JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN Vol. 17, SUPPLEMENT A-II, 1962
INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

# II-5-15. On the mechanism of the Cosmic-Ray Storm

Masatoshi KITAMURA
*Meteorological Research Institute, Tokyo, Japan*

On the basis of the observed facts of the cosmic-ray storm, a model of the mechanism of the cosmic-ray storm is proposed, considering the connexion with other related phenomena, such as the solar and terrestrial phenomena. As a result of the investigation, it is concluded that the essential mechanism of the cosmic-ray storm is the deceleration of the cosmic-ray particles in the magnetic cloud due to its expansion.

Moreover, it is shown that DS of the cosmic-ray storm is originated by the same magnetic cloud responsible for the world wide decrease of the cosmic-ray intesity (Dst) due to the anisotropy of the expansion velocity of the magnetic cloud.

## § 1. Deceleration of the Cosmic-ray Particles due to the Expanding Magnetic Cloud.

In this paper we shall consider a model of the cosmic-ray storm on the basis of the observational facts.

First, the observation of the cosmic-ray storm by Explorer VI suggests the mechanism of the cosmic-ray storm to be the interplanetary space origin in which cosmic-ray particles interact with the moving gas cloud emitted from the sun, instead of the geocentric model of the cosmic-ray storm.

It is presumed that there are two kinds of the solar gas clouds, the one being the cloud in which the magnetic field is frozen and the other the nonmagnetized cloud, and the former corresponds to a cosmic-ray storm with a geomagnetic storm and the latter corresponds to a geomagnetic storm without a cosmic-ray storm.

This consideration is also supported by the relation between the cosmic-ray storm and the solar radio outburst of type IV because the solar radio outburst of type IV is regarded as synchrotron radiation and so it is supposed that the magnetic field is frozen in the solar gas cloud.

From the connexion between the position of the type IV outburst and the occurrence of the cosmic-ray storm, it is supposed that the magnetic cloud emitted from the sun are expanding and spreading widely in the interplanetary space and the magnetic turbulence may occur in the outer region of the magnetic cloud which is responsible for the cosmic-ray storm, and that in the inner region of the gas cloud the particle density is so high to produce a geomagnetic storm. When the particle density in the magnetic cloud is not so high as to produce a geomagnetic storm, a cosmic-ray storm without a geomagnetic storm is expected to occur.

From the facts of the polar cap blackout during the cosmic-ray storm (for example, July, 1959 event and November 15, 1960 event) which show that low energy particles (~10 Mev) emitted from the sun reach the earth during the cosmic-ray storm, it may be supposed that the magnetic cloud is linked up with the sun and so, the dimension of the

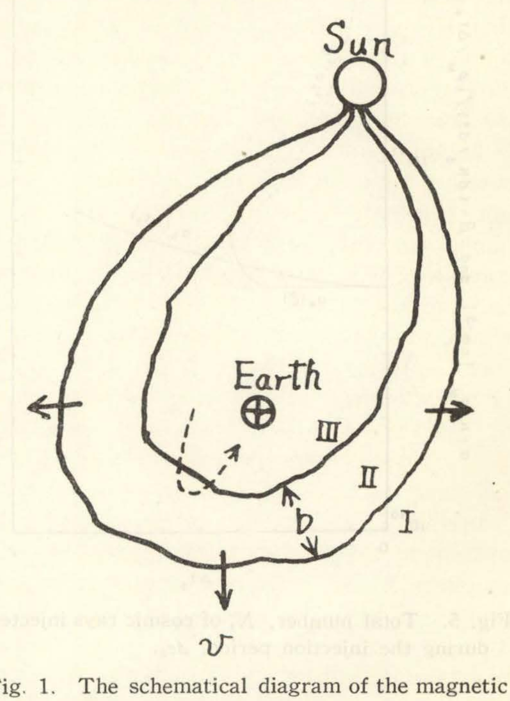


Fig. 1. The schematical diagram of the magnetic cloud emitted from the sun.

magnetic cloud is order of $10^{13}$ cm, being shown in Fig. 1. In Fig. 1, the region I is the free space and the region II is the outer region of the magnetic cloud in which the outward magnetic turbulent flow with the velocity $v$ is developed and the width of the region II is denoted by $b$. Furthermore, it is presumed that the solar corpuscles of such a high density as to produce the geomagnetic storm are contained in the region III, where the magnetic field is supposed to be weak and ordered.

On the model of the magnetic gas cloud, the deceleration process of the cosmic-ray particles colliding with the expanding magnetic gas cloud will be discussed in the subsequent pages.

(i) *The width of the region II.*

Low energy particles of the cosmic-rays scattered by the disordered magnetic field in the region II cannot directly penetrate into the region III through the region II from the region I unless they come in by the diffusion process, while particles of higher energy can easily go in and out across the region II.

Here, we assume that the width of the region II, $b$, is $(2\sim3)\times10^{12}$ cm and the average intensity of the magnetic field in the region II, $H$, is $\sim10^{-4}$ gauss. Then it follows that $E^*$ is $\sim$60 Bev, where $E^*$ is the upper limit of the energy of the cosmic-ray particles responsible for the cosmic-ray storm, because the particles, the energy of which is higher than $E^*$, can directly go in and out through the region II and, therefore, they are not responsible for the cosmic-ray storm. Numerical values of $E^*$ mentioned above is consistent with that obtained by M. Kodama and the author from the observational data which was presented at the Moscow Cosmic-Ray Conference (1959).

(ii) *Estimation of the energy loss of the cosmic-ray particle by the overtaking collisions with the outward moving magnetic field.*

In Fig. 2, we let the system of $S'$ be the system of coordinates which moves with the magnetic cloud in the region II in the direction of $x$ with the relative velocity $v$ to the system of coordinates $S$. Now, we consider overtaking collisions of the cosmic-ray particles in the region III with the region II ($S'$). The energy change of the particle is shown in the following.

Now we observe that in the system $S'$, there is no electric field, but only the magnetic field. Hence in the system $S'$, the particle experiences a change in $x$-component of the velocity $U_x'$ from $U_{x0}'$ to $U_{x1}'$ due to the magnetic field within the region II.

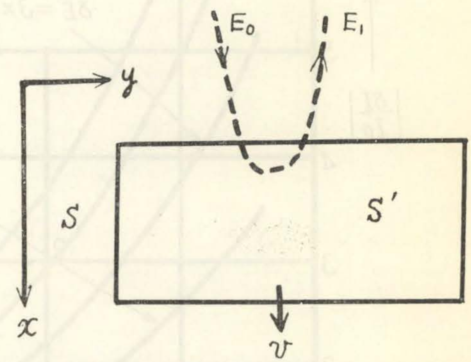


Fig. 2. The illustration of the system of coordinates.

When the energy of the particle is denoted by $E$, in general, $E$ is represented as follows:

$$E=(E'+\beta U_x'E'/c) ,$$

where $\beta=v/c$ and dashed letters refer to the system $S'$.

When the particle experiences a change in $U_x'$ from $\sim C$ to $\sim -C$, since $E'$ does not change is $S'$ as mentioned previously we shall have a change in $E$ denoted by $\delta E$, as follows:

$$\delta E\approx -2n\beta E ,$$

where $n$ represents the number of collisions of the cosmic-ray particle.

Now, if we assume that the escaping probability of a particle from the region III to the region I through the region II is proportional to the energy of the particle, then we can put as follows:

$$n\propto 1/E .$$

Therefore $n=E_c/E$ , where $E_c$ is a constant.

When we put $E_c\approx$60 Bev and the mean expansion velocity $v\sim10^8$ cm/sec, then it follows that

$$\delta E\approx -4\times10^8 \text{ ev} .$$

We can see that this value of $\delta E$ fully explains the cosmic-ray decrease, as shown in

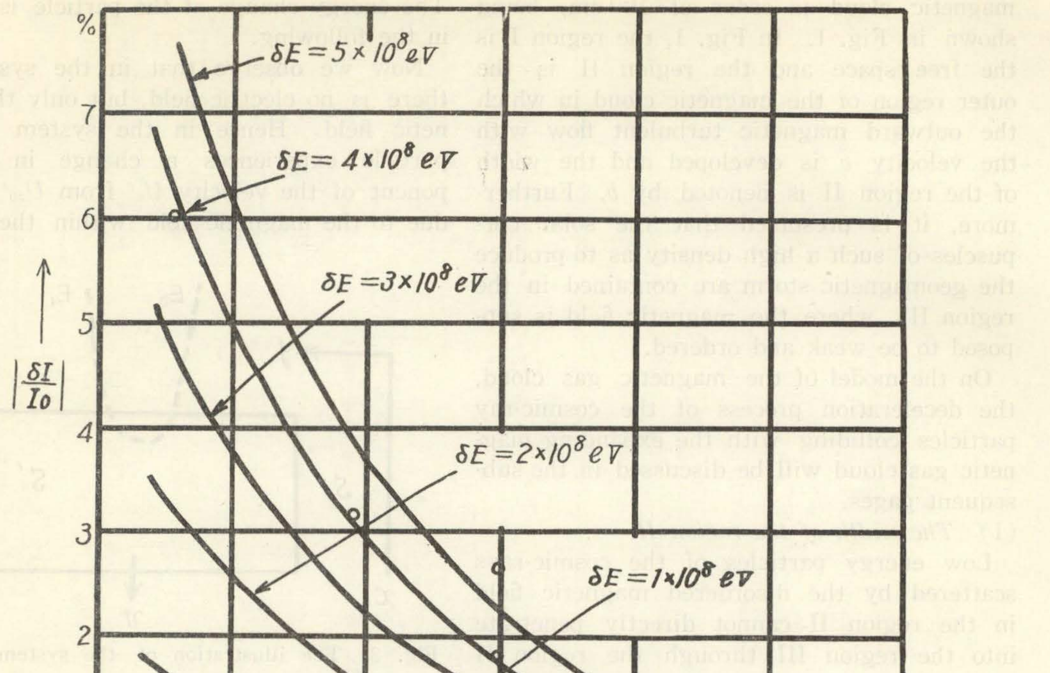


Fig. 3. The energy dependence of the cosmic-ray decrease of the integral intensity calculated by the expansion model of the magnetic cloud.

Fig. 3, where circles show the observed values of the cosmic-ray decrease at the mountain altitude and solid lines are theoretical curves for 680 gr/cm² of atmospheric depth calculated by the following equation:

$$\frac{\delta I}{I_0}=\frac{\int_{E_\lambda}^{\infty} m(E)\{j_0(E-\delta E)-j_0(E)\}dE}{\int_{E_\lambda}^{\infty} m(E)j_0(E)dE},$$

where $j_0(E)$ represent the normal spectrum of the primary cosmic-ray particles, $E_\lambda$ is the magnetic cutoff and $m(E)$ is the overall multiplicity.

(iii) *The time variation of the cosmic-ray decrease.*

The time sequence of the energy dependence of both theoretical curves and observed values of the cosmic-ray decrease is shown in Fig. 4, where $t=0$ day represents the day of the minimum intensity of the cosmic-rays during the cosmic-ray storm.

Thus, the time variation of $\delta E$ is shown in connexion with that of $|I/I_0|$ at Climax in Fig. 5.

(iv) *The diffusion time of the cosmic-ray particle.*

In our model mentioned above, the width of the region II, $b$, is $(2\sim3)\times10^{12}$ cm and the average intensity of the magnetic field, $H$, is $10^{-4}$ gauss. And so, it follows that the diffusion time, $\tau_d$, of the cosmic-ray particle, for instance, of the energy of 3 Bev is $\sim10^4$ sec.

On the other hand, when we put $E_c\sim$ 60 Bev, then

$$n=20 \quad \text{for} \quad E=3\,\text{Bev}\ .$$

Therefore, the storage time, $\tau_s$, of the cosmic-ray particle within the region III is $\sim10^8$ sec. Then,

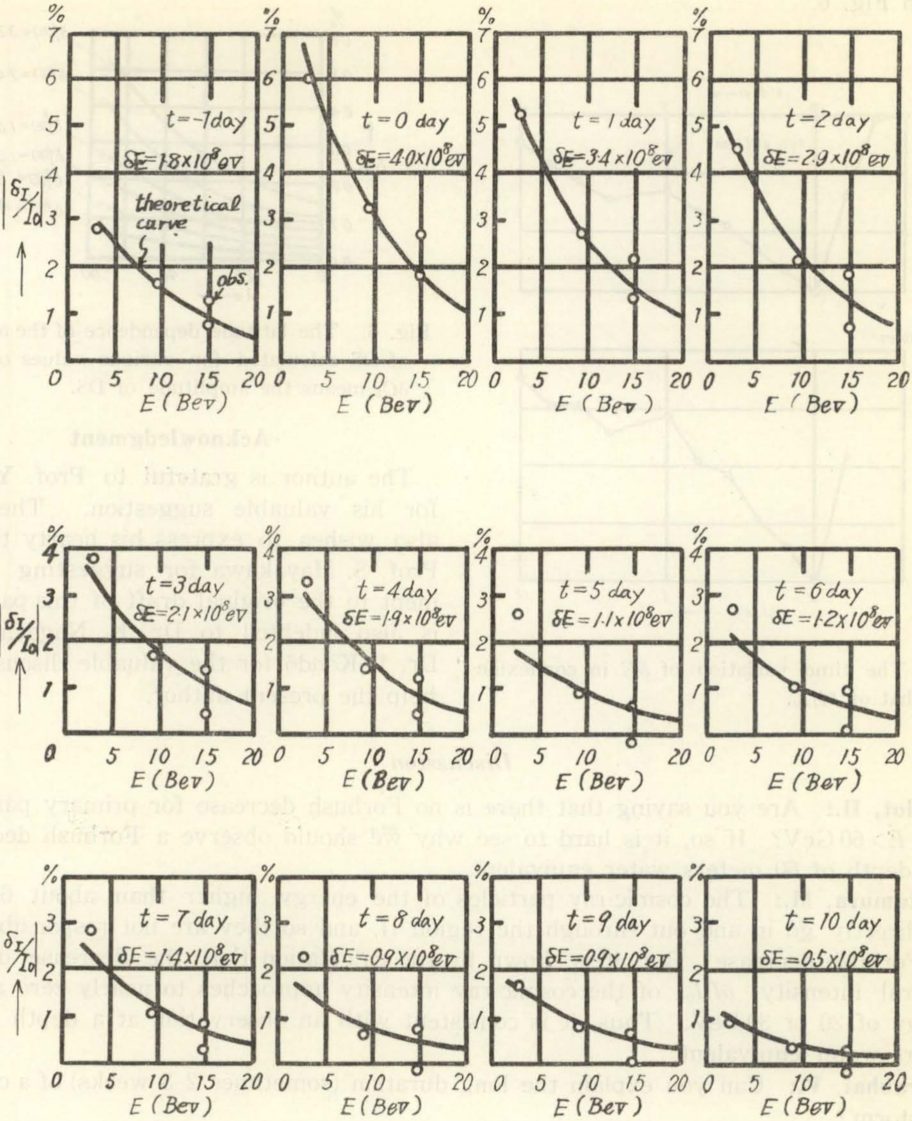


Fig. 4. The time sequence of the energy dependence of the cosmic-ray decrease. Solid lines show the theoretical curves for the presented values of $\delta E$ and circles show the observed values.

$$\tau_d > \tau_s \ .$$

Therefore, we come to the conclusion that the deceleration mechanism of the cosmic-rays by the expansion of the magnetic cloud is fully effective.

## § 2. The Mechanism of DS of the Cosmic-ray Storm.

Finally, we should like to point out that the possibility that DS of the cosmic-ray storm is produced by the magnetic cloud as well as Dst, considering the anisotropy of the expansion velocity of the magnetic cloud. That is, when

$2\delta f(E)=$(the energy loss at dark hemisphere of the earth)
$-$(that at sunlit hemisphere of the earth).

which is caused by the anisotropy of the expansion velocity of the magnetic cloud, then the theoretical curves of the latitude dependence of the amplitude of DS is obtained as shown in Fig. 6.

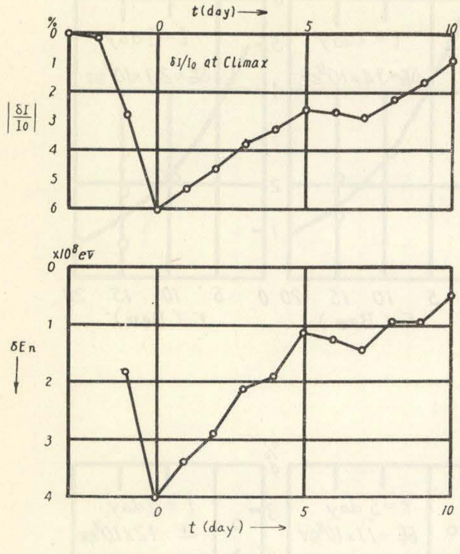

Fig. 5. The time variation of $\delta E$ in connexion with that of $\delta I/I_0$.

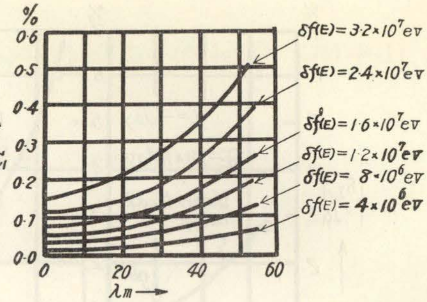

Fig. 6. The latitude dependence of the amplitude of DS calculated for various values of $\delta f$ $(E)$. $\delta C_1$ means the amplitude of DS.

**Acknowledgment**

The author is grateful to Prof. Y. Sekido for his valuable suggestion. The author also wishes to express his hearty thanks to Prof. S. Hayakawa for suggesting improvement to the original draft of this paper. He is also indebted to Dr. K. Nagashima and Dr. I. Kondō for the valuable discussions to help the present author.

## *Discussion*

**Elliot, H.:** Are you saying that there is no Forbush decrease for primary particles with $E>60$ GeV? If so, it is hard to see why we should observe a Forbush decrease at a depth of 60 meters water equivalent.

**Kitamura, M.:** The cosmic-ray particles of the energy higher than about 60 BeV can directly go in and out through the region II, and so they are not responsible for the Forbush decrease. But, it is shown by the calculation that the decrease of the integral intensity, $\delta I/I_0$, of the cosmic-ray intensity approaches to nearly zero at the energy of 20 or 30 BeV. Thus, it is consistent with an observation at a depth of 60 meters water equivalent.

**Sarabhai, V.:** Can you explain the long duration (sometimes 2-3 weeks) of a cosmic ray storm?

**Kitamura:** We did not discuss the cosmic-ray storm of the long duration such as about 3 weeks in this paper.

**Gold, T.:** Would Dr. Kitamura like to say whether the exclusion time-constant will get long as the size of a region is increased. Can this get long enough to account for the 11 year cycle?

**Kitamura:** The storage time of a particle in the region III becomes larger as the size of the region is increased. And when the width $b$ of the diffusion region II is large enough, it may be explained by such a mechanism as mentioned here. I think that the 11 year variation is produced by the large scale modulation mechanism in the solar system.