Dorman L.I.

CR and other space climate factors influenced on the Earth's climate change

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Prof. Lev I. Dorman, Head of Israel Cosmic Ray and Space Weather Center, Institute of Advanced Study of Tel Aviv University and Israel Space Agency, Chief Scientist of Cosmic Ray Department of N.V. Pushkov IZMIRAN, Russian Academy of Science (Troitsk, Russia)
E-mail: lid@physics.technion.ac.il

It is obviously now that according to data for the past on big variations of planetary surface temperature in scales of many millions and thousands years the Earth's global climate change is determined mostly by space factors: moving of the Solar system around the center of our Galaxy with crossing galactic arms and dust-molecular clouds, nearby supernova and supernova remnants. Important space factor is also the cyclic variations of solar activity and solar wind (mostly in scales of hundreds years and decades). The action of space factors on the Earth's climate is realized mostly through cosmic rays (CR) and space dust influenced on formation of clouds controlled the total energy input from the Sun into the Earth's atmosphere. The propagation and modulation of galactic CR (generated mostly during Supernova explosions and in Supernova remnants in our Galaxy), in the Heliosphere are determined by their interactions with magnetic fields frozen in solar wind and in coronal mass ejections (CME) with accompanied interplanetary shock waves (produced big magnetic storms during their interactions with the Earth's magnetosphere). The most difficult problem of monitoring and forecasting the modulation of galactic CR in the Heliosphere is that the CR intensity in some 4D space-time point is determined not by the level of solar activity at this time of observations and electro-magnetic conditions in this 4D-point but by electromagnetic conditions in total Heliosphere. These conditions in total Heliosphere are determined by development of solar activity during many months before the time-point of observations. It is main cause of so called hysteresis phenomenon in connection galactic CR — solar activity. From other hand, detail investigations of this phenomenon give important possibility to estimate conditions in and dimension of Heliosphere. To solve described above problem of CR modulation in the Heliosphere, we considered as the first step behavior of high energy particles (more than several GeV, for which the diffusion time of propagation in Heliosphere is very small in comparison with characteristic time of modulation) on the basis of neutron monitor data in the frame of convection diffusion theory, and then take into account drift effects. For small energy galactic CR detected on satellites and space probes we need to take into account also additional time lag caused by diffusion in the Heliosphere. Then we consider the problem of CR modulation forecasting for several months and years ahead, what gives possibility to forecast some part of global climate change caused by CR.

Keywords: galactic cosmic rays (CR); Earth's climate; solar activity level; Maunder minimum; magnetic field of the Earth; climate factors (cloudiness, raining, surface temperature).

1. Introduction

It is now obvious, according to past data on large variations in planetary surface temperature over timescales of many thousands (even millions) of years, that the Earth's global climate change is determined not only by internal factors but also by factors originating in space. These include the moving of the solar system around the center of our galaxy, thus crossing galactic arms, clouds of molecular dust, nearby supernovae and supernova remnants. Another important space factor is the cyclic variations of solar activity and the solar wind (mostly on the scales of decades and hundreds of years). The space factors which influence Earth's climate most, however, are cosmic rays (CR) and space dust, which influence the formation of clouds and therefore control the total energy transferred from the Sun to the Earth's atmosphere. The propagation and modulation of galactic CR (generated mostly during supernova explosions and in supernova remnants in our galaxy) is determined within the heliosphere by their interaction with magnetic fields frozen in the solar wind and in coronal mass ejections (CME) with accompanying interplanetary shock waves (that produce big magnetic storms during their interactions with the Earth's magnetosphere). The most difficult problem of monitoring and forecasting the modulation of galactic CR in the heliosphere is that the CR intensity at some 4D point in space-time is determined not only by the level of solar activity at the time of the observations or the electromagnetic conditions at this point, but rather, by the electromagnetic conditions in the total Heliosphere. These conditions in the total heliosphere are determined by the development of solar activity during many months leading up to the time-point of observations. This is the cause of the so-called hysteresis phenomenon in connecting galactic CR and solar activity. On the other hand, detailed investigations of this phenomenon yield the important possibility to estimate conditions in and the dimensions of the heliosphere. To solve the problem described above of CR modulation in the heliosphere, we considered as the first step the behavior of high energy particles (more than several GeV, for which the diffusion time of propagation in the heliosphere is very small in comparison with the characteristic time of modulation) on the basis of neutron monitor data in the frame of convection diffusion theory. We then take into account drift effects. For low energy galactic CR detected on satellites and space probes, we also need to take into account the additional time lag caused by diffusion in the heliosphere. Then, we consider the problem of CR modulation forecasting for several months and years ahead, which gives the possibility to forecast some part of the global climate change caused by CR.

2. Solar activity and CR variations as possible causes of climate change

The solar activity level is known from direct observations over the past 450 years and from data of cosmogenic nuclides (through CR intensity variations) for more than 10,000 years (see details in Chapters 10 and 17 in *[Dorman M2004]*). Over this period there is a striking qualitative correlation between cold and warm climate periods and high and low levels of galactic CR intensity, correspondingly (low and high solar activity). As an example, **Fig. 1** shows the change in the concentration of radiocarbon ^{14}C during the last millennium (a higher concentration of radiocarbon corresponds to a higher intensity of galactic CR and to lower solar activity).

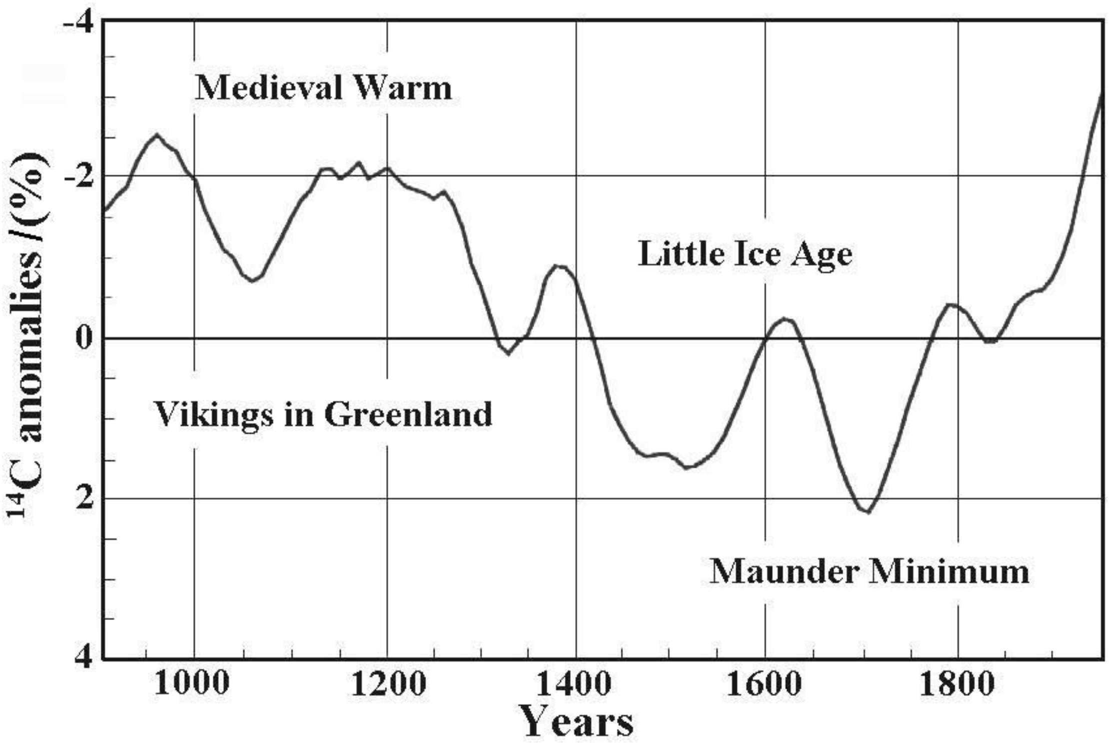

Figure 1. The change of CR intensity reflected in radiocarbon concentration during the last millennium. The Maunder minimum refers to the period 1645—1715, when number of sunspots was very small. According to *[Svensmark 2000]*.

It can be seen from **Fig. 1** that during 1000—1300 the CR intensity was low and solar activity high, which coincided with the warm medieval period (during this period Vikings settled in Greenland). After 1300 solar activity decreased and CR intensity increased, and a long cold period followed (the so called Little Ice Age, which included the Maunder minimum 1645—1715 and lasted until the middle of 19th century).

3. The possible role of solar activity and solar irradiance in climate change

Friis-Christensen and Lassen found *[Friis-Christensen and Lassen 1991; Lassen and Friis-Christensen 1995]*, from four hundred years of data, that the filtered solar activity cycle length is closely connected to variations of the average surface temperature in the northern hemisphere. Labitzke and Van Loon showed *[Labitzke and Van Loon 1993]*, from solar cycle data, that the air temperature increases with increasing levels of solar activity. Svensmark *[Svensmark 2000]* and Shapiro et al. *[Shapiro et al. 2011]* also discussed the problem of the possible influence of solar activity on the Earth's climate through changes in solar irradiance. But the direct satellite measurements of the solar irradiance during the last two solar cycles showed that the variations during a solar cycle was only about 0.1%, corresponding to about 0.3 W/m^2. This value is too small to explain the observed climate changes during solar cycles *[Lean et al. 1995]*. The reconstruction of solar irradiance from 7000 BC up to 500 AD shows variations from 1358 up to 1370 W/m^2, i.e. not more than 1% *[Shapiro et al. 2011]*. Much bigger changes during a solar cycle occur in UV radiation: according to Shapiro et al. *[Shapiro et al. 2011]*, the flux of solar irradiation during 1600—2000 in interval 500—600 nm varied in limits of 0.4%, in 370—400 nm (CN violet system) — 3.2%, in 200—242 nm (Herzberg continuum) — 10.9%, and in 175—200 nm (Schumann-Runge bands) — 26.6% (these changes are important for variations in formation of the ozone layer). Haigh *[Haigh 1996]*, and Shindell et al. *[Shindell et al. 1999]* suggested that the heating of the stratosphere by UV radiation can be dynamically transported into the troposphere. This effect might be responsible for small contributions towards 11 and 22 years cycle modulation of climate but not to the 100 years or more of climate changes that were observed in the past and during the last hundred years *[Dobrica et al. 2009]*. Hong et al. *[Hong et al. 2011]* examined the effect of the 11-year solar cycle and quasi-biennial oscillation on the 27-day solar rotational period detected in tropical convective cloud activity (it was analyzed data of outgoing long wave radiation for 1979—2004).

4. Cosmic rays as an important link between solar activity and climate change

Many authors have considered the influence of galactic and solar CR on the Earth's climate. Cosmic radiation is the main source of air ionization below 40—35 km (only near the ground level, lower than 1 km, are radioactive gases from the soil also important in air ionization — see review in *[Dorman M2004]*). The first who suggest a possible influence of air ionization by CR on the climate was Ney *[Ney 1959]*. Svensmark *[Svensmark 2000]* noted that the variation in air ionization caused by CR could potentially influence the optical transparency of the atmosphere, by either a change in aerosol formation or influence the transition between the different phases of water. Many authors considered these possibilities *[Dickinson 1975; Pudovkin and Raspopov 1992; Pudovkin and Veretenenko 1995, 1996; Belov et al. 2005; Dorman 2005a,b, 2006, 2007]*. The possible statistical connections between the solar activity cycle and the corresponding long term CR intensity variations with characteristics of climate change were considered in *[Dorman et al. 1987, 1988a,b]*. Dorman et al. *[Dorman et al. 1997]* reconstructed CR intensity variations over the last four hundred years on the basis of solar activity data, and compared the results with radiocarbon data.

Cosmic rays play a key role in the formation of thunder-storms and lightnings (see extended review in *[Dorman M2004]*, Chapter 11). Many authors *[Markson, 1978; Price, 2000; Tinsley, 2000; Schlegel et al., 2001; Dorman and Dorman, 2005; Dorman et al., 2003]* have considered atmospheric electric field phenomena as a possible link between solar activity and the Earth's climate. Barnard et al. *[Barnard et al. 2011]* used data on cosmogenic nucleus in ice for about 9300 years for investigation of great solar energetic particle events and long-time galactic cosmic ray variations for research of space climate in the past and possible predictions for some time ahead. The obtained important information can be used for investigation of the link between cosmic ray intensity and the Earth's climate change. Also important in the relationship between CR and climate, is the influence of long term changes in the geomagnetic field on CR intensity through the changes of cutoff rigidity (see review in *[Dorman M2009]*). It can be considering the general hierarchical relationship: (solar activity cycles + long-term changes in the geomagnetic field) → (CR long term modulation in the Heliosphere + long term variation of cutoff rigidity) → (long term variation of clouds covering and aerosols + atmospheric electric field effects) → climate change.

5. The Connection between galactic CR solar cycles and the Earth's cloud coverage

Recent research has shown that the Earth's cloud coverage (observed by satellites) is strongly influenced by CR intensity *[Svensmark 2000; Marsh and Svensmark 2000a,b]*. Clouds influence the irradiative properties of the atmosphere by both cooling through reflection of incoming short wave solar radiation, and heating through trapping of outgoing long wave radiation (the greenhouse effect). The overall result depends largely on the height of the clouds. According to *[Hartmann 1993]*, high optically thin clouds tend to heat while low optically thick clouds tend to cool (see **Table 1**). According to *[Smith at al. 2011]*, the Clouds and Earth Radiant Energy System (CERES) project's objectives are to measure the reflected solar radiance (shortwave) and Earth-emitted (longwave) radiances and from these measurements to compute the shortwave and longwave radiation fluxes at the top of the atmosphere and the surface and radiation divergence within the atmosphere. Connection of CR intensity global variation with the Earth cloud covering is illustrated by **Fig. 2**, and separately with different types of clouds — by **Fig. 3**.

Table 1

Global annual mean forcing due to various types of clouds, from the Earth Radiation Budget Experiment (ERBE),
according to *[Hartmann 1993]*

The positive forcing increases the net radiation budget of the Earth and leads to a warming; negative forcing decreases the net radiation and causes a cooling. (Note that the global fraction implies that 36.7% of the Earth is cloud free.)

Parameter	High clouds		Middle clouds		Low clouds	Total
	Thin	Thick	Thin	Thick	All	
Global fraction /(%)	10.1	8.6	10.7	7.3	26.6	63.3
Forcing (relative to clear sky):						
Albedo (SW radiation)/(Wm^{-2})	-4.1	-15.6	-3.7	-9.9	-20.2	-53.5
Outgoing LW radiation /(Wm^{-2})	6.5	8.6	4.8	2.4	3.5	25.8
Net forcing /(Wm^{-2})	2.4	-7.0	1.1	-7.5	-16.7	-27.7

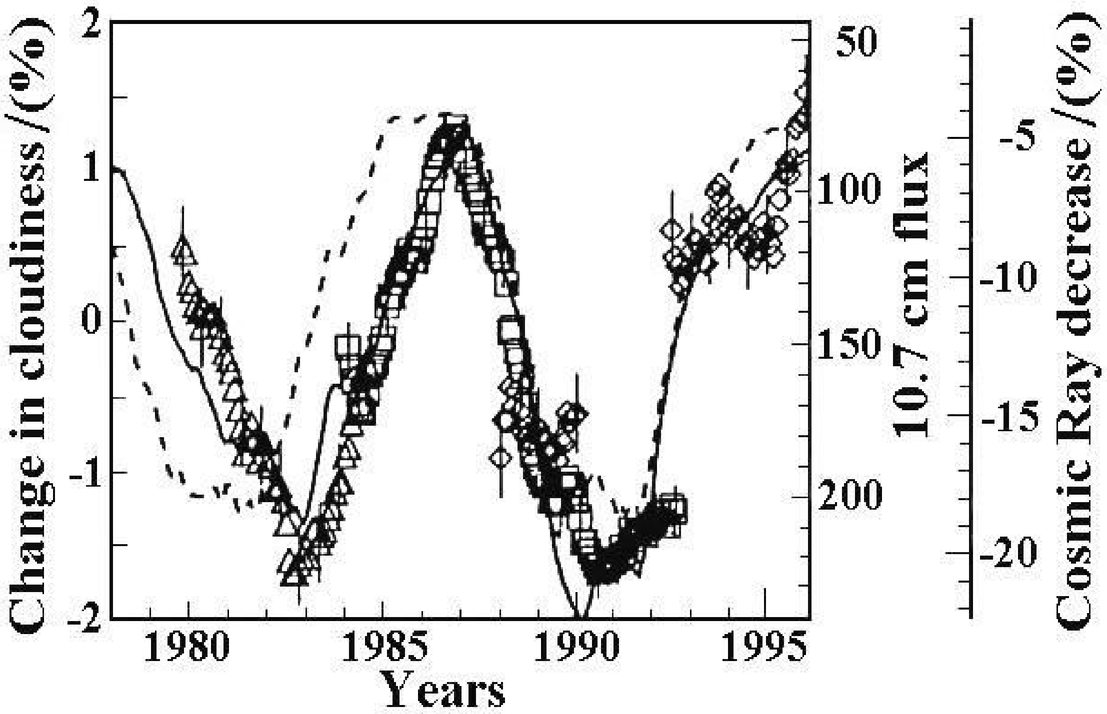

Figure 2. Changes in the Earth's cloud coverage: triangles — from satellite Nimbus 7); squares — from the International Satellite Cloud Climatology Project); diamonds — from the Defense Meteoroloical Satellite Program). Solid curve — CR intensity variation according to Climax neutron monitor, normalized to May 1965. Broken curve — solar radio flux at 10.7 cm. All data are smoothed using twelve months running mean. According to *[Svensmark 2000]*.

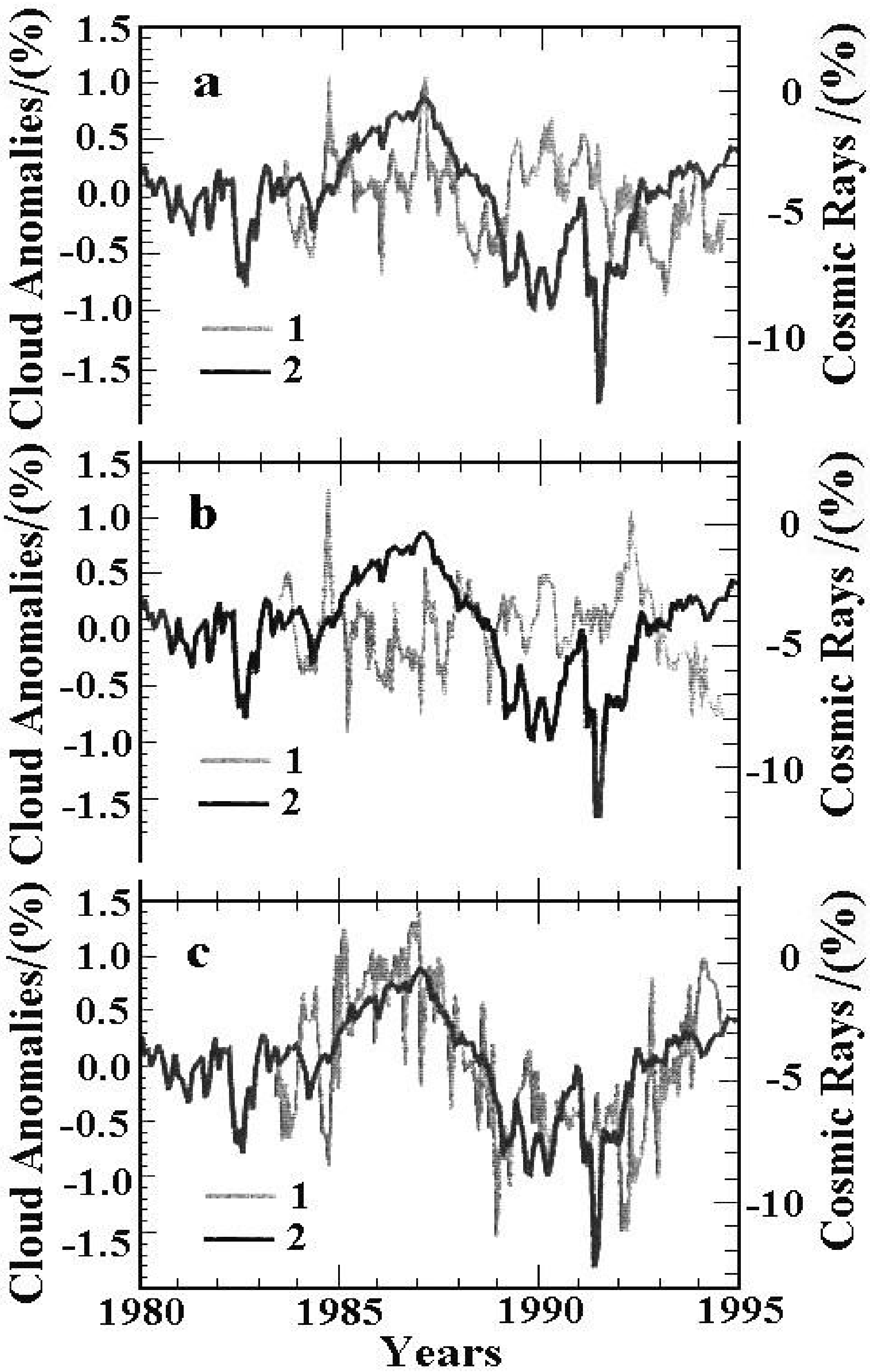

Figure 3. CR intensity obtained at the Huancayo/Haleakala neutron monitor (normalized to October 1965, curve 2) in comparison with global average monthly cloud coverage anomalies (curves 1) at heights, H, for: **a** — high clouds, H > 6.5 km, **b** — middle clouds, 6.5 km >H > 3.2 km, and **c** — low clouds, H < 3.2 km. According to *[Marsh and Svensmark 2000]*.

From **Fig. 2** it can be seen that variation in cloudiness corresponds very well to variation in CR without any time lag, and the decreasing of CR intensity in Climax neutron monitor on 15% corresponds decreasing in cloudiness on about 3% (positive correlation). From other hand, from **Table 1** we can see that the total cloudiness gives input of solar energy — 27.7 W/m^2, so 3% decreasing of cloudiness will give about + 1 W/m^2.

From **Fig. 3** it can be seen that practically is no connection between CR intensity variations and changes in cloudiness for high and middle altitude clouds (panels **a** and **b**), but is a high positive correlation for low altitude clouds (panel **c**).

6. On connection of CR variation with surface planetary temperature during the last thousand years and during 1935—1995

From Section 4 it follows that with CR intensity decreasing, planetary cloudiness decreases leading to increase of solar energy input in the low atmosphere and increase of planetary surface temperature. This can be demonstrated by data of radiocarbon for the last thousand years (see **Fig. 1**) and by direct CR measurements for about 60 years from 1935 to 1995 (see **Fig. 4**).

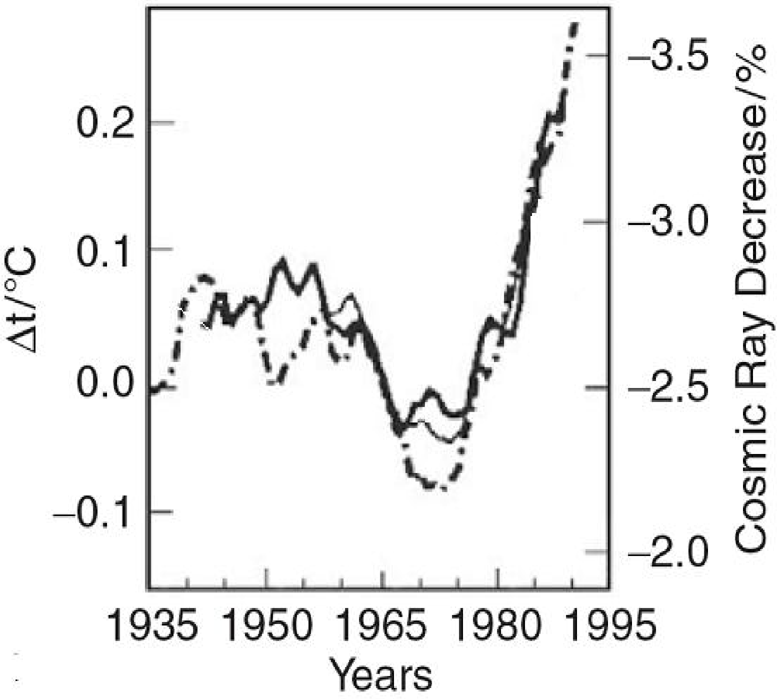

Figure 4. Eleven year average Northern hemisphere marine and land air temperature variation Δt (broken curve), compared with eleven year average CR intensity (thick solid curve — from data of Compton type ionization chambers shielded by 10 cm Pb (1937—1994, normalized to 1965), and thin solid curve — from Climax neutron monitor (normalized to ion chambers, 1953—1994). According to *[Svensmark 2000]*.

7. Solar irradiance and cosmic ray fluxes during Maunder minimum: influence on climate change

During the Maunder minimum the CR intensity was very high, so the planetary surface temperature is expected to be lower than in years with high level of solar activity. As was shown above (see **Fig. 1**), exactly this was observed by using ^{14}C data. More detail data on solar irradiation flux, CR intensity (through ^{10}Be), and the air surface temperature are shown in **Fig. 5**. From **Fig. 5** can be clear seen that non solar irradiance, but CR intensity variation is mostly responsible for observed climate change during Maunder minimum.

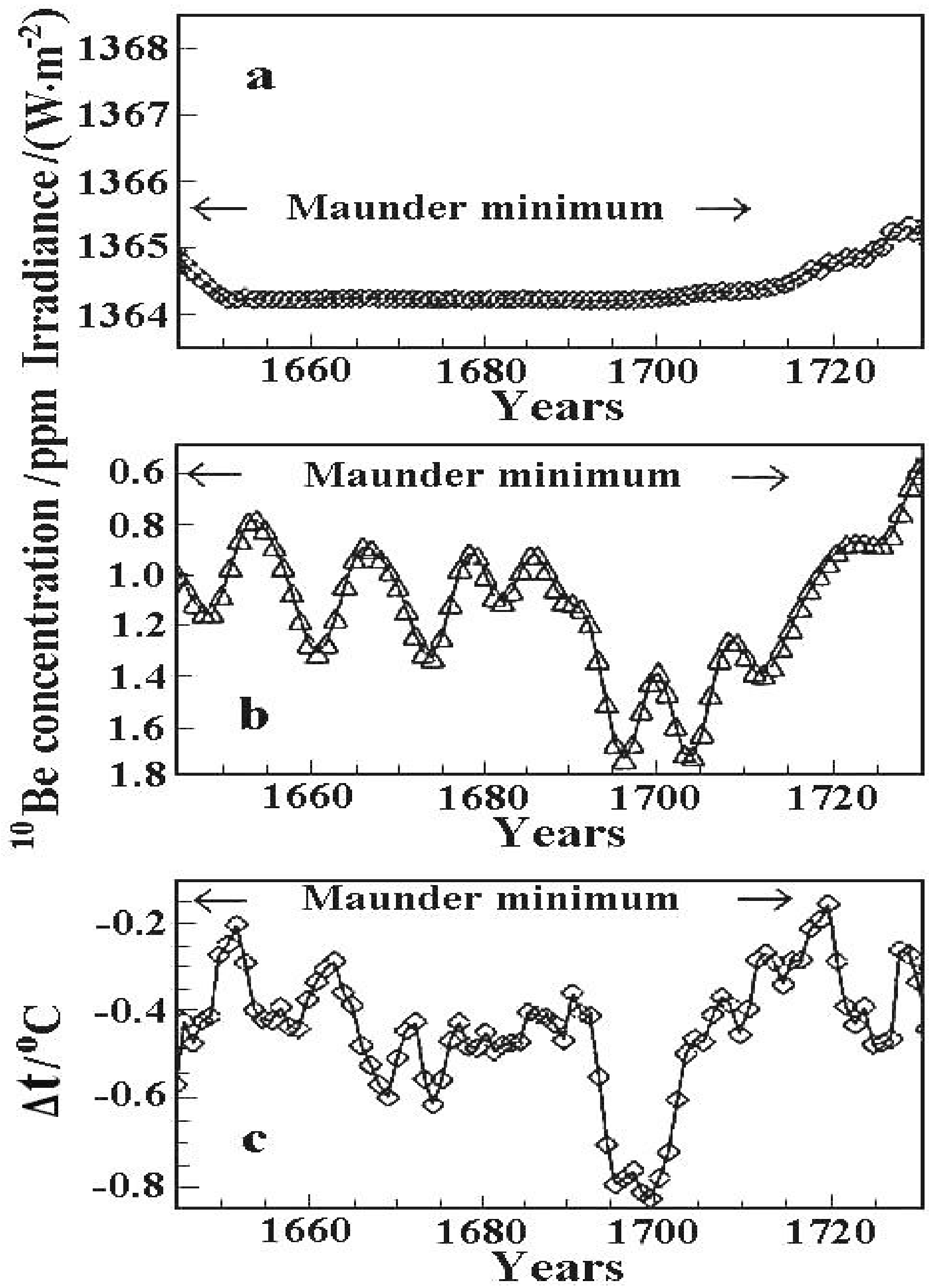

Figure 5. Situation in the Maunder minimum: **a** — reconstructed solar irradiance *[Labitzke and Van Loon 1993]*; **b** — CR intensity according to concentration of ^{10}Be *[Beer et al. 1991]*; **c** — reconstructed relative change of air surface temperature, Δt, for the Northern hemisphere *[Jones et al. 1998]*. According to *[Svensmark 2000]*.

8. On the Influence of galactic CR Forbush decreases and solar CR increases on rainfall and air temperature

A decrease of atmospheric ionization leads to a decrease in the concentration of charge condensation centres. In these periods, a decrease of total cloudiness and atmosphere turbulence together with an increase in isobaric levels is observed *[Veretenenko and Pudovkin 1994]*. As a result, a decrease of rainfall is also expected. Stozhkov et al. *[Stozhkov et al.1995a,b, 1996]*, and Stozhkov *[Stozhkov 2002]* analyzed 70 events of Forbush decreases (defined as a rapid decrease in observed galactic CR intensity, and caused by big geomagnetic storms) observed in 1956—1993 and compared these events with rainfall data over the former USSR. It was found that during the main phase of the Forbush decrease, the daily rainfall levels decreases by about 17%. Similarly, Todd and Kniveton *[Todd and Kniveton 2001, 2004]* investigating 32 Forbush decreases over the period 1983—2000, found reduced cloud cover on 12—18%. Laken and Kniveton *[Laken and Kniveton 2011]* investigate 47 Forbush decreases over the period 1985—2006 and confirmed this result of Todd and Kniveton *[Todd and Kniveton 2001, 2004]*. Artamonova and Veretenenko *[Artamonova and Veretenenko 2011]*, using the Apatity neutron monitor data, analyzed daily averaged values of geo-potential heights (GPH) of the main isobaric levels 1000, 850, 700, 500, 300 and 200 mb (NCEP/NCAR data) and found effects of Forbush decreases on the variations of pressure in the lower atmosphere during 48 events in October–March for the period 1980—2006. Mansilla *[Mansilla 2011]* found that big magnetic storms (produced Forbush decreases) lead to increasing of air temperature and wind's velocity.

During big solar CR events, when CR intensity and ionization in the atmosphere significantly increases, an inverse situation is expected and the increase in cloudiness leads to an increase in rainfall. Studies of Stozhkov et al. *[Stozhkov et al.1995a,b, 1996]*, and Stozhkov *[Stozhkov 2002]* involving 53 events of solar CR enhancements, between 1942—1993, showed a positive increase of about 13% in the total rainfall over the former USSR.

9. Convection-diffusion and drift mechanisms for long-term galactic CR variation: possible forecasting of some part of climate change caused by cosmic rays

From above consideration follows that CR may be considered as sufficient link determined some part of solar wind as element of space weather influence on the climate change. From this point of view it is important to understand mechanisms of galactic CR long-term variations and on this basis to forecast expected CR intensity in near future. In *[Dorman 2005a,b, 2006]* it was made on basis of monthly sunspot numbers W with taking into account time-lag between processes on the Sun and situation in the interplanetary space as well as the sign of general magnetic field (convection diffusion + drift modulations, see **Fig. 6**).

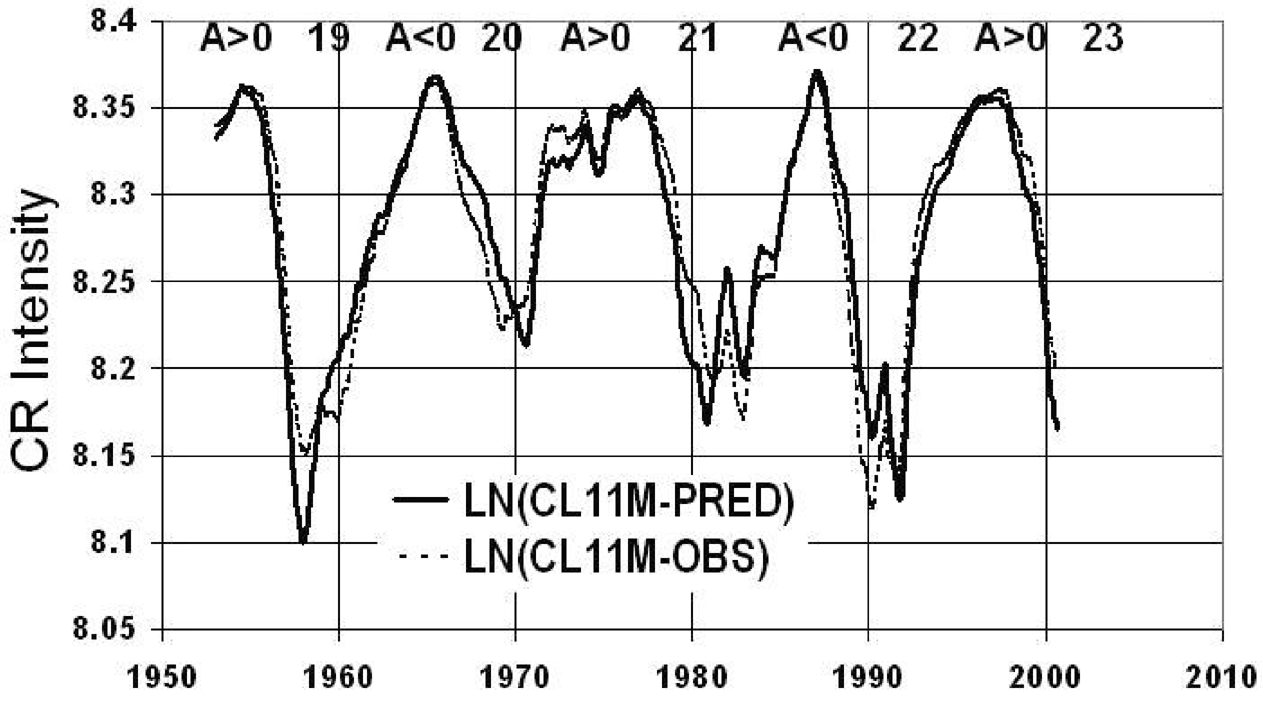

Figure 6. Comparison of observed galactic CR variations during about 50 years (as 11 month moving averaged at Climax NM) — ln(CL11M-OBS) with predicted in the frame of convection-diffusion and drift modulations ln(CL11M-PRED). According to *[Dorman 2006]*.

From obtained results it follows that in the frame of convection-diffusion and drift models can be determined with very good accuracy expected galactic CR intensity in the past (when W are known) as well as behaviour of CR intensity in future (if sunspot numbers W can be well forecast).

10. Influence of main geomagnetic field on global climate change through CR cutoff rigidity variation

When we consider galactic CR variations $\Delta I/I_0$ as a factor influencing global climate change, we need to take into account not only the effects of the solar wind and Heliosphere, but also cutoff rigidity R_C changes on CR intensity variation: $\Delta I/I_0 = -\Delta R_C \times W(R_C, R_C)$, where ΔR_C is the change of cutoff rigidity and $W(R_C, R_C)$ is the coupling function $W(R_C, R)$ at $R = R_C$ (see in details in *[Dorman M2004]*). Expected changes of cutoff rigidities were found in many papers (e.g. *[Bhattacharyya and Mitra 1997; Shea and Smart 2003; Kudela and Bobik 2004]*; see review in *[Dorman M2009]*). Results of trajectory calculations of R_C changes are shown in **Table 2** (from *[Shea and Smart 2003]*).

Table 2

Vertical cutoff rigidities R_C (in GV) for epochs 1600, 1700, 1800, 1900, and 2000, as well as change from 1900 to 2000

According to *[Shea and Smart 2003]*.

Lat.	Long. (E)	Epoch 2000	Epoch 1900	Epoch 1800	Epoch 1700	Epoch 1600	Change 1900–2000	Region
55	30	2.30	2.84	2.31	1.49	1.31	−0.54	Europe
50	0	3.36	2.94	2.01	1.33	1.81	+0.42	Europe
50	15	3.52	3.83	2.85	1.69	1.76	−0.31	Europe
40	15	7.22	7.62	5.86	3.98	3.97	−0.40	Europe
45	285	1.45	1.20	1.52	2.36	4.1	+0.25	N. Amer.
40	255	2.55	3.18	4.08	4.88	5.89	−0.63	N. Amer.
20	255	8.67	12.02	14.11	15.05	16.85	−3.35	N. Amer.
20	300	10.01	7.36	9.24	12.31	15.41	+2.65	N. Amer.
50	105	4.25	4.65	5.08	5.79	8.60	−0.40	Asia
40	120	9.25	9.48	10.24	11.28	13.88	−0.23	Asia
35	135	11.79	11.68	12.40	13.13	14.39	+0.11	Japan
−25	150	8.56	9.75	10.41	11.54	11.35	−1.19	Australia
−35	15	4.40	5.93	8.41	11.29	12.19	−1.53	S. Africa
−35	300	8.94	12.07	13.09	10.84	8.10	−3.13	S. Amer.

It can be seen from **Table 2** a big changes of cutoff rigidities in some places. We suppose to investigate this problem in near future in more details in possible connection with historically known places on the World where local climate changes pressed people to move to other places with better climate. It is not excluded that observed 22-year hurricane cycle connection with geomagnetic and solar activity cycles *[Mendoza and Pazos 2009]* may be caused also by the link of these cycles with cosmic rays and their influence on on meteorological processes.

11. Solar system moving around the galactic centre and crossing Galaxy's arms: influence on the Earth's climate through CR and dust

Above we considered space factors acted on the Earth's Climate mainly through CR in frame of scales not bigger than one thousand years. In **Fig. 7** are shown data on planetary surface temperature changing during the last 520 million years, caused to the moving of the Solar system around the centre of our Galaxy and crossing galactic arms with bigger probability to interact with molecular-dust clouds and supernova remnants (with bigger intensity of CR and higher density of space dust, which both lead to increasing of cloudiness and decreasing of planetary surface temperature).

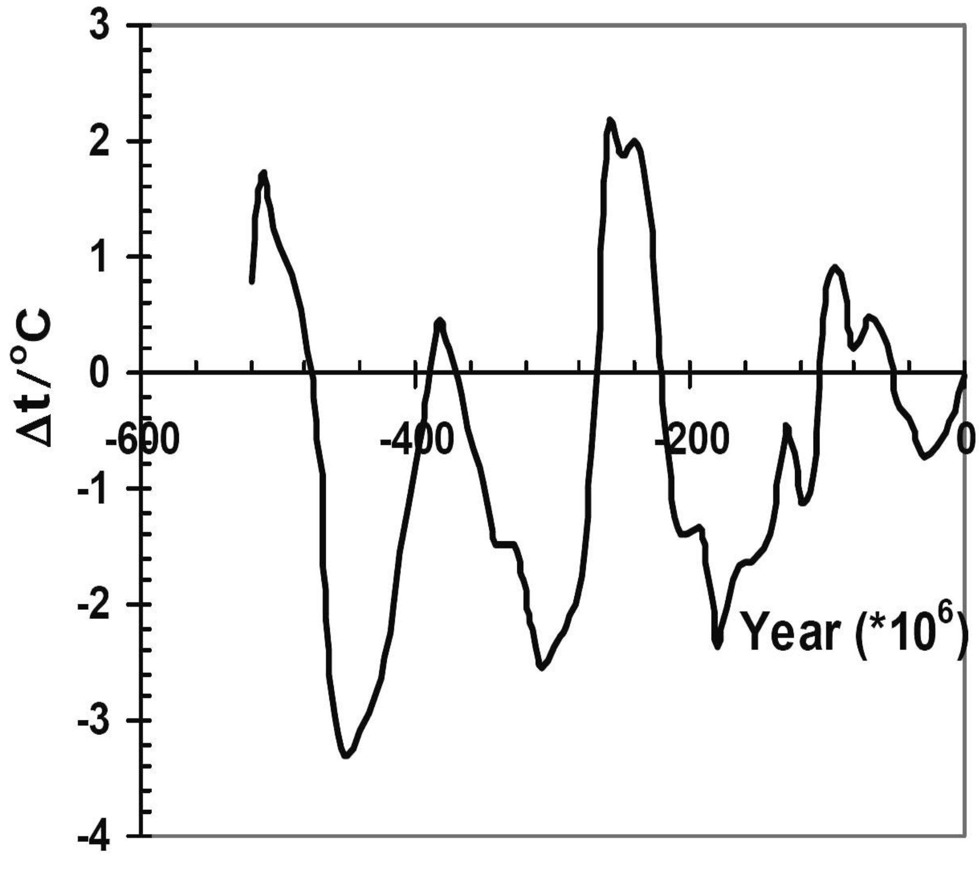

Figure 7. Changes of planetary air temperature, Δt, near the Earth's surface for the last 520 million years according to the pale-environmental records. According to *[Veizer et al. 2000]*.

From **Fig. 7** it can be seen that during the past 520 million years, there were four periods with surface temperatures lower than at present time and four periods with higher temperatures.

12. Discussion

Let me note with gratitude to both Referees that this Section was induced by their comments. We considered above the change of planetary climate as caused mostly by two space factors: cosmic rays and space dust. This we advocate with the use of results obtained over long time periods, from about ten thousand years to many millions of years. We also considered very short events of only one or a few days, such as Forbush effects and Ground Level Enhancements (GLE). In these cases, it is necessary to use a superposed method, summing over many events to sufficiently reduce the relative role of meteorological factors, active incident to the aforementioned short events (see Section 9).

Analysis of Kristjánsson and Kristiansen *[Kristjánsson and Kristiansen 2000]* contradicts the simple relationship between cloud cover and radiation assumed in the cosmic-ray-cloud-climate hypothesis, because this relationship really is much more complicated and is not the main climate-causal relationship. I agree with this result and with result of Erlykin et al. *[Erlykin et al. 2009a,b]* and Erlykin and Wolfendale *[Erlykin and Wolfendale 2011]* that there is no simple causal connection between CR and low cloud coverage (LCC), that there is no correlation between CR and LCC for short-term variations, and that while there is correlation between CR and LCC for long-term variations, that this connection can explain not more than about 20% of observed climate change. But the supposition of Erlykin et al. *[Erlykin et al. 2009a,b]* that the observed long-term correlation between cosmic ray intensity and cloudiness may be caused by parallel separate correlations between CR, cloudiness and solar activity contradicts the existence of the hysteresis effect in cosmic rays caused by the big dimensions of the Heliosphere *[Dorman and Dorman 1967a,b; Dorman et al., 1997; Dorman 2005a,b, 2006]*. This effect, which formed a time-lag of cosmic rays relative to solar activity of more than one year (different in consequent solar cycles and increasing inverse to particle energy), gives the possibility of distinguishing phenomena caused by cosmic rays from phenomena caused directly by solar activity (i.e. activity without time lag) (see **Fig. 2**). The importance of cosmic ray influence on climate compared with the influence of solar irradiation can be seen clearly during the Maunder minimum (see **Fig. 5**). Cosmic ray influence on climate over a very long timescale of many hundreds of years can be seen from **Fig 1** (through variation of ^{14}C).

It is necessary to take into account that the main factors influencing climate are meteorological processes: cyclones and anticyclones; air mass moving in vertical and horizontal directions; precipitation of ice and snow (which changes the planetary radiation balance, see *[Waliser et al. 2011]*); and so on. Only after averaging for long periods (from one-ten years up to 100-1000 years and even million of years) did it become possible to determine much smaller factors that influence the climate, such as cosmic rays, dust, solar irradiation, and so on. For example, Zecca and Chiari show *[Zecca and Chiari 2009]* that the dust from comet 1P/Halley, according to data of about the last 2000 years, produces periodic variations in planetary surface temperature (an average cooling of about 0.08°C) with a period 72 ± 5 years. Cosmic dust of interplanetary and interstellar origin, as well as galactic cosmic rays entering the Earth's atmosphere, have an impact on the Earth's climate *[Ermakov et al., 2006, 2007, 2009; Kasatkina et al., 2007a,b]*. Ermakov et al. *[Ermakov et al.2006, 2009]* hypothesized that the particles of extraterrestrial origin residing in the atmosphere may serve as condensation nuclei and, thereby, may affect the cloud cover. Kasatkina et al. *[Kasatkina et al. 2007a,b]* conjectured that interstellar dust particles may serve as atmospheric condensation nuclei, change atmospheric transparency and, as a consequence, affect the radiation balance. Ogurtsov and Raspopov *[Ogurtsov and Raspopov 2011]* show that the meteoric dust in the Earth's atmosphere is potentially one of the important climate forming agents in two ways: (i) particles of meteoric haze may serve as condensation nuclei in the troposphere and stratosphere; (ii) charged meteor particles residing in the mesosphere may markedly change (by a few percent) the total atmospheric resistance and thereby, affect the global current circuit. Changes in the global electric circuit, in turn, may influence cloud formation processes.

Let me underline that there is also one additional mechanism by which cosmic rays influence lower cloud formation, precipitation, and climate change: the nucleation by cosmic energetic particles of aerosol and dust, and through aerosol and dust-increasing of cloudiness. It was shown by Enghoff et al. *[Enghoff et al. 2011]* in the frame of the CLOUD experiment at CERN that the irradiation by energetic particles (about 580 MeV) of the air at normal conditions in the closed chamber led to aerosol nucleation (induced by high energy particles), and simultaneously to an increase in ionization (see also *[Kirkby et al., 2011]*).

Let me note that in our paper, we considered cosmic rays and dust aerosols separately, but acting in the same direction. Increasing cosmic ray intensity and increasing of aerosols and dust leads to increasing of cloudiness and a corresponding decrease of planetary surface temperature. Now, consistant with the experimental results of Enghoff et al. *[Enghoff et al.2011]* on aerosol nucleation in the frame of the CLOUD Project on the accelerator at CERN (see short description of this Project in *[Dorman M2004]*), it was found that with increasing intensity of energetic particles, the rate of formation of aerosol nucleation in the air at normal conditions increased sufficiently. This result can be considered as some physical evidence of the cosmic ray — cloud connection hypothesis.

13. Conclusions

When considering CR variations as one of the possible causes of long-term global climate change, we need to take into account not only CR modulation by the solar wind but also the changing of geomagnetic cutoff rigidities (see **Table 2**). This is especially important when we consider climate change on a scale of between 10^3 and 10^6 years. Paleomagnetic investigations show that during the last 3.6×10^6 years, the magnetic field of the Earth has changed polarity nine times. The Earth's magnetic moment has changed as well, sometimes having a value of only one-fifth of its present value *[Cox et al. 1967]*. This corresponds to a decreasing of the cutoff rigidity, which in turn leads to an increasing of CR intensity and a decreasing of the surface temperature. When we consider the situation in the frame of timescales of many thousands and millions of years, we need to take into account also possible changes of galactic CR intensity out of the Heliosphere. It is furthermore not excluded that the gradual increasing of planetary surface temperature observed in the last hundred years is caused not by anthropogenic factors, but by space factors (mainly by CR intensity variation, see **Fig. 4**). In my opinion, it is necessary to continue investigations on the connection between CR intensity and climate factors like cloudiness, raining, and surface temperature, not only by statistical investigations in the frame of different timescales, but also by special experiments on accelerators and through the development of physical models. As we mentioned in Section 11, it will also be important to investigate the possible connection between big changes in cosmic ray cutoff rigidity and historically known places in the world where local climate change pressed people to move to other places with better climates.

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КОСМИЧЕСКИЕ ЛУЧИ И ИНЫЕ КОСМИЧЕСКИЕ ФАКТОРЫ, ВЛИЯЮЩИЕ НА ИЗМЕНЕНИЕ КЛИМАТА ЗЕМЛИ

Профессор Лев И. Дорман, руководитель Израильского центра по изучению космических лучей и космической погоды (Тель-Авивский университет и Израильское Космическое Агентство), главный научный сотрудник отдела космических лучей ИЗМИРАН, Российская Академия Наук (г. Троицк)

E-mail: lid@physics.technion.ac.il

Данные исследований больших колебаний температуры поверхности нашей планеты, имевших место в прошлом с периодом во многие миллионы и тысячи лет, очевидным образом показывают, что глобальные изменения климата Земли определяются, по большей части, космическими факторами: движением Солнечной системы вокруг центра нашей Галактики с пересечением галактических «рукавов» и облаков межзвёздного газа, вблизи от Сверхновых и остатков Сверхновых звёзд. Важным космическим фактором являются также периодические колебания солнечной активности и солнечного ветра (обычно с периодом в десятки и сотни лет). Воздействие космических факторов на климат Земли осуществляется главным образом посредством влияния космических лучей (КЛ) и межзвёздного газа на формирование облаков, регулирующих общий приток энергии от Солнца в атмосферу Земли.

Распространение и модуляция в гелиосфере галактических космических лучей (генерируемых, главным образом, во время взрывов Сверхновых и в остатках Сверхновых в нашей Галактике) определяются их взаимодействием с магнитными полями, вмороженными в солнечный ветер и в корональные выбросы массы (КВМ), сопровождаемыми межпланетной ударной волной (порождающих сильные магнитные бури при их взаимодействии с магнитосферой Земли).

Наиболее сложной проблемой мониторинга и прогнозирования модуляции галактических КЛ в гелиосфере является то, что интенсивность космических лучей в некоторой четырёхмерной точке пространства-времени определяется не уровнем солнечной активности во время этих наблюдений и не электромагнитными условиями в этой четырёхмерной точке, а электромагнитными условиями во всей гелиосфере в целом. Эти условия в гелиосфере определяются ходом развития солнечной активности в течение многих месяцев, предшествующих моменту наблюдений. Именно это и является главной причиной так называемого явления гистерезиса в зависимости потока галактических космических лучей от солнечной активности.

С другой стороны, детальные исследования этого явления предоставляют серьёзную возможность оценить как условия в самой гелиосфере, так и её величину. Для решения описанной выше проблемы модуляции космических лучей в гелиосфере мы в качестве первого шага, используя данные нейтронного монитора, рассматривали в рамках теории конвективной диффузии поведение частиц высоких энергий — с энергиями, большими, чем несколько ГэВ. Для таких частиц время диффузионного распространения в гелиосфере очень мало по сравнению с характерным временем модуляции. Затем, в качестве последующего шага, мы учитывали эффекты дрейфа.

Для галактических космических лучей низких энергий, обнаруженных спутниками и космическими зондами, мы должны принять во внимание ещё и дополнительное запаздывание, вызванное диффузией в гелиосфере. Затем мы рассмотрим проблему прогноза на несколько месяцев и лет вперед модуляции космических лучей, что позволяет дать прогноз для той части глобальных климатических изменений, которые обусловлены воздействием космических лучей.

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Ключевые слова: космические лучи, солнечный ветер, корональные выбросы массы, гелиосфера, глобальные изменения климата Земли, Солнце, Галактика.