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Theoretical investigation of cosmic ray processing of solar system ices

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Abstract. Space ices containing water, carbon- and nitrogen-rich structures are important in certain chemical and radiation induced processes in Solar System dust systems. Up to now there are no detailed investigations on an energetic particle processing of various ices by ions and electrons, modeling the cosmic ray irradiation over the whole energy range from eV to GeV. Our studies on the ion induced conversion of ices include an examination of the linear energy transfer due to stopping processes, by which the input projectile loses its original energy to particles in the target. This deposited energy rate has been calculated for various species and for different cosmic ray spectra inside and outside of the heliosphere. The results can be used to predict a radiation induced chemical conversion rate of simple chemical species to complex ones by means of forthcoming experimental data.

1 Introduction

Predicted long ago to be present on far-away bodies and recently shown by observations to be ubiquitous in the Solar System, ices in a broad sense have become an extremely important subject in planetary research. Ices found on objects formed in the remote parts of the Solar System contain information about the composition and details of formation of our planetary system. There are also objects that contain icy materials that bear signatures of past events on a very long timescale (Hudson and Moore, 2001). An important point regarding the comparison of UV- versus ion-irradiation has been studied and compared to those effects known to occur in interstellar and Solar System ices by Gerakines et al. (2001) and Baratta et al. (2002).

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There is a lack of detailed investigations on an energetic particle processing of various ices modeling the cosmic ray irradiation over the whole energy range from eV to GeV (Cooper et al., 2003).

In this paper we study the ion induced alteration of Solar System ices by examining the linear energy transfer due to stopping processes, where the input projectile loses its original energy to particles in the target. This deposited energy rate per unit length over the wide energy range (eV-GeV) for various species has been calculated using the ion impact computer code SRIM (Ziegler et al., 2003). The results will be used to predict the radiation induced chemical conversion rate of some ices, including simple and complex hydrocarbons, by means of forthcoming experimental data.

2 Dosages for relevant time-scales

Cosmic rays (CR) and the solar radiation have altered the chemical composition of ices on objects in the Kuiper Belt (KBO) and the Oort Cloud (OC), so that what we observe today is the product of a complex interaction of UV-photo- and energetic particle induced chemistries and internal processes. On the surfaces of KBO the UV irradiance is dominant, greater than that of from cosmic rays by many orders of magnitude, while cosmic ray induced radiation chemical alteration dominates in deeper layers of ices and should be necessarily considered in addition to the UV radiation effects. Modeling the interaction of energetic particles with ices in the Solar System requires basic information about their fluxes over the wide energy range from eV to GeV. Recently Cooper et al. (2003) have published summary observational and model data of solar (SCR), anomalous (ACR) and galactic (GCR) CR inside the heliosphere (at 40 AU and 85 AU) and outside of it. Data sources were available from operational interplanetary spacecraft to construct the composite of proton flux spectra at plasma to cosmic ray ener-

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Table 1. Dosage rates D_r (eV/s) and dosages D (eV) for species at 40 AU on surfaces of KBOs and at 10 000 AU on surfaces of comets of the OC. The values for equivalent 16 amu are presented.

Specie	Dosage Rate, D_r, KBO	Dosage, D, t=1 Ma, KBO	Dosage Rate, D_r, OC	Dosage, D, t=1 Ma, OC
	eV/s, 10^{-12}	eV, 10^2	eV/s, 10^{-12}	eV, 10^1
CH_4	5.49	1.73	2.74	8.65
C_2H_6	5.71	1.80	2.71	8.55
C_2H_2	7.16	2.26	2.60	8.21
C_2H_4	6.27	1.98	2.68	8.47
C, graphite	9.58	3.02	2.32	7.32
H_2O	5.45	1.72	2.52	7.94
CO	8.90	2.81	2.15	6.79
CO_2	8.68	2.74	2.10	6.62
NH_3	5.53	1.74	2.66	8.41
N_2	9.19	2.90	2.19	6.93

gies, along with low and high limits on suprathermal fluxes in between these energy regimes. We have chosen their low suprathermal limit model curves. A decrease of the SCR flux level between keV and GeV energies is caused by the solar wind modulation, preventing the low energy particles of GCR to be entered into the heliosphere. A sharp maximum at a few keV corresponds to the solar wind protons, flowing upward with an average velocity of 450 km/s in the ecliptic plane. We will use these data to model irradiation of some KBOs and OC comets, located at distances 40 AU and 10 000 AU, respectively.

When energetic ions enter into a medium they immediately start to interact with it and lose their kinetic energy (see Ziegler et al., 2003, where all the details regarding the stopping can be found). Knowing the stopping power of a substance for energetic ions is necessary for describing the penetration of these particles through matter and the calculation of dosages under different environment conditions and over relevant astrophysical time-scales. Linear stopping powers of 10 astrophysically important ice analogs for proton irradiation have been calculated by means of SRIM code (Ziegler et al., 2003). Densities at corresponding temperatures have been compiled from various sources: as is known, stoppings are scaled linearly to the density. Results are nearly equal for all of the species: the highest value (graphite, due to the largest density) and the lowest one (CO, which has only two atoms) differ by less than a factor of 3. To calculate a dosage rate (D_r) one needs to convolute the energy dependent stoppings $S(E)$ with the (interpolated) values of the corresponding cosmic ray fluxes $F(E)$ (we assume here, for simplicity, that fluxes are normal to targets):

$$N \cdot D_r = \int_{E_1}^{E_2} S(E)F(E)dE, \quad (1)$$

where D_r is in units eV/s, N is a concentration of the target's atoms (cm^{-3}) and E_1 and E_2 are equal to 10^0 eV and 10^{10} eV, respectively. The units of $S(E)$ and $F(E)$ are eV/micron and particle $\cdot\, \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{eV}^{-1}$, respectively. It should be stressed that electronic stoppings of heavy ions begin to increase more than by one order of magnitude at 1 MeV and higher. The maximum values of both kinds of stoppings (electronic and nuclear) for heavy ions are shifted to larger energies as compared to that of for hydrogen. Total dosage rates D_r and accumulated dosages $D = D_r \cdot t$ in various species during irradiation times t of 1 million years (Ma), are presented in Table 1.

3 Astrophysical implications in short

A difference between the dosage rates is no larger than a factor of 2 (a factor of 4 for some other species, see Table 1), that is there is no a strong radial dependence of dosages in the Solar System. It should be stressed here that the larger dosage rate on the KBOs surfaces as compared with that of for the OC is just a result of our conservative choice of the low suprathermal limit in the low energy spectra, otherwise a reversal relation is valid (see for details Cooper et al., 2003, their Fig. 5). The same is true and for all other species and for contributions by electronic and nuclear stoppings, respectively. In particular, the maximum contribution to the dosage rate on the surfaces of comets in the OC is caused by the elastic nuclear collisions due to the fact that in this case the local maximum at 1 keV of the spectral flux is absent.

The dosages presented in Table 1 are high enough to initiate chemical changes of all species. To be more correct a few million years of irradiation is able to convert, say, a significant fraction of methane in the KBO and in the OC into heavy hydrocarbons. For example, polycyclic aromatic hydrocarbons and aliphatic hydrocarbons (alkanes, alkenes), have been synthesized in prebiotic simulation experiments (Kaiser and Roessler, 1998, and references therein). A radiation chemical yield of the synthesized alkane molecules (up to 28 carbon atoms) has been estimated as $G \sim 1$ molecule/100 eV (Yeghikyan et al., 2001, and references therein). Then the fraction of initial methane Q to be converted to the mentioned oligomer is equal to $Q = G \cdot D$ and close to 1 in only 1 Ma of irradiation. In fact, various matrices where methane can be frozen may either inhibit (H_2O) or catalyze (CO and CO_2) the growth of polymer chains (Ivanov, 1992). New experimental data are necessary to reveal the details of such processes. In any case it is well known that complex organics on the surfaces of KBOs may be responsible for their photometric data (Luu and Jewitt, 2002; Cooper et al., 2003). These authors discuss to what extent initially light icy species can be reddened by the ion irradiation and a resurfacing by collisions during KBOs evolution. In particular, Cooper et al. (2003) have noted an important contribution of ACR, dominated at keV energies and which radial variation might account for the KBOs color diversity. One may suggest an additional process needs to be taken into account in this problem, namely a considerable change of energetic particle spectra at KBOs during frequent passages of the Solar System through relatively dense interstellar clouds (Fahr et al., 2006, and references therein). The number of encounters has been estimated as 135 and 16 traversings of clouds denser than 10 cm^{-3} and 10^3 cm^{-3}, respectively. A cross-over time for an usual diffuse cloud ($n_c > 10\,cm^{-3}$) of 10 pc with a $v = 20$ km/s relative velocity is about 0.5 Ma (much larger than the orbital time of a KBO about of a few 1000 years at a usual distance of a few 100 AU). This means that during that time there would be no solar wind protons, ACR particles upstream, or modulated GCR particles at KBOs surfaces upstream, i.e. along the direction of the Solar System motion. Instead, a spectrum of cosmic rays with $E > 1$ MeV exists, which is usual for interiors of interstellar clouds. All of the KBOs are located in this upstream case outside of the compressed heliosphere. Because the GCR spectrum at MeV energies inside the diffuse clouds is a few ten times larger (McCall et al., 2003) this means first, that the dosage rate may be of the same order as compared with that of the OC, and second, deeper layers can be processed. More important is that the irradiance at 1 keV – 1 MeV in the downstream region is by two orders of magnitudes higher, due to the increased flux of ACR, which is linearly scaled with the cloud number density n_c (Fahr et al., 2006). Thus one can draw a conclusion that during the total 50 Ma pass-over time through the more than 100 diffuse clouds, the KBO surfaces have accumulated dosages of the same order or even more than in the other 99% of their lifetime. Furthermore, the encounters with a few molecular clouds ($n_c \geq 10^3\,cm^{-3}$, $v = 5 - 10$ km/s) might have had the same total effect during even one passage provided that KBOs could cross the mentioned downstream region (heliotail). The case is that orientation of the heliotail in turn depends on the angle between the ecliptic plane and an incoming cloud's velocity vector. This may cause some discrimination between different populations of the KBOs: depending on their own spatial distribution the time-scale of the accumulated dosages may be essentially different as compared to a collissionally induced resurfacing time (Luu and Jewitt, 2002) with the result of the observed color diversity. An observed correlation between inclination and color in the classical Kuiper Belt (Trujillo and Brown, 2002) probably reflects records of such events. A quantitative description of such a model will be presented separately.

4 Conclusions

Whether the ices exist as surface layers, that are subjected to modification processes such as the cosmic ray and UV irradiation, solar heating or meteoritic impact, or are buried masses, ice-rich regions of the KBO can form very different repositories of material. Similarly, analysis of the ice-enriched subsurface of an active comet provides clues about the formation histories of such bodies and their subsequent evolution. Information on the primary dosage modes of solid icy species following the absorption of radiation is very important from the astrophysical point of view. It can be revealed by examining the stopping of energetic protons under conditions directly applicable to environments associated with surfaces of KBOs and comets in the Oort Cloud. We have calculated the energy loss of protons in 10 species by SRIM code (Ziegler et al., 2003). The resulting energy dependent stoppings are convoluted with the cosmic ray spectral fluxes (inside and outside of the heliosphere) adopted from Cooper et al. (2003), to get the values of final interest, the dosage rates and dosages. Calculated dosages show that the energies absorbed by species on the surfaces of the Solar System bodies like KBOs and comets during 1 Ma or more may be significant and initiate drastic changes in their structure and composition. The contribution of GCRs to the dosage inside of the heliosphere is negligible, excluding specific cases of the encountered dense interstellar clouds. In this case the different groups of KBOs depending on their spatial distribution, might have received different dosages, which may cause the different reddening of their surfaces, in addition to other possible mechanisms, discussed in the literature. Such studies on the proton irradiation of species with the details of the absorbed energy accumulation in the different classes of compounds, followed by possible chemical reactions, are necessary to enhance the ability to predict the radiation chemical conversions on the icy surfaces of the outer Solar System bodies.

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