i is the molecular weight of the i-th substance in the mixture with a weighting coefficient k_i and irradiation dose D_i.

The interaction of cosmic rays with matter is also characterized by the maximum range (the thickness of a layer in which all particles in a beam are trapped),

$$P(E_0) = \int_{E_0}^{0} \frac{dE}{[-S(E)]} = \int_{E_0}^{0} \frac{dE}{n \cdot f(E)}, \tag{13}$$

and the mean free path $R < P$ (the thickness of a layer through which the particles will pass on the average), while the product of the thickness of the maximum (average) path and the density of the medium is a constant, i.e., $P \cdot n = \text{const}$ and $R \cdot n = \text{const}$ [16-18]. The maximum range is obviously greater than the mean free path, since as the particle energy is reduced, the contribution of nuclear slowing-down increases, with substantial deflections of the beam from its initial path. This usually occurs at energies on the order of 1-10 keV. From the standpoint of the penetration depth of cosmic rays in an interstellar cloud with a concentration of, say, $n \sim 10^3$ cm^{-3}, it is interesting to note that protons with energies $E \le 1$ MeV (as an example) are characterized by a mean free path between interactions of

$$\lambda \sim [\sigma(1\,\text{MeV}) \cdot n]^{-1} \sim 3 \cdot 10^{13}\,\text{cm}, \tag{14}$$

where the ionization cross section for molecular hydrogen $\sigma(1\,\text{MeV}) \sim 3 \cdot 10^{-17}$ cm^2 [19]. For energies $10\,\text{keVd} \le E \le 1\,\text{MeV}$, s lies between $1.8 \cdot 10^{-16}$ and $3 \cdot 10^{-17}$ cm^2, so that, assuming a maximum energy loss $Q \sim 2 \cdot 10^{-3} E$ in a single interaction event (as implied directly by the conservation of energy and momentum during ionization), on the order of $m \approx 3400$ such collisions will be needed to slow a particle down from 1 MeV to 10 keV; this will correspond to a total maximum path length of $P \sim \lambda \cdot m \sim 10^{17}$ cm. The condition $R \cdot n = \text{const}$ shows that under these conditions the mean free path is also on the order of the maximum, with $R \sim 10^{17}$ cm. (See Fig. 2, which shows the ion mean free paths calculated using the SRIM program in gaseous molecular hydrogen with a density of $n = 5.37 \cdot 10^{19}$ cm^{-3}, rescaled to $n = 10^3$ cm^{-3}.) Note that the theoretically calculated ionization cross sections for molecular hydrogen by protons at energies of 1 MeV-1 GeV with all the possible corrections included [19] are in outstanding agreement with the approximation formulas in the SRIM program [17] (within less than 1%). For 1 GeV-10 GeV, the difference is not as small, on the order of 2-3%. A large amount of experimental data on the irradiation of various substances by protons and heavier ions has been compared with SRIM computations [17]. In every case the difference is at most 5-10%, which confirms the validity of using the results from the SRIM program.

Given the above, it is evident that: (1) galactic cosmic rays with $E < 1$ MeV are completely absorbed in the outer layers of typical molecular clouds with a column density $N \sim R \cdot n \sim 10^{20}$ cm^{-2} of hydrogen atoms (molecules) along the line of sight; (2) particles with energies $E \geq 1$ propagate mostly linearly; and, (3) the energy spectrum of cosmic rays inside clouds changes as a result of interactions with the medium with a redistribution of the particle energies from higher to lower values. The quantitative description of cosmic ray transport at energies $1\,\mathrm{MeVd} \leq E \leq 10\,\mathrm{GeV}$ on the scales of interstellar clouds is greatly simplified because of the absence of sources, the possibility of neglecting diffusion because it is small, and the use of a power-law approximation for the stopping power of the particles; this permits an analytic description with an adequate one-dimensional cloud model. This approach has been used, for example, in Ref. 20, where the conversion of the proton energy spectrum in a protosolar disk is treated in just this way. In that case, for a particle with energy E_1 entering the cloud and ending up with energy E_2 at a distance x from the boundary with $1\,\mathrm{MeVd} \leq E_2 < E_1 \leq 10\,\mathrm{GeV}$, Eq. (7) becomes

$$-\frac{d\varepsilon}{dx} = q_i \cdot \bar{\rho} \cdot \varepsilon^{\alpha}\,, \tag{15}$$

where $\varepsilon = E/1\,\mathrm{MeV}$, $\bar{\rho} = \rho/\left(1\,\mathrm{g/cm^3}\right)$, $\alpha = -0.8$ for all nuclei, and q_i = 640 and 3440 cm^{-1}, calculated by the SRIM computer model [17] for protons and α-particles, respectively (with a threshold energy of 1 MeV), in molecular hydrogen with a density of $8.99 \cdot 10^{-5}$ g/cm^3, given the above mentioned fact that the product of the path length and the density are constant [18]. As a result of energy losses, after crossing a layer with a mass density $N_M = \rho \cdot x$, a particle with energy E_1 slows down to energy E_2 if

$$\varepsilon_2^{1-\alpha} = \varepsilon_1^{1-\alpha} - N_M \cdot q_i (1-\alpha), \tag{16}$$

is positive, or is completely absorbed otherwise. If the incident particles are characterized by a spectrum $F_1(E)$, then the emerging particles have

$$F_2(\varepsilon_2) = F_1(\varepsilon_1) \cdot \left(\frac{\varepsilon_2}{\varepsilon_1}\right)^{-\alpha}, \tag{17}$$

where ε_1 and ε_2 are related by Eq. (16).

4. Computational results and discussion

The variations in the proton flux along the radius of a typical cloud (n~10^3 cm^{-3}) and a densification in a cloud (n~10^6 cm^{-3}) calculated using Eq. (17) are plotted in Figs. 3 and 4, respectively, as functions of the column density $N = n \cdot x$ for both types of proton flux distributions with respect to energy [13,14], with x = 0, 1, 5, 10, 15, and 30 pc. We emphasize that the variations in the particle fluxes depend specifically on N, and not on n or x separately; thus, to avoid repetition, Fig. 4 shows the results for the same values of x as in Fig. 3, but with N up to

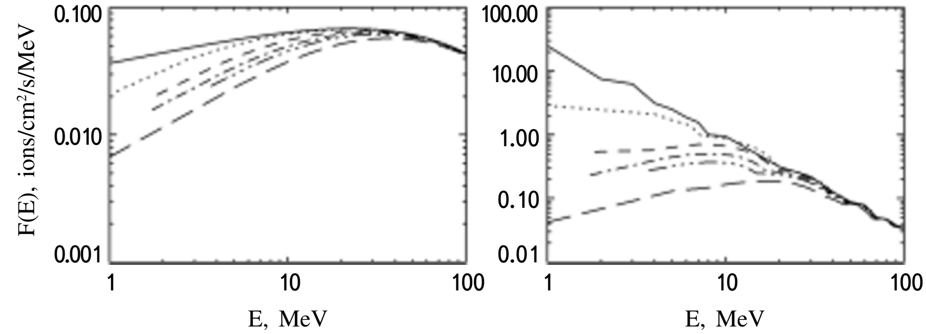

Fig. 3. Differential fluxes of protons inside a molecular cloud with an average density $n = 10^3$ cm^{-3}. The curves (from top to bottom) correspond to distances from the cloud boundary of 0, 1, 5, 10, 15, and 30 pc or column densities of 0, 3, 15, 30, 45, and 90 (in units of 10^{21} cm^{-2}), respectively. Calculations for the distributions of Refs. 12 and 13 are shown on the left and for Ref. 14, on the right.

10^{26} cm^{-2}. Since densifications larger than 0.1 pc do not exist, it is clear that the curves in Fig. 4 (as well as Fig. 6) for $N \geq 10^{23}$ cm^{-2} actually assume a mesh of values of $0 \leq x_i \leq 0.1$ pc with densities exceeding 10^6 cm^{-3}, as $n_i = N_i / x_i$. The irradiation doses to $H_2O : CH_3OH : NH_3 : CO$ ices in the proportion 100:50:1:1 as functions of cloud radius obtained using Eq. (11) and corresponding to accumulation times t = 10 and 50 million years, are plotted in Figs. 5 and 6 for the particle fluxes of Figs. 3 and 4, respectively, multiplied by 2 in order to include the contribution from α-particles. Outside the clouds, the doses for water ice from protons and a-particles calculated using Eqs. (8) and (10) are 1.086±0.1 and 1.091±0.1 eV/amu, respectively, for the cosmic ray flux from Ref. 14 with a helium nucleus content He/H = 0.1. (For the flux from Ref. 13, this gives 0.01793 ± 0.001 and 0.02061 ± 0.001 eV/amu, respectively.) According to calculations with the SRIM program for all the targets over the entire 1 MeV-10 GeV range, the numerical values of the stopping power $S(E)$ for a-particles are roughly an order of magnitude greater than for protons. Thus, instead of doing the cumbersome numerical calculations including α-particles, it is possible simply to multiply the results for protons by a factor of 2 to account approximately for the contribution from the helium

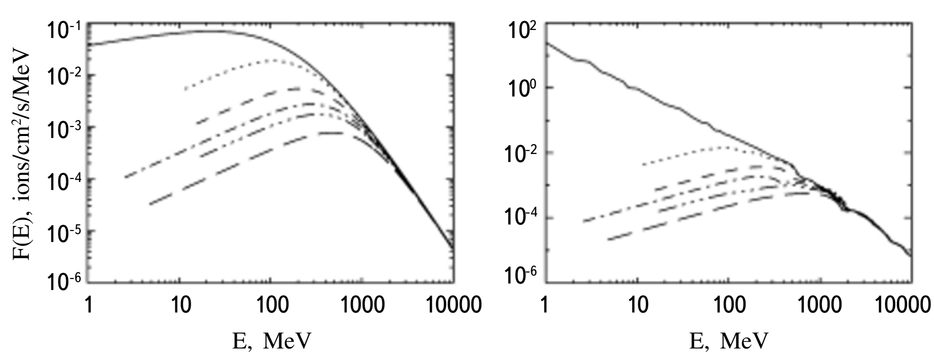

Fig. 4. As in Fig. 3, for the case of a densification inside a molecular cloud with an average density of $n = 10^6$ cm^{-3} with the values of x from Fig. 3, for column densities up to 10^{26} cm^{-2} (see text).

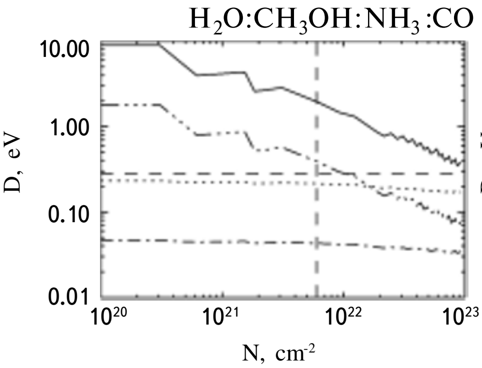

Fig. 5. Absorbed energy doses for a $H_2O:CH_3OH:NH_3:CO$ ice mixture in the proportions 100:50:1:1 from protons and α-particles as functions of the concentration of the cloud along the line of sight (cm^{-2}). The curves (from top to bottom, in pairs) correspond to accumulation times of 50 and 10 million years with the distributions of Ref. 14 (upper two) and Refs. 12 and 13 (lower two). The vertical dashed line indicates the limit for ice formation and the horizontal dashed line, the threshold dose for production of vinyl alcohol (see text).

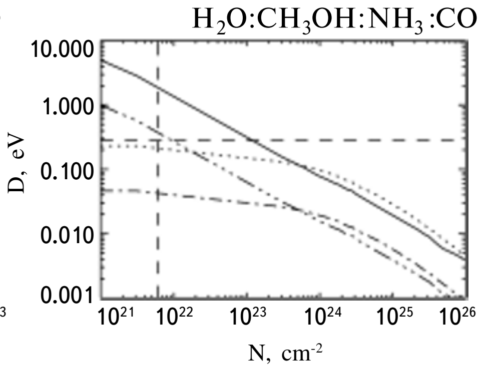

Fig. 6. As in Fig. 5 for a densification with an average density $n = 10^6$ cm^{-3} inside a molecular cloud for the values of x from Fig. 3 and for column densities up to 10^{26} cm^{-2} (see text).

nuclei. In the 1 MeV-10 GeV range the mean free paths of the α-particles are somewhat shorter than those of the protons (Fig. 2), so the flux of the former will fall off somewhat faster. On the other hand, estimates using Eq. (9) show that the main contribution to the integral in Eq. (8) is from low energies, MeV to tens of MeV, where the calculations show that the proton (and α-particle) flux does not fall off (Fig. 3) or even rises (Fig. 4). As a result, the contribution of the α-particles is the same as outside a cloud, i.e., equal to that of the protons, to within 10%.

The doses of the ingredients were also calculated using Eqs. (8) and (11), using functions $S(E)$ obtained from the SRIM program and fluxes $F(E)$ based on Eqs. (16) and (17). The densities of the ices specified in the SRIM program were taken from published data corresponding to measurements at 20-50 K.

An analysis of Figs. 5 and 6 shows that the irradiation doses in regions where ice mantles exist on dust particles are on the order of or less than 0.1-1 eV/amu, which is 1-2 orders of magnitude lower than the doses owing to UV photons [1]. The numerical calculations imply that the doses to the ingredients containing molecules with H, C, N, and O atoms are low and differ from one another within a factor of 1.5, so that, according to Eq. (11) the doses for a mixture will be similar to that for individual compounds. Experimental data on the irradiation of ice mixtures by high energy particles, as noted in the Introduction are qualitatively the same as for UV irradiation: quite complicated compounds are synthesized [2,6,7] but there are no quantitative data on the radiation-chemical yield for many mixtures, including mixtures of the type $H_2O:CH_3OH:NH_3:CO$ [8-11]. There are also no quantitative experimental data on the combined effect of UV and high-energy particle irradiation of ices. Thus, we limit ourselves just to a qualitative comparison of the experimental data from Refs. 8-11 with the theoretical doses plotted in Figs. 5 and 6. As noted above, radiation-chemical conversion occurs at a threshold dose of 0.28 eV/amu during high-energy particle irradiation of an ice mixture, with, for example, the formation of vinyl alcohol. This threshold is indicated by a horizontal dashed line in Figs. 5 and 6. Since the initiation of radiation-chemical transformations by high-energy particles is essentially independent of the type of chemical bonds between the atoms in the target (H, C, N. O), this value of the threshold dose should be fairly general [16-18]. Taking it as a threshold for other mixtures, in particular for a $H_2O:CH_3OH:NH_3:CO$ mixture, we can get an impression of several details of the radiation-chemical transformations in the inner regions of clouds. First, it is clear from Figs. 5 and 6 that the flux of cosmic rays from Ref. 13 is low to the extent that it is incapable of producing doses equal to or above the threshold over cloud lifetimes on the order of 10-50 million years within any part of the cloud. Second, Fig. 5 implies that the flux of cosmic rays from Ref. 14 can produce doses in excess of the threshold beyond the limit for formation of ices in the standard cloud model (n~10^3 cm^{-3}) over a lifetime on the order of 10 million years in regions where the density N along the sight reaches $N = 1.0 \cdot 10^{22}$ cm^{-2}. When no star-formation regions are present, the lifetime of a cloud is on the order of 50 million years and then the dust particles in the cloud receive the required dose. For a dust/gas ratio (in terms of mass) on the order of 0.01, even in the first case we are speaking of the irradiation of a dust mass of several times the mass of the sun. The data of Fig. 6, in turn, show that in densifications with n~10^6 cm^{-3} and R~0.1 pc, a mass of dust on the order of a few times the mass of Jupiter receives a dose in excess of the threshold over a time of ~10 million years, and on the order of several tens of times the mass of Jupiter over a time of ~50 million years. To avoid misunderstandings, we emphasize that here we are not speaking of densifications subject to collapse in the presence of the Jeans instability: in those case the irradiation time obviously cannot exceed the characteristic Jeans time of order 1 million years or less. The existence of densifications that are in equilibrium is a reliably established observational fact [2,6]. Third, if the fluxes of Ref. 13 do not provide, but those of Ref. 14 do, provide the irradiation doses required for radiation-chemical transformations in molecular clouds, then we may ask, "which is closer to an actual distribution?" Unfortunately, observational data on the amounts of radiolysis products do not provide a direct answer to this question, since the same vinyl alcohol [9], for example, is formed in the laboratory by photolysis and by radiolysis. The sole exception is azide, the N_3 radical, which is formed only by radiolysis of solid N_2 [21] but has not yet been observed in molecular clouds. Only observations of the infrared absorption lines of H_3^+, as noted above, will help in directly evaluating the flux of soft cosmic rays inside clouds, since the abundance of H_3^+ is directly related to the rate ζ of ionization of molecular hydrogen by energetic particles (Eq. (10)). The next paper in this series will be devoted to the theoretical calculation of the rate of ionization inside clouds and a comparison with available observations. Fourth, besides its dependence on the cosmic ray flux, the combined effect of UV radiation and cosmic rays on ice should always be taken into account, at least in those regions of a cloud which can be reached by 6-13 eV UV photons in amounts sufficient to provide an irradiation dose high enough for radiation-chemical transformations [1]. In fact, as opposed to the interaction of a UV photon with a target molecule or atom, which can be characterized as a single quantum process, particles with energies on the order of 1 MeV or more generate nonthermal electrons and atoms in cascade processes that ultimately lead to the formation of a great number of radicals (on the order of 10^5) and a readjustment of chemical bonds, thereby significantly affecting the parallel processes owing to photolysis [22]. From Fig. 2 it can be seen for the case of water ice that the mean free path of an ion with an energy of 1 MeV or more is much longer than the size of the average dust particle in a cloud, d~0.1 mm. The time between successive collisions of a given dust particle with high-energy cosmic ray particles with an integrated flux F can be estimated using the formula

$$\tau = \frac{1}{\pi d^2 F}, \qquad (18)$$

and the changes in this time inside the cloud can be followed for the two distributions [13,14]. It is easy to see that in either case this time does not exceed a few years in the cloud on the average, even in densifications up to $N = 1.0 \cdot 10^{23}$ cm^{-2}, i.e., in regions where 6-13 eV UV photons still penetrate. Clearly, both processes must be simultaneously taken into account in these cases. Despite all the technical difficulties of conducting combined experiments on the irradiation of ices, the quantitative characteristics of these kinds of processes are vital to a correct interpretation of the observations.

Here we have not considered the role of magnetic fields which may affect the transport of cosmic rays inside dense molecular clouds, since such an effect depends significantly on the geometry of the cloud magnetic field and on its strength [23], the former characteristic being unknown for almost all clouds and the latter known only as an average for a few clouds. If a magnetic field could have an effect on the cosmic ray flux inside a cloud, then, according to Eq. (10), the ionization rate should also change; a good indicator of this is the concentrations of H_3^+ and some other molecules obtained in detailed astrochemical calculations. If observational data from particular clouds are available for these molecules, then the additional effect of magnetic fields on the transport of cosmic rays should be modelled for the interiors of these clouds. This kind of analysis will be done for several clouds in a later article.

5. Conclusion

Fluxes of the soft component (1 MeV-10 GeV) of cosmic rays inside molecular clouds and in densifications within them have been calculated in this paper. It has been shown that cosmic rays with the energy distributions of Refs. 112-14 are capable of providing an irradiation dose on the order of 0.1-1 eV/amu to the ice mantles of dust particles in clouds over cloud lifetimes on the order of 10-50 million years. The masses of irradiated dust are on the order of a few solar masses in a model for a standard cloud, and a few times the mass of Jupiter or more in densifications. A $H_2O:CH_3OH:NH_3:CO$ mixture in the proportion 100:50:1:1, which is regarded as a good analog of the ice coatings on dust particles in clouds and forms very complex compounds under UV irradiation, has been taken as a typical mantle composition. The yields of the products of combined photo- and radiolysis of a mixture of ices are now known, but would be extremely useful for quantitative interpretation of model calculations of irradiation doses. It is certain, however, that product compounds similar to the amino acids [1] and hydrocarbon oligomers containing more than 20 carbon atoms [2] could play an important role in the prebiological evolution of matter.

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