Cosmic Rays in Solar System

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Introduction

The earth atmosphere is bombarded with the energetic particles originating from the outer space called cosmic rays. The energy of the nuclei in the comic rays is enough to interact with matter while penetrating the solar system. The nature of cosmic rays within the solar system can be investigated by studying the reaction products left from these interactions such as nuclides, chemical effects or atomic displacement. There are two main types of energetic particles at the earth environment which are known as galactic cosmic rays (GCR) and solar cosmic rays (SCR). The GCR come from outside the solar system when the SCR originate from the sun.

Nature of cosmic rays

The nuclei of both types of cosmic rays mostly consist of proton (89%), alpha particles (10%) and heavy (z=3 to 90) nuclei (1%). Particles have different energies and fluxes in either two categories. GCR particles have high energies and low flux when the energy of the SCR particles is lower with higher flux. The interaction mechanism of a particle with matter is controlled by its energy and charge [1, 2].

Galactic cosmic rays (GCR)

The exact sources of the GCR are still unknown but supernovae and interstellar medium are its main candidate [3, 4]. Once they diffuse or enter into the solar system various interaction or acceleration may occur [5]. In the interplanetary region the GCR particles spectra are affected by the magnetic field. Near the earth, the fluxes of GCR particles with $E<$ 1GeV nucleon^{-1} are modulated by an order of magnitude during an 11-

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year solar cycle. The solar activities can not affect the spectrum of the particles with energies higher than 5-10 GeV $nucleon^{-1}$.

Solar cosmic rays (SCR)

Sun expels countless particles due to flares and eruptions which are an important source of nuclei with energies lower than 300 MeV at the earth (at a distance 1 AU from the sun). Particles in the solar wind are 95% protons and electrons, 4% alpha particles and the remaining 1% are isotopes of helium and neon. Large flares produce most of the SCR particles emitted during 11-year solar cycle while few particles are observed when the solar activity is low. Since any solar event lasts at least for a couple of days, time averaged flux of SCR is higher than the GCR flux.

Calculations predict that the momentary flux of the solar particles behaves as $R^{-3.7}$ in the early phases, but the integrated particles obey inverse square law (R^{-2}), where R is the distance from sun [6]. The observations prove the theoretical approach. Analysis of SCR events detected by pioneers 10 and 11 showed that, the flux decreases by increasing the distance from the sun and is closed to the calculated ratio [7].

Cosmic ray interactions with magnetic field

When a charged particle meets an electromagnetic field deflects. The same happens for cosmic ray particles facing different electromagnetic fields including galactic, interstellar, solar and of course the earth magnetic field. So it is impossible to realize the source of GCR via their incoming direction. The last two are not constant magnetic fields; there are long term (solar cycle) and short term (magnetic clouds

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originating from solar flares) variations of the sun magnetic field. In addition variations of solar wind cause the change in the earth magnetic field.

Cosmic ray interactions with matter

Based on the energy, charge and mass of the energetic particle the nature of interaction process and its products can be estimated. Since there are a wide range of cosmic ray particles with different modes of interaction, the effective length of interaction as well as their products varies widely.

Table 1Energies, mean flux and interaction depths of two types of cosmic ray particles

Radiation	Energies (MeV nucleon^{-1})	Mean flux (particles cm^{-1} s^{-1})	Effective depth (cm)
Solar cosmic rays			
Protons and helium nuclei	5-100	~ 100	0-2
Heavier nuclei	1-50	~1	0-0.1
Galactic cosmic rays			
Protons and helium nuclei	100-3000	3	0-100
Heavier nuclei	~100	0.03	0-10

In the earth atmosphere there are few cosmic ray particles which have been remained from nuclear reactions or stopping by ionization energy losses. It is so hard to follow the interaction of these few particles in such a depth and it is on the surface in which the cosmic ray records can be readily determined.

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Nuclide production

When cosmic ray particles fall on a matter, cosmogenic and radioactive nuclides are probable to be produced. When the primary cosmic ray particles including protons and alpha particles strike an atom in Earth's atmosphere for example, the collision may produce one or more new energetic particles called "secondary" cosmic ray particle. These secondary particles especially neutrons and pions strike other atmospheric atoms producing still more secondary cosmic rays. The whole process is called an atmospheric cascade. If the primary cosmic ray has enough energy -- greater than 500 million electron volts -- the nuclear by products of the cascade can reach Earth's surface.

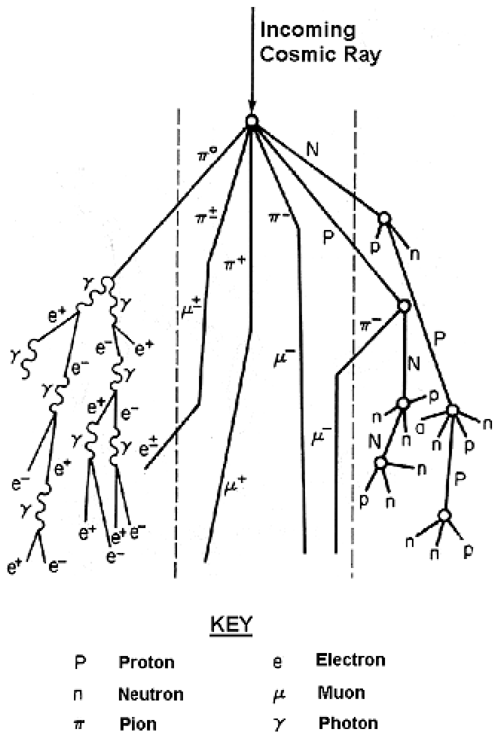

Figure 1 Produced secondary particles produced from the primary cosmic ray due to the collision of cosmic ray and the matter

The low energy solar protons and alpha particles can not penetrate deep into the material since they stop very close to the surface by ionization energy loss. The secondary neutrons produced from SCR induce nuclear

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reactions which are not of interest. It is because of the mass equality of these product nucleuses with the target nucleuses. In addition the SCR-produced nuclides loose their activity deep in the material.

On the other hand, high energy GCR particle which have low interaction length produce many secondary particles especially neutrons and pions before they stop in the matter. The GCR flux decreases exponentially with depth. Near the surface, fluxes of the produced secondary neutrons increase and then start to decrease exponentially with depth [1, 8]. As mentioned before the GCR flux varies with the solar activity but its shape of production rate versus depth is the same over a solar cycle [9]. Theoretical approach is one of the methods to understand the nature of the cascade caused by GCR particles and their distribution [8, 9]. In addition accelerator bombardment of thick targets (38, 39), measurements in the earth atmosphere [10] and study of cosmogenic nuclides [1, 2] can help.

Earth

In general, the flux of the cosmic ray encounter the earth atmosphere is varied by two processes; the sun solar wind and the earth magnetic field [11]. The distribution (temporal and spatial) of the cosmic ray particles entering into the solar system are influenced by the interplanetary magnetic fields [12]. The magnetic field repels some particles; those that get through are deflected by the magnetic field. Computer simulation is used to track cosmic ray paths through Earth's magnetic field, and to determine how the starting direction ("asymptotic direction") is related to the impact point.

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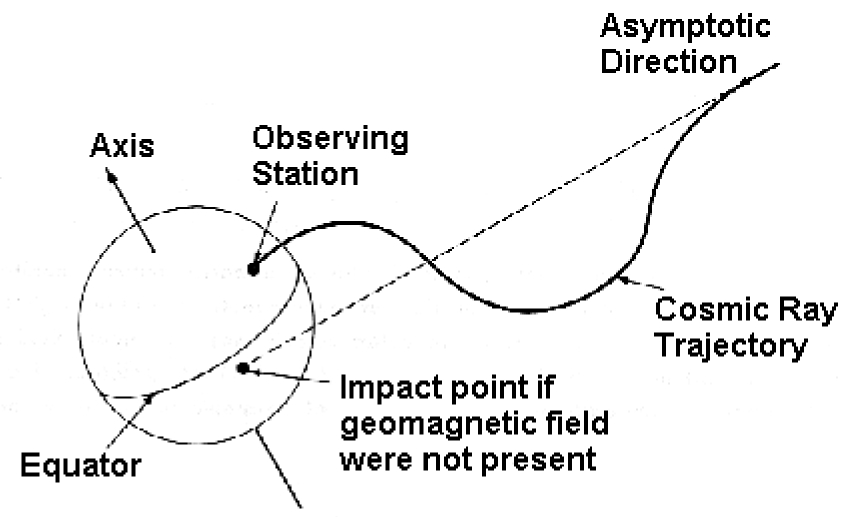

Figure 2 Trajectory of a cosmic ray approaching the earth

The solar wind consists of charged particles (magnetized plasma) generates in the interior of the sun and ejects outward through the interplanetary space. These charged particles have the ability to either decelerate the incoming particles (including cosmic rays) or excluding the particles with energies below 1GeV. Since the amount of solar wind is not constant its level of modulation varies with solar activities.

Low energy cosmic rays like those originating from sun cause the ionization in the upper atmosphere. In the lower atmosphere, muons ionize the gas molecules. The ionization creates a positive ion out of the molecule. The released electron is captured either by another gas molecule (creating negative ion) or it neutralized an already created positive ion (recombination). The ionization and recombination effect is balanced and hence positive and negative ions have the same density. But the negative ions are more mobile which results in an electric field (100 V/m on a quiet day).

The negative ions are lifted up and positive ions are pushed down, forming an electric field for a thunderstorm to be created. Discharge (lightening) happens if the electric field is high enough. So cosmic rays have a direct influence on earth weather.

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Based on the observations, the intensity of the cosmic ray particles, either GCR or SCR, is related to the solar activities or phenomena [12].

In the last few million years the earth has experienced climate changes like ice ages, sea-level changes and etc. In addition, magnetic variations and polarity reversal have been occurred. The most famous cosmogenic radionulide is ^{14}C [13]. It has observed that there is a correlation between solar activity indices, climate variables (especially temperature) and ^{14}C activity. When there are low numbers of sunspots, the activity of ^{14}C is higher and the climate is colder [14]. The higher content of ^{14}C is the consequence of weak solar field which allows more GCR protons to reach the earth. But the correlation of solar activity and climate is less clear. In the last 10^3 years the dominant effect has been the variation in the earth magnetic field. Before this, the main dipole field was weaker, so that more cosmic rays were entering into the atmosphere and the production rate of ^{14}C was higher.

There are at least three different ways for longer-lived cosmogenic radionuclides to enter the terrestrial environment. 1) They can be carried by meteoritic material which has been bombarded in space. The ^{53}Mn, for example, is the main nuclide produced from iron-group in target. 2) The second way of the production of longer lived cosmogenic radionuclige is by spallation reactions in the atmosphere. This is what that happens when ^{10}Be is made from nitrogen and oxygen [11]. 3) Finally, reaction of neutrons and muons on the surface of rocks and soil cause the production of small amount of radionuclides.

The mentioned radionuclides are detected using high-sensitive methods such as activation analysis for ^{53}Mn [15] and accelerator for high-energy counting [16]. In addition Raisbeck et. al. have reported the measurements of ^{10}Be in a series of papers [17-19].

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