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(Received 18 March, 1972; accepted 2 May, 1972.)

Latitude Distribution of Cosmic Rays at Sea Level from 1963 to 1970

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The latitude distribution of cosmic rays at sea level, in the region of the Cape Town Magnetic Anomaly, compares well with the distribution in the North American region when vertical cutoff rigidities computed from particle trajectories in a simulated geomagnetic field are used. From the North American latitude distribution during minimum modulation of cosmic rays in May 1965, the distributions in January of each year from 1963 through to 1970 were calculated. They were found to compare well with the survey data if uncertainties in air pressure and changes in the rigidity dependence of the modulation of cosmic rays in 1969 and 1970 were taken into consideration.

Die breedtegraadspreiding van kosmiese strale op seevlak in die gebied van die Kaapstadse Magnetiese Anomalie vergelyk goed met die spreiding oor Noord-Amerika indien vertikale afsnystyfhede, bereken met deeltjiebane in 'n gesimuleerde geomagnetiese veld, gebruik word. Uitgaande van die Noord-Amerikaanse breedtegraadspreiding gedurende minimummodulasie van kosmiese strale in Mei 1965 is die breedtegraadspreiding vir Januarie van elke jaar van 1963 tot 1970 bereken. Die waargenome breedtegraadspreiding vergelyk goed met hierdie berekende spreidings as die onsekerhede in lugdruk en die veranderinge in styfheidsafhanklikheid van die modulasie van kosmiese strale in 1969 en 1970 in aanmerking geneem word.

Introduction

The intensity of the horizontal component of the geomagnetic field reaches a local maximum in a region slightly to the south of South Africa, the region being known as the South African or Cape Town Magnetic Anomaly. This is a true geomagnetic anomaly in the sense that it cannot be explained only by a magnetic dipole. The Brazilian Magnetic Anomaly is characterized by a minimum in the total intensity of the earth's field, situated at and off the coast of Brazil. This anomaly can be explained by a magnetic dipole displaced from the centre of the earth in the direction opposite to the Brazilian region.

Since the trajectories of cosmic rays are greatly influenced by the magnetic field they traverse, the effect of the anomaly should be apparent on cosmic rays recorded on earth in the region of the South African Magnetic Anomaly. *Van der Walt et al.* (1969) have shown that the effect of the anomaly on cosmic rays recorded in the vicinity of South Africa can be explained when vertical cutoff rigidities from computer-calculated trajectories of cosmic rays in a simulated geomagnetic field are used. This is also apparent from the surveys conducted by *Kodama*

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(1968) from Japan via Cape Town to the Japanese Antarctic base Syowa.

The results obtained during the research flights undertaken by the South African Air Force, on behalf of the CSIR Cosmic Ray Research Unit at the Potchefstroom University and the Department of Physics of the University of Stellenbosch, showed that the modulation of cosmic rays during August 1969 was anomalous, and according to neutron monitor data this anomalous modulation continued during the greater part of 1970 (*Stoker et al.*, 1972). The data obtained from the ship-borne neutron monitor during relief voyages of the M.V. *RSA* of the Department of Transport were therefore analyzed to investigate this period of anomalous modulation, which occurred during the time of maximum activity in the present solar cycle.

Modulation of Cosmic Rays observed at Airplane Altitude

If $j_\infty(P)$ is the differential intensity of galactic cosmic rays of rigidity P outside the interplanetary magnetic field region, the intensity at the orbit of the earth inside this field at a time t may be written (*Jokipii*, 1971) for $P \gtrsim 1$ Gv as

$$j(P,t) = j_\infty \exp\,[-\varphi(P,t)], \qquad (1)$$

where $\varphi(P,t)$ is the modulation function for cosmic ray particles of rigidity P due to the state of the interplanetary magnetic field at the time t.

From this equation it follows that the differential intensities of cosmic rays at two different times of solar activity, t and t_0, are interrelated by

$$\begin{aligned} j(P,t) &= j(P,t_0) \exp\,[-\varphi(P,t)+\varphi(P,t_0)] \\ &= j(P,t_0) \exp\,[-M(P,t,t_0)], \qquad (2) \end{aligned}$$

where $M(P,t,t_0)$ is the modulation function of cosmic rays recorded on earth at a time t relative to a time t_0. For the long-term or eleven-year variation of cosmic rays the modulation at a time t is usually taken relative to the modulation at the time t_0 of minimum cosmic ray modulation during the period of minimum solar activity. From experimental data, it appears that the long-term or eleven-year modulation of cosmic rays, which is controlled by the quasi-steady state of the interplanetary magnetic field, may be represented (*Mathews et al.*, 1971; *Webber*, 1968) by a modulation function of the form

$$\begin{aligned} M(P,t,t_0) &= \frac{\eta(t)}{P} - \frac{\eta(t_0)}{P} \\ &= \frac{\triangle\eta}{P}, \qquad (3) \end{aligned}$$

where $\triangle\eta = \eta(t) - \eta(t_0)$ is the modulation parameter for the time t relative to t_0.

This modulation function (3) was found to be in accordance with the modulation of cosmic rays as recorded during the survey flights at 30 000 feet pressure altitude along the Cape Town magnetic meridian in October 1964 and August 1966. But a much more strongly rigidity-dependent modulation function was effective during the time of the flights in August 1969 (*Stoker et al.*, 1972), having a form like

$$M(P,t,t_0) = \frac{\triangle\eta(t)}{P} + \frac{4{,}0}{P^2}. \qquad (4)$$

This function is confirmed by an analysis of ground-based neutron monitor data.

Apparatus

When the research vessel *RSA* of the South African Department of Transport became available in 1962 for cosmic ray latitude surveys during annual voyages from Cape Town to Antarctica, Marion Island, Gough Island and Tristan da Cunha, a neutron monitor was installed.

This was a Simpson type monitor, modified for a high counting rate with a small set-up. In 1963 this apparatus was replaced by an IQSY-type 1-NM-64 neutron monitor.

The neutron monitor was sealed in a steel box and placed on the deck of the *RSA*. In order to eliminate effects due to the severe change in air temperature during voyages to the Antarctic region, the temperature of the neutron monitor was thermostatically controlled. Furthermore, the thickness of the reflector of the IQSY-type monitor was increased to 20 cm in order to minimize effects on the counting rate due to the changes in environment.

The barometric pressure was recorded on a barograph, and also measured every two hours with a mercury barometer by the officer on duty. The latter readings were used to correct the counting rate of the neutron monitor for variations in the air pressure.

Results

The results for the years of decreasing solar activity, 1963, 1964 and 1965, are represented in Fig. 1, while the results for subsequent years of increasing solar activity are presented in Fig. 2. The two-hourly values of pressure-corrected counting rate for the surveys between July of the one year and June of the following year were corrected for secular variation in cosmic ray intensity. This was done by utilizing the counting rates of the neutron monitors at Deep River ($P_c = 1{,}0$ Gv) and Hermanus ($P_c = 4{,}9$ Gv) in relation to the average counting rate in January of that year. For the correction of secular variations in cosmic rays recorded at cutoff rigidities between 2,0 and 4,9 Gv, a sliding weighted average of the counting rates of both these neutron monitors were used, while at rigidities at and above 4,9 Gv only the counting rates of

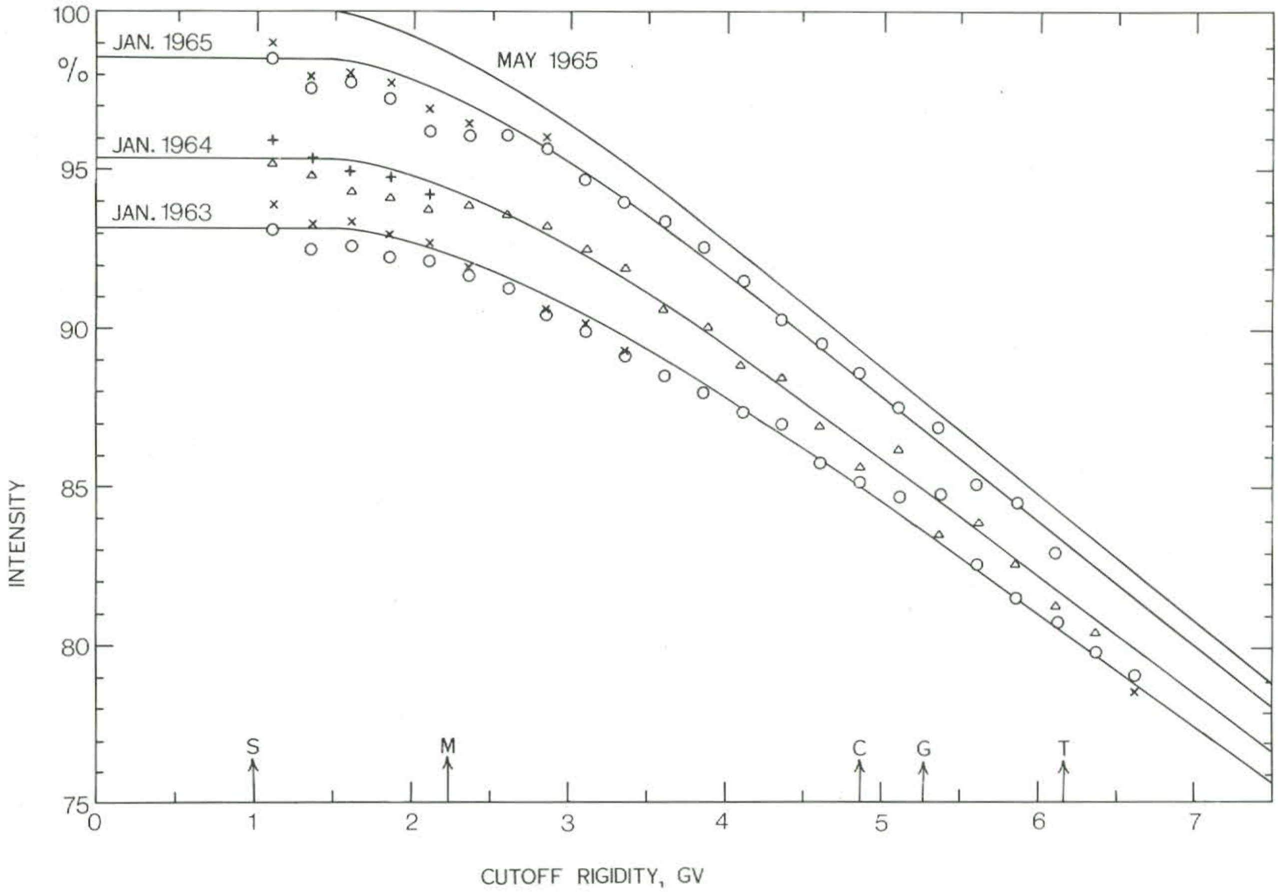

Fig. 1. The calculated and measured latitude distributions of the intensity of cosmic rays during the last years of the previous solar cycle. The open symbols represent the data corrected for changes in air pressure with a barometric coefficient given by equation (5); the crossed symbols are for a barometric coefficient independent of cutoff rigidity. The positions of the arrows correspond to the cutoff rigidities at Sanae (S), Marion Island (M), Cape Town (C), Gough Island (G), and Tristan da Cunha (T).

the Hermanus neutron monitor were used, and at cutoff rigidities below 2,0 Gv only those of the Deep River neutron monitor.

In the Figures the averages of the six-hourly values of counting rate over intervals of 0,25 Gv are given. Cutoff rigidities for the six-hourly points were interpolated from $2^\circ \times 2^\circ$ grid values of cutoff rigidities, interpolated by *Shea & Smart* (1966) from computer-calculated values. The results were corrected by means of a regression techique for small drifts in neutron monitor sensitivity during different voyages, probably due to changes in the extra-high tension supply. The annual intensity-latitude curves were normalized in such a way that the mean intensity at rigidities below 1,5 Gv for May 1965 at minimum modulation of cosmic rays was 100. This corresponds to a counting rate of approximately 60 000 counts per hour. Furthermore, a correction was applied to the annual curves in order to have the mean intensity at rigidities below 1,5 Gv the same as the normalized mean intensity for January for the neutron monitor at Deep River. This correction amounted to less than 2 per cent for any year.

Counting rates were corrected for variation in air pressure according to the findings of *Carmichael & Bercovitch* (1969) using a barometer coefficient that changes with cutoff rigidity. This barometer coefficient was represented by

$$\beta = (\beta_5 - \beta_2)\,\frac{P_c - 2}{3} + \beta_2 \qquad (5)$$

where

$$\beta_2 = 0{,}00737 \text{ mbar}^{-1},$$
$$\beta_5 = 0{,}0072 \text{ mbar}^{-1}$$

and P_c is the cutoff rigidity.

This dependence on cutoff rigidity of the barometer coefficient for the neutron monitor on the *RSA* was suggested by the analyses of *Joubert* (1968). The effect of a constant barometer coefficient instead of the rigidity dependent coefficient is also shown in Fig. 1.

The latitude distribution at minimum modulation of cosmic rays in May 1965, during the period of minimum solar activity, is represented by the upper curve in both figures. This is the intensity distribution at sea level reported by *Carmichael & Bercovitch* (1969) for a latitude survey across North America at the time of solar minimum. Using the modulation function (3), the parameter $\triangle\gamma_l$ was obtained from the average intensity of cosmic rays recorded by ground-based neutron monitors in January of each of the years concerned, relative to May 1965. The solid curves in

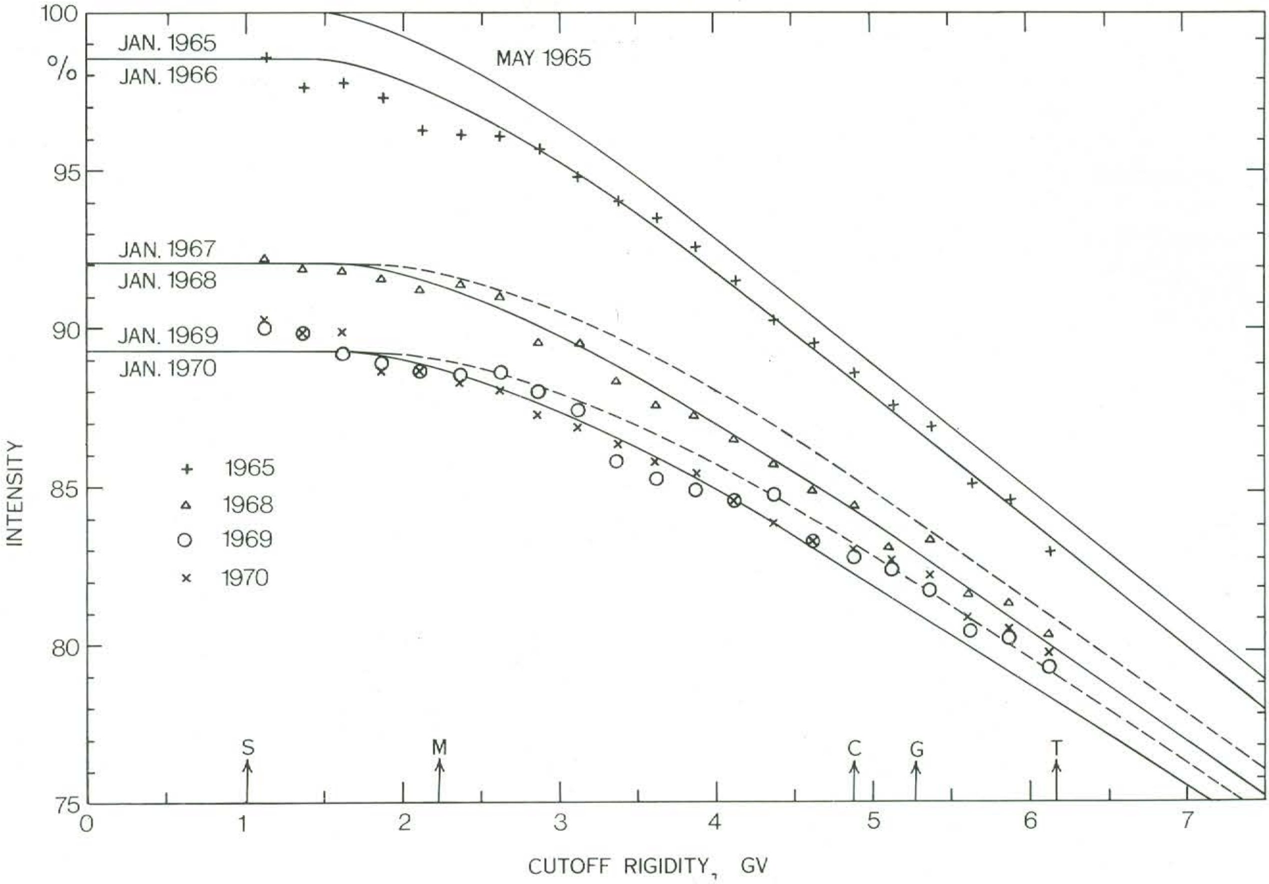

Fig. 2. The calculated and measured latitude distributions of the intensity of cosmic rays during the rising part of the present solar cycle. The positions of the arrows correspond to the cutoff rigidities at Sanae (S), Marion Island (M), Cape Town (C), Gough Island (G) and Tristan da Cunha (T).

the Figures were calculated from the solar minimum distribution of Carmichael & Bercovitch, by using these values of $\triangle\eta$ and the modulation function (3). The broken curves for 1968, 1969 and 1970 were calculated by using the modulation function (4), with $\triangle\eta$ again determined from ground-based neutron monitor data. The modulation of cosmic rays in January of 1969 and 1970, of 1967 and 1968, and of 1965 and 1966, were very nearly the same and could be represented by the same latitude curve. The data points for 1966 and 1967 were omitted for clarity.

Discussion

When comparing the experimental latitude distribution for a particular year with the calculated distribution, one must take into account the error due to the effect of wind on the measured barometric pressure. Although the indoor air pressure was measured accurately by a Fortin barometer, strong winds can change this pressure by up to about 1,5 mbar. This changes the pressure-corrected counting rate by about 1%. Wind effect can therefore introduce systematic errors of up to about 1% in the six-hourly values of pressure-corrected counting rates. Although the statistical error for the counting rates should be ±0,2%, a root mean square analysis of the deviations of these counting rates in the intervals of 0,25 Gv in cutoff rigidity from the average in each interval shows a distribution that varies from 0,2% to 1,6%, which confirms that there is a varying systematic error in the six-hourly counting rates.

The experimental data points in Fig. 1 for the years 1963 through to 1965 follow quite well the distributions calculated from the distribution found by *Carmichael & Bercovitch* across North America for May 1965, taking varying errors due to wind into account. These results confirm the form of the modulation function (3) for the recovery of the previous solar cycle. Furthermore, they also confirm that the latitude distribution at sea level, in terms of vertical cutoff rigidities calculated from trajectories of cosmic ray particles in the simulated geomagnetic field, is the same in the region of the Cape Town Magnetic Anomaly as that outside the anomaly across North America.

The conclusion for the rising part of the present solar cycle for the years 1965 through to 1968 is, according to the data presented in Fig. 2, the same as for the recovery part of the previous solar cycle. During 1967 and 1968 the experimental data clearly followed the distribution obtained from the modulation function (3). For 1969 and 1970, during solar maximum, the experimental data tended to follow the distribution predicted by the modulation function (3) at low cutoff rigidities, but at higher cutoff rigidities the modulation appears to be relaxed, as predicted by the modulation function (4). According to the survey at an altitude of 30 000 feet pressure, the modulation corresponded to this latter function along the whole range of cutoff rigidities in August 1969 (*Stoker et al.*, 1972). *Verschell et al.* (1971) concluded from observations on polar flights at very high altitudes that the hardening of the primary spectrum of cosmic rays was a variable function of rigidity in 1969, while *Stoker & Carmichael* (1971) reported a marked change in June 1968 and again in July 1969 in the modulation of cosmic rays as observed by neutron monitors in low latitudes relative to that observed by monitors in high latitudes. Since our surveys by ship-borne neutron monitor along lower cutoff rigidities to Sanae and along higher cutoff rigidities to the islands Gough and Tristan da Cunha were always two to four months apart, this rigidity-dependent variability in modulation should be reflected in the experimental data presented in Fig. 2 for 1969 and 1970. It is however interesting to note that the experimental distributions for these two years follow each other very closely and that they differ from the distributions of the previous year, in particular for the higher rigidities in the vicinity of Gough Island and Tristan da Cunha. It has also to be noted that these distributions were not recorded simultaneously with the aircraft surveys, and that they need not be accounted for by the same modulation function as they were taken in a period when the rigidity dependence of the modulation function was varying.

Conclusions

The latitude distribution of cosmic rays at sea level in the region of the Cape Town Magnetic Anomaly is explained, within the accuracy of the data, by vertical cutoff rigidities obtained from the study of trajectories of cosmic rays in a sixth-degree simulation of the earth's magnetic field.

The latitude distribution of cosmic rays during the last few years of the previous solar cycle and the first few years of the present solar cycle can be accounted for by a modulation function of the form $\triangle\eta/P$. The distribution during the time of solar maximum of the present solar cycle is in accordance with a more strongly rigidity-dependent modulation function at middle latitudes.

The annual surveys of cosmic rays by the neutron monitor on the M.V. *RSA* may yield definite information on variations in rigidity dependence of the modulation of cosmic rays if the existing uncertainty due to the effects of wind on the recorded air pressure is eliminated. The latitude distributions, as represented by a pair of broken and solid curves in Fig. 2, differ most strongly at middle latitudes. This is a consequence of the P^{-2} term in (4) and the different values of $\triangle\eta$ in the modulation functions (3) and (4) for the same integral intensity at low latitudes.

Acknowledgements

We gratefully acknowledge the co-operation of the Department of Transport and in particular of Captain McNish of M.V. *RSA* and his officers.

The Editor thanks H. Carmichael and J. R. Jokipii for their assistance in evaluating this paper.

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(Received 13 April, 1972; accepted 8 June, 1972.)