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-4-20 The Energy Spectrum and the Energy Balance of Cosmic Radiation

H. KOMORI

Physical Institute, Yamanashi University, Kofu, Japan

The energy spectrum of cosmic radiation in the geomagnetic field sensitive region has been obtained taking account of the modified dipole field as the geomagnetic field, and of splash albedo which is considered only in the case of the proton. For example, the integral energy spectrum of the proton with the kinetic energy from 0.5 GeV to 15 GeV is expressed by $0.353\,(Mc^2+E)^{-1.0}$, where Mc^2 is the rest mass of the proton and E the kinetic energy in unit of GeV. The above spectrum is derived from the data of quiet solar years.

Since the cutoff rigidity depends not only on the geomagnetic latitude but also on the geomagnetic longitude, the energy balance of cosmic rays at four stations, *i.e.* Saskatoon (Geomagnetic latitude 60.5°, geomagnetic longitude 311.9°), Minneapolis (55.2°, 330.9°), San Angelo (41.3°, 317.3°), and Guam (3.6°, 212.9°) has been analyzed. Adopting the revised energy spectrum and taking account of the under-estimation in the nuclear disintegration, one could expect a good agreement between the incident energy and the energy dissipated in the atmosphere at any place. If it is so, the fact that the pure dipole field does not well explain the phenomena would be also derived from this point of view.

§ 1. Introduction

It is important to determine an accurate primary energy spectrum in the investigation of the cosmic rays, especially, in the analysis of the energy balance. Previously, the author[1] investigated the energy balance, and concluded that the difference between the incident energy and the energy loss seems to be considerable. It was attributed to albedo which was not studied well at that time. The same conclusion has also been obtained by Puppi independently[2]. The experimental study on splash albedo has been made recently[3]. Further, it has been made clear that the pure magnetic dipole field failed to reveal the various observations well; for example the neutron latitude survey, the helium nuclei cutoff rigidity at high latitudes, and the particle distribution at the time of solar flare. Therefore, it would be worthwhile to reinvestigate the energy balance taking care of the above two points, *i.e.* albedo and the surface geomagnetic field. The same attentions are paid to the determination of the energy spectrum in this paper.

§ 2. Energy Spectrum

In this paper, the cutoff rigidity in the geomagnetic field sensitive region is calculated under three geomagnetic fields, *i.e.* pure ec-

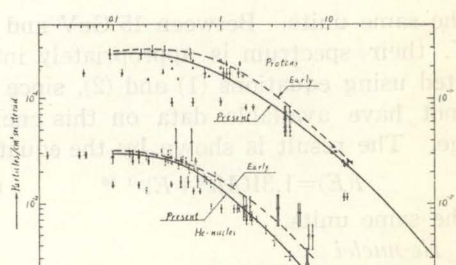

Fig. 1. Integral intensity-energy spectra for protons (upper curve) and *He*-nuclei (lower curve) in the solar minimum years. Solid curves represent the present spectra and dotted curves express the early spectra. Open triangles (△) show the cutoff energy under Rothwell's modified field theory, solid triangles (▲) show that under Quenby and Webber's modified field theory, and squares (□) show that under pure eccentric dipole field theory. So, three points which correspond to three theories on the cutoff rigidity stand abreast, in principle. Crosses give the experimental data which are directly determined by ionization or scattering, not by geomagnetic effect.

centric dipole field, Rothwell's[4] modified field, and Quenby and Webber's[5] modified field.

2.1 Protons

According to reference 3, five percent of fast particles is subtracted as splash albedo from the absolute intensity of the primary proton without any consideration on albedo. The energy spectrum of protons is constructed by a large number of experimental data on the primary intensity and is shown in Fig. 1.

Present integral energy spectrum of protons for the energies 0.5 GeV $\leqq E \leqq$ 15 Gev may be expressed by the equation

$$I(E)=0.353(Mc^2+E)^{-1.0} \qquad (1)$$

in units of (cm^2 sec sterad)$^{-1}$, with E measured in Gev, where Mc^2 is the rest mass of a proton. For the energy range from 10^3 GeV to 10^6 GeV, their spectrum may be represented by the equation

$$I(E)=8.79(Mc^2+E)^{-1.73} \qquad (2)$$

in the same units. For the energies greater than 10^6 GeV, their spectrum may be given by the equation

$$I(E)=3.6\cdot 10^{-10}\left(\frac{10^6}{E}\right)^{(1.74\pm 0.09)+0.02\ln(E/10^6)} \qquad (3)$$

in the same units. Between 15 GeV and 10^3 GeV, their spectrum is appropriately interpolated using equations (1) and (2), since we do not have available data on this energy range. The result is shown by the equation

$$I(E)=1.31(Mc^2+E)^{-1.46} \qquad (4)$$

in the same units.

2.2 He-nuclei

The same procedures as protons are taken to determine the integral energy spectrum of *He*-nuclei. The energy spectrum of *He*-nuclei is constructed by a good deal of experimental data on the primary intensity and is shown in Fig. 1, where E must be read as kinetic energy per nucleon. We can determine the spectrum accurately, since we have many experimental data which are directly determined by ionization or scattering, not by geomagnetic effect. The integral energy spectrum of *He*-nuclei for the energies 0.5 GeV/nucleon $\leqq E \leqq$ 8 GeV/nucleon may be represented by the equation

$$I(E)=3.32\cdot 10^{-2}(Mc^2+E)^{-1.4} \qquad (5)$$

in units of (cm^2 sec sterad)$^{-1}$, with E measured in GeV/nucleon. The slope on energy of equation (5) may be more correct than that of early work from the above reason.

2.3 Heavy Primaries

(i) *Light elements*

On the light elements ($3 \leqq Z \leqq 5$), we have relatively a small number of experimental data. However, we can draw the spectrum assuming that the light elements also have the same slope as that of *He*-nuclei in the geomagnetic field sensitive region. Thus, the integral energy spectrum for energies 1.5 GeV/nucleon $\leqq E \leqq$ 8 GeV/nucleon may be given by the equation

$$I(E)=5.13\cdot 10^{-4}(Mc^2+E)^{-1.4} \qquad (6)$$

in units of (cm^2 sec sterad)$^{-1}$, with E measured in GeV/nucleon.

(ii) *Medium elements*

On the medium elements ($6 \leqq Z \leqq 9$), we have many experimental data. The integral energy spectrum for energies 1.5 GeV/nucleon $\leqq E \leqq$ 8 GeV/nucleon may be expressed by the equation

$$I(E)=2.60\cdot 10^{-3}(Mc^2+E)^{-1.4} \qquad (7)$$

in units of (cm^2 sec sterad)$^{-1}$, with E measured in GeV/nucleon.

(iii) *Heavy elements*

On the heavy elements ($Z \geqq 10$), we have a good many experimental data. The integral energy spectrum for energies 1.5 GeV/nucleon $\leqq E \leqq$ 8 GeV/nucleon may be represented by the equation

$$I(E)=6.49\cdot 10^{-4}(Mc^2+E)^{-1.4} \qquad (8)$$

in units of (cm^2 sec sterad)$^{-1}$, with E measured in GeV/nucleon.

§ 3. Incident Energy

The incident energy at a place is obtained by integrating the energy spectrum with respect to energy from the cutoff energy to infinity. In the calculation of cutoff energies for heavy primaries, the average values for atomic number and for mass number have been taken from the experimental data on abundance. They are for *L*-elements, *M*-elements, and *H*-elements, (4.2, 9.7), (6.95, 14.0), and (14.2, 30.5), respectively.

The values integrated are given in Table I.

§ 4. Energy Dissipated in the Atmosphere

Using the intensity *vs.* atmospheric depth

Table I. Incident and dissipated energies in units of MeV cm^{-2} sec^{-1} $sterad^{-1}$. The indicated errors represent statistical errors.

		Saskatoon	Menneapolis	San Angelo	Guam
Incident	Protons	1000	889	565	346
	He-nuclei	205	200	178	78
	L-elements	6	6	4	1
	M-elements	48	47	28	21
	H-elements	40	40	21	5
	Sum	1300±30	1180±30	796±18	451±10
Dissipated	Protons, ionization loss	131	129	76	16
	$\pi^{\pm}$-mesons	423	416	356	208
	π^0-mesons	278	265	227	157
	Nuclear disintegrations	314	301	139	53
	Sum	1150±80	1110±80	798±40	434±20

curves for total intensity and the method described in § 2 of reference 1, one obtains the intensity *vs.* atmospheric depth curves for various components.

4.1 Protons

The average collision loss of protons with range $R \geqq 100\ g\,cm^{-2}$ air is taken as equal to 2.0 Mev per $g\,cm^{-2}$. The average collision loss of protons with R between $2\ g\,cm^{-2}$ and $100\ g\,cm^{-2}$ is given to be 6.6 Mev per $g\,cm^{-2}$. Then, the collision losses of protons are immediately obtained and are shown in Table I.

4.2 π-Mesons

(1) $\pi^{\pm}$-Mesons

The generation functions of $\pi^{\pm}$-mesons are obtained by the same method as the method given in reference 2 from the energy spectrum of μ-mesons and the intensity *vs.* altitude curve of μ-mesons. These functions are shown in Fig. 2. Assuming that the $\pi^{\pm}$-mesons are alone responsible for the μ-mesons, the energies of $\pi^{\pm}$-mesons are calculated from Fig. 2 and are given in Table I.

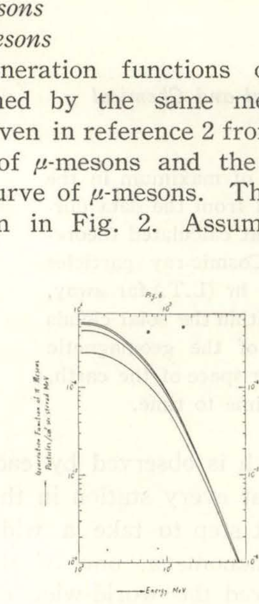

Fig. 2. Generation function of π-mesons. Curves for Saskatoon, Minneapolis, San Angelo, and Guam are given in order of above.

(2) π^0-Mesons

The electron component is generated through the μ-e decay, the nuclear collision, and the conversion of the π^0-mesons. The energies of electrons are immediately obtained from their intensity-altitude curves as the method in reference 1. Subtracting the energies for μ-e decay and the nuclear collision from the above energies for electrons, we can estimate the energies for π^0-mesons. The results are given in Table I.

4.3 Nuclear Disintegration

There is an unavoidable difficulty for the estimation of the nuclear disintegration caused by some uncertainties due to ambiguities for the slow neutron data. If we assume that the neutrons are produced in nuclear disintegrations with kinetic energy of 4 MeV, we find that the number of neutrons produced must be $(22 \pm 4)\ cm^{-2}\ sec^{-1}$ at the geomagnetic latitude about 50°[6]. However, we take the value of $18\ cm^{-2}\ sec^{-1}$ for the number of neutrons at that latitude, since it is fortunate if we find a good agreement between the incident energy and the energy dissipated even if we underestimate the energy losses of nuclear distintegrations. The intensities of neutrons at other latitudes are estimated from the data of the neutron latitude survey[7]. The energies for nuclear disintegrations are calculated by the same way as the method given in reference 2, and are given in Table I.

§ 5. Conclusion

We find a good agreement between the incident energy and the energy dissipated, taking into account the underestimation in the nuclear disintegration. In fact, at Saskatoon about 50 MeV $cm^{-2} sec^{-1} sterad^{-1}$ may be added to the preceding value. Therefore, adopting the revised energy spectra, one could expect a good agreement between them at any place. If it is so, the fact that the pure dipole geomagnetic field theory does not well explain the phenomena would be also derived from this point of view.

The author wishes to express his cordial thanks to Professor K. Nagashima for valuable discussions.

References

1) H. Komori: Progr. Theor. Phys. **13** (1955) 205.
2) G. Puppi: *Progress in Cosmic Ray Physics* **3** ed. by J. G. Willson: (North-Holland Publishing Co. Amsterdam, 1956) 341.
3) F. B. McDonald and W. R. Webber: Phys. Rev. **115** (1959) 194.
4) P. Rothwell: Phil. Mag. **3** (1958) 961.
5) J. J. Quenby and W. R. Webber: Phil. Mag. **4** (1959) 90.
6) M. Galli: Nuovo Cimento **10** (1953) 1187.
7) J. A. Simpson: Phys. Rev. **83** (1951) 1175.

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-4-21. On the World-wide Distribution of the Daily Variation of the Cosmic-Ray Neutron Intensity and Its Variation

Tsunekichi KANNO
Department of Physics, Fukushima University, Fukushima, Japan

AND

Kazuaki MURAKAMI
Cosmic-Ray Laboratory, The Institute of Physical and Chemical Research, Tokyo, Japan

The world-wide distribution of T_m (the local time of maximum in the diurnal variation of cosmic-ray intensity) was derived from the data during the period of I.G.Y. and was compared with that calculated theoretically. The following results were obtained. (1) Cosmic-ray particles seem to have an anisotropy in the direction of 17 hr (L.T.) far away, and to be modulated in the direction of 12 hr (L.T.) within the solar clouds in the interplanetary space. (2) The lines of force of the geomagnetic field may be assumed to bend westwards in the outer space of the earth. (3) The cosmic-ray equator may be changing from time to time.

§ 1. Introduction

If the time variation of the world-wide distribution of cosmic-ray intensity is measured continuously and thoroughly, we can easily carry out analysis to find the mechanism of the modulation of cosmic rays in the interplanetary space. However, it is rather difficult, at present, to normalize the counting rate which is observed by each cosmic-ray monitor at every station in the world.

As the first step to take a wide view of cosmic-ray phenomena, one of the authors (T. K.)[1] derived the world-wide distribution of the time of maximum in the diurnal variation of cosmic-ray intensity (T_m). The time variation of the distribution of T_m was also