Directional Studies of Muons Near Sea Level

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By

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ABSTRACT

A continuation of R. P. Bukata's experiments using rotating muon telescopes during the period May 7th, 1965 to October 21st, 1966, with several improvements in apparatus and procedures is described.

Analysis of the experimental data has shown different results than those of Bukata. No indications for the large anisotropies (up to 15%) of the primary radiation, as reported by him, were found. Rather typical small anisotropies (~ 1%) were determined.

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INTRODUCTION

One of the most important branches of cosmic ray physics research during the last four decades, has been the study of the intensity of cosmic radiation and its variation with time and location. Research deep in the atmosphere has involved various difficulties as a result of secondary radiation production by primary cosmic rays at various levels of the atmosphere, geomagnetic effects, atmospheric effects and a lack of knowledge about effects on the primary radiation in outer space.

However a great leap forward in this subject has taken place with the development of space satellites which have enabled a direct investigation of the primary radiation from outer space.

This is giving a clearer picture on many effects which are concerned with the primary radiation intensity as for example: the nature of interplanetary magnetic fields, Forbush decreases, the correlation between solar activity and intensity time variations and the anisotropy of the primary radiation. The early researchers in time variation studies, for example: Kolhorster and Salis (1923), Lindholm (1928), Compton (1932), Hess and Graziadei (1936), used ionization chambers to study the intensity variation of the secondary radiation with sidereal and solar times. One of their main problems was deciding whether the observed daily variation arises only from atmospheric effects. By using two counter telescopes to measure the intensity variations inclined in two directions with equal zenith angles, Alfvén and Malmfors (1943), Malmfors (1949), Elliot and Dolbear (1950, 1951), established that some of the observed variation is certainly due to an anisotropy of the primary radiation. A further advance in these studies was made after Simpson (1953) introduced the neutron monitor technique for investigating the intensity time variations of the nucleonic component of the secondary radiation. This component has different atmospheric effects than has the meson component, and in general it reflects the behavior of the low energy part of the primary spectrum (<~10 BeV). Meson telescopes on the other hand respond to primaries >~10 BeV.

In general it has been found that the primary radiation is nearly isotropic in space and varies in intensity slowly with time. Observed average daily variations due to primary anisotropies are found to be small, less than one percent. A recent summary has been given by McCracken (1965). Quantitive theories of Parker (1964) and Axford (1965) provide a mechanism which produces the above variations. These involve the interaction of the solar wind, the interplanetary magnetic field and the interplanetary cosmic ray gas.

However, R. P. Bukata (1963-1964), using a new experimental technique involving rotating muon telescopes found large anisotropies (up to 15%), which persisted for many months and gradually faded away. The purpose of this work was essentially to continue similar observations for a further period.

CHAPTER II

Nature of the Experiment

Bukata's experiment using rotating muon telescopes represented a new technique in this kind of study. It consisted of two identical muon telescopes perpendicular to each other and mounted perpendicular to a polar axis (i.e. an axis set parallel to the earth's axis of rotation). The telescopes were thus set to be parallel to the plane containing the celestial equator. We let the projection of the earth-sun line on this equatorial plane be defined as the PES line. The polar axis was rotated at the constant angular velocity of 1 revolution per solar day in such a manner that the telescopes scanned the celestial equator once per solar day and were kept in a fixed orientation relative to the PES line. Since they were bi-directional, they defined four fixed viewing directions relative to the PES line (two viewing directions per telescope). Due to its rotation, a given telescope was looking through a variety of zenith angles and thus through a variety of muon fluxes. The muon intensity zenith angle distribution near sea level, is given according to an empirical formula of the form: $j = j_o \cos^n\phi$, where ϕ is the zenith angle, n is a constant, j_o is the vertical muon intensity and j the intensity at zenith angle ϕ. Thus a plot of counting rate vs. time during a 24-hour period for each telescope should yield two peaks (one for each of the corresponding viewing directions relative the the PES line, of the telescope) separated by 12 hours.

For isotropic primary radiation the two peaks are identical and separated by exactly 12 hours. As discussed extensively by Bukata (1964) the main virtues of this experiment are : (1) it represents a new approach to such studies and (2) the appropriate asymptotic cones of acceptance for such telescopes are relatively narrow in asymptotic longitude and therefore any smearing out of anisotropies in the equatorial plane is minimized.

The muon flux near sea level can be affected by atmospheric effects, (i.e. pressure and temperature). The problem of treating these effects in this experiment is obviously more complicated than for a stationary muon telescope. Bukata (1964) calculated the effects of pressure changes and found them to be negligible. In what follows no attempt was therefore made to correct raw data for such atmospheric changes.

The results obtained by Bukata during the period March 1963 to July 1964 indicated large anisotropies (~4-15%) for a primary radiation $\gtrsim$40 BeV (the energy range of primaries for which the telescope respond). These anisotropies persisted for many months and gradually began to fade away at the end of his experiments. They had completely faded away by the end of 1964,(Bukata and Standil (1965)). Preferred arrival directions defined by hour circle locations on the celestial equator were found to be around: 20.5 h., 10 h., 16 h. and 4-6 h.

Also, during a long run (March 1st 1963 to November 1st 1963) with narrow angle telescopes set at viewing directions of 17.5° E, 162.5° W, 107.5°E and 72.5° W of the PES line, Bukata found a large peak shift to an earlier than expected time for the viewing direction 17.5° E. This shift amounted to 40-50 minutes. Further, he determined that this particular peak area has $5 \pm 2\%$ less than the area of the other three peaks.

The main purpose of the present work was to continue (with some technical improvements) the above experiment for a further extended period, in order to see whether the large anisotropies would recur.

CHAPTER III

Experimental Equipment and Operation

(a) Telescope Geometries

In the experimental work to be described two telescope geometries (essentially the same as those used by Bukata) were utilized.

Figure 1(a) indicates the geometry during the Wide Angle Run (May 7th, 1965 to February 10th, 1966), while Figure 1(b) shows the telescope geometry for the Narrow Angle Run (March 25th, 1966 to October 21st, 1966).

(b) Electronics

Figure 2 is a schematic diagram of the electronic system (for one of the telescopes) which operated according to the same principles during the Wide Angle Experiment (May 7th, 1965 to February 10th, 1966) and the Narrow Angle Experiment (March 25th, 1966 to October 21st, 1966).

However, before the narrow angle experiment began, the system was completely rebuilt and transistorized. New plastic NE102 scintillators and photomultipliers were used and new solid state electronic units built.

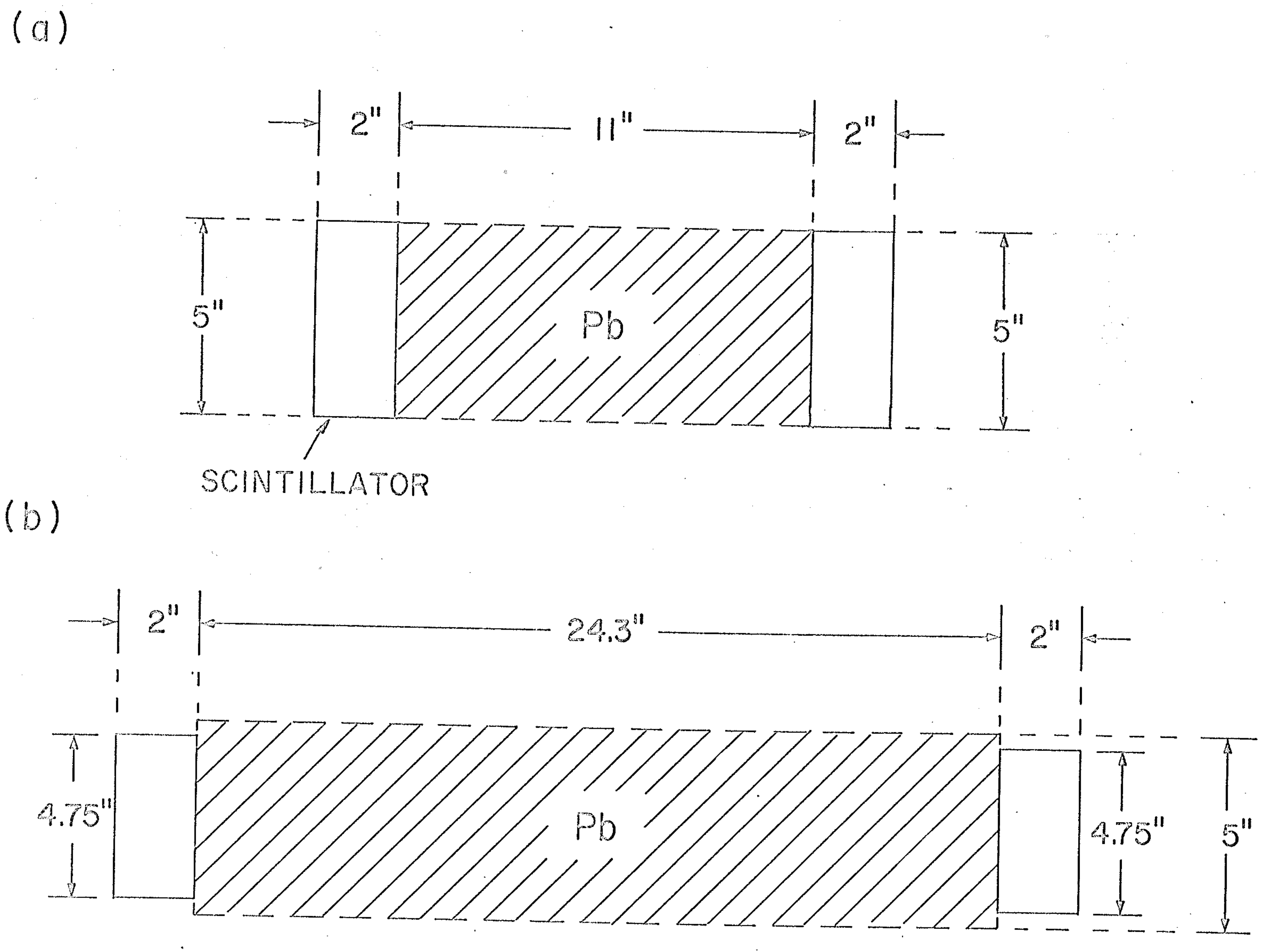

FIGURE 1

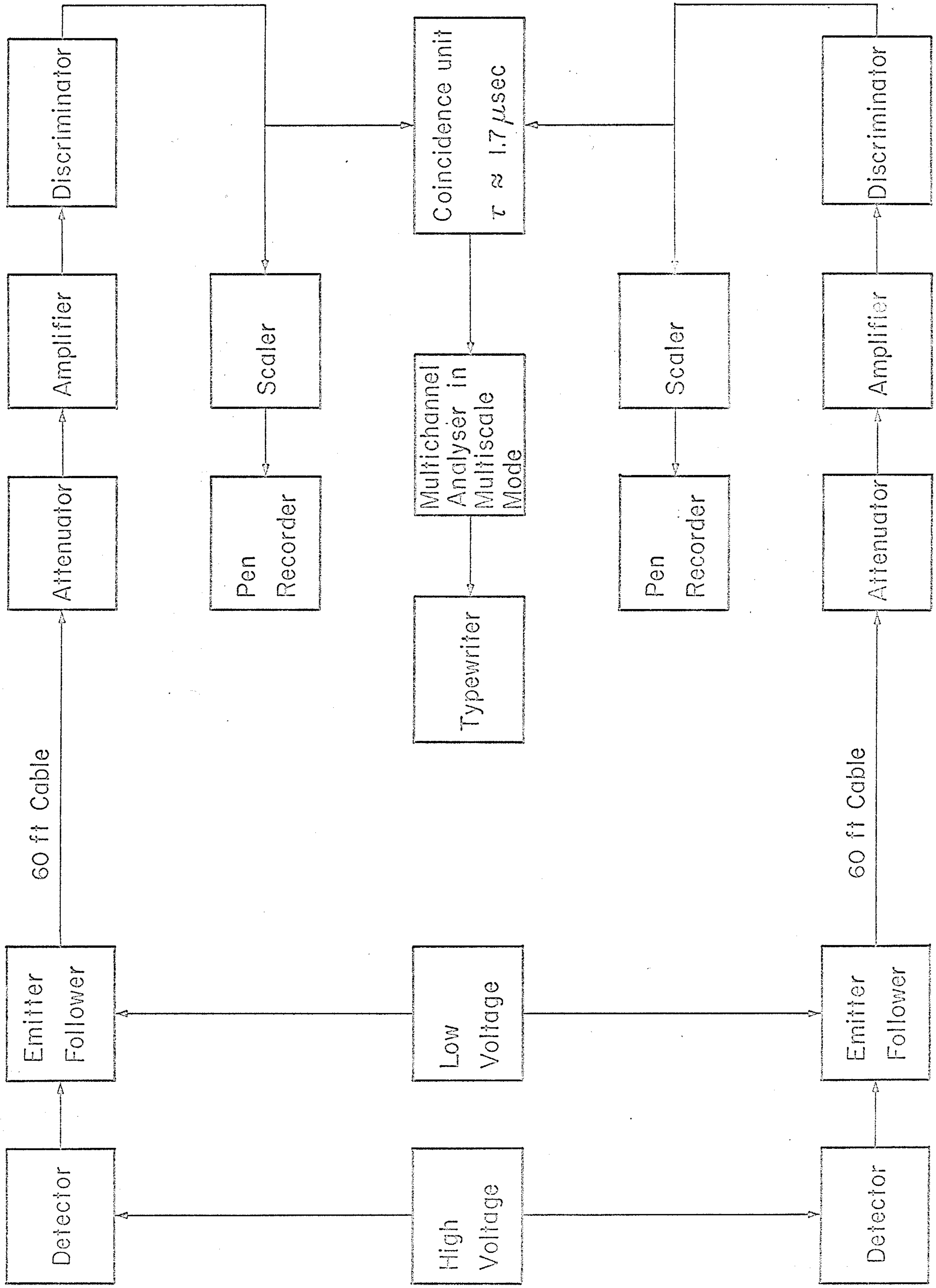
Detector
Emitter Follower
60 ft Cable
Attenuator
Amplifier
Discriminator
Scaler
Pen Recorder
High Voltage
Low Voltage
Typewriter
Multichannel Analyser in Multiscale Mode
Coincidence unit
τ ≈ 1.7 μsec
Pen Recorder
Scaler
Detector
Emitter Follower
60 ft Cable
Attenuator
Amplifier
Discriminator

FIGURE 2

The main purpose of this system was to detect the time coincident pulses from the telescope scintillators due to μ mesons passing within the coincidence angle of the telescope. (However time coincident pulses could be produced by two different particles passing simultaneously through both scintillators (i.e. showers).

These are clearly "unwanted coincidence". In order to minimize their number, the discriminator output pulses (i.e. singles) of the other telescope were used to anti-coincidence gate the coincidence unit. This is not shown in Figure 2.) Genuine muon coincidence pulses were then fed to a multichannel analyser operated in multiscale mode. They were counted in time intervals (i.e. channels) of 14.4 minutes (i.e. 0.01 day).

One day's data consisted then of 100 channels of information for each telescope. The last three channels of each day were missed to provide sufficient analyser readout time. Daily data collection started at 9 h. 48 m. 16 sec. (C.S.T.) (i.e. the beginning of channel 1).

Figure 3 is a typical result obtained for one telescope and shows clearly the two peaks about 12 hours (i.e. 50 channels) apart, each corresponding to a definite viewing direction. This figure represents the integrated data over a 16 day period for viewing directions 107.5° E and 72.5° W of PES line.

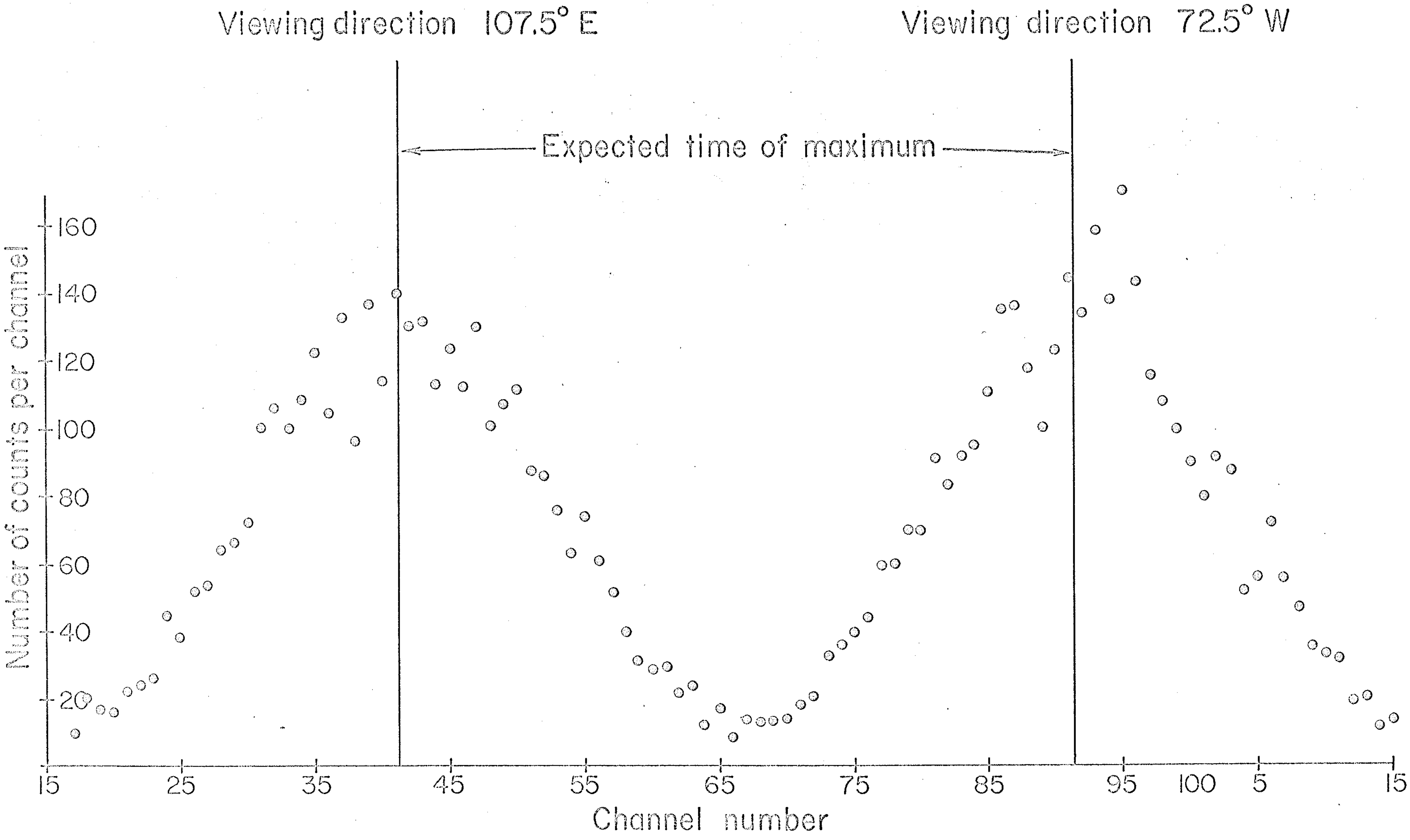
Viewing direction 107.5° E
Viewing direction 72.5° W
Expected time of maximum
Number of counts per channel
160
140
120
100
80
60
40
20
15
25
35
45
55
65
75
85
95
100
5
15
Channel number

FIGURE 3

This method of data collection is a major improvement over that used by Bukata who manually counted pen recorder pulses.

(c) Calibration Procedure

Before beginning the experiment it was necessary to determine discriminator levels, such that they would be triggered by all the pulses which were due to directional μ mesons (within the coincidence angle of the telescope).

A setting of low discriminator levels would ensure this, but if set too low would lead to excessively high accidental coincidence rates.

In spite of mu metal shields on the photomultipliers, their gain was found to vary with orientation in the laboratory by about 20%. The position of each detector for minimum gain was approximately determined and in this position discriminator levels corresponding to energies E, 2E, ... 8E (where E was the pulse height due to the maximum γ ray energy in a Na^{22} spectrum, namely 1.28 MeV) were found. With a given telescope in its minimum zenith angle orientation (i.e. maximum counting rate) coincidence rates were determined for various discriminator level settings. A typical result for one of the telescopes is shown in Figure 4.

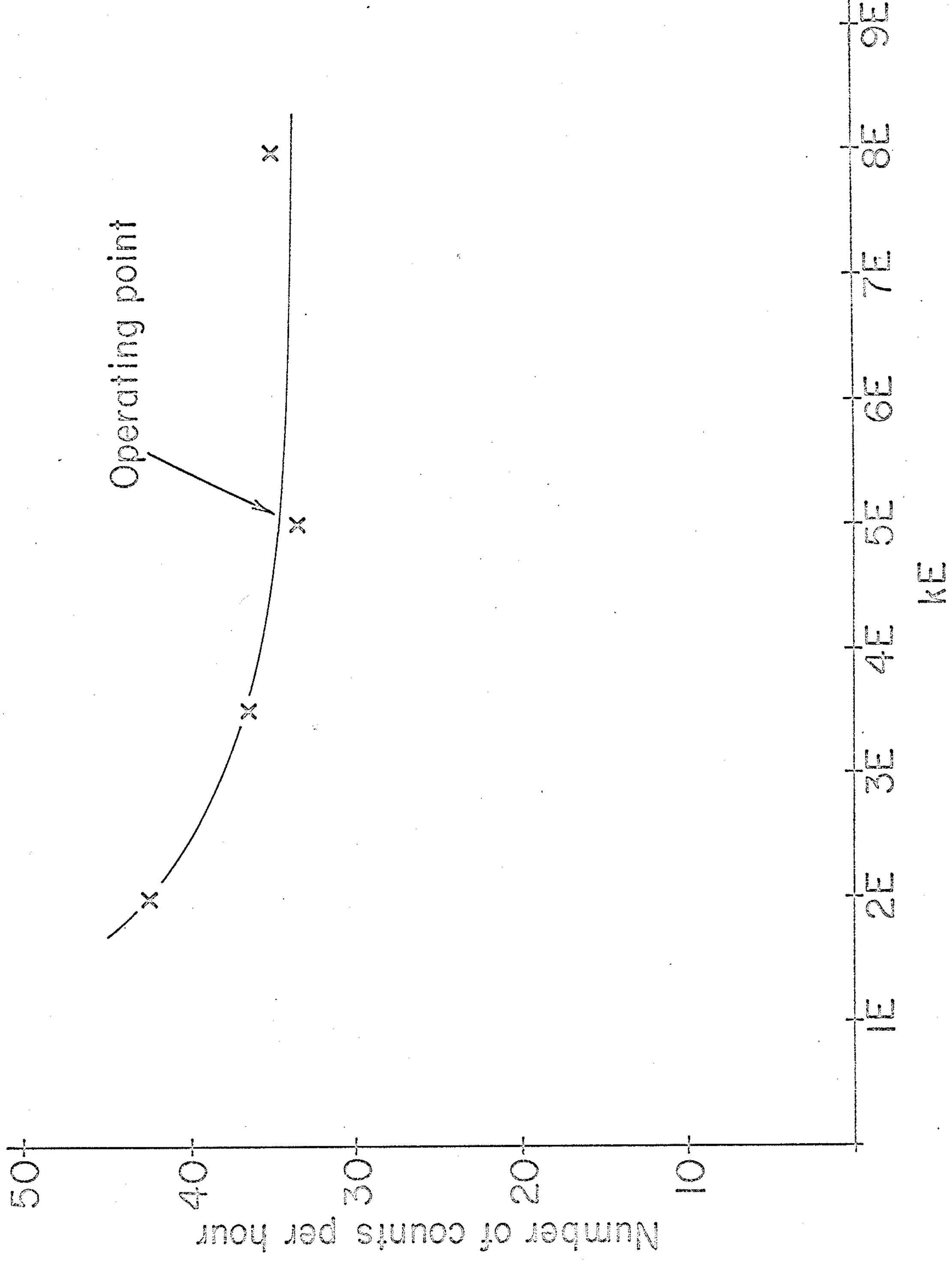
Operating point
Number of counts per hour
10
20
30
40
50
1E
2E
3E
4E
5E
6E
7E
8E
9E
kE

FIGURE 4

The plateau is to be expected for discriminator settings lower than those corresponding to muon energy loses in the scintillators (estimated at ~8 - 10 MeV). The rise at low discriminator settings is due to increased accidental coincidence rates which result because of rapidly increasing singles rates. An operating point on this plateau at discriminator settings corresponding to 5 E was chosen for the experimental work. With this operating point accidental coincidences amounted to <0.3% of the observed coincidence rate and muons within the telescope coincidence angle were detected with effectively 100% efficiency. The electronic stability was checked daily in two ways: (1) by monitoring the singles rates (using pen recorders) and (2) by counting (using fixed high system gain) gamma rays from weak Na^{22} sources attached permanently near each detector. Any system malfunction was thus easily detected and the daily calibrations at high gain were not at all dependent on atmospheric conditions.

CHAPTER IV

Wide Angle Experiment

(a) Method

The procedure here was the same as that followed by Bukata (Dec. 25th, 1963 to December 18th, 1964). After accumulating data for two days for 4 viewing directions, the telescopes were shifted by 30° and 4 new viewing directions were then followed for two days and so on. Thus every 6 days the celestial equator was scanned in 12 equal 30° steps.

(b) Results

Typical integrated results, after fourteen complete scans between May 7th, 1965 and August 29th, 1965 for the viewing directions 15° E and 165° W is shown in Figure 5. Theoretical times of maximum are indicated in this figure. For each peak corresponding to each viewing direction the area under the peak to the left of the theoretical maximum, Σ^-, and to the right, Σ^+, was determined. The total peak area, $\Sigma^+ + \Sigma^-$, is designated Σ. We define a peak anisotropy δ as:

$$\delta = \frac{\Sigma^+ - \Sigma^-}{\Sigma^+ + \Sigma^-} \times 100\%$$

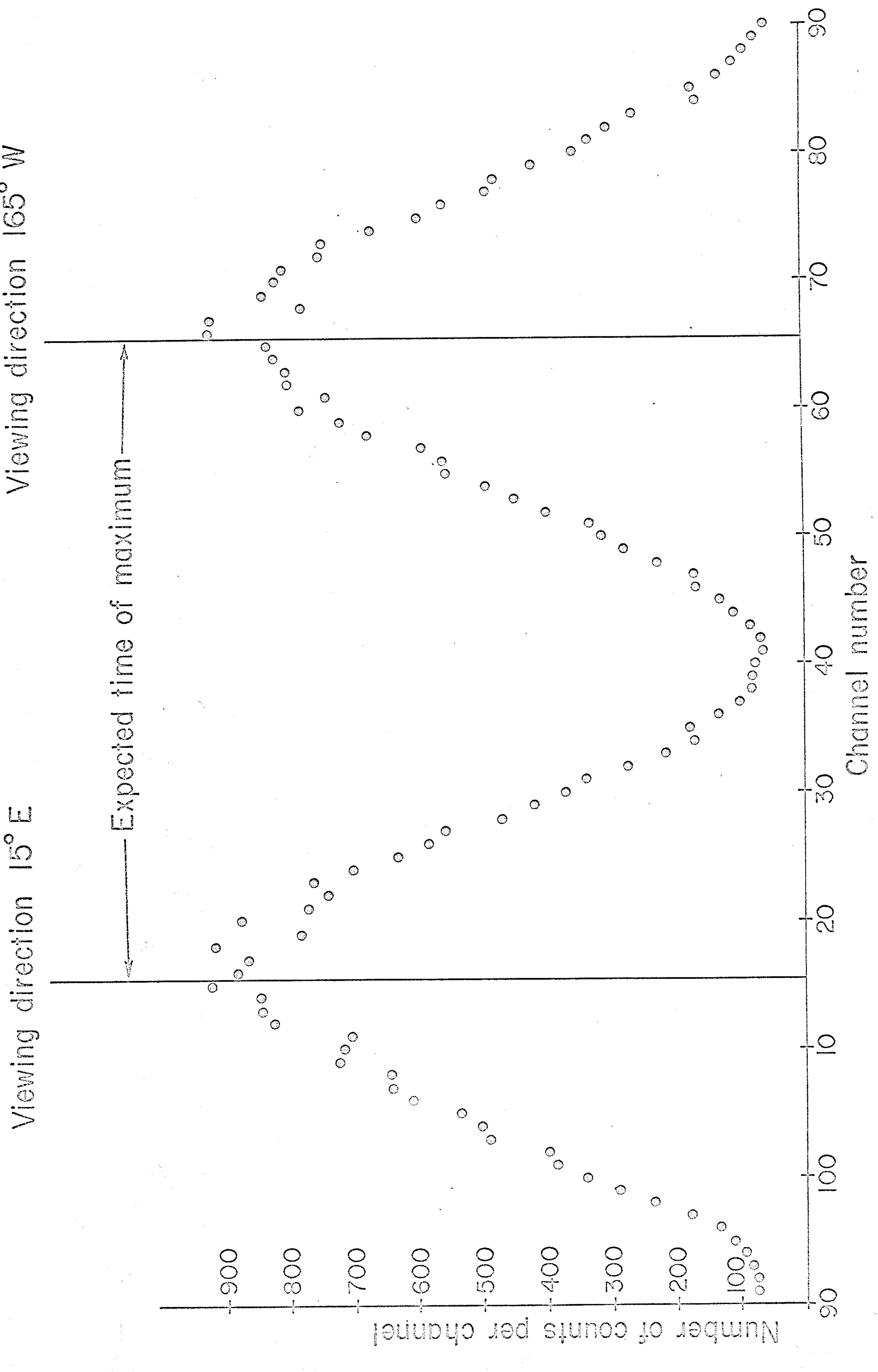
Viewing direction 15° E
Viewing direction 165° W
Expected time of maximum
Number of counts per channel
100
200
300
400
500
600
700
800
900
Channel number
90
100
10
20
30
40
50
60
70
80
90

FIGURE 5

Combined results obtained for all twelve viewing directions during the first fourteen complete scans are given in Table 1. Also given in this table are centres of gravity positions relative to their expected positions for complete symmetry.

Similar results for eighteen scans obtained between September 10th, 1965 and February 10th, 1966 are given in Table 2 and the combined results of all 32 scans are summarized in Table 3.

Inspection of Tables 1 - 3 indicate no large peak anisotropies. As an estimate of the possible primary anisotropy we can calculate

$$D = \frac{\Sigma_{max} - \Sigma_{min}}{\Sigma_{max} + \Sigma_{min}} \times 100\%$$

using the data of Table 3 and find that $D \sim 1.9\% \pm 0.8\%$ with Σ_{max} occuring at viewing direction 75^{o} E and Σ_{min} at viewing direction 135^{o} W or 75^{o} W. This anisotropy is an order of magnitude smaller than those reported by Bukata and is of the same order as the fairly well known diurnal variation amplitude which arises because of a streaming of cosmic rays from a direction $\sim 90^{o}$ E of the earth-sun line (Parker (1964), Axford (1965), McCracken (1965)).

TABLE 1

Viewing Direction	Σ No. of Count	δ %	Centre of Gravity Position Relative to Expected Position (Channels)
15° E	23362	-0.35 ± 1	-0.158 ± 0.068
165° W	23075	0.44 ± 1	-0.089 ± 0.068
105° E	22887	0.12 ± 1	-0.094 ± 0.068
75° W	22640	0.28 ± 1	-0.051 ± 0.069
165° E	22385	-1.02 ± 1	-0.105 ± 0.069
15° W	22970	0.93 ± 1	0.014 ± 0.068
75° E	23504	0.19 ± 0.97	-0.113 ± 0.068
105° W	23170	0.68 ± 1	-0.097 ± 0.069
135° E	22912	3.06 ± 1	0.229 ± 0.067
45° W	23177	3.08 ± 1	0.252 ± 0.067
45° E	23657	1.58 ± 1	0.114 ± 0.067
135° W	23120	2.44 ± 1	0.226 ± 0.067

TABLE 2

Viewing Direction	Σ No. of Count	δ %	Centre of Gravity Position Relative to Expected Position (Channels)
15° E	34775	1.97 ± 0.93	0.241 ± 0.055
165° W	34205	-1.06 ± 0.92	-0.102 ± 0.057
105° E	34970	-1.38 ± 0.89	-0.119 ± 0.057
75° W	34320	-0.45 ± 0.93	-0.039 ± 0.057
165° E	34926	0.03 ± 0.94	-0.042 ± 0.056
15° W	34817	0.53 ± 0.91	0.052 ± 0.056
75° E	35584	-0.27 ± 0.88	-0.006 ± 0.056
105° W	34550	-1.82 ± 0.93	-0.219 ± 0.057
135° E	34260	-0.93 ± 0.92	-0.139 ± 0.057
45° W	34289	1.33 ± 0.9	0.199 ± 0.056
45° E	34080	0.12 ± 0.94	0.003 ± 0.057
135° W	33688	0.9 ± 0.94	0.134 ± 0.057

TABLE 3

Viewing Direction	Σ No. of Count	δ %	Centre of Gravity Position Relative to Expected Position (Channels)
15° E	58137	1 ± 0.86	0.08 ± 0.044
165° W	57280	-0.45 ± 0.87	-0.096 ± 0.045
105° E	57857	-0.78 ± 0.84	-0.109 ± 0.045
75° W	56960	-0.1 ± 0.86	-0.043 ± 0.045
165° E	57311	-0.37 ± 0.86	-0.067 ± 0.045
15° W	57787	0.65 ± 0.86	0.035 ± 0.045
75° E	59088	-0.1 ± 0.82	-0.048 ± 0.045
105° W	57720	-0.82 ± 0.87	-0.181 ± 0.045
135° E	57172	0.67 ± 0.86	0.01 ± 0.045
45° W	57466	1.98 ± 0.86	0.207 ± 0.044
45° E	57737	0.71 ± 0.86	0.048 ± 0.046
135° W	56808	1.53 ± 0.87	0.163 ± 0.045

CHAPTER V

Narrow Angle Experiment

(a) Method

During this experiment, one of the telescopes was set to look in the viewing directions 107.5° E and 72.5° W, while the other looked at 17.5° E and 162.5° W. Their position was interchanged every 16 days (1 run) by stopping the polar axis motor after the readout of the 16th day and starting it after 6 hours. These viewing directions are the same used by Bukata in his "narrow angle" experiment and in which he observed very large peak shifts for 17.5° E viewing direction.

(b) Results

Combining the first four runs (March 25th, 1966 to June 6th, 1966) and analyzing as already described gave the results in Table 4.

Table 4

Viewing Direction	Σ No. of Count	δ%	Centre of Gravity Position relative to Expected Position (Channels)
107.5° E	15239	-0.36 ± 1.1	-0.048 ± 0.085
72.5° W	15111	1.34 ± 1.1	0.31 ± 0.084
17.5° E	15195	0.77 ± 1.1	0.173 ± 0.084
162.5° W	15011	0.92 ± 1.1	0.176 ± 0.085

Table 5 presents the analysis results from the last six runs combined (June 6th, 1966 to October 21st, 1966) for each viewing direction.

Table 5

Viewing Direction	Σ No. of Count	δ %	Centre of Gravity Position Relative to Expected Position (Channels)
107.5° E	20786	-0.3 ± 0.98	0.08 ± 0.072
72.5° W	20361	1.28 ± 0.98	0.208 ± 0.072
17.5° E	20450	2.13 ± 1.00	0.251 ± 0.072
162.5° W	20223	1.17 ± 1.00	0.175 ± 0.073

The results from the total ten runs combined (March 25th, 1966 to October 21st, 1966) are given in Table 6.

Table 6

Viewing Direction	Σ No. of Count	δ %	Centre of Gravity Position Relative to Expected Position (Channels)
107.5° E	36025	-0.32 ± 0.88	0.025 ± 0.057
72.5° W	35472	1.3 ± 0.88	0.251 ± 0.057
17.5° E	35645	1.55 ± 0.88	0.217 ± 0.056
162.5° W	35234	1.06 ± 0.88	0.175 ± 0.056

Table 7 presents the values of $D = \frac{\Sigma_{max} - \Sigma_{min}}{\Sigma_{max} + \Sigma_{min}} \times 100\%$ for the above periods of time.

Table 7

Period	D%	Viewing Direction of Maximum Intensity
March 25th, 1966 to June 6th, 1966	0.75 ± 1.6	107.5° E
June 6th, 1966 to October 21st, 1966	1.37 ± 1.4	107.5° E
March 25th, 1966 to October 21st, 1966	1.11 ± 1.0	107.5° E

These results too indicate no large primary anisotropies. No anomalous results are found for viewing direction 17.5° E (Bukata's results indicate a Σ for this viewing direction some 2 - 5% less than for the other directions and a centre of gravity shift for this peak of ~3 - 4 channels).

The results now obtained, again agree qualitatively with what would be expected on the basis of the fairly well known diurnal variation.

CHAPTER VI

Conclusions

A continuation of R. P. Bukata's experiments using both wide and narrow angle geometries for an extended period has failed to establish the large anisotropies which were originally found by him. It is true that these anisotropies had faded away by December 1964 (Bukata and Standil (1965)). This work established no reason for the fading away (i.e. no instrumental explanations were uncovered) and no evidence for their return during the following two years.

APPENDIX I

Alignment of the Telescopes

The procedures of aligning the polar axis on which the telescopes were mounted, are described in R. P. Bukata's Ph.D. thesis.

The two telescopes were perpendicular to each other so that when one of them was horizontal (at zenith angle of 90^{o}), the other was "vertical" (at its minimum zenith angle 49.9^{o}). The horizontal position of a telescope was fixed using a transit (which was aligned to look at the vertical plane which contained the polar axis). This procedure was followed during the Wide Angle Run, where the checking could conveniently be done every 24 hours.

During the time of the Narrow Angle Run (March 25th, 1966 to October 21st, 1966) four spirit levels were fixed on the edges of the telescopes (two for each telescope), to indicate the horizontal position. The advantage of this procedure was that the horizontal position of the telescopes could easily be checked every 6 hours.

Intercomparison of the "spirit level method" and "transit method" for measuring the apparatus orientation enabled an estimate of the possible error in an expected time of peak maximum (i.e. minimum telescope zenith angle) of ~ 0.1 channels. This has been taken into account in all calculations.

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