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The Increase in the Primary Cosmic-Ray Intensity at High Latitudes, and the Non-Existence of a Detectable Permanent Solar Magnetic Field*

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The primary cosmic-ray intensity at Churchill, Manitoba (geomagnetic latitude 69° N) has been compared directly with that at Swarthmore, Pennsylvania (geomagnetic latitude 52° N). The measurements, obtained with identical vertical quadruple-coincidence counter trains, have revealed an increase at the more northern station caused by the presence in the primary radiation of particles having energies below that which would have been permitted had the sun's magnetic field been effective to the extent previously assumed. The ratio of intensities is $I_T(0, 69°)/I_T(0, 52°) = 1.46$. *Intensity vs. altitude* curves were obtained with several different thicknesses of absorber interposed in the counter trains.

These experiments have revealed the absence of a sharp cut-off at the low energy end of the spectrum, imposed by a permanent solar dipole-moment having a magnitude consistent with certain controversial astrophysical determinations. Such a dipole-moment would have produced a knee in the latitude effect at about 50° N geomagnetic latitude. Furthermore, there is no indication of any diurnal variation which could be in conformity with the existence of a permanent dipole-moment at the sun.

The differential energy distribution at the low energy end of the primary cosmic-ray spectrum cannot be evaluated exactly because of absorption considerations, but it is doubtful that the exponent in an inverse power-law representation is as large as has usually been assumed heretofore.

Alternative explanations of the observed increase in counting rates, by invoking trapped orbit or re-entrant particle hypotheses, have been considered and rejected. It is concluded that the sun possesses no detectable permanent magnetic field and, on the basis of the present experiments, an upper limit of 0.6×10^{33} gauss-cm^3, as compared with the previously quoted value of 10^{34} gauss-cm^3, may be assigned as a maximum possible value of the dipole-moment, if indeed it exists at all.

I. INTRODUCTION

THAT the magnetic field of the sun imposes a sharp cut-off at the low energy end of the spectrum of primary cosmic rays, and hence precludes the presence near the earth of any such particles having momenta below that required for entrance at a geomagnetic latitude of about 50°, has become generally accepted as a well-established fact. This almost universal agreement among physicists as regards the magnitude of the effect is paradoxical indeed in view of the fact that even the very existence of a permanent solar magnetic dipole-moment is a controversial issue among astronomers.

Discordant results have been reported by different investigators as a consequence of the extremely difficult nature of the observations. The only method available to the astrophysicist for detecting a magnetic field at the sun involves a search for a splitting of spectral lines arising from the Zeeman effect. The measurements, just on the fringe of feasibility, involve displacements as small as one-thousandth of the line width.

The original determinations of Hale *et al.*[1] were reported as being consistent with a value of field strength of 50 gauss at the poles. However, the results apparently depended upon which point on the sun served as source, and the measured field dropped rapidly in the outer regions of the solar atmosphere. Factors such as the grain of the photographic plates, distortions, local magnetic fields, and other technical difficulties complicated the problem. Of a group of independent measurements, three yielded confirmation of the polarity and magnitude of the field, whereas three indicated zero results. Subsequent remeasurements by Hale[2] indicated no shift. Evershed,[3] following a different procedure in the analysis of Hale's plates, independently concluded that no field exists, whereas Thiessen[4]* applied an interferometric method which presumably confirms the maximum value originally quoted by Hale.

It had been realized for more than a decade that the knee of the latitude effect at sea level would be expected where the minimum energy required for penetration of the atmosphere is equal to the low energy limit permitted by the earth's magnetic field. However, Cosyns,[5] who operated an ionization chamber in a balloon which was floating over Europe between $\lambda = 47°$ and $\lambda = 51°$, reported that the position of the knee was independent of altitude up to a height corresponding to a pressure of 70 mm of Hg. This prompted the suggestion by Janossy[6] and by Vallarta,[7] later extended by Epstein,[8] that a permanent solar magnetic dipole-moment of the magnitude cited earlier could cut off rays of energy less than 3×10^9 ev. This appeared to be consistent with the aforementioned constancy of intensity at

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* Assisted by the Joint Program of the ONR and the AEC.

[1] Hale, Seares, Van Maanen, and Ellerman, Astrophys. J. **47**, 206 (1918).

[2] Carnegie Institution Year Book **34**, 157 (1935); **35**, 173 (1936).

[3] Evershed, M.N.R.A.S. **99**, 438 (1939).

[4] G. Thiessen, Ann. Astrophys. **9**, 101 (1946); Himmelswelt **55**, 22 (1947).

* *Note added in proof:* Subsequent investigations by Thiessen revealed that the earlier result was too high because of an insufficient number of observations. G. Thiessen, Zeits. f. Astrophys. **26**, 16 (1949). Very recent measurements with modified apparatus yielded a value for the polar field strength of -1.5 ± 0.5 gauss. G. Thiessen, Observatory **69**, 228 (1949).

[5] M. Cosyns, Nature **137**, 616 (1936).

[6] L. Janossy, Zeits. f. Physik **104**, 430 (1937).

[7] M. S. Vallarta, Nature **139**, 839 (1937).

[8] P. S. Epstein, Phys. Rev. **53**, 862 (1938).

latitudes north of λ = 50° where the lowest permitted energy was also 3×10^9 ev.

Experimental verification of this hypothesis was sought simultaneously by Carmichael and Dymond[9] and by Johnson.[10] The conclusion regarding the imposition by a solar magnetic field of a low energy limit in the cosmic-ray spectrum appeared inescapable in the light of the results obtained by the former with ionization chambers, and with coincidence counters which yielded an *intensity vs. altitude* curve near the north magnetic pole of the same general shape as that of Pfotzer[11] at λ = 49°. Inasmuch as an enormous difference between the appearance of these curves was anticipated (on the basis of shower production considerations) in accordance with the concepts then prevalent regarding the nature and properties of the primary cosmic radiation, the comparison from this point of view was regarded as meaningful. In the light of the present state of our knowledge concerning the composition of the primaries, it seemed probable that the net effect of the entrance of lower energies at latitudes north of the knee might be considerably smaller than had been expected earlier on the basis of an exclusively electronic primary radiation, and hence could have remained undetected as a consequence of the rather gross procedures which had seemed warranted previously.

Various factors had precluded the discovery of an increase at high latitudes of a magnitude which would seem reasonable now. First, for reasons stressed previously[12,13] the comparison between the results of different observers on the basis of an arbitrary normalization could easily mask an appreciable effect. Secondly, inasmuch as the measurements involved the total intensity, considerable ambiguity is introduced by differences in the effect of thicknesses of counter walls, as pointed out earlier.[13] Furthermore, fluctuations produced by variations in the softer radiation from one day to another could be important. As a matter of fact, the conclusion that there is no sharp cut-off at an altitude corresponding to 1.5 m of H_2O as far north as 60° geomagnetic latitude was vitiated somewhat by such considerations.[14] In the third place, coincidence data were available from only a single flight at λ = 88°, and it was necessary to compare these with averages obtained by Pfotzer in a number of flights yielding widely varying results and requiring instrumental corrections comparable with the recorded counting rates. These separate measurements were then fitted to a common scale at ground level. Finally, a period of several years had elapsed between the experiments of Pfotzer and of Carmichael and Dymond.

Although the electroscope measurements of Bowen, Millikan, and Neher[15] showed an increase in ionization between Omaha, Nebraska (geomagnetic latitude 51° N) and Saskatoon, Saskatchewan (geomagnetic latitude 60° N) this was not interpreted until very recently[16] as evidence against the existence of a sharp cut-off. However, the situation in this instance is beclouded by an uncertainty in the net contribution to the integrated ionization measurements arising from small geomagnetic directional effects.

It was therefore deemed important to seek independent confirmation of these results, particularly in view of their rather fundamental significance in cosmic-ray physics as well as in astrophysics. Techniques which have been subjected to repeated tests during the course of an extensive program of investigations at very high altitudes were well adapted to this purpose.

II. EXPERIMENTAL PROCEDURE

The experiment essentially comprised a direct comparison by identical instruments of the vertical cosmic-ray intensity near the "top of the atmosphere" at Swarthmore, Pennsylvania (geomagnetic latitude 52° N) with that at Fort Churchill, Manitoba (geomagnetic latitude 69° N). The necessary data were obtained with standard quadruple-coincidence counter trains similar to those utilized previously.[12] Radio signals indicating atmospheric pressure, temperature within the gondola, and cosmic-ray events were continuously transmitted to the ground receiving station installed inside a house-trailer equipped as a mobile laboratory. Here the information was recorded on a paper tape by means of a high speed direct-inking recording oscillograph arrangement.[17]

TABLE I. Summary of ground runs of instruments prepared for this series of flights. No interposed absorber.

Flight number	Ground counting rate
1*C*	0.886±0.010
2*C*	0.906±0.013
3*C*	0.918±0.017
4*C*	0.914±0.010
5*C*	0.910±0.012
6*C*	0.900±0.012
7*C*	0.899±0.009
8*C*	0.910±0.014
9*C*	0.915±0.011
10*C*	0.911±0.009
11*C*	0.915±0.011
12*C*	0.897±0.011
13*C*	0.895±0.012
15*C*	0.920±0.014
16*C*	0.894±0.009
17*C*	0.915±0.010
18*C*	0.889±0.015
19*C*	0.895±0.012
20*C*	See 17*C*
21*C*	0.906±0.008
Average	0.905±0.003

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[9] H. Carmichael and E. G. Dymond, Nature **141**, 910 (1938); Proc. Roy. Soc. **171**, 321 (1939).

[10] T. H. Johnson, Phys. Rev. **54**, 151 (1938).

[11] G. Pfotzer, Zeits. f. Physik **102**, 23 (1936).

[12] M. A. Pomerantz, Phys. Rev. **75**, 69 (1949).

[13] M. A. Pomerantz, Phys. Rev. **75**, 1721 (1949).

[14] Biehl, Montgomery, Neher, Pickering, and Roesch, Rev. Mod. Phys. **20**, 360 (1948).

[15] Bowen, Millikan, and Neher, Phys. Rev. **53**, 855 (1938).

[16] Biehl, Neher, and Roesch, Phys. Rev. **76**, 914 (1949).

[17] M. A. Pomerantz and R. C. Pfeiffer, J. Franklin Inst. **248**, 305 (1949).

TABLE II. Comparison of counting rates on the ground at Churchill, Manitoba, and Swarthmore, Pennsylvania. Flight 15C with no interposed absorber. The stated uncertainties are statistical standard deviations. The rate at Churchill would be expected to be slightly lower owing to the difference in altitudes.

Station	Average counting rate	Average station pressure, mm of Hg	Altitude above sea-level, feet
Swarthmore	0.920±0.014	758	296
Churchill	0.890±0.013	762	0

In accordance with the philosophy formulated during the early stages of development of the experimental techniques utilized in this program, the policy of confining the observations to a single type of measurement per flight was adopted; many simple flights are preferred over a few complicated ones. Numerous practical advantages accrue from this approach.

The desirability of reducing the complexity of an individual instrument to an absolute minimum need hardly be stressed. Furthermore, the accompanying reduction in weight simplifies the launching procedure to an extent far out of proportion to the load. It becomes feasible to conduct repeated flights with identical arrangements, thereby providing independent checks which experience has dictated must be regarded as indispensable in view of the unique conditions prevailing in radiosonde operation. Complications associated with telemetering various types of information simultaneously are avoided, and the receiving and recording systems are readily adaptable to field operation. It is also possible to follow the progress of a flight without analyzing a photographic record, and audibly to determine counting rates as frequently as necessary to facilitate immediate preliminary plotting of the results. Thus, the flight program during the course of a field expedition may be modified in a manner which is most advantageous in the light of the actual results. This feature was especially important during the Fort Churchill expedition.

Finally, the consequences of failure of any essential component are far less serious. Particularly valuable, moreover, is the "hedging" thereby afforded against inevitable premature bursting of balloons. A flight which does not attain an altitude sufficiently high to provide all of the desired data need not be discounted as a total loss. On the contrary, the data may nevertheless serve quite satisfactorily as a confirmation of results obtained in another higher ascent.

Each apparatus was operated on the ground for a long period during which the internal consistency of the runs was continuously checked. As may be seen in Table I, the average counting rates with no interposed

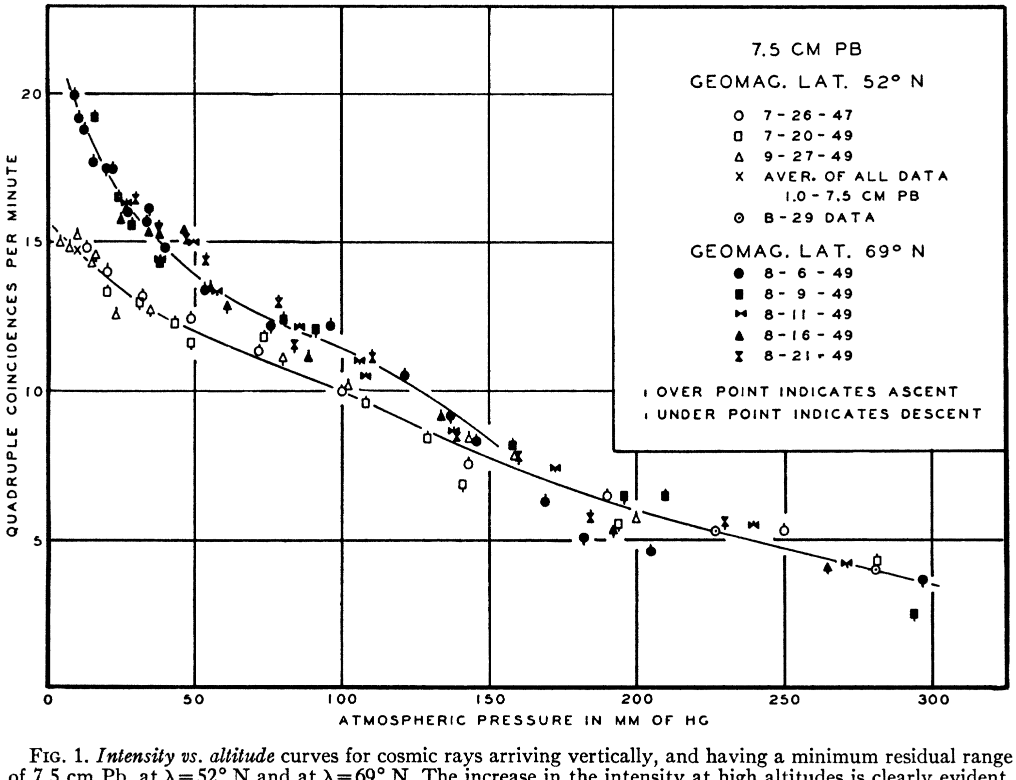

FIG. 1. *Intensity vs. altitude* curves for cosmic rays arriving vertically, and having a minimum residual range of 7.5 cm Pb, at λ=52° N and at λ=69° N. The increase in the intensity at high altitudes is clearly evident. The point X previously obtained with similar instruments does not include the present data, and the points ⊙ were obtained during B-29 flights (see reference 13). The reproducibility of the data from flight to flight, and year to year, should be noted.

absorber agreed within a statistical uncertainty of approximately 1 percent.

Although a detailed description of instrumental techniques will be omitted for the present, it is perhaps worthwhile mentioning by way of example one of the precautionary measures to which good reproducibility from flight to flight and the extremely small shrinkage rate are attributable. Vacuum tubes which are entirely satisfactory and uniform according to the standards established for commercial test instruments may be very dissimilar as regards performance in specialized equipment of the type designed for operation in free-balloon flights. Rather severe tests are therefore conducted on all tubes under the circuit conditions actually encountered in the specific application. Among other requirements, characteristics must remain constant during the final portion of an aging process, and subsequently throughout the long period of pre-flight operation in an apparatus. Furthermore, the characteristics of tubes incorporated in a particular set must be closely matched. Tests of the various tubes as well as of the complete instruments prior to release reveal their ability to operate satisfactorily over a range of battery voltages down to values much lower than the minima which could prevail during a flight. The enforcement of such severe requirements results in the rejection of a very large percentage of stock tubes, but assures reliability and stability of components throughout the course of a flight, of extremely short duration in comparison with the entire period of operation of a set.

It was most expedient for the present purposes to utilize ballooning techniques which cause the flights to rise relatively rapidly (approximately 800 feet per minute) through the lower regions of the atmosphere, and then more slowly from about 40,000 feet to the ceiling altitude. Rates of rise between 200 and 500 feet per minute in the upper regions, considerably smaller than have been customary, reduce statistical uncertainties. It is evident that the number of counts recorded by a given instrument is inversely proportional to the ascent rate. It was also advantageous for the descent to commence immediately after the ceiling was reached, so that the original curve could be retraced.

In order to minimize any possible complications which might have been introduced by the frequently-cited non-reproducibility in the results obtained at different times[14,18] with coincidence-counter trains containing no absorber other than the counter walls, the initial flights were conducted with 7.5 cm of interposed lead. This would certainly preclude the observation of particles in the lower portion of the new band of energies which would be permitted at 69° N in the absence of a solar dipole-moment. In any event, even the small amount of residual atmosphere above the apparatus (approximately 11 g/cm^2 at the highest altitudes attained) would absorb such low energy primaries. However, the absence at the "top of the atmosphere" of absorption in small thicknesses of lead, observed in earlier experiments,[12] had indicated that if particles having less than the geomagnetic cut-off energy at Swarthmore were in fact entering at higher latitudes, their presence would be detected by this arrangement.

III. RESULTS

The results of flights in which an absorber of 7.5 cm of Pb was interposed in the coincidence train are plotted in Fig. 1. It is clear that near the "top of the atmosphere" a real increase of about 40 percent occurs in the intensity of particles having the aforementioned residual range. In the lower atmosphere, points recorded over Swarthmore and Fort Churchill overlap within rather large statistical uncertainties.[19] On the ground, the counting rate was the same at the two stations as is shown for a typical instrument in Table II. At an altitude corresponding to somewhat less than 150 mm of Hg the departure becomes quite unambiguous.

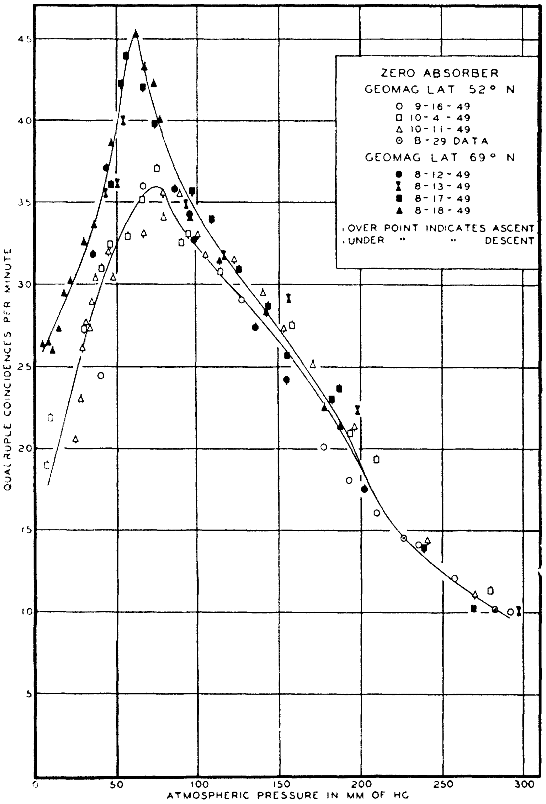

FIG. 2. *Intensity vs. altitude* curves, obtained with no interposed absorber other than the counter walls (mean thickness 4.4 g/cm^2), for cosmic-rays arriving vertically at $\lambda = 52°$ N and $\lambda = 69°$ N. (Correction: The first line in the box in the upper right-hand corner of the figure should read: 0 9–16–47.)

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[18] D. J. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton 1949), p. 164.

[19] See reference 13 for the causes of large statistical uncertainties in data obtained in the lower atmosphere.

The point × at 52° N represents an average (standard deviation ±2 percent) of all previous data obtained at altitudes exceeding 90,000 feet with vertical coincidence counter trains.[12] It is based upon the results of 9 flights containing different amounts of interposed material (1.0–7.5 cm Pb). The data obtained in 1949 have not been incorporated in this value. A considerable body of data accumulated in another series of measurements at small zenith angles and correspondingly higher altitudes also confirms this value of the primary relative intensity[20] near Swarthmore.

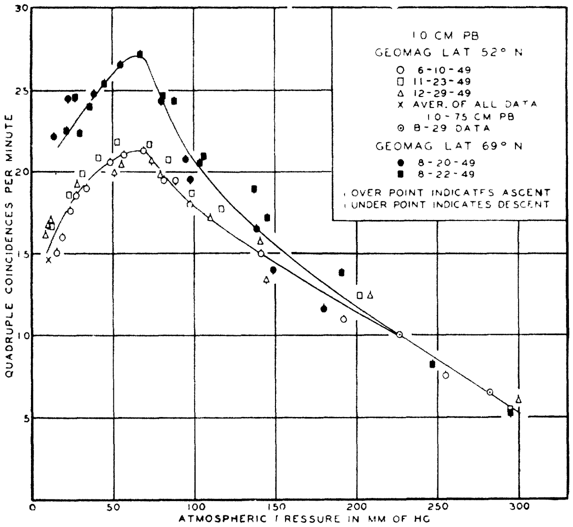

FIG. 3. *Intensity vs. altitude* curves, obtained with 1 cm of Pb interposed in the coincidence-counter train, for cosmic rays arriving vertically at λ = 52° N and λ=69° N. (Correction: The first line in the box in the upper right-hand corner of the figure should read: 0 16–10–48.)

The agreement between ascent and descent and between individual flights is satisfactory. It should be noted that flights immediately preceeding departure and following the return of the expedition yielded results in good accord with those obtained two years earlier.

Following verification of the results of the initial flight, which had revealed the presence in the primary radiation of particles having energies below that which would have been permitted had the sun's magnetic field been effective to the extent previously assumed, the program was extended to include flights with no interposed absorber as well as with intermediate thicknesses. In every case, the increase with latitude of the intensity at very high altitudes is clearly evident.

Figure 2 shows the results for the so-called "total" intensity, i.e., for all particles which can penetrate the counter walls (4.4 g/cm^2 = 1.8 g/cm^2 Cu+2.6 g/cm^2 glass, mean thickness between sensitive volumes of extreme counters). The shape of the *intensity vs. altitude* curves has also been altered, with a sharper peak occurring at about 60 mm of Hg for the more northern latitude.

Data obtained with 1 cm of Pb interposed in the counter train are plotted in Fig. 3. Because the maxima are relatively broad, it is not clear whether a shift has occurred in this case.

Although the detection of a very small diurnal variation was not specifically attempted, the data may be examined for evidence of such an effect. Despite the fact that flights were conducted at different times of the day, there is no indication of any marked differences which could be attributable to a diurnal effect. Table III is a summary of the flights at Churchill showing the time of day at which the maximum altitude was attained in each case.

Additional verification of the absence of an appreciable diurnal variation was provided by data obtained in a flight which fortuitously leveled off at about 35 mm of Hg, and remained here for 7 hours. During this period, owing to the presence of a strategically situated hole in one of the balloons, the flight oscillated above and below a pressure reference point. Counts were recorded continuously between contacts. The counting rates averaged over the individual intervals between pressure signals are listed in Table IV. It is seen that the average intensity remained constant within statistical uncertainties of less than 3 percent.

There is little doubt that the diurnal variation predicted for the top of the atmosphere (and exceeding the aforementioned statistical uncertainty) should propagate itself to this depth, and, in fact, undergo amplification. Furthermore, even though data are available from only one flight, there are no grounds for doubting the validity of the negative conclusion. If a variation following a particular trend had been indicated, the single result could have been challenged on the basis of possible systematic instrumental changes. The observed constancy, on the contrary, is not vulnerable to such potential criticism.

IV. DISCUSSIONS

A. Solar Dipole-Moment

In view of the fact that the Störmer cone created at the earth by a permanent solar magnetic field would not move with respect to a coordinate system fixed on the sun, the rotation of the earth would produce an apparent motion of the forbidden regions past a particular point of observation. Thus, particles having certain energies would be excluded during some portions of the day and permitted at others, giving rise to a diurnal effect. Calculations by Dwight[21] have already been discussed,[22] and quantitative considerations have led to the conclusion that it is not possible to account for

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[20] Geometrical factors for computing absolute intensities are given in reference 13.

[21] K. Dwight, Princeton University thesis (1949), unpublished.

[22] M. A. Pomerantz and M. S. Vallarta, Phys. Rev. **76**, 1889 (1949)

TABLE III. Resume of flights conducted at Churchill. As may be seen from a comparison of points plotted in Figs. 1–3, no dependence upon time is indicated within the limits of the present experiments.

Flight No.	Time of arrival at ceiling altitude, local solar time	Date
1*C*	9:31 a.m.	Aug. 23
2*C*	4:24 p.m.	Aug. 11
3*C*	9:56 a.m.	Aug. 20
4*C*	4:55 p.m.	Aug. 18
5*C*	10:13 a.m.	Aug. 21
6*C*	10:17 a.m.	Aug. 16
9*C*	8:40 a.m.	Aug. 9
10*C*	8:23 a.m.	Aug. 12
11*C*	10:32 a.m.	Aug. 6
12*C*	8:42 a.m.– 3:42 p.m.	Aug. 13
13*C*	9:31 a.m.	Aug. 22
15*C*	7:19 a.m.	Aug. 17

TABLE IV. Summary of data recorded during Flight 12*C* after leveling-off at an altitude corresponding to approximately 38 mm of Hg. Counting rates have been averaged over the entire intervals between successive pressure signals, about the mean local solar times indicated. The stated uncertainties are statistical standard deviations.

Pressure range[a]	Mean local solar time	Average counting rate
Above pressure contact— Average pressure approx. 34 mm of Hg	10:27 a.m. 2:17 p.m.	33.3±0.8 33.8±0.6
Below pressure contact—	8:52 a.m.	35.2±1.1
Average pressure	11:42 a.m.	36.2±1.2
approx. 42 mm of Hg	12:42 p.m.	35.2±1.1

[a] The pressure signal was transmitted continuously while the instrument was in the pressure interval 40 mm–36 mm, and no counts were recorded during these periods.

these results by a shift in the latitude of the knee caused by a diurnal variation of the vertical intensity. Actually, according to these computations, the vertical intensity at 69° N should be 7 percent *less* than that at 52° N in the early morning.

It is possible to assign an upper limit to the magnetic dipole-moment of the sun, if indeed it exists at all, on the basis of the present data. The value of 0.6×10^{33} gauss-cm^3 replaces, as a maximum possible value, that previously assumed of 10^{34} gauss-cm^3. This limit in turn pushes a possible knee of the latitude effect to 75° N. geomagnetic latitude.

Unfortunately, considerations which will be discussed later probably preclude any further reduction in this upper limit by a repetition of measurements of this type at more northerly latitudes. Particles with energies below the geomagnetic cut-off at Churchill would in fact be absorbed before reaching balloon-borne instruments.

B. Low Energy Spectrum

The total measureable unidirectional primary cosmic-ray intensity is given by:

$$I_T(\theta,\lambda)=\sum_1^n\int_{\epsilon_n(t,\lambda)}^{\infty} i_n(\epsilon)d\epsilon, \tag{1}$$

where $i_n(\epsilon)$ is the spectral intensity, the index n represents a particular type of particle, t is the thickness of the atmosphere above the detecting apparatus plus the counter walls which must be penetrated to record a coincidence, θ is the zenith angle, and λ is the geomagnetic latitude.

Ideally, at a point sufficiently near the top of the atmosphere so that multiplicative effects are relatively small, the lower limit $\epsilon_n(t,\lambda)$ of the above integral will be either the geomagnetic cut-off energy at latitude λ *or* the minimum energy required by a primary particle (or its progeny) to penetrate the thickness t. The larger of these two quantities is the governing factor. At 52° N the minimum energy for entrance of protons in the vertical direction is 1.6 Bev, and experiments have revealed[12] that this exceeds the energy required to penetrate the absorbing layer. At Churchill, however, even though the geomagnetic cut-off energy is only 0.1 Bev, lower energy primaries could not be detected. Considering ionization losses alone, 0.09 Bev would be required for a primary proton to reach 110,000 feet. Obviously, penetration of the counter walls further increases the requisite energy, and other modes of energy loss raise $\epsilon_n(t, 69°)$ to an extent which cannot now be specified because of the lack of information regarding the primary interaction.

In principle, the nature of the spectral energy distribution may be determined from a comparison of the primary intensities at two different latitudes. Following earlier practice, this would be accomplished by assuming an inverse power function of the energy:

$$i_n(\epsilon)d\epsilon=k\epsilon^{-\gamma}d\epsilon. \tag{2}$$

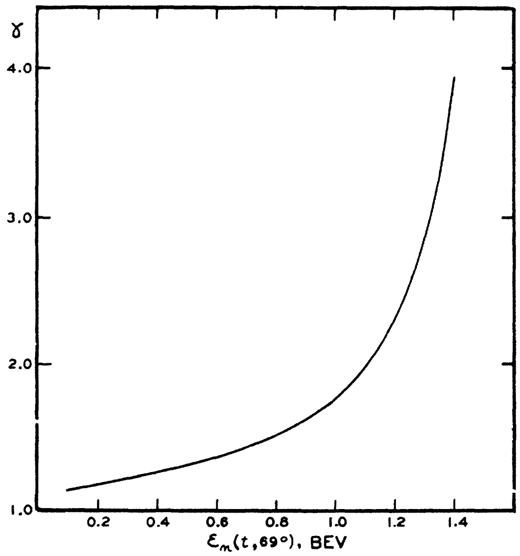

FIG. 4. The power γ, in the differential energy distribution, $i_n(\epsilon)d\epsilon=ke^{-\gamma}d\epsilon$, plotted as a function of $\epsilon_n(t, 69°)$ for the case of the experimentally-determined ratio of primary intensities at Churchill, Manitoba, and Swarthmore, Pennsylvania, $I_T(0, 69°)/I_T(0, 52°)=1.46$. Here, $\epsilon_n(t, 69°)$ is determined by the thickness, t, of air above the ceiling altitude plus the counter walls.

Integration of Eq. (1) then leads to the result:

$$I_n(\theta, \lambda) = k[\epsilon_n(t, \lambda)]^{1-\gamma}/(\gamma-1). \quad (3)$$

From this the ratio of intensities of a particular primary component at two different latitudes is:

$$[I_n(\theta, \lambda_1)]/[I_n(\theta, \lambda_2)] = [\epsilon_n(t, \lambda_2)/\epsilon_n(t, \lambda_1)]^{\gamma-1}. \quad (4)$$

Actually the measurements yield values of the ratio $I_T(0, 69°)/I_T(0, 52°)$. Determination of the energy distribution of the different components at latitudes south of 50° where $\epsilon_n(t, \lambda)$ is well defined presupposes a knowledge of the relative composition of the primary radiation at the two different locations. Even if it were assumed quite arbitrarily that the energy distribution of the various components were initially the same at very large distances from the earth, the sorting effect of the terrestrial magnetic field for rays below the lower limit would alter the percentage composition of the primary beam as a function of latitude, inasmuch as the geomagnetic effects depend fundamentally upon magnetic-rigidity. Thus, strictly speaking, ratios of total intensities can only provide a magnetic-rigidity distribution.

It has been demonstrated by means of particle-discriminating counter trains[23] and by photographic emulsion techniques[24] that at 52° N approximately one-third of the incoming cosmic rays are alpha-particles, and the remainder are predominantly protons. To a first approximation, it can be assumed that this does not change appreciably at 69° N. As a matter of fact, the ratio of cut-off energies is $\epsilon_p(0, 52°)/\epsilon_p(0, 69°) = 16$ for protons and $\epsilon_\alpha(0, 52°)/\epsilon_\alpha(0, 69°) = 19$ for α-particles. Hence $I_T(0, 69°)/I_T(0, 52°) \approx I_n(0, 69°)/I_n(0, 52°)$. Figure 4 shows the power γ in the differential energy distribution plotted as a function of $\epsilon_n(t, 69°)$, for the case of the experimentally determined value $I_T(0, 69°)/I_T(0, 52°) = 1.46$.

The extreme value of 1.14 for γ would apply if all of the primaries incident at the top of the atmosphere would register an event. Although the correct value is necessarily higher, it is unlikely that the power is as great as 3. Although this had previously appeared to be consistent with observation[25] on the basis of assumptions which are no longer tenable, it has been propagated through the literature and more or less accepted as a law even though the failure at the low energy end of the spectrum was recognized. As a matter of fact, there is no reason to expect that the distribution function is a constant independent of energy. Furthermore, it is obvious that the validity of a law of this form down to zero energy leads to a divergence, and implies an infinite amount of energy in the form of cosmic-rays.

The correct value of $\epsilon_n(t, 69°)$ at Churchill is actually quite difficult to predict. The range of a primary particle could conceivably be either reduced or enhanced by conversion into secondaries. A mesotron may have considerably greater range than the proton which produces it. The net result depends of course upon the multiplicity, the division of energy among secondaries, and similar considerations. A knowledge of the spectrum and its rate of change just south of Swarthmore would conversely permit an approximate evaluation of $\epsilon_n(t, 69°)$ on the basis of Fig. 4.*

C. Intensity vs. Altitude Curves

Various features of the *intensity vs. altitude* curves may be commented upon at least qualitatively, pending detailed theoretical analysis. The pronounced alterations in the shapes of the curves are all indicative of the addition of a group of low energy particles at the more northerly location.

It is not surprising that, in Fig. 1, the shape of the Churchill curve in the upper portion of the atmosphere becomes steeper than that representing the Swarthmore results. The low energy particles which contribute to the higher intensity at 69° N are rapidly absorbed. Furthermore, the maximum for the "total intensity" (Fig. 2) is displaced toward higher altitudes because of the combination of this factor together with lower average secondary energies and correspondingly diminished mean-free-paths. Finally, absorption is observed to occur in small thicknesses of material at the highest altitudes attained over Churchill but not over Swarthmore.

D. Trapped Orbit Hypotheses and Similar Considerations

It might be suggested that the increase in cosmic-ray intensity observed at high latitudes is produced by the presence of particles deflected to directions forbidden by the sun's magnetic field. For example, Alfven[26] has pointed out that particles coming in from infinity on unbounded orbits may be scattered by the earth's magnetic field into bound orbits. This occurs when they approach the earth so closely that the radius of curvature in the terrestrial magnetic field is of the same order as the distance to the earth's magnetic dipole. Here they are trapped, and circulate until they eventually (about 5,000 years) are absorbed by interplanetary matter or by striking some heavenly body or the earth, in the latter case from a normally forbidden region. In this manner, it is supposed that the intensity in forbidden directions may be appreciable in comparison with that in allowed directions. This idea was subsequently carefully investigated quantitatively by Kane, Shanley, and Wheeler.[27]

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[23] M. A. Pomerantz and F. L. Hereford, Phys. Rev. **76**, 997 (1949).

[24] Goldfarb, Bradt, and Peters, Bull. Am. Phys. Soc. **24**, No. 7, 19 (1949); Phys. Rev. **77**, 54 (1949).

[25] T. H. Johnson, Phys. Rev. **53**, 499 (1938).

* *Note added in proof:* The Princeton group has recently obtained very important pertinent data which is in good accord with the above considerations. K. Dwight, R. Sabin, T. Stix, J. R. Winckler, Bull. Am. Phys. Soc. **25**, No. 1. (1950), p. 17.

[26] H. Alfven, Phys. Rev. **72**, 88 (1947).

[27] Kane, Shanley, and Wheeler, Rev. Mod. Phys. **21**, 51 (1949).

It is not the purpose of the present paper to discuss the assumptions underlying these hypotheses, which initially had their inception in an attempt to account for the absence of the large diurnal effect in the cosmic-ray intensity expected previously on the basis of the value of the solar magnetic moment heretofore assumed. Actually, the theoretical conclusion about rough equality of intensity incident from allowed and forbidden directions was inferred solely from the absence of an observable diurnal variation in the cosmic-ray intensity. A powerful argument against invoking this type of explanation of the present experimental results is based upon the observation of low energy particles in the primary beam at Churchill, as has been pointed out in the preceding section. A solar magnetic moment of 10^{34} gauss-cm^3 permits no particles having momenta less than 2.3×10^9 ev/c to reach the region where scattering by the earth's field could occur under any circumstances. The particles deflected into forbidden directions can have energies only between this lower limit and $p_{\max} = [(2)^{\frac{1}{2}}+1]^2\times p_{\min} = 13.5\times 10^9$ ev/c. The absorption in small thickness of lead at Churchill and not at Swarthmore indicates the presence of primary particles below this range at the more northern location. It need hardly be mentioned that the present conclusions directly explain the absence of such diurnal variations.

Another alternative explanation of the increase at high latitudes might, in principle, be sought in a contribution to the counting rate by either primaries or secondaries which initially pass outside the solid angle of the coincidence-counter train, suffer energy loss in the atmosphere, and are subsequently bent around by the earth's magnetic field so that they enter the telescope from below. It can be seen on the basis of some pertinent theorems by Swann[28] that no pencils of either protons or mesotrons which have undergone large angular deviation can be expected with any appreciable intensity. As a matter of fact, this effect would be in the wrong direction to account for the increase at high latitudes even qualitatively, inasmuch as a decrease in H actually reduces the fraction of the rays surviving along the deflected path.

E. The Sun as a Source of Cosmic-Rays

The sudden worldwide increases in the intensity of cosmic radiation accompanying solar flares, originally reported by Forbush,[29] indicated that the sun might be the source of at least some cosmic-ray particles. The sun's magnetic field was invoked to account for the fact that only relatively few flares produced such an increase.[30] According to Vallarta[31] a permanent dipole moment of 10^{32} gauss-cm^3 would suffice from this point of view.

Reference has already been made to the possibility that a variable solar magnetic field† could account for the acceleration of cosmic rays in the neighborhood of the sun. Should this be substantiated by future experiments, the sun may eventually be regarded as the source of practically all of the cosmic-radiation reaching the earth. This would indeed alleviate the difficulties regarding the total energy associated with a uniform distribution of cosmic rays throughout space.

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[28] W. F. G. Swann, Phys. Rev. **76**, 157 (1949). Analogous considerations have subsequently been applied to protons, and lead to similar conclusions.

[29] S. E. Forbush, Phys. Rev. **70**, 771 (1946).

[30] Forbush, Gill, and Vallarta, Rev. Mod. Phys. **21**, 44 (1949).

[31] M. S. Vallarta, private communication.

† *Note added in proof:* Babcock has reported that of 42 sets of lines measured, including spectrograms in 1940, 1941, 1943, 1946, and 1947, 18 support Hale's conclusions, with intensity at the pole ranging from 6 to 60 gauss, whereas the remaining 24 show either no field or small negative values. H. D. Babcock, P.A.S.P. **60**, 224 (1948). Owing to difficulties associated with sunspots, there is no information regarding the possibility of a periodic variation. Although the value of 50 gauss has become imbedded in the literature by repetition, the mean of several lines was actually about 20 gauss. The author is indebted to Dr. H. W. Babcock for enlightening discussions of this subject.