THE USE OF COSMIC RAYS FOR CONTINUOUS MONITORING AND PREDICTION OF SOME DANGEROUS PHENOMENA FOR THE EARTH'S CIVILIZATION

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Abstract. The main idea of the International Cosmic Ray Service (ICRS) is to combine satellite and spaceprobe cosmic rays, magnetic and plasma data with groundbased cosmic ray data (exchanged in real time) for obtaining continuous information on the electromagnetic and radiation situation in the interplanetary space and Earth's magnetosphere: prediction of great geomagnetic storms, big increases of radiation hazards and other dangerous phenomena in space and on the Earth for people and technology. ICRS can predict not only geomagnetic storms and unfavorable days in the environment (especially important for old people and people with some diseases), but, in combination with astrophysical methods, can predict big increases of radiation hazards very dangerous for the Earth's civilization and big changes in the environment due to extremely powerful solar flares and local supernova explosions. We hope that, after some additional investigation of high energy cosmic-ray distribution function outside the heliosphere, it could be possible to solve by ICRS more complicated problems: to determine in combination with astrophysical methods the location and velocity of nearest dust-molecular galactic clouds with frozen-in magnetic fields and predict the expected time of the Sun capturing by some clouds with possible changes of Earth's global climate. The foundation of ICRS could bring a new possibility of development to the cosmic ray observatories, release scientists from a lot of routine work and increase the fundamental and applied research efficiency.

1. Introduction

Several theoretical problems have been solved in the past for understanding, from the continuous observations of the cosmic-ray intensity, the very broad and important information on the processes and conditions in the Earth's magnetosphere, in the interplanetary and galactic space, and on the Sun. We are now in a favorable condition to start thinking at a different and complementary use of the network of cosmic ray detectors. Until now this network had the scientific purpose of studying interplanetary phenomena connected with cosmic-ray time variations and anisotropies; the solution of some theoretical problems, and of the related experimental aspects, makes it possible to realize with the data of the cosmic-ray network,

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analysed in real time, a service (International Cosmic Ray Service) for forecasting radiation, geomagnetic hazards, and other dangerous phenomena for the human civilization on Earth and in space.

2. Continuous Observations of Cosmic-Ray Time Variations

The first equipment for continuous registration of cosmic ray intensity — the automatic ionization chamber, 50 liters of volume, shielded by 10 cm Pb — was developed in 1934 by A. Compton. By these chambers S.E. Forbush established the first world network of cosmic ray observatories (2 in the northern hemisphere, 1 near the equator and 1 in the southern hemisphere) for the study of cosmic ray variations. A big (a volume of 1000 liters) ionization chamber of Compton type was developed in USSR in 1950–1951 and the first Soviet network of 7 cosmic-ray observatories was constructed. The method of ionization chambers gives continuous information on the cosmic ray variations only in the energy interval from ~ 10 to ~ 50 GeV (see Dorman (1981) and Dorman (1989) for the history on the first steps of cosmic-ray time variation investigations).

In 1951–1952 J. Simpson (Chicago University) constructed a neutron monitor based on 12 small $^{10}BF_3$ neutron counters (4 cm diameter, 105 cm length) with 4,000 kg of lead as generator of secondary neutrons, and paraffin for moderation and thermalization of neutrons. Simpson's type neutron monitor was sensitive to primary cosmic ray particles in the energy interval from ~ 2 to ~ 20 GeV, but the effective area of this monitor was only 2 m^2 and the probability of detecting a locally-produced neutron only 1.2%. Simpson equipped the American cosmic ray observatories and some observatories from other countries by neutron monitors. At the beginning of IGY (International Geophysical Year, July 1957–December 1958) about 60 stations were equipped by Simpson-type neutron monitors.

The next very important step was made in connection with the preparation of the IQSY (International Quiet Solar Year, 1964–1965): a super neutron-monitor NM-64 of IQSY type was developed in Canada by H. Carmichael. The effective area of the monitor is 18 m^2 (for 18 counters of big dimension — 15 cm diameter and 200 cm length — and 32 ton lead) and the probability of detecting locally-produced neutrons is about 5.5%. Now practically all cosmic ray observatories in the world are equipped by NM-64 super neutron-monitors of different dimensions.

Super neutron-monitors located at low latitudes and high altitudes are very sensitive to solar neutrons generated in nuclear interactions in the solar atmosphere by flare-accelerated particles (charged solar cosmic rays). For higher particle-energy important information on cosmic ray variations are obtained by muon telescopes in underground cosmic-ray observatories (in USA, Italy, Japan, Russia, Georgia, Australia, at various depths from several to ~ 2000 meter). These observations cover the energy interval of primary cosmic ray particles from ~ 30 GeV up to $\sim 10{,}000$ GeV. For the highest energy interval from $\sim 10^4$ to $\sim 10^{11}$ GeV there are special equipment for continuous registration of EAS (Extensive Air Showers) in

USA, Australia, UK, Russia and Kasakhstan where it has been planned to build the biggest in the world EAS equipment with effective area of 1000 km^2.

On the other hand, for a very small energy region of cosmic ray primary particles (smaller than few hundreds MeV) it is not possible to obtain information of cosmic-ray time variations from ground-based observations. For this purpose there are regular cosmic ray observations on balloons from 1957 in USA, USSR and Antarctica, and on many satellites and space probes since 1960–1962.

Therefore now we have practically continuous observations of the intensity of primary particles in a very broad energy interval from ~ 0.1 MeV up to $\sim 10^{11}$ GeV.

3. Five Solved Problems in Cosmic-Ray Investigation

It was necessary to solve several very important theoretical problems to understand, from the data of cosmic-ray observatories, the processes in the Earth's atmosphere and magnetosphere, in the interplanetary space and on the Sun, and in the Galaxy.

First problem: Investigation of a method for determining the cosmic-ray variations of atmospheric origin. For this purpose Dorman developed in 1951–1954 a full theory of cosmic ray atmospheric variations on the base of modern theory and experimental data on meson-nucleonic and electromagnetic cosmic ray cascades in the Earth's atmosphere. In the frame of this theory, the cosmic-ray variation of atmospheric origin can be written, for each cosmic ray component of type i (muon, neutron, electron-photon and other components) and for any point k on the Earth, as

$$\left(\frac{\Delta I}{I}\right)_{ik}^{\mathrm{atm}} = \beta_{ik}\Delta h_0 + \int_0^{h_0} \alpha_{ik}(h)\Delta T(h)\,\mathrm{d}h; \tag{1}$$

the coefficients β_{ik} and $\alpha_{jk}(h)$ were calculated with high accuracy according to Dorman's theory. The summary of these results and full theory of cosmic-ray atmospheric variations can be found in Dorman (1957) monograph. Many scientists in Canada, Italy, Japan, USA and USSR controlled this theory and found a good coincidence between the observed atmospheric cosmic-ray variations and those predicted by Dorman's theory. Later this theory was generalized by taking into account some additional processes in the cascade model (Dorman, 1972).

For the nucleonic component, which has the biggest effect for atmospheric changes, it was necessary to apply very accurate corrections; the atmospheric coefficients have been determined for different phases of solar activity cycle and for different threshold rigidities and altitudes above sea level (Bachelet *et al.*, 1965a, 1967; Carmichael and Bercovitch, 1969), by using regression analyses techniques on cosmic-ray station data and measurements obtained by mobile neutron monitors.

Second problem: Determine the primary cosmic-ray variations out of the Earth's atmosphere from the data of the cosmic ray intensity recorded by ground-based observatories.

For this purpose Dorman in 1954–1957 developed a theory of connection between observed secondary variation (corrected for meteorological effects) $(\Delta I/I)_{ik}$ of type i in the point k (characterised by cut-off rigidity R_k) and primary variation $\Delta D(R)/D_0(R)$ of differential rigidity spectrum for primary cosmic rays out of the Earth's atmosphere. According to this theory

$$\left(\frac{\Delta I}{I}\right)_{ik} = -\Delta R_k W_{ik}(R_k, h_k) + \int_{R_k}^{\infty} \frac{\Delta D(R)}{D_0(R)} W_{ik}(R, h_k)\, \mathrm{d}R \tag{2}$$

where $W_{jk}(R, h_k)$ is the special coupling function determined by the cosmic ray cascade process in the atmosphere and ΔR_k the change of cut-off rigidity caused by the variation of main magnetic field of the Earth and by the variation of magnetospheric current system. The results of the determination of $W_{jk}(R, h_k)$ from geomagnetic cosmic-ray effects (for $R \leq 15$ GV) and from calculations on the base of one dimensional cascade model (for $R > 15$ GV) were reviewed in Dorman (1957, 1963a, b, 1974, 1975a). The solution of the equation system (2) for several components gives the unknown values of ΔR_k and $\Delta D(R)/D_0(R)$ (this is the so-called spectrographic method developed by Dorman *et al.*, 1968 and reviewed in Dorman, 1975b).

For the low-energy nucleonic component the coupling functions are much dependent on the phase of solar activity cycle, so that for the study of short-term perturbations it is necessary to determine the actual coupling functions, by means of accurate latitude curves obtained by latitude surveys and intercalibration of the station network (Amaldi *et al.*, 1963; Bachelet *et al.*, 1965b; Carmichael and Bercovitch, 1969; Kodama and Inoue, 1970; Sporre and Pomerantz, 1970).

Third problem: On the base of the known ΔR_k, and of contemporary geomagnetic observations, determine the strength and geometry of magnetospheric currents that caused magnetic storms.

This problem has been solved on the base of theory on magnetospheric currents, by taking also into account the influence of $\Delta D(R)/D_0(R)$ on the structure of penumbra and on effective cut-off rigidities (Dorman *et al.*, 1971, and 1972).

Fourth problem: The possibility of utilizing detectors with different coupling functions and with different asymptotic cones of acceptance for the incoming particles made it possible to determine, from the observed $\Delta I/I$, the cosmic-ray distribution over the magnetosphere in the interplanetary space and its time development.

This problem has been solved by the special method of spherical global survey developed in USSR and Japan about 20 years ago (see review in Dorman, 1974). This method can be applied only during magnetically quiet periods when $\Delta R_k = 0$. The idea of this method was to solve the system of equations

$$\left(\frac{\Delta I}{I}\right)_{ik} = \int \mathrm{d}Q \int_{R_k}^{\infty} \frac{\Delta D(R, \theta, \varphi)}{D_0(R)} W_{ik}(R, h_k)\, \mathrm{d}R \tag{3}$$

where $\Delta D(R,\theta,\varphi)$ is the variation of primary spectrum of cosmic ray distribution function out of the magnetosphere. By using data of many cosmic ray stations and taking into account information on asymptotic directions of cosmic ray particles in the Earth's magnetosphere, it is possible to find the first and some other spherical harmonics of cosmic-ray distribution function in the interplanetary space.

Recently Baisultanova *et al.*, (1987) and Antonova *et al.*, (1990) developed a new method, the spherical spectrographic global survey, to solve the second and the fourth problems. The global spectrographic method consists in solving the system of equations

$$\left(\frac{\Delta I}{I}\right)_{ik} = -\Delta R_k W_{ik}(R_k,h_k) + \int \mathrm{d}\Omega \int_{R_k}^{\infty} \frac{\Delta D(R,\theta,\varphi)}{D_0(R)} W_{ik}(R,h_k)\,\mathrm{d}R. \quad (4)$$

By this method we can obtain a continuous information on the distribution of ΔR_k (and from that on magnetospheric currents) and cosmic ray distribution function in the interplanetary space, simultaneously.

Fifth problem: Finally, on the base of the evaluation of the cosmic-ray distribution near the Earth, determine the situation in space: information on moving magnetic clouds and interplanetary shock waves, on space-time distribution of radiation dose. The theoretical base of the solution of this problem was given by the cosmic-ray anisotropic diffusion theory and the kinetic theory of cosmic-ray propagation, modulation and scintillation in the heliosphere, by taking into account the cosmic-ray acceleration and interaction with solar wind, moving magnetic clouds, high speed streams, shock waves and other moving disturbances in space (Dorman, 1959; Dorman, 1963a, b; Parker, 1963; Dorman and Miroshnichenko, 1968; Dorman, 1971; Krymsky and Transky, 1973; Dorman, 1975a, b; Dorman and Kats, 1977; Krymsky *et al.*, 1977; Dorman, 1978; Alaniya and Dorman, 1981; Toptygin, 1983; Dorman and Libin, 1984; Alaniya *et al.*, 1987; Dorman *et al.*, 1987; Berezhko *et al.*, 1988; Dorman, 1991). The simultaneous analysis of solar data, interplanetary parameters and ground-based cosmic-ray observations made it possible to determine most of the phenomenological aspects of the observed cosmic-ray modulation and of the associated interplanetary perturbations, as flare-generated shock waves, magnetic clouds and fast streams ejected by coronal holes (Iucci *et al.*, 1979a; 1979b; 1984a, 1984b; 1986; 1989), and of the propagation of solar cosmic rays in interplanetary space.

4. The Sixth Unsolved Problem in Cosmic Ray Investigation. The International Cosmic Ray Service

The *sixth problem* is very important for practical applications and is very difficult to be solved. The matter of this problem is the following: from the beginning of the IGY (1957–1958) up today all cosmic ray observatories are sending their data to the World Data Centers of Boulder, Tokyo and Moscow with a delay time from 6 to 12 months. For this reason until now the cosmic-ray observation data have been used only for fundamental research (cosmic ray propagation and acceleration, influence of moving magnetic clouds and shock waves, structure of the heliosphere, nonlinear effects, influence of solar and geomagnetic activity, etc.), but not for real-time applications. Therefore the planetary network of cosmic ray observatories, which are working now, cannot be considered as an International Cosmic Ray Service (ICRS). For this reason it is necessary to found a special Real-Time Cosmic Ray World Data Center so that the cosmic ray station network could be transformed in a real-time ICRS. If the data are exchanged and analysed in real-time we could solve the very important problems on the determination of the plasma-magnetic and radiation situation in the space at any moment, and make predictions of their space-time evolution to dangerous conditions for the life on Earth.

In Figures 1 and 2 we show schematically the project of the ICRS. Figure 1 summarizes the data and information the ICRS needs for forecasting the different dangerous phenomena, listed in Figure 2, for the Earth's civilization, due to dramatic changes in plasma-magnetic and radiation situation in space. This Service will be based on real-time collection and exchange of the data from all cosmic-ray stations of the network by satellite communications. Then computerised data analysis and computerised interpretation will be done on the base of modern theory of galactic-cosmic ray modulation and solar cosmic-ray propagation. For a better use of the ICRS it will be necessary to use also cosmic ray data from satellites and spaceprobes in real time (as information on cosmic ray variations in small and very small energy regions), together with interplanetary magnetic field and solar wind data. The neutron monitor stations of the network should have a counting rate of 250–300 Hz and a data collection time of 1 minute.

5. Prediction of Strong Geomagnetic Storms and Intense Solar-Flare Particle Radiation

The investigation methods of cosmic-ray time variations developed so much that the community of scientists in this branch of Cosmic-Ray Physics can solve two very important problems for the Earth's civilisation.

a. *Continuous prediction of time commencement of big geomagnetic storms; this advertisement, with high occurrence probability, can be given 15–20 hours before the event.*

It is well known that geomagnetic storms affect adversely man's high technology systems. High frequency radio communications are disrupted, electric power distribution grids are blacked out when geomagnetically induced current causes safety devices to trip, and atmospheric warming causes increased drag on satellites. Many laboratories and scientists studied the problem on possible prediction of big geomagnetic storms, especially the NOAA Space Environment Laboratory.

Moreover, according to statistical data taken in the past years in the former

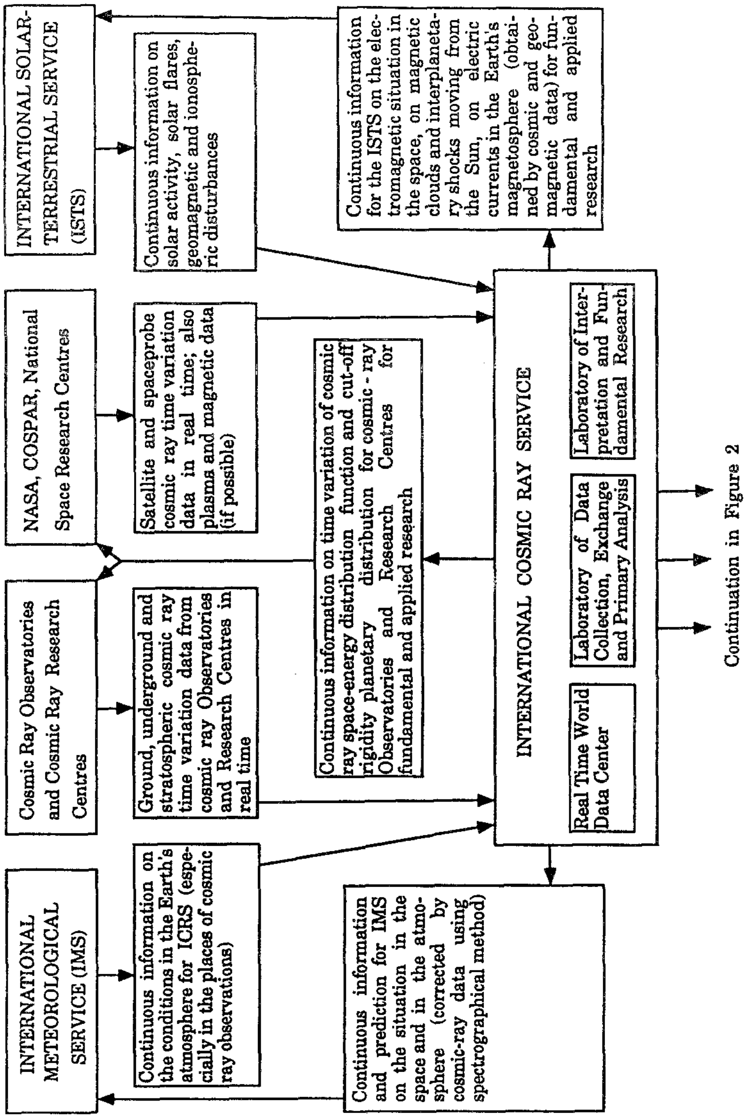

Fig. 1. Scheme of the data needed by ICRS.

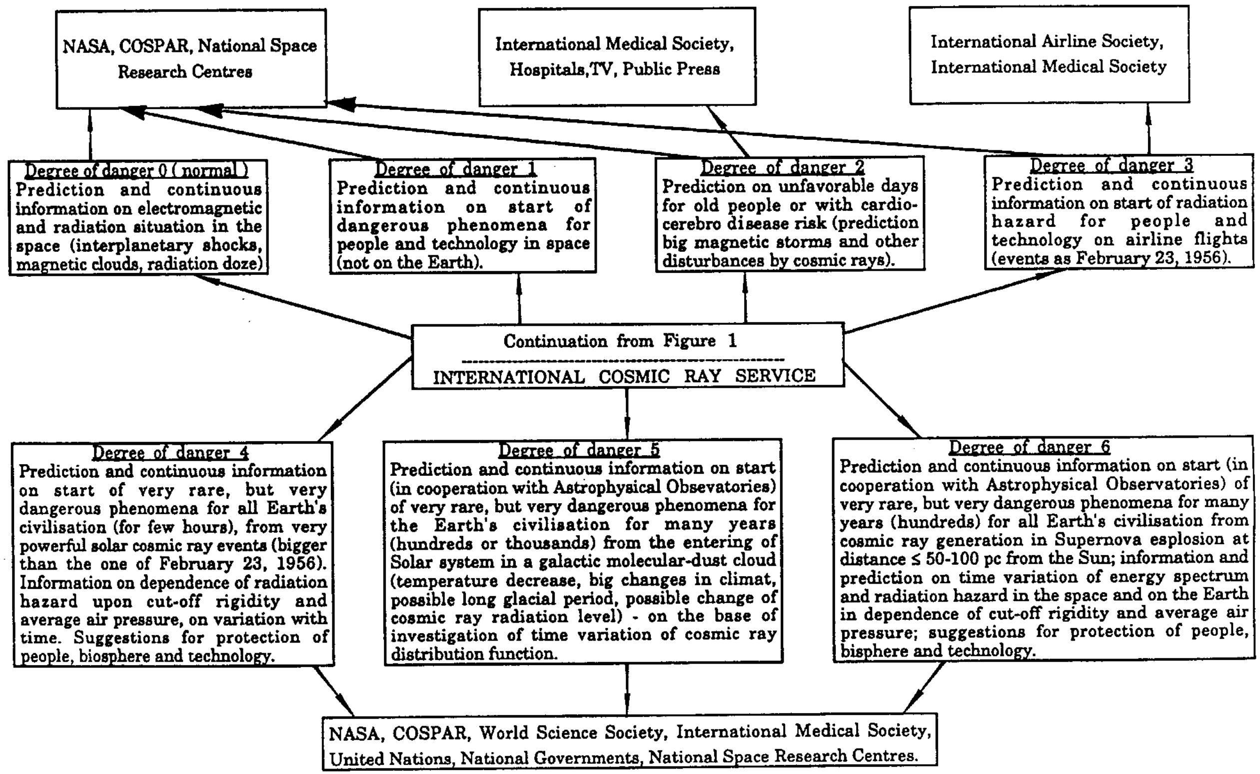

Fig. 2. Scheme of dangerous phenomena which could be forecast by ICRS. (Continuation from Figure 1).

USSR (more than 7 millions ambulance calls) days with very high occurrence of myocardial infarctions and cerebro-vascular diseases are characterised by big geomagnetic storms (Breus *et al.*, 1992).

Under big geomagnetic storms with sudden commencement and lasting approximately for three days, with a Z-component change greater than 140 nT, the number of automobile accidents increases sharply, and more work accidents occur in those places in which complicated technology and intensive rhythms of labour are required. The analysis of accidents caused by human factors in the biggest atomic station of USSR, "Kurskaya", during 1985–1989, showed that $\sim$ 70% of these accidents happened in the days of magnetic storms. (See References on geomagnetic and solar activity influence on medical factors).

Therefore it follows from the above considerations that it is necessary for the life of people to provide the health authorities, road police and other organisations of an efficient real-time prediction of geomagnetic storms to apply the appropriate preventive procedures.

The usual methods of geomagnetic storm predictions based only on solar data may give a very low occurrence probability because the majority of solar flares do not generate shock waves and magnetic clouds causing geomagnetic storms. On the other hand by cosmic rays we can "see" the moving magnetic clouds and interplanetary shocks 15–20 hours before they reach the Earth, measure their velocity and other parameters and predict with high probability if a magnetic storm will be present at the Earth or not, giving the expected time of geomagnetic storm commencement, the expected duration and strength. For this purpose it is necessary to utilise 1-minute or 5-minute real-time data of 50–60 Super Neutron Monitors for determining every hour (by computer calculation) the cosmic-ray distribution function and the spectrum of cosmic-ray oscillations (an illustration of this method is given in Figure 3).

b. *Continuous prediction of intense radiation hazards for people on regular airline flights due to solar flare cosmic rays; this advertisement, with high occurrence probability, can be given 30–60 minutes before the arrival of the more dangerous particle flux.*

This method is based on the very well known fact that the main part of radiation hazard in space and in higher atmosphere is caused by particles with small energy (few hundreds MeV) that reach the Earth 1–2 hours after their acceleration on the Sun; on the contrary the relatively small flux of high-energy ($\geq$ 2 GeV) particles, which can be detected by Super Neutron Monitors and practically are not involved in the radiation hazard, reach the Earth much more quickly. Several minutes of observation of the first-coming solar high-energy particles can give enough information on intensity, energy spectrum, transport parameters to make it possible to predict the time-space distribution of radiation hazard in interplanetary space (for astronauts and space-probe technology) and in the Earth atmosphere as a function of latitude (geomagnetic cut-off rigidity) and altitude. Also for this project we need Super Neutron Monitor data in real time, one-minute scale.

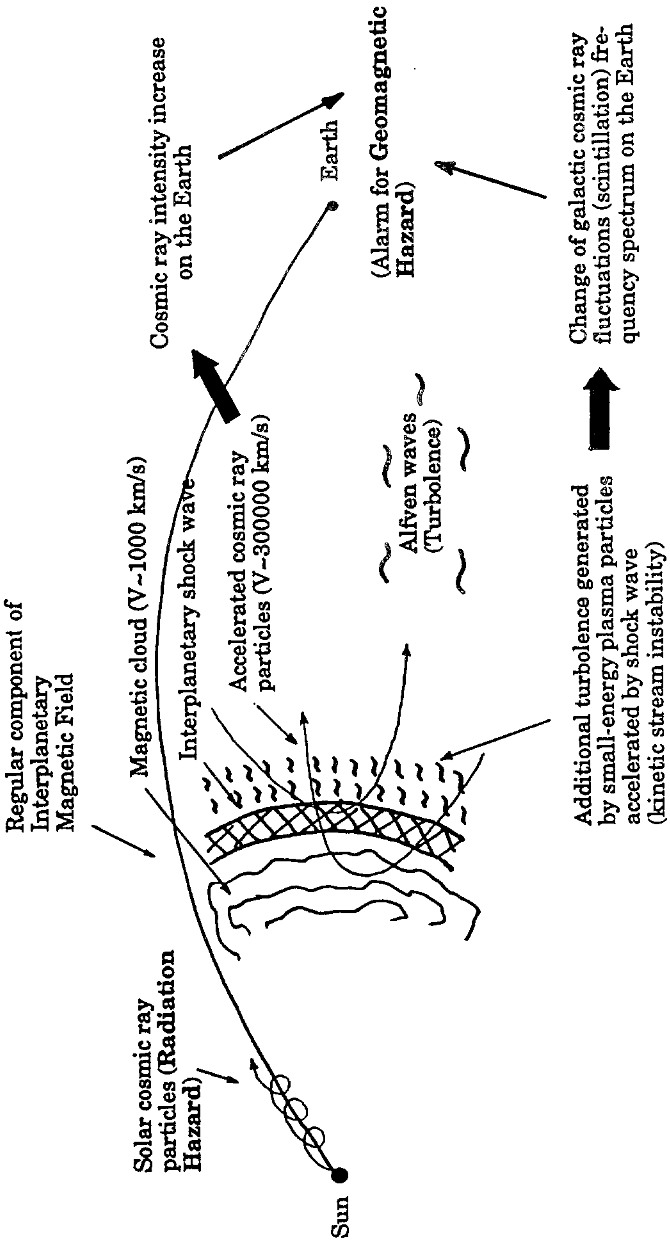

Fig. 3. Cosmic ray effects induced by moving magnetic clouds and shock waves

6. The Possibility of Other Predictions

a. *Prediction of the interaction of a molecular dust cloud with the solar system by the changes in the galactic cosmic-ray distribution function.*

The plasma in a moving molecular dust cloud contains a frozen-in magnetic field; this field can modify the stationary galactic cosmic ray distribution outside the heliosphere. The change in the distribution function can be significant, and it should be possible to identify these changes when the distance between the cloud and the Sun becomes comparable with the dimension of the cloud. The continuous observation of a time variation of the cosmic ray distribution function for many years, should provide the possibility of determining the direction and the speed of the cloud relative to the Sun, as well its geometry. Therefore one could predict its evolution in space and determine whether it will catch the Sun or not. In the case of high probability of capture, we could predict the time of the capture and how long the solar system will be inside the cloud. This work must be done in cooperation with NASA, COSPAR and Astrophysical Observatories.

We remark that this problem is very complicated because it is necessary to take into account also the disturbance of the cosmic-ray distribution function out of the heliosphere due to magnetic fields inside the heliosphere. It will be easier to solve this problem by high-energy particles, by using continuous data from underground muon telescopes and observations from small-dimension EAS (10^{13}–10^{14} eV).

b. *Prediction of the radiation hazard produced by high-energy cosmic-ray particles generated in a nearby Supernova explosion.*

From the energetic balance of cosmic rays in the Galaxy (Ginzburg and Syrovatsky, 1963; Berezinsky *et al.*, 1984), it was estimated that the full power for cosmic ray production is $W_{cr} \sim 3 \times 10^{40}$ erg s^{-1}. If the Supernova (SN) explosions are the main source of galactic cosmic rays and at each explosion the average energy transferred to cosmic rays is ESN $\sim 10^{50}$ erg, the expected frequency of SN explosions will be $\nu_{SN} = W_{cr}/\text{ESN} \sim 10^{-2}$ year^{-1}. Being the number of stars in our Galaxy $\sim 2 \times 10^{11}$, we expect that the average explosion probability of any star is $\sim 10^{-13}$ year^{-1}.

If we consider the region $R < 10$ pc from the Sun, in this region there are $\sim 10^4$ stars and the probability of SN explosion in this region will be $P \sim 10^{-9}$ y^{-1}. Being the average energy of cosmic ray particles $E_{av} \sim 10$ GeV, the number of expected accelerated particles will be $S \sim \text{ESN}/E_{av} \sim 10^{52}$. We do not know exactly the diffusion coefficient in the vicinity of the Sun, but, for an average value $k \sim 10^{29}$ cm^2 s^{-1}, the expected time of maximum radiation in the solar system will be $t_{max} \sim R^2/4k \sim 100$ y after the explosion, with an expected cosmic-ray intensity increase by a factor $\sim 10^3$ bigger than the average level. Moreover we expect also a second maximum after ~ 1000 y when the shock wave reaches the Sun (an average speed of 10^4 km s^{-1} is assumed); the expected cosmic ray intensity increase could be also very big (Kocharov *et al.*, 1991). For $R \sim 30$ pc ($P \sim 3 \times 10^{-8}$ y^{-1}), an increase of a factor ~ 30 is expected; for

$R \sim 100\,\mathrm{pc}\,(P \sim 10^{-6}\,\mathrm{y}^{-1})$, an increase of a factor ~ 2. These estimations are very approximated (about a factor 10 in accuracy) because they depend on the values of the spectrum of generation, ESN and of diffusion coefficient k. Nevertheless, these computations show that SN explosions not far from the Sun can have, at a certain time, a great influence on the Earth's civilisation.

After the observation of a near Supernova explosion by Astrophysical Observatories, it is possible to estimate the total power released and the energy available for cosmic ray acceleration. One can also determine the energy spectrum and the time of cosmic ray generation. Then it is possible to calculate the cosmic ray propagation time from the Supernova to the Earth and its dependence on the energy of the particles, by taking into account also the effect of interplanetary modulation and the influence on the cosmic ray flux of the geomagnetic field and of the Earth's atmosphere. More detailed information and prediction could be done by the first observations of high- energy particles from the Supernova. The flux of these particles will be very small and the related radiation doze negligible, but they can give very important information on electromagnetic situation in the space between the Supernova and the Sun, and on the energy spectrum of the accelerated particles. On the base of these information it will be possible to correct the first rough estimate and give a more exact prediction of the time development of the radiation hazard from the Supernova. Particles with energies between 10 and 100 GeV can be detected by muon telescopes and neutron monitors and the space-energy distribution function can be measured; by this information it will be possible to give more precise prediction for near future times.

This work must be done in cooperation with NASA, COSPAR and Astrophysical Observatories.

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