Arrival Directions of Cosmic-Ray Air Showers from the Equatorial Sky*

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The celestial arrival directions of over 100 000 showers with sizes greater than 10^5 particles have been determined by fast timing in observations at an altitude of 2034 m. The observations covered a band of declinations from $-30°$ to $+50°$ with an angular resolution of 4°, and they extended a survey begun in an earlier experiment that covered the northern sky. As in the earlier experiment no significant deviation from isotropy was found. The atmospheric attenuation of the shower intensity was determined from the zenith angle distribution, and also from a comparison of the absolute shower intensity at 2034 m and at sea level. Within an experimental uncertainty of about 5%, both methods yield an exponential attenuation length consistent with the value of 107 g cm^{-2} previously found at sea level. The absolute intensity of showers with more than 10^5 particles at 2034 m was found to be $(1.11\pm0.30)\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1}.

I. INTRODUCTION

A PREVIOUS survey of the arrival directions of 2660 extensive cosmic-ray air showers from the northern sky (from declination $+20°$ to $+70°$) has been reported in an earlier paper.[1] In that survey the arrival direction of each detected shower was determined from measurements of the differences in arrival times of the shower particles at four scintillation detectors located at the corners of a square. Showers in the size range from 10^5 to 10^6 particles at sea level were recorded. The observed distribution of the arrival directions was found to be consistent with the assumption that the flux of primary particles which generate showers in this size range is isotropic within the uncertainty due to the statistical fluctuations in the data. Similar conclusions have been drawn from the results of other surveys,[2] carried out by different experimental methods.

The detection of a deviation from isotropy of the flux of high-energy primaries would give important clues to the origin and propagation of cosmic rays in the galaxy. Alternatively, a reduction in the observed upper limit to anisotropy serves the useful purpose of restricting the choice of models for the explanation of the origin of cosmic rays. The earlier survey was, therefore, extended to the equatorial sky (from declination $-30°$ to $+50°$) using the same experimental method that is described in detail in I, but with a large increase in the number of events recorded. This region of the sky is of particular interest because it contains the galactic center. As a byproduct, the new data make possible a comparison of the zenith angle distribution of arrival directions and the absolute shower intensity at different altitudes, and this comparison gives information on the development of extensive air showers in the atmosphere.

Since the present experiment is largely an extension of the earlier one, the results will be presented in essentially the same form as in I, but abbreviated to avoid repetition and with detailed descriptions of only those features of the analysis which are significantly different. Reference will be made to the earlier paper for details of the abbreviated descriptions.

II. DESCRIPTION OF THE METHOD

For each shower event we determined the relative arrival times (t_1, t_2, t_3, t_4) of the first shower particles to traverse each of four detectors at the corners of a square. From these data, together with the time and date of occurrence, we computed the zenith angle, azimuth, declination, and right ascension of the shower axis, and the quantity $\Delta=c(t_1+t_4-t_2-t_3)$ which indicates the goodness of the least squares fit of the data to the calculated arrival directions. The formulas for these computations are given in I.

III. EXPERIMENTAL ARRANGEMENT

For the present survey a new and improved fast timing apparatus was constructed which is described in detail elsewhere.[3] In this apparatus we used four plastic scintillation detectors with high-gain RCA 6810 photomultipliers connected to a fast oscilloscope. The detectors were located at the corners of a square 35.5 m

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[1] G. Clark, Phys. Rev. **108**, 450 (1957), referred to as I.

[2] F. J. M. Farley and J. R. Storey, Proc. Phys. Soc. (London) **A67**, 996 (1954); T. E. Cranshaw and W. Galbraith, Phil. Mag. **45**, 1109 (1954); J. K. Cranshaw and H. Elliot, Proc. Phys. Soc. (London) **A69**, 102 (1956); P. Rothwell, B. Wade, and A. Goodings, Proc. Phys. Soc. (London) **A69**, 902 (1956); J. Daudin, P. Auger, A. Cachon, and A. Daudin, Nuovo cimento **3**, 1017 (1956); T. E. Cranshaw and W. Galbraith, Phil. Mag. **2**, 804 (1957).

[3] G. Clark, Rev. Sci. Instr. **28**, 907 (1957).

on a side, at an altitude of 2034 m in Kodaikanal, South India, which is located at 10° N geographic latitude and 78° E longitude. Approximately 40 000 showers were recorded during a "fast run" with scintillators that were cylindrical slabs 16 in. in diameter and $2\frac{1}{2}$ in. thick with a total surface area of 1300 cm^2. About 70 000 more showers of four times larger average size were recorded during a "slow run" with smaller scintillators made by cutting a 16-in. scintillator into four equal segments.

The photographic record of the timing pulses on the fast oscilloscope was projected and measured, and the data were transferred to IBM cards. The remainder of the data processing was carried out on the IBM 704 computer in the MIT Computation Laboratory. Data were processed at the rate of about 5000 events per hour of computer time.

IV. RESPONSE OF THE DETECTOR ARRAY

In I we calculated the response of the detector array to showers of various sizes on the assumption that the lateral distribution can be represented by the function

$$f(r)=(N/2\pi)\frac{e^{-r/r_0}}{rr_0},$$

and that the integral size spectrum has the form

$$K(N,\theta)=K(10^6,\theta)(N/10^6)^{-\Gamma(N)}.$$

We repeated this calculation for the present experiment using for r_0 the value 101 m which is the Molière unit at Kodaikanal. According to the results obtained by Greisen[4] from an analysis of the density spectrum at

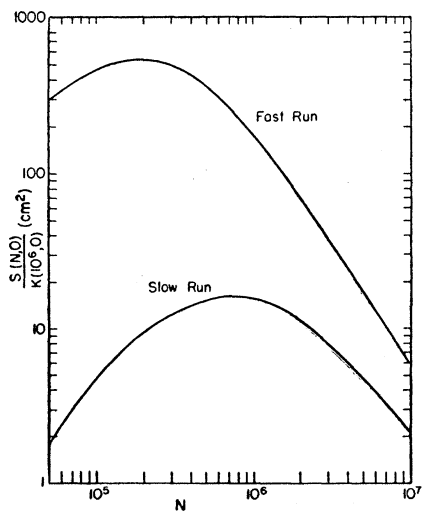

FIG. 1. Distributions in size of showers recorded during the fast and slow runs.

[4] K. Greisen, *Progress in Cosmic-Ray Physics*, edited by J. G. Wilson (North Holland Publishing Company, Amsterdam, 1956), Vol. III, Chap. 1.

mountain altitudes, the value of $\Gamma(N)$ changes only slightly over the range of sizes of most of the showers detected in this experiment. We therefore used for $\Gamma(N)$ the constant value 1.50. The results are presented in Fig. 1, which shows the distributions in sizes of showers detected in the fast and slow runs.

V. EXPERIMENTAL RESULTS

A. Angular Resolution

The angular resolution of the timing method for determining the arrival directions of extensive air showers is limited primarily by the lack of perfect coplanarity of the shower particles. The quantity Δ, defined above, differs from zero by an amount that depends on the degree of noncoplanarity of the shower particles which first traverse the four detectors. Following a procedure described in I, we can determine the uncertainty in a measurement of the arrival direction of a shower from the observed distribution of Δ. The distributions of Δ for large samples of events recorded during the fast and the slow runs are essentially identical to the distribution observed at sea level. As in the previous experiment, the contribution of purely instrumental and reading errors to the breadth of the distribution is negligible, and essentially the entire breadth of the distributions is due to a lack of coplanarity of the shower particles. The standard deviations of the two distributions are not significantly different from one another or from the value observed at sea level, and they indicate that the error in an arrival direction determination corresponds to a circle of confusion with a radius of 5°. As in the sea-level experiment, we increase the effective resolution of the instrument by rejecting events in which Δ exceeds 6.4 m so that the angular resolution for showers selected according to this criterion is about 4°.

B. Zenith Angle Distribution

The slant thickness x of atmosphere traversed by a shower whose axis is inclined at a zenith angle θ is given by the relation

$$x=x_0(\sec\theta-1),$$

where x_0 is the vertical thickness from the top of the atmosphere to the point of observation. Thus the relative intensity of showers arriving from various zenith angles is related to the growth and absorption of showers in the atmosphere.

Figure 2 shows semilogarithmic plots of the observed rates of selected showers per unit solid angle $\Delta R/\Delta\Omega$ versus the atmospheric thickness x. The slopes of these two plots are constant for $x-x_0\leqq 170$ g cm^{-2} corresponding to $\theta\leqq 35°$. It was shown in I that at sea level the effective sensitive area of the detector array projected onto a plane perpendicular to the arrival direction is approximately constant and independent of the arrival direction out to zenith angles near 45°. Consequently, the dependence of the observed counting rate on x is determined essentially only by the zenith angle dependence of the shower intensity K. The same conclusion is valid in the present experiment. Therefore, the constant slopes of the two plots for values of x corresponding to zenith angles less than 35° indicate that K can be approximately represented by the formula

$$K(N,\theta)=K(N,0)\exp[-(x-x_0)/\Lambda(N)],$$

where $\Lambda(N)$ may change slowly with N.

For Λ we find the values 100 ± 6 g cm^{-2} and 106 ± 5 g cm^{-2}, respectively, for the fast and slow runs. These values are the reciprocal slopes reduced by 5% to take into account the broadening effect of timing errors on the observed zenith angle distribution. Within the limits of the experimental errors, both values are the same as the value found at sea level, namely 107 ± 11 g cm^{-2}.

C. The Absolute Intensity

If the lateral distribution is independent of size and the size spectrum is a power law, then the counting rate of our apparatus for vertical showers is related to the area of the detectors by a power law with the same exponent as the size spectrum. This conclusion follows from a simple calculation well known in the analysis of measurements of the density spectrum. Thus the ratio

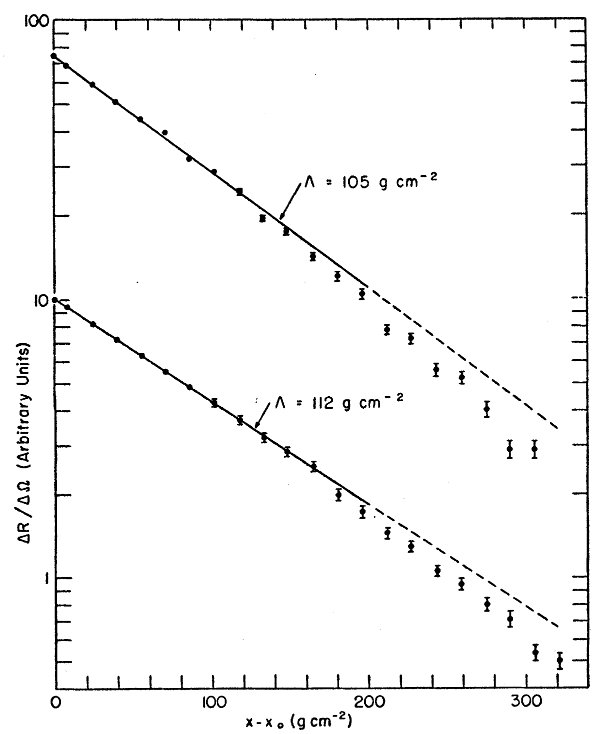

FIG. 2. Semilogarithmic plots of shower intensity versus atmospheric thickness as derived from the observed distributions in zenith angle for the fast (upper plot) and slow (lower plot) runs.

of the counting rates for vertical showers in the fast and slow runs should be the ratio of the areas of the detectors raised to the exponent of the size spectrum, namely $4^{1.5}=8$. The experimentally determined ratio of counting rates for vertical showers is 8.4 ± 0.5. The indicated error arises in part from the uncertainties in the zenith angle distributions on which the evaluation of the vertical rates depends, and in part from the magnitudes of the fluctuations in rates observed during the best selected periods of observation. These fluctuations are due primarily to small variations in the efficiencies of the detectors. The agreement between the expected and observed ratios indicates a satisfactory degree of internal consistency in the data analysis.

According to Greisen's analysis, $\Gamma(N)$ changes only slightly between sea-level and mountain altitudes. Therefore, to a good approximation, we can attribute the change in the value of $K(N,0)$ between sea level and Kodaikanal entirely to atmospheric absorption. At Kodaikanal we find $K(10^6,0)=(3.5\pm1.0)\times10^{-11}$ cm^{-2} sec^{-1} sr^{-1}. At sea level we found $K(10^6,0)=(3.0\pm1.0)\times10^{-12}$ cm^{-2} sec^{-1} sr^{-1}. In both cases the errors are intended to indicate the possible systematic errors in the calculations of the responses of the detector arrays. Since the calculations are essentially identical in the two cases, their fractional systematic errors should be nearly identical. Thus, if we assume that K is an exponential function of the vertical depth in the atmosphere, we can find a value for the absorption length Λ' whose uncertainty will not be seriously affected by these systematic errors. We find for Λ' the value

$$\Lambda'=103\pm5 \text{ g cm}^{-2},$$

which agrees with the values found from the zenith angle distributions.

Assuming the above value of $K(10^6,0)$ and $\Gamma=1.5$, we find the vertical intensity of showers with more than 10^5 particles at an altitude of 2034 m to be $(1.11\pm0.30)\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1}.

D. Distribution of Celestial Arrival Directions

The principle problem in the analysis of the distribution of the celestial arrival directions is to make proper allowance for the fact that the experiment was interrupted occasionally for maintenance and by power failures. As a result of these interruptions, some regions of the sky were under observation longer than others. Thus the number of showers observed to come from those regions would be expected to be greater even if the primary flux were isotropic. In order to keep track of the time during which various regions of the sky were under observation, we kept a running record of ON-TIME $Q(\gamma)$ which we define to be the number of days on which the apparatus was functioning at the sidereal time γ. We then prepared a plot of Q versus γ for a given group of events to be analyzed, and determined the average $\bar{Q}_i$ of $Q(\gamma)$ for each of m equal intervals of sidereal time for that group (for most of the analysis $m=36$, and for the rest $m=24$). Finally, for each interval of sidereal time we calculated a weight factor w_i according to the formula

$$w_i=\frac{1}{m}\left(\sum_{j=1}^{m}\bar{Q}_j\right)\Big/\bar{Q}_i,$$

and assigned this weight to each event in the group which was recorded during the ith sidereal time interval. In practice, the groups into which we divided the data were large enough and covered enough days of observation so that the values of w_i were always in the range from 0.85 to 1.15. Thus the effect of this procedure is to even out the effective exposure time for all portions of the sky without significantly changing the statistical significance of each event from what it would have been if it were given unit weight. The weights determined in the above manner are called weights based on logged ON-TIME. We combined the data from the steadiest periods of operation during the fast and slow runs and tabulated the total weights of events in $10°\times10°$ areas of a Mercator projection of the celestial sphere. The results of this tabulation are shown in Fig. 3.

In view of the difficulty of maintaining very uniform triggering efficiencies which is inherent in a detector system utilizing scintillation detectors, and also in view of the difficulty of maintaining an exact record of the operation of the apparatus, it seemed advisable to use, in addition to the weighting procedure outlined above, another one which would remove nearly all trace of anisotropy due to systematic errors in the evaluation of ON-TIME. This other procedure is a conservative one which removes the suspicion of instrumental cause from any observed anisotropy. It is made possibly by the fact that at any given moment the apparatus views a circular region of the sky which is limited by atmospheric absorption to a solid angle of approximately 30° in radius. As the earth turns during a day, this broad circular region sweeps out a band on the celestial sphere extending approximately 30° in declination on either side of the zenith. If, in the tabulation of the celestial arrival directions, the same number of events are included from each of $M(M\gg360°/60°)$ equal sidereal time intervals, then the observed intensity from any part of the sky will be approximately normalized to the average intensity within the large field of view. Consequently, if the primary flux is isotropic, and if M is sufficiently large, this procedure should give an observed distribution with statistical fluctuations less than those expected in an analysis with weights based on an accurate ON-TIME calculation. On the other hand, if the primary flux is anisotropic with a broad first harmonic variation in right ascension, this procedure would give an observed distribution with nearly isotropic characteristics, since the broad variation would not produce a large variation in intensity within any given field of view. Suppose, however, that an anisotropy of the primary flux existed in the form of a concentrated source, or of a ridge of high or low intensity. Such an anisotropy, highly localized in celestial coordinates, would affect the observed distribution of arrival directions in a small por-

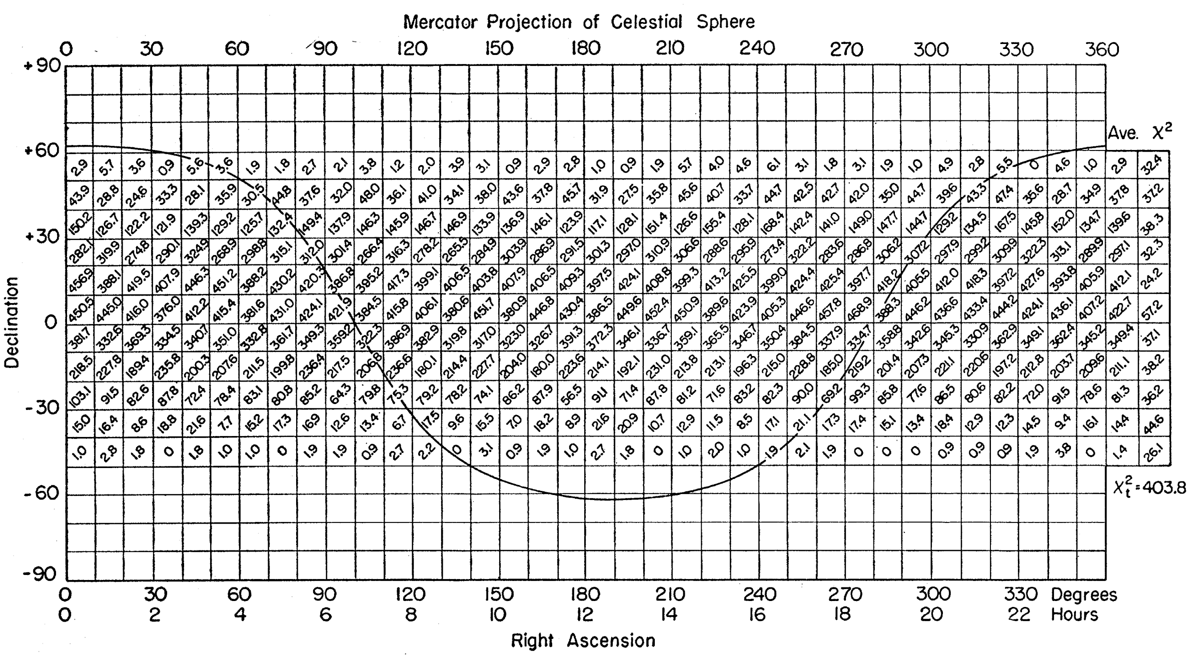

FIG. 3. Total weights based on logged ON-TIME for events recorded within $10°\times10°$ intervals tabulated on a mercator projection of the celestial sphere. The declination band averages are indicated on the right-hand side together with the values of χ_i^2 and χ_t^2.

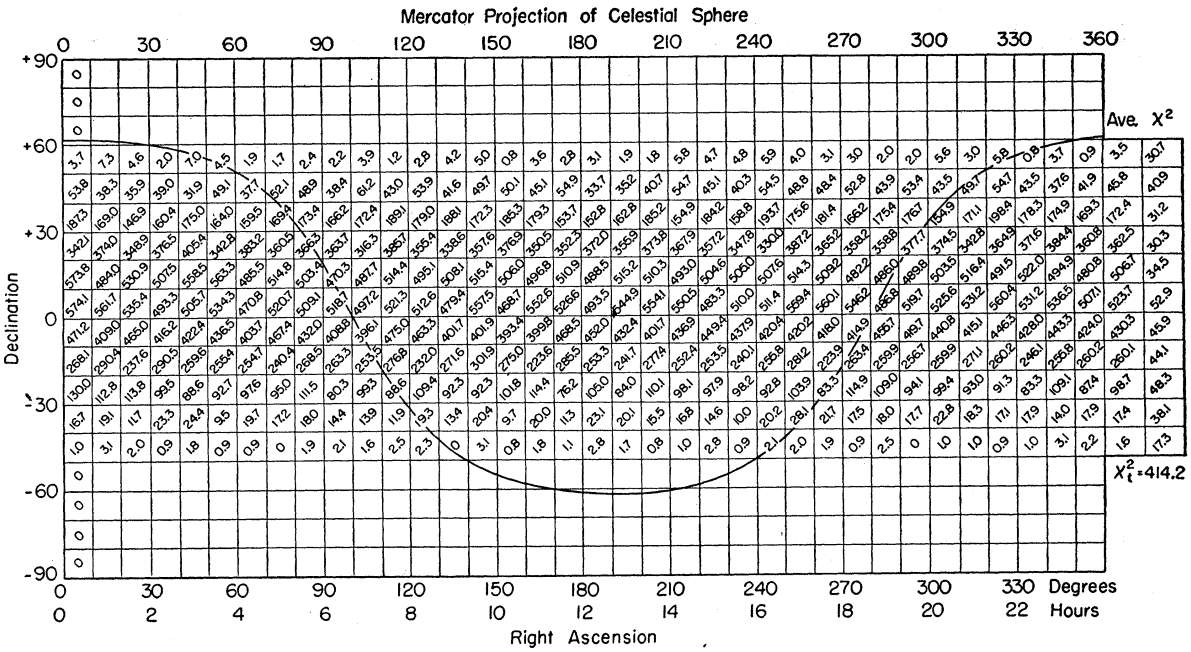

FIG. 4. Total weights based on numbers of events recorded during equal intervals of sidereal time.

tion of the field of view during three or four sidereal hours. This weighting procedure would therefore only slightly reduce the magnitude of the observed anisotropy. It is clear, consequently, that this procedure is a conservative one which eliminates false effects due to nonuniform ON-TIME and which tends to suppress real anisotropies. However, if the observed distribution obtained in this way reveals evidence of anisotropy, then this evidence is specially significant.

In practice, we carried out this procedure by first counting the numbers N_i of accepted events in each of M equal intervals of sidereal time in each of several large ($\sim$6000) groups of events (for most of the analysis $M=36$, and for the rest $M=24$). For each sidereal time interval we then calculated a weighting factor W_i according to the formula

$$W_i=\frac{1}{M}\left(\sum_{j=1}^{M} N_j\right)\Big/ N_i.$$

We then assigned the weight W_i to each accepted event which occurred during the ith sidereal time interval, and tabulated the total weight of the events in $10°\times10°$ areas of a mercator projection of the celestial sphere. The results of this tabulation are shown in Fig. 4. More events are included in this tabulation than in the previous one (Fig. 3) because this more conservative procedure for the calculation of the weights removes the requirement that only events recorded during steady periods of equipment operation be accepted.

Once the distributions of total weights were tabulated on Mercator projections of the celestial sphere, a series of statistical tests were applied in order to determine whether the observed distributions were consistent with the hypothesis that the flux of primary particles is isotropic. These tests are all based on the observation that if the primary flux were, indeed, isotropic, then the observed intensity of events should be independent of right ascension. This conclusion follows from the fact that, as the earth revolves, all points on the celestial sphere with a given declination pass through the field of view in exactly the same way. Thus one can determine for a given band of declinations on a Mercator tabulation an average weight of events for a series of equal intervals of right ascension. One can then compare the fluctuations of the observed weights of events in the intervals with that to be expected on the hypothesis of isotropy. In addition, one can compare the total weight of events observed to lie in a certain pre-selected region, (e.g., near the plane of the galaxy) with the total weight expected on the basis of the averages calculated for each declination band.

The fluctuations from the declination band averages are summarized in Fig. 5 where the sizes of the fluctuations are indicated by characteristic markings in each $10°\times10°$ interval. We recognize no significant pattern in these fluctuations.

The following specific tests for isotropy were applied to the Mercator tabulations:

(a) Chi-squared tests: We call C_{ij} the total weight of events which arrived from directions in the ith ($i=1,\cdots 18$) declination and jth ($j=1,\cdots 36$)

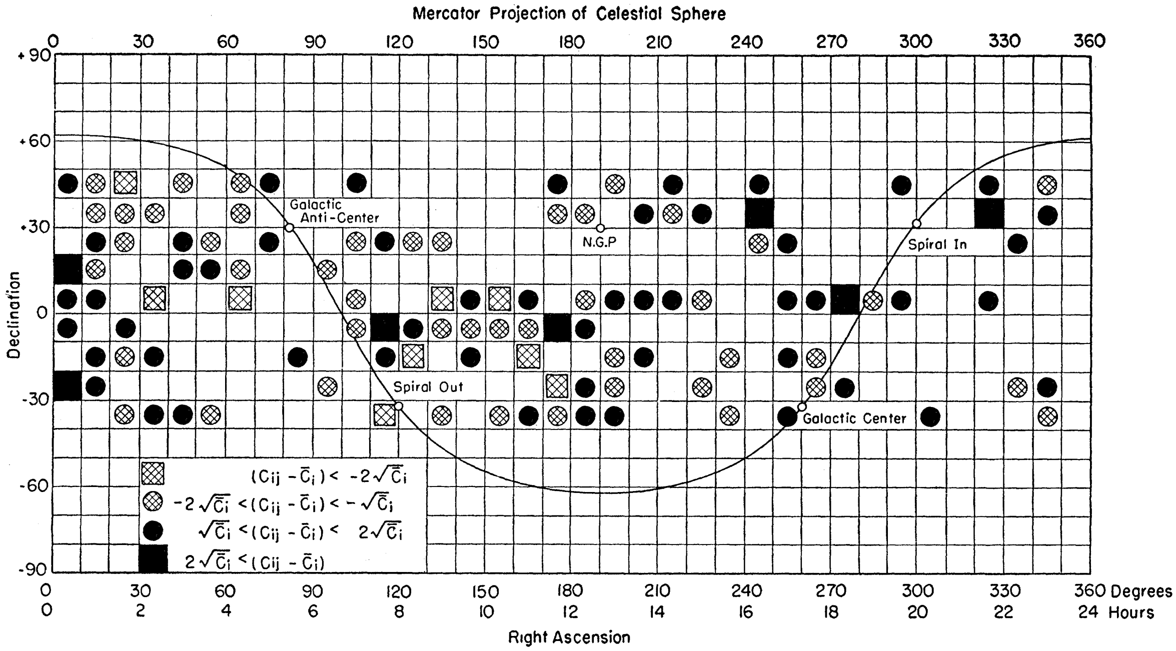

FIG. 5. Fluctuations from declination band averages of the tabulation (Fig. 3) based on logged ON-TIME.

right ascension intervals. We call $\bar{C}_i$ the declination band average and define it by the equation

$$\bar{C}_i=\frac{1}{36}\sum_{j=1}^{36} C_{ij}.$$

Then the value of chi-squared for each declination band is

$$\chi_i^2=\frac{1}{\bar{C}_i}\sum_{j=1}^{36} (C_{ij}-\bar{C}_i)^2,$$

and for an entire tabulation is

$$\chi_t^2=\sum_{i=a}^{b} \chi_i^2,$$

where a and b are chosen so that only declination bands with a significant weight of events are included. If n intervals are included in an evaluation of χ^2, then the value of $(2\chi^2)^{\frac{1}{2}}-(2n-3)^{\frac{1}{2}}$ should have an approximately normal distribution, provided the primary flux is isotropic.

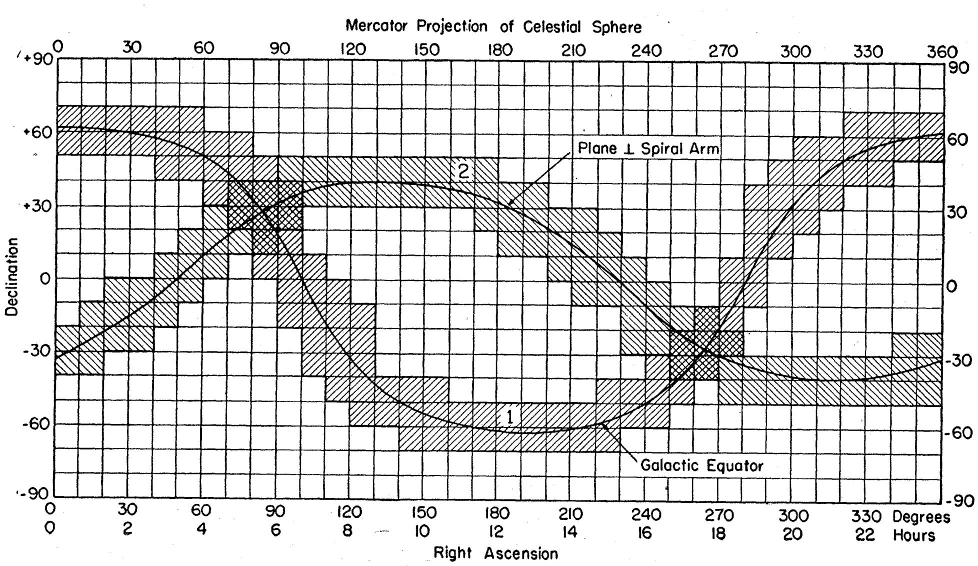

FIG. 6. Diagram showing special regions (1) near the galactic plane, and (2) near the plane normal to the spiral arm.

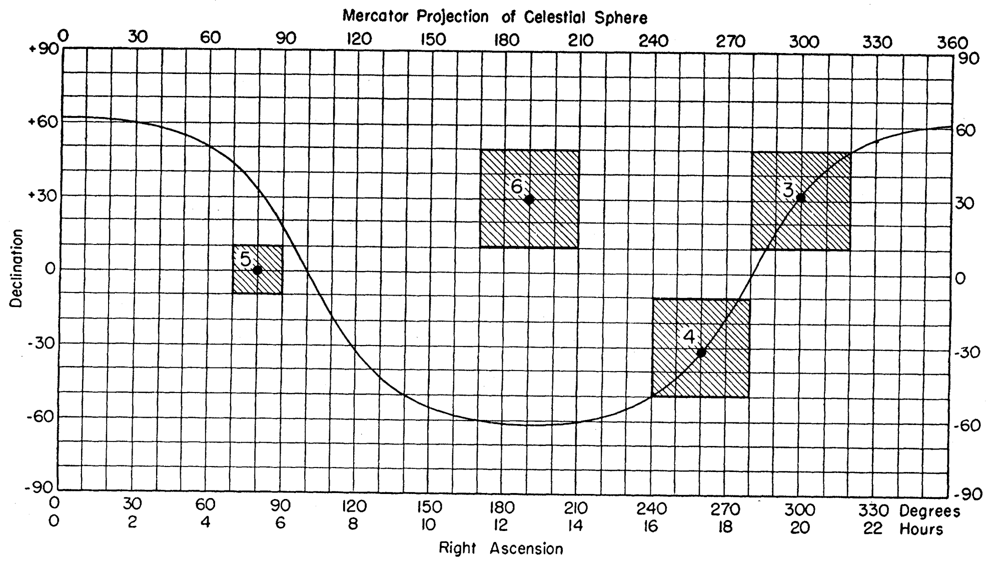

FIG. 7. Diagram showing special regions (3) near the direction along the spiral arm, (4) near the galactic center, (5) near the location where Sekido found evidence of a point source, and (6) near the north galactic pole.

The values of χ_i^2 and χ_t^2 for the two tabulations are listed in Figs. 3 and 4. The largest value of χ_i^2 for either tabulation is 57.2, and the probability that χ_i^2 should have exceeded this value for one or more of eleven independent bands is 0.09. The probability that χ_t^2 exceed the largest of the two values quoted is 0.54. Thus the chi-squared tests show no evidence of a "lumpy" anisotropy in the tabulated distributions.

(b) We compared the expected and observed total weights within special regions including the 10°×10° areas whose centers (on a Mercator projection) lie:

1. Within 10° of the galactic plane (Fig. 6).
2. Within 10° of the plane normal to the spiral arm (Fig. 6).
3. Within 20° of the direction in along the local spiral arm of the galaxy ($\alpha=20^h$, $\delta=35°$ N; Fig. 7).
4. Within 20° of the galactic center ($\alpha=17^h\ 20^m$, $\delta=42°$ S; Fig. 7).
5. Within 10° of the location where Sekido[5] has found evidence of a point source of high-energy particles ($\alpha=5^h\ 30^m$, $\delta=0.5°$ N; Fig. 7).
6. Within 20° of the north galactic pole ($\alpha=12^h\ 40^m$, $\delta=30°$ N; Fig. 7).

TABLE I. Expected and observed weights of showers from several special regions of the sky.

	Expected	Observed
1. Galactic equator	13 528.6	13 555.3
2. Perpendicular to spiral arm	17 880.6	17 949.9
3. Along the spiral arm ($\alpha=20^h$, $\delta=35°$)	3546.4	3583.2
4. Galactic center ($\alpha=17^h\,20^m$, $\delta=42°$ S)	1232.8	1267.3
5. Sekido's point source ($\alpha=5^h\,30^m$, $\delta=0.5°$ N)	1544.2	1566.1
6. North galactic pole ($\alpha=12^h\,40^m$, $\delta=30°$ N)	3546.4	3501.8

The results of these tests are summarized in Table I. They show no significant evidence of anisotropy. It should be emphasized in connection with region 5 that the results of this experiment are not directly comparable to those of Sekido since the average energy of the primaries we observed is at least 100 times the average energy of those observed by Sekido.

All of the above tests yield no evidence of anisotropy in the celestial arrival directions of over 100 000 showers with an average size of about 3×10^5 at 2034 m as observed from a station at 10° N latitude.

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