Sea level cosmic ray intensity and threshold rigidity

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ABSTRACT

The intensity of the nucleon component has been measured with a shipboard neutron monitor during a number of voyages between Oct. 1956 and March 1959. After reduction and normalization the intensity has been plotted as a function of the rigidity value computed by Quenby and Wenk. Four limited regions excepted, the point distribution is confined to a comparatively narrow band corresponding to the errors of measurement. Corrected threshold values are given for the regions in which the points fall outside the general distribution. These regions are all inside the geomagnetic latitudes between which Quenby and Wenk had to interpolate for the penumbral effect.

Introduction

The cosmic ray threshold rigidities have been the subject of much discussion since it was found that even the eccentric dipole model failed as an appropriate approximation of the terrestrial magnetic field (ROSE, FENTON, KATZMAN and SIMPSON 1956, ROTHWELL 1958, KATZ, MEYER and SIMPSON 1958). Several authors have carried out calculations accounting for the nondipole terms of the Gaussian expansion of the field (ROTHWELL, 1958; QUENBY and WEBBER, 1959; KELLOGG, 1960; QUENBY and WENK, 1962). The most advanced work until date is that of Quenby and Wenk, who, in addition, introduced corrections for the penumbral effects.

From Oct. 1956 to Jan. 1958 a neutron monitor mounted on board M/S Lommaren made 4 double voyages between Scandinavian ports and South Africa. After being transferred to M/S Stratus it made two voyages (March 1958 to Febr. 1959) via South Africa to Australia and back across the Indian Ocean (Fig. 1). Part of the data from these expeditions have been employed for studies of the cosmic ray equator and the latitude knee (POMERANTZ, SANDSTRÖM and ROSE, 1958; POMERANTZ, POTNIS and SANDSTRÖM, 1960; POMERANTZ, SANDSTRÖM, POTNIS and ROSE, 1960; SANDSTRÖM, POMERANTZ and GRÖNKVIST, 1962). In the present paper the data from this survey are employed for a study of the threshold rigidities published by Quenby and Wenk.

The experimental set up has been described elsewhere (POMERANTZ, 1957). Altogether there were 10 passages west of Africa, 2 passages from South Africa to Australia and one passage each along two tracks across the Indian Ocean (Fig. 1).

Analysis of data

The data reductions were done for intervals of one hour. The mean counting rates for six hours were employed for the final analysis. The corresponding positions were obtained from the ship's log. Concerning the periods passed in port a mean has been calculated for the whole stretch of such a period.

To eliminate long time intensity variations the data have been normalized by comparison with fixed monitors. All the data were normalized with respect to the neutron monitor at Uppsala. In addition the data from the two voyages of M/S Stratus were normalized to the monitors at Huancayo *and* Uppsala by means of a linear equation. In the first case a period at the start of the whole series of voyages was

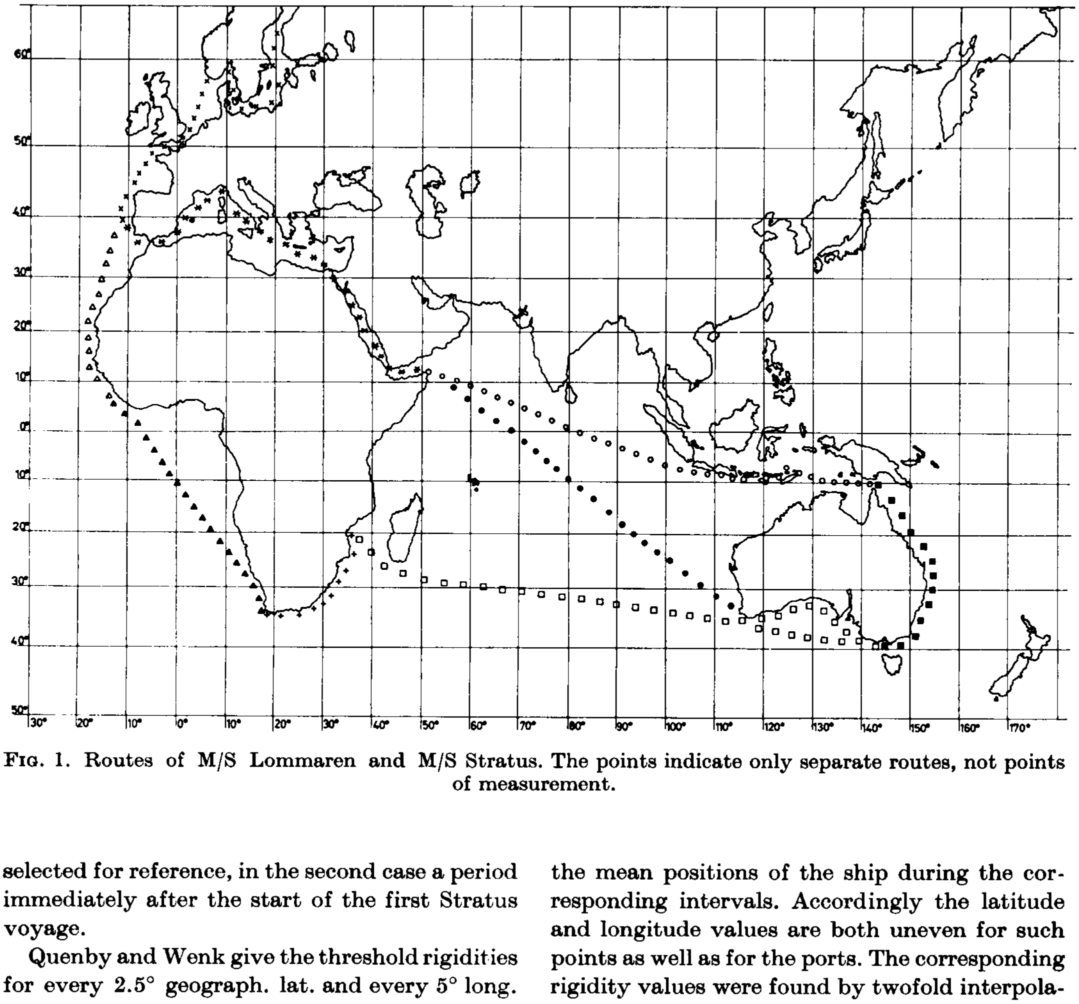

FIG. 1. Routes of M/S Lommaren and M/S Stratus. The points indicate only separate routes, not points of measurement.

selected for reference, in the second case a period immediately after the start of the first Stratus voyage.

Quenby and Wenk give the threshold rigidities for every 2.5° geograph. lat. and every 5° long. It was deemed appropriate to follow the same pattern in dealing with the present experimental data. For the determination of the relative intensity, corresponding to any point along the tracks, nomograms were constructed by plotting intensity, longitude, and latitude as functions of the time of passage. This method was applied only to those parts of the voyages where the routes of the ships coincide approximately with great circles. In coastal waters course and speed have to be changed frequently thus making it difficult to correlate the 6 hr averages of intensity with a definite position of the ship. Consequently, in these cases the data from the ships' visits to ports have been preferred to those from the short cruises from one port to the next. In some cases the latter data have been employed to cover gaps. The 6 hr values were ascribed to the mean positions of the ship during the corresponding intervals. Accordingly the latitude and longitude values are both uneven for such points as well as for the ports. The corresponding rigidity values were found by twofold interpolations from the tables by Quenby and Wenk. When the nomograms could be used the relative intensities were read for each 2.5° lat. or each 5° long. depending on the course of the ship. The nomograms ensure a partial elimination of the influence from random errors. The relative intensities recorded in ports have considerably smaller standard errors than those recorded at sea.

The voyages took place during a period characterized by big geomagnetic disturbances accompanied by prominent Forbush decreases. Consequently, as concerns the intensity values normalized to the Uppsala monitor alone, overcorrections are to be suspected for some of the values referring to low latitudes. Such overcorrections became apparent when the intensity was plotted as a function of cut off rigidities,

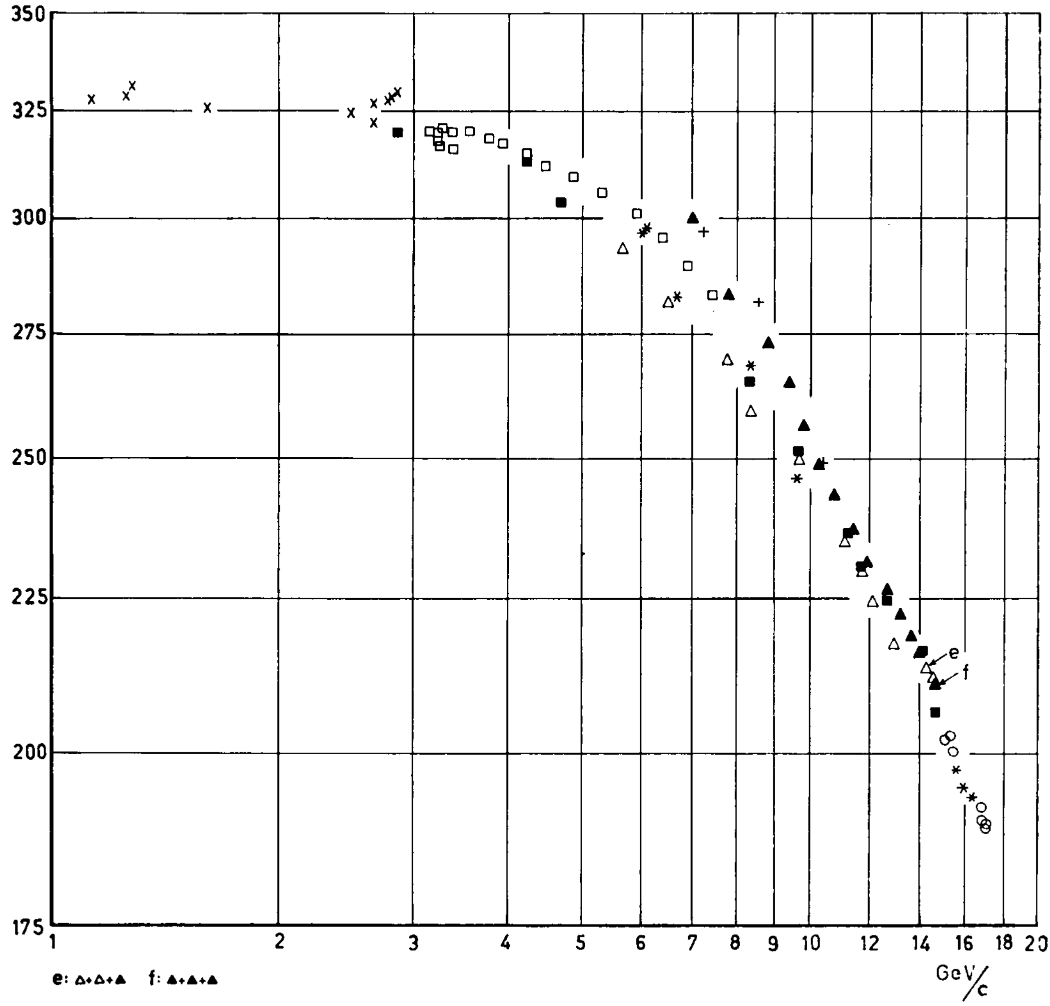

FIG. 2. The cosmic ray intensity records from the first voyage of M/S Stratus as a function of the threshold rigidities computed by Quenby and Wenk (1962). The diagram includes points obtained in regions where the threshold values have been found to be erroneous. The intensity scale refers to counts/6 hrs with a scaling factor of 192. The standard error is 0.5 per cent concerning points obtained when the ship was at sea. As concerns points from the ship's visits to ports the standard error varies but it is always ≤ 0.3 per cent.

single points of measurement in the equatorial region falling "out of line" when corresponding to records covering the most disturbed part of a decrease. To guard against errors being introduced through this effect all those values were excluded which had been recorded during prominent cosmic ray storms at geomagnetic latitudes below 40°. As a result the whole part below 40° of the first voyage of M/S Lommaren had to be discarded.

The relative intensities were plotted versus the threshold rigidities from the tables by Quenby and Wenk. In the first instance diagrams were drawn separately for each one of the six complete voyages (outbound and homebound in the same diagram). This set of diagrams was employed for the first scrutiny.

The first voyage of M/S Stratus took place during a period comparatively free from major disturbances. The results from this voyage are

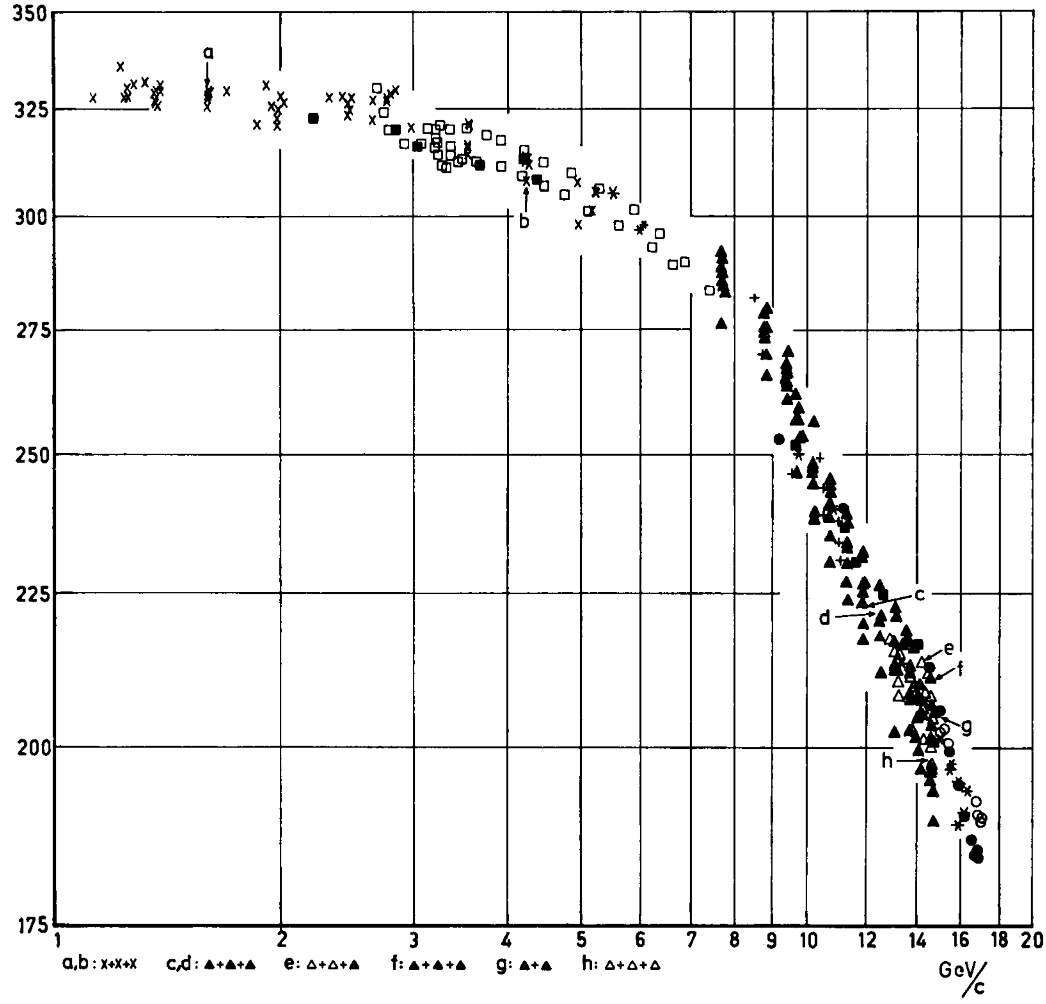

FIG. 3. The cosmic ray intensity as a function of the threshold rigidities computed by Quenby and Wenk (1962). From the records of all six voyages with exclusion of points obtained in regions where the threshold values have been found to be erroneous. The intensity scale refers to counts/6 hrs. Cases where two or several points coincide are indicated by arrows and lettering explained in the figure. The standard error is 0.5 per cent concerning points obtained when the ships were at sea. As concerns points from the ships' visits to ports the standard error varies but it is always $\leqslant 0.3$ per cent.

illustrated in Fig. 2. As concerns both Stratus voyages diagrams were plotted also with the values normalized to Uppsala *and* Huancayo. When compared to the corresponding diagrams of the values normalized to Uppsala alone the point distributions turned out to be almost identical. This proves the reliability of normalizations to a fixed monitor at high latitudes, at least after the removal of data from prominent Forbush decreases in the equatorial region.

It has been demonstrated by the results from "Project Magnet" (POMERANTZ and AGARWAL, 1962) that some of the threshold rigidities, computed by Quenby and Wenk, may be slightly in error between the Canaries and the Iberian Peninsula. This region was easily traced through the first scrutiny of the present data. Systematic deviations were found in some other instances, also. To establish a reliable reference curve these parts were excluded in a second scrutiny illustrated by Fig. 3. The differing values are plotted in Fig. 4. By comparison with Fig. 1 it is possible

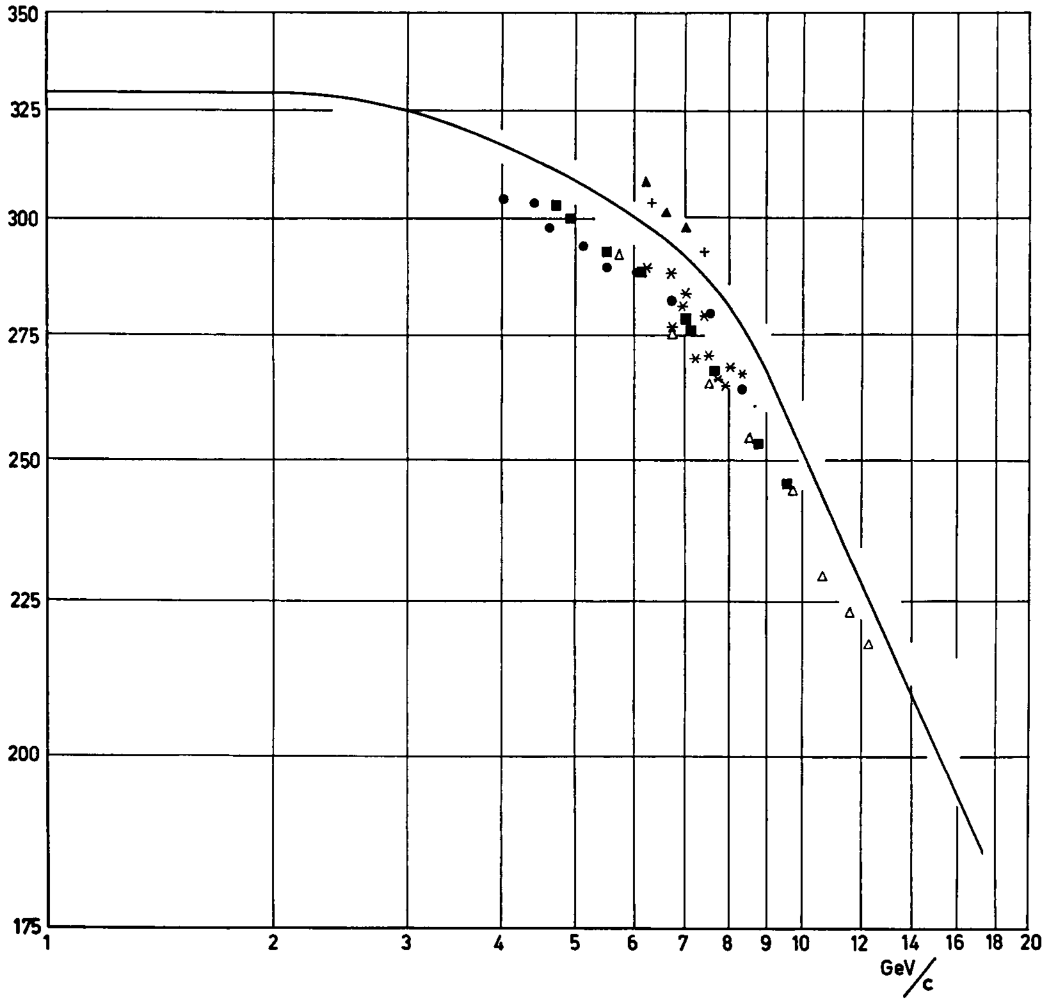

Fig. 4. Resultant curve from the points in Fig. 3. Points plotted between 4.0 and 12.2 GeV/c indicate regions where the computed threshold rigidities have been found to be erroneous. These regions can be identified by comparison with Fig. 1 and Table 5. The standard error is 0.5 per cent concerning points obtained when the ships were at sea. As concerns points from the ships' visits to ports the standard error varies but it is always $\leqslant 0.3$ per cent.

to identify part of the ships' routes to which the points belong.

The angular coefficient of the rectilinear part of the log-log diagram has been determined by means of a least square fit for points corresponding to rigidities bigger than 9.0 GeV/c. For comparison, this was done separately for each one of the six complete passages with and without data recording during Forbush decreases included (Table 1).

As concerns the two voyages of M/S Stratus the coefficient of the rectilinear part of the curves was determined also for the point distribution obtained from the normalization to Uppsala *and* Huancayo (Table 2). This normalization eliminates the influence of Forbush decreases. Comparisons between the values in Tables 1 and 2 confirm the conclusions from the close similarity of the point distributions corresponding to the two methods of normalization. Consequently we feel confident that the data normalized to Uppsala alone are as reliable as those normalized to Uppsala *and* Huancayo.

It is a remarkable fact that the slope of the

TABLE 1. *Exponent of effective integral spectrum. Data normalized to the Uppsala monitor.*

		Data from F.d:s in the equat. reg. removed		Data from F.d:s in the equat. reg. included	
		Exponent	Number of points	Exponent	Number of points
M/S Lommaren:	first voyage	—	0	−0.59 ± 0.02	29
	sec. voyage	−0.57 ± 0.02	29	−0.57 ± 0.02	29
	third voyage	−0.61 ± 0.03	16	−0.58 ± 0.04	30
	fourth voyage	−0.55 ± 0.01	30	−0.55 ± 0.01	30
M/S Stratus:	first voyage	−0.53 ± 0.02	42	−0.53 ± 0.02	42
	sec. voyage	−0.61 ± 0.03	16	−0.56 ± 0.02	38

rectilinear part of the log-log diagrams remains the same inside the limits of error when data are also included which were recorded during prominent decreases (Table 1). Indeed, for the second Stratus voyage the values remain the same for the two normalization methods although there is a difference of 0.04 when the Forbush decreases are excluded.

Between being taken off M/S Lommaren and subsequently mounted on M/S Stratus the monitor was stored ashore for about one month. The equipment was thoroughly readjusted before the second set of voyages. Judging from the spread of values in Table 1 it does not appear as if the dismounting and re-erection of the monitor can be the cause of any change in the values. However, the coefficient has been computed directly from all points of both sets of voyages (Table 3 and 4).

The two extreme values of −0.61 refer to cases where the rectilinear part of the diagram is determined by only 16 points.

The spread of the values in Table 1 is illustrated by Fig. 5. Concerning the voyages of Stratus the values are plotted also for the primary data being normalized to Uppsala *and* Huancayo. However, all the available points give the value of −0.56 for the coefficient of the inclined rectilinear part of the curve in Fig. 4. This is within twice the standard errors of the individual values. It is very close to the value obtained from the two Stratus voyages normalized to Uppsala *and* Huancayo.

The rectilinear part of the curve in Fig. 4 has been fitted to all the points of measurement above 9.0 GeV/c except those corresponding to observations during prominent Forbush decreases. The plateau region below 3 GeV/c has been discussed in a previous paper (SANDSTRÖM, POMERANTZ and GRÖNKVIST, 1962). The curved part between 3.0 and 9.0 GeV/c was determined by computing the mean intensities for points corresponding to the same rigidity or falling inside a very narrow rigidity interval. The latter never exceeded 0.3 GeV/c. Values recorded while the ships were in port have not been included in the computations of means. The errors from the Poisson distribution are very small in most of these cases. Consequently the values referring to ports were given the same weight as the means corresponding to positions on the open sea. Between the rigidities 3.0 and 9.0

TABLE 2. *Exponent of effective integral spectrum. Data normalized to Uppsala and Huancayo.*

		Data from F.d:s in the equat. reg. removed		Data from F.d:s in the equat. reg. included	
		Exponent	Number of points	Exponent	Number of points
M/S Stratus:	first voyage	−0.53 ± 0.01	42	−0.53 ± 0.01	42
	sec. voyage	−0.57 ± 0.03	16	−0.56 ± 0.02	38

TABLE 3. *Exponent of effective integral spectrum. Data normalized to the Uppsala monitor.*

	Data from F.d:s in the equat. reg. removed		Data from F.d:s in the equat. reg. included	
	Exponent	Number of points	Exponent	Number of points
M/S Lommaren	-0.57 ± 0.01	75	-0.56 ± 0.01	118
M/S Stratus	-0.54 ± 0.01	58	-0.53 ± 0.02	80
M/S Lommaren – M/S Stratus	-0.56 ± 0.01	133	-0.55 ± 0.01	198

TABLE 4. *Exponent of effective integral spectrum. Data normalized to Uppsala and Huancayo.*

	Data from F.d:s in the equat. reg. removed		Data from F.d:s in the equat. reg. included	
	Exponent	Number of points	Exponent	Number of points
M/S Stratus	-0.55 ± 0.01	58	-0.54 ± 0.01	80

GeV/c the curve was fitted as close as possible to the points thus obtained but with regard also for the point distributions in general. The curve was assumed to turn smoothly into the two rectilinear parts. Thus it cannot be avoided that points in the region 3–4 GeV/c are below the curve, the latter being forced upwards by the point distribution in the region 2–3 GeV/c. None of the points in the former region falls off the curve with more than twice the standard error. The curve fits especially well the points from the first Stratus voyage which was rather undisturbed by Forbush decreases. The region 4–9 GeV/c, which is essential for part of the following discussion, is not seriously affected by the difficulties arising from the fact that no simple mathematical expression has been found for the fitting of the curve to the points in the region 3.0 to 9.0 GeV/c and, at the same time, approaching smoothly to the rectilinear parts.

Discussion

In Fig. 4 all the points have been plotted which belong to regions where the first scrutiny indicated that the threshold values by Quenby and Wenk might be in error. The regions are marked in Fig. 1.

In most cases the points are removed from the curve by many times their standard errors. The geographical coordinates are to be found in Table 5. There are four regions to be considered.

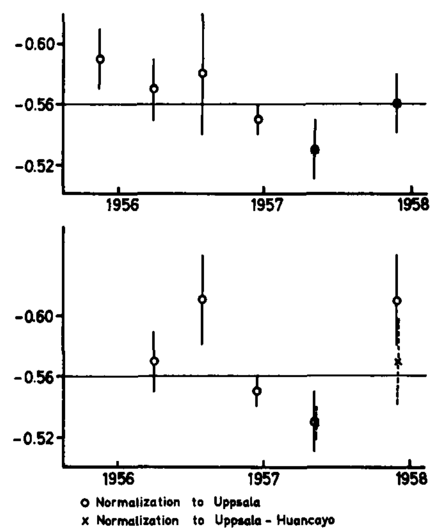

FIG. 5. The exponent of the effective integral spectrum 9–15 GeV/c as a function of time. Upper diagram for all available data. Lower diagram with exclusion of data recorded during Forbush decreases.

TABLE 5. *Threshold rigidities referred to geographical coordinates.*

Region	Latitude	Longitude	Threshold values acc. to Quenby-Wenk	Corr. threshold values	Estimated error
West Africa	40.0 N	10.7 W	5.7	7.0	±0.4
	37.5	11.8	6.7	8.5	
	35.0	12.7	7.5	9.1	
	32.5	13.8	8.5	9.8	
	30.0	14.7	9.7	10.5	±0.3
	27.5	15.5	10.6	11.8	
	25.0	16.4	11.5	12.4	
	22.5	17.2	12.2	12.9	
Mediterranean	37.5 N	17.0 E	8.3	9.0	±0.3
	40.0	13.1	7.0	7.8	±0.4
	40.0	1.5	6.7	7.4	
	38.7	0.4 W	7.4	8.2	
	37.4	1.0	7.5	8.7	
	36.5	2.9	8.0	9.1	
	36.1	5.0	7.9	8.9	±0.3
	36.3	6.3	7.7	9.1	
	36.8	8.2	7.2	8.8	
	37.3	9.1	6.9	8.0	
	37.8	9.3	6.7	8.4	
	38.9	9.8	6.2	7.3	±0.4
South Africa	32.5 S	17.2 E	7.0	6.2	
Cape Town	33.9	18.4	6.6	5.8	
	35.0	20.6	6.2	5.0	±0.4
Port Elisabeth	34.0	25.7	6.3	5.6	
Durban	29.9	31.1	7.4	6.9	
East Australia: Newcastle	32.9 S	151.8 E	4.7	5.6	
	32.3	152.6	4.9	6.0	
	30.7	153.2	5.5	6.8	±0.4
	29.4	153.5	6.1	7.4	
Brisbane	27.5	153.0	7.0	8.2	
	27.2	153.4	7.1	8.4	
	26.4	153.6	7.6	8.9	
	24.4	153.2	8.7	9.8	±0.3
	23.0	152.0	9.5	10.4	
West Australia	32.0 S	111.0 E	4.0	5.0	
	30.9	109.3	4.4	5.6	
	29.9	107.6	4.6	6.2	
	28.7	105.9	5.1	6.7	±0.4
	27.7	104.4	5.5	7.2	
	26.7	102.9	6.1	7.4	
	25.6	101.4	6.7	7.9	
	24.5	99.8	7.5	8.2	
	23.4	98.2	8.3	9.1	±0.3

The most important one is that west of Africa already located in part by "Project Magnet" (POMERANTZ and AGARWAL, 1962). Obviously it extends into the Mediterranean (to 17° E). Its extension in latitude is between 22° N and 40° N in the Atlantic.

The second region is a very small one around the tip of South Africa. The third and fourth regions are located close to Australia. As shown by the results from "Project Magnet" these two regions must be separated. That west of Australia is also separated from the region around South Africa as shown by the values from one of the tracks across the Indian Ocean (Fig. 1).

Table 5 lists the corrected threshold values obtained from Fig. 4, i.e. the values which will bring the deviating points back to the curve determined from the bulk of measurements. For comparison the threshold values are also given according to the tables by Quenby and Wenk. When possible the threshold values are given either for each 2.5° lat. or each 5° long. However, for the sake of accuracy the corresponding second coordinate is that on the ship's course. The ports are marked specially in the table because of the high degree of accuracy to be affixed to these points. The three smaller regions as well as the cruise through the Mediterranean enclose parts of the ships' tracks which do not follow great circles. Consequently the geographical positions refer to the mean position during each counting interval. An interpolation, and in many cases also an extrapolation, would have been necessary for establishing the threshold values for each 2.5° lat. and 5° long.

The accuracy of the corrected values depends on the error in the intensity measurements as well as on the accuracy to be attached to the curve in Fig. 4. Rigidities bigger than 9 GeV/c are not affected by the difficulties accompanying the fitting of the curve to the points of measurement in the knee region. In this region also the standard errors of the intensity measurements gather in importance. Careful considerations point by point have resulted in the values listed in the last column of Table 5. When judging the accuracy it is also necessary to distinguish between the regions as concerns confirmative evidence.

In the Atlantic the primary data were obtained during eight passages covering two years. For part of the region the deviations have been confirmed by results from "Project Magnet". Consequently there does not seem to be any doubt about the real threshold values differing in this region from those calculated by Quenby and Wenk.

Only two crossings of the Mediterranean are available. They join those in the Atlantic at approximately 39° N, 10° W where the observed and calculated values still differ. Consequently it appears well established that the region west of Africa extends into the Mediterranean.

The reality of the deviations around the tip of South Africa is well established through the number of visits to the ports. However, the values belong to the knee region which makes the accuracy less good.

The values obtained for latitudes between 23° S and 33° S east of Australia are based on two and three passages, the ship having been cruising back and fourth between ports. In every case two of the visits are six months apart. This has to be regarded as a comparatively good confirmation as to the observed differences being real.

There is only one passage between latitudes 23° S and 32° S west of Australia. The route of the ship crosses one of the flights of "Project Magnet" at approximately 35° S, 115° E. At this point the present observations fall inside the point distribution illustrated by Fig. 3. Thus "Project Magnet" as well as the present survey both confirm the computed threshold value for this point. But at approximately 25° S, where the routes of M/S Stratus and "Project Magnet" have one common point, the present observations reveal a difference from the calculated threshold value. However, according to the diagrams from "Project Magnet" the latter ought to be right. Nothing has been found to have been wrong with the equipment on M/S Stratus during this part of the voyage. Consequently further confirmations are desirable concerning the extension to the north of this region displaying discrepancies in the computed threshold values. From all appearances the discrepancies are localized to a narrow latitude region. The extension to the east of the ship's route must be small also, as an adjacent "Project Magnet" flight does not reveal any discrepancies.

Conclusion

Quenby and Wenk (1962) have pointed out that their computed threshold values might be slightly in error between 20° and 40° geomagnetic latitude where they had to interpolate for the penumbral effect. The sea level measurements of the nucleon intensity confirm the existence of certain regions where a correction has to be applied to their values. These regions fall inside the geomagnetic latitude region 20° to 40°. In general they appear to touch the upper limit or even extend slightly beyond it.

The observations refer to a period of big solar activity. Plans are being made for a resurvey along the same ship-routes during low solar activity.

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