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An Experiment of the Time Variations of Cosmic Rays Underground

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AN EXPERIMENT ON THE TIME VARIATIONS OF COSMIC RAYS UNDERGROUND

By

Mercedes Merner Agogino

A Dissertation
In partial fulfillment of the
Requirements for the Degree
Doctor of Philosophy

The University of New Mexico
1954

This dissertation, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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DATE

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Roy Thomas

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CHAPTER I

INTRODUCTION AND SUMMARY

Ever since the discovery of cosmic rays, investigations of time variations in their intensity have been carried out in the hope of obtaining information on their nature and origin. Early experiments were somewhat contradictory, but it was soon clear that any variation present could be no larger than a few per cent at the most. This meant that experiments had to be carefully planned and carried out over a long period of time to attain the statistical accuracy necessary for clear-cut results. In addition, the influence of the atmosphere and the earth's magnetic field made it very difficult to interpret the experiments in terms of properties of the primary radiation.

In the experiment to be described in this dissertation, the intensity of three-fold cosmic ray coincidences fifty feet underground at Albuquerque, New Mexico, was measured over a period of one year from March 21, 1953 to March 21, 1954. The equipment consisted of two counter tube telescopes, one directed east and the other west, both making an angle of 45° with the horizontal. The two telescopes were rotated through an angle of 180° each hour, thus interchanging their positions. Any peculiarity of

CHAPTER I

INTRODUCTION AND SUMMARY

Ever since the discovery of cosmic rays, investigations of time variations in their intensity have been carried out in the hope of obtaining information on their nature and origin. Early experiments were somewhat contradictory, but it was soon clear that any variation present could be no larger than a few per cent at the most. This meant that experiments had to be carefully planned and carried out over a long period of time to attain the statistical accuracy necessary for clear-cut results. In addition, the influence of the atmosphere and the earth's magnetic field made it very difficult to interpret the experiments in terms of properties of the primary radiation.

In the experiment to be described in this dissertation, the intensity of three-fold cosmic ray coincidences fifty feet underground at Albuquerque, New Mexico, was measured over a period of one year from March 21, 1953 to March 21, 1954. The equipment consisted of two counter tube telescopes, one directed east and the other west, both making an angle of 45° with the horizontal. The two telescopes were rotated through an angle of 180° each hour, thus interchanging their positions. Any regularity of operation of either of the two channels should therefore have affected the results for both the east and the west in the same way. The accumulated counts were recorded separately at the surface for each telescope. The average counting rate for one telescope was about 1600 per hour.

During the year's run, data for 255 complete days was obtained. This was analyzed in two ways. First, the solar and sidereal twenty-four hour harmonic components for each day were calculated. These were then combined to find the average amplitude and phase of the solar and sidereal daily waves. In the second method, the pressure-corrected average deviations from the mean of the cosmic-ray intensity during each solar and sidereal hour were calculated. A harmonic analysis of these values was then made to obtain the amplitude and phase of the twenty-four hour and twelve-hour solar and sidereal time variations. Based on a total of some 350,000 coincidences for each telescope for each hour, a standard error of .05% in the calculated amplitudes of the solar and sidereal waves could be expected. If a daily variation with amplitude larger than this standard error does exist, it could be expected to appear in the west with a maximum about six hours later than in the east.

The interpretation of the results is simplified by the fact that the influence of the earth's magnetic field

and of some atmospheric effects is greatly reduced for underground measurements due to the high energy of the μ-mesons penetrating so much earth. A minimum of about 100 Bev. is estimated for the energy outside the atmosphere of the primary particles producing the mesons causing the three-fold coincidences measured in this experiment.

Examination of the amplitudes and phases calculated by the two methods of analysis of the data showed no solar or sidereal variation that was both larger than the standard error and also associated with a similar wave of suitably differing phase in the other direction. The experiment, therefore, gave no positive indication of a solar or sidereal time variation with amplitude larger than the standard error.

CHAPTER II

THEORIES OF SIDEREAL AND SOLAR TIME VARIATIONS OF COSMIC RAYS

The presence or absence of time variations in cosmic rays has been suggested on the basis of various theories concerning their production and distribution in the universe and the effect on this distribution of the earth's and the sun's magnetic fields. Unfortunately, none of the theories of the origin of cosmic rays has been successful enough in accounting for all the properties of this radiation to gain general acceptance. If cosmic rays were distributed throughout the universe with the same density as is present just outside the earth's atmosphere, their total energy would exceed that present in any other form except that contained in the rest mass of matter.[1] This is not impossible, but it is difficult to conceive of a mechanism for their creation with a high enough efficiency to achieve such an enormous total energy. It is always possible, of course, that cosmic rays are left over from the formation of the universe itself, possibly maintained to a certain

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[1] R. D. Richtmeyer and Edward Teller, "On the Origin of Cosmic Rays," The Physical Review, 75:1729, June 1, 1949.

extent by various acceleration processes.

If cosmic rays are distributed uniformly throughout intergalactic space, the rotation of our galaxy should create an increase of a few tenths of one per cent in their intensity when measured from the front of the moving earth and a decrease when measured from the back. This is usually called the Compton-Getting effect[2] and will be discussed in detail later.

I. GALACTIC THEORIES OF THE ORIGIN OF COSMIC RAYS

The theories of the origin of cosmic rays most commonly considered at the present time are the acceleration of protons by collision with moving magnetic clouds in interstellar space,[3] acceleration in the vicinity of strongly magnetic stars,[4] and acceleration in the strong magnetic flares of the sun.[5]

If the first theory is correct, no sidereal variation is to be expected as the cosmic rays are accelerated by

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[2] Arthur H. Compton and Ivan A. Getting, "An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays," The Physical Review, 47:817-821, June 1, 1935.

[3] Enrico Fermi, "On the Origin of the Cosmic Radiation," The Physical Review, 75:1169-1174, April 15, 1949.

[4] A. Unsold, "Cosmic Radiation and Cosmic Magnetic Fields," The Physical Review, 82:857-863, June 15, 1951.

[5] Richtmeyer and Teller, op. cit., pp. 1729-1731.

collisions with wandering magnetic clouds distributed in a random fashion throughout the galaxy. Recently the acceleration of charged particles by successive collisions or "reflections" between two moving magnetic clouds in the spiral arms of the galaxy has been considered.[6] This process would tend to accelerate particles back and forth along lines of magnetic force parallel to the spiral arms until they had enough energy to escape the two trapping magnetic fields. They would then, however, be very likely to escape from the galaxy completely, and the continued series of accelerations necessary to achieve the very high energies observed in many cosmic rays would be impossible. Irregular deflections at magnetic discontinuities associated with the boundaries of magnetic clouds have been suggested as a mechanism for destroying this directional property and confining the particles to the galaxy.

In the second theory, the cosmic rays are accelerated in the magnetic fields of stars, and either the nucleus of the galaxy or various strongly magnetic stars should appear as point sources. The absence of any strong apparent point sources for cosmic rays is taken to indicate the presence of a galactic magnetic field which circulates the rays until

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[6] E. Fermi, "Galactic Magnetic Fields and the Origin of Cosmic Radiation," The Astrophysical Journal, 119:1-6, January, 1954.

they are nearly isotropic. The existence of a sidereal time variation would then be interpreted as an indication of the magnitude of the trapping galactic magnetic field.[7]

According to the third theory, the cosmic rays are formed in bursts of solar radiation. The lack of a strong solar time variation of cosmic rays requires the assumption of a weak but extensive solar magnetic field which circulates the rays until they acquire the necessary isotropy. No sidereal variation would be expected, and the size of the solar variation would give an indication of the magnitude of the trapping magnetic field. In addition, local bursts of particles emitted by the sun could be expected to arrive directly from time to time.

Thus, none of these theories predicts the existence of a certain solar or sidereal time variation. The first two would allow a small general sidereal variation, and the third would allow a solar variation but no sidereal variation. Since in all of them the cosmic rays are formed inside our galaxy, no Compton-Getting effect would be expected.

II. THE COMPTON-GETTING EFFECT

As part of the Milky Way, the earth partakes of the

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[7] Giuseppe Cocconi, "On the Origin of the Cosmic Radiation," The Physical Review, 83:1193-1195, September 15, 1951.

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[7] Giuseppe Cocconi, "On the Origin of the Cosmic Radiation," The Physical Review, 83:1193-1197, September 15, 1951.

rotation of the galaxy. This, together with the proper motion of the solar system, gives the earth a velocity with respect to intergalactic space of about 300 km./sec. in the direction of right ascension 20 hr. 40 min. and declination $+47^\circ$.[8] If the distribution of cosmic rays is assumed to be isotropic in the frame of reference at rest with respect to the universe of galaxies, then the rotation of our own galaxy will cause an increase in the cosmic ray intensity as measured at the front of the moving earth.

This intensity change is brought about in three ways: the solid angle of the telescope measuring the intensity will be different in the system in which the incoming particles are isotropic than it is in the system in which it is at rest, the energy of the particles in the two systems will be different, and the average time interval between the arrival of individual particles will be different. These effects will be treated separately and then combined to give the final result.

The change in solid angle. Call the system at rest with respect to intergalactic space the 0 system and that moving with the earth at a velocity V the 0' system (Figure 1.a, p. 13). Then the problem is to find the cosmic ray

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[8] Compton and Getting, *op. cit.*, p. 217.

intensity per solid angle, n', in the earth's system if this intensity in the stationary system, n, is isotropic. With the O and O' systems as defined above, the relationship between the solid angle $d\Omega$ seen in the O system, and the same angle $d\Omega'$ as seen in the O' system is, to within the first order of $\beta = V/c$

$$d\Omega = d\Omega'(1-2\beta \cos \theta')$$

where θ' is the angle made by the momentum vector P' of the particle with the velocity vector of the earth. Since $d\Omega = 2\pi \sin \theta d\theta$, the transformation of $d\Omega$ will be given if those for $\sin \theta$ and $d\theta$ are known. Taking the transformation for $d\theta$ first, it is clear from Figure 1.a that

$$\theta = \text{arc tan} \frac{\sin \theta}{\cos \theta} = \text{arc tan} \frac{P_{\perp}}{P_{\parallel}}$$

where $P_{\perp}$ is the component of P at right angles to V and $P_{\parallel}$ is the component parallel to V. Therefore, since by the well-known relativistic equations

$$P_{\perp} = P'_{\perp}$$

and

$$P_{\parallel} = \frac{P'_{\parallel} + \beta E'/c}{\sqrt{1-\beta^2}}$$

then

$$\theta = \text{arc tan} \frac{P'_{\perp}\sqrt{1-\beta^2}}{P'_{\parallel} + \beta \frac{E'}{c}} = \text{arc tan} \frac{\sin \theta'}{\cos \theta' + \beta \frac{E'}{cP'}} .$$

Since $\frac{cP'}{E'} = \gamma'$ where γ' is the ratio of the speed of the incoming particle, v', to the speed of light, then

$$\theta = \text{arc tan } \frac{\sin \theta' \sqrt{1-\beta^2}}{\cos \theta + \beta/\gamma'} .$$

Differentiating to obtain dθ gives

$$d\theta = d\theta' \frac{\sqrt{1-\beta^2}}{1 + \frac{\sin^2\theta'(1-\beta^2)}{(\cos \theta' + \beta/\gamma')^2}} \left[\frac{\cos \theta'}{\cos \theta + \beta/\gamma'} + \frac{\sin^2 \theta'}{(\cos \theta' + \beta/\gamma')^2} \right]$$

$$= d\theta' \; 1-\beta^2 \left[\frac{1 + \beta/\gamma' \cos \theta'}{(1 + 2\beta/\gamma' \cos \theta' + \beta^2/\gamma^2)} \right].$$

Assuming that the particles are traveling at a speed near that of light, we can set $\gamma' = 1-A$ where A is much smaller than unity. Expanding this expression for dθ, keeping only terms of the first order in β and A finally gives

$$d\theta = d\theta' \, (1-\beta \cos \theta').$$

Now to obtain the transformation of sin θ, it is obvious from Figure 1.a, since $P_\perp = P \sin \theta$, that

$$\frac{\sin \theta}{\sin \theta'} = \frac{P_\perp P'}{PP_\perp'} = \frac{P' \sqrt{1-\beta^2}}{\left[(P_{\parallel}' + \beta E'/c)^2 + P_\perp'^2\right]^{\frac{1}{2}}} = \frac{\sqrt{1-\beta^2}}{(1 + 2\beta/\gamma' \cos \theta' + \beta^2/\gamma'^2)^{\frac{1}{2}}} .$$

Again set $\gamma' = 1-A$, expand, and keep only terms of the first order in β and A. This gives

$$\sin\theta = \sin\theta' (1-\beta\cos\theta').$$

Combining the results for $d\theta$ and $\sin\theta$ gives finally

$$d\Omega = d\Omega' (1-2\beta\cos\theta')$$

again correct to first order terms in the small quantities A and β.

A counter tube telescope collecting particles over the solid angle $d\Omega'$ will receive the same number of particles per second as viewed from either system, or

$$d\Omega' n'_\Omega = n_\Omega d\Omega = \frac{n'_\Omega \, d\Omega}{(1-2\beta\cos\theta')}$$

and

$$n'_\Omega = n_\Omega (1-2\beta\cos\theta')$$

where n'_Ω and n_Ω are the counting rates in the two systems considering only the angular dependence.

The change in energy. Proceeding to the energy change effect, the relation between the energies in the O and O' systems is given by the relativistic energy transformation

$$E = \frac{E' + \beta c P' \cos \theta'}{\sqrt{1-\beta^2}} \, .$$

Again set $\gamma' = 1-A$ where A will be small since the particles are traveling at nearly the speed of light. Then since β is also small, we have to the first order of small quantities

$$E = E'(1 + \beta \cos \theta')$$

Since the number of particles whose energy is higher than E is proportional to $E^{-1.8}$, a telescope surrounded by an absorber such that only particles of energy higher than E can penetrate will receive the same number of particles per second as viewed in either system, or

$$n'_E (E')^{-1.8} = n_E E^{-1.8} = n_E (E')^{-1.8} \, (1 + \beta \cos \theta')^{-1.8}$$

Thus

$$n_{E'} = n_E (1 + \beta \cos \theta')^{-1.8}$$

where $n_{E'}$ and n_E are the counting rates in the two systems considering only the energy dependence.

<u>The time change</u>. Besides the change in solid angle and energy, there is also a change in the average time interval between arrival of particles as seen in the two

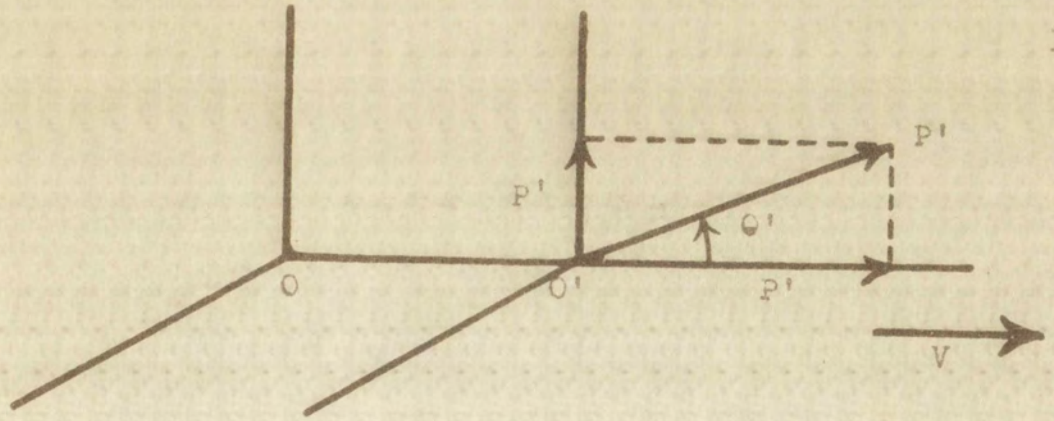

FIGURE 1.a

THE O AND O' FRAMES OF REFERENCE

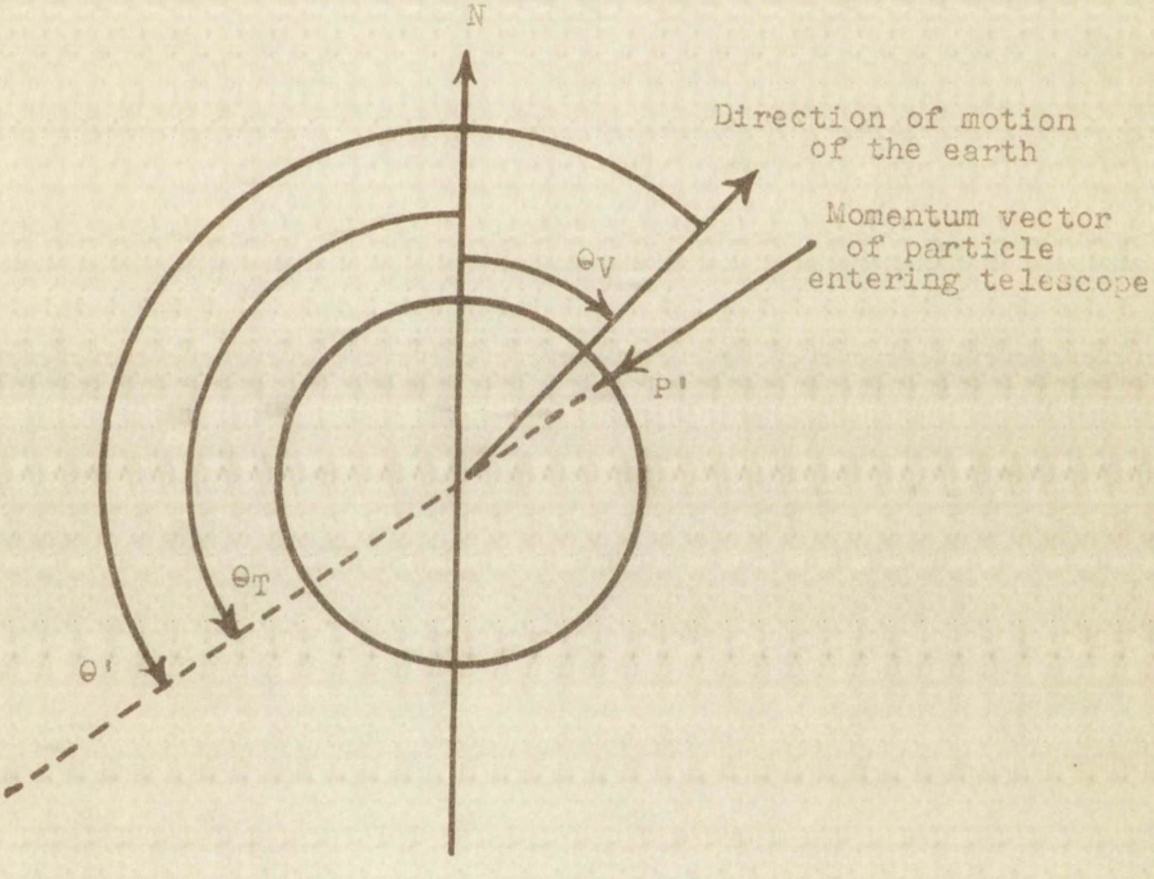

FIGURE 1.b

ORIENTATION OF THE EARTH, THE TELESCOPE, AND THE DIRECTION OF MOTION

systems. The reciprocal of this time interval is n, the number of particles arriving per second. With velocities near that of light, the number of particles arriving per second behaves in exactly the same way as the number of wave crests of light arriving per second. Thus, we have here the relativistic Doppler effect and

$$n_T = \frac{n_T' \sqrt{1-\beta^2}}{1-\beta\cos\theta'}$$

To the first order of β this gives

$$n_T' = n_T(1-\beta\cos\theta').$$

<u>The total change in intensity seen from the earth.</u> Multiplying the results for these three effects together and neglecting terms higher than first order in and $A = 1-\gamma'$ gives the final relation between the total intensities n' and n in the two systems as

$$n_T' = n_T(1-4.8\beta\cos\theta').$$

This means that a daily sidereal variation of amplitude 4.8β or .48% (since $\beta = V/c = .001$) with a maximum at 20 hr. 40 min. sidereal time is to be expected if cosmic rays originate outside our galaxy. The full .48% variation can never be observed, however, due to the inclination of the earth's axis to its motion through space. Figure 1.b, p. 13,

shows the relation between the earth's axis, the direction in which the earth is traveling with respect to intergalactic space, and the momentum of the particles entering a vertical telescope of small solid angle at a latitude of 35°N. The angle between the direction of motion of the earth and the momentum P' of the particles entering the telescope is θ'. The cosine of this angle is given by

$$\cos\theta' = \cos\phi_V\sin\theta_V\cos\phi_T\sin\theta_T + \sin\phi_V\sin\theta_V\sin\phi_T\sin\theta_T + \cos\theta_V\cos\theta_T$$

$$= \cos\theta_V\cos\theta_T + \sin\theta_V\sin\theta_T\cos(\phi_T-\phi_V)$$

where θ_V and ϕ_V are the spherical polar coordinates of the unit vector in the direction of the earth's motion, and θ_T and ϕ_T are the corresponding coordinates for the direction of particles entering the telescope. θ_V, ϕ_V, and θ_T are fixed while ϕ_T goes through 360° as the earth rotates.

The size of the factor $\sin\theta_V\sin\theta_T$ thus determines the size of the variation to be expected at a given latitude and given orientation of the telescope. The declination of the direction of the earth's motion = 47° or

$$\theta_V = 90^\circ - 47^\circ = 43^\circ.$$

For a telescope at the latitude of Albuquerque, N. M., 35°N, and pointed toward the zenith

$$\theta_T = 90^\circ + 35^\circ = 125^\circ$$

and $\sin \theta_V \sin\theta_T = \sin 43^\circ \sin 125^\circ = .558$. This reduces the effect from .48% to .27%. In the present experiment, the telescopes have a zenith angle of 45°. They are oriented east and west and as the earth turns sweep out a band of sky of constant declination, 24°N. Thus, $\sin\theta_V \sin\theta_T = .624$ and an effect of .30% can be expected.

The influence of the magnetic fields of the earth and the galaxy. In their original article, Compton and Getting indicated that the earth's magnetic field should cut down the magnitude of the effect but did not make any detailed calculations.[9] In 1939 Vallarta, Graef, and Kusaka[10] worked out in detail the intensity variation due to galactic rotation taking into account the influence of the earth's magnetic field for the case of particles incident in the plane of the geomagnetic equator. They found that for the integrated effect over the whole energy spectrum a great change in both magnitude and phase would result, depending on the form of primary spectrum chosen and on the ratio of positive to negative particles assumed. Most of this change in the integrated effect, however, is due

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[9] Ibid., p. 820.

[10] M. S. Vallarta, C. Graef, and S. Kusaka, "Galactic Rotation and the Intensity of Cosmic Radiation at the Geomagnetic Equator," The Physical Review, 55:1-5, January 1, 1939.

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to the large deflection of the low energy particles. For a particle with an energy of 100 Bev., the maximum angle of deflection is about 50° (for a particle coming in horizontally from the east), and the average is under 20°. Thus, for experiments carried on with particles of similar or higher energy, their deflection in the earth's magnetic field should not greatly change the phase and magnitude of the effect of galactic rotation.

The effect of galactic magnetic fields presents another problem. The vast distances which an extragalactic cosmic ray would have to cover before reaching the earth would allow even a very weak magnetic field, if sufficiently extended in space, to bend all but the highest energy particles so that any previous directional properties would be lost. Until more knowledge of these fields is available, however, it is difficult to estimate their exact effect.

In addition to the time variations predicted or at least allowed by various hypotheses concerning the origin of cosmic radiation, there are other variations which could be expected due to changes in the pressure and temperature of the atmosphere. Their effect on the analysis and interpretation of this experiment will be discussed later.

CHAPTER III

PREVIOUS RESEARCH ON TIME VARIATIONS OF COSMIC RAYS UNDERGROUND

Much work has been done on the time variations of cosmic rays, but most of it has been carried out at the surface rather than underground. These surface experiments will not be described here in detail as the large effects of the earth's magnetic field, atmospheric pressure, and atmospheric temperature on the relatively low-energy cosmic rays involved make it difficult to interpret the results and the evidence is often conflicting.

In summary, it may be said that only three periodic variations are at all generally accepted as present, and even with these there is considerable disagreement about their exact amplitude and phase. The first of these has a period of one solar year with an amplitude of about 2% and a maximum in mid-summer[11] which may very well be due to a yearly temperature variation. The next has a period of one solar day with an amplitude of about .2% and a maximum in the afternoon.[12] However, there is some conflicting

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[11] H. Elliot, "Time Variations of Cosmic Ray Intensity," Progress in Cosmic Ray Physics (J. G. Wilson, editor; New York: Interscience Publishers, Inc., 1952), pp. 461-466.

[12] Ibid., pp. 461-481.

evidence as to both the amplitude and phase. There is no general agreement as to whether this represents an atmospheric effect, a magnetic effect, or is a characteristic of the primary radiation. The third has a period of twelve solar hours and has been found by many workers but with widely differing amplitude and phase.[13] It is usually found to be smaller than the diurnal variation by a factor of ten.

A brief individual account of those underground experiments in which the time variations of cosmic rays were investigated will now be given.

Observations of Rau. Using ionization chambers suspended at a depth of about 40 meters in Lake Constance, Germany, at an altitude of 1300 ft. above sea level, Rau made cosmic ray intensity measurements from 1936 to 1938.[14] The water level of the lake varied as much as two meters over the total time during which the experiments were being carried out, but remained practically constant during the individual runs lasting usually only a few days. Therefore, each run was corrected as a whole for the change in depth

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[13] Ibid., pp. 481-484.

[14] Walter Rau, "Die Intensitätsschwankungen der harten Komponente der kosmischen Ultrastrahlung," Zeitschrift fur Physik, 114:265-295, 1939.

of water over the equipment, but no hourly corrections were considered necessary. An atmospheric pressure coefficient of -0.04% per cm. Hg. was found, but since this was smaller than the experimental error no correction for pressure was considered necessary.

The data were analyzed according to the solar year, solar hour, and sidereal hour. An annual variation of 2% (with a standard deviation of .9% on the monthly means) with a maximum in June was found. The hourly mean values for the solar and sidereal day each had a standard deviation of about 0.1%. No twenty-four hour solar period was found but harmonic analysis of the hourly means gave a twelve hour period with amplitude of .18% and a maximum at 9 A.M. and at 9 P.M. local time. The harmonic analysis of the sidereal hourly means gave an amplitude of .07% with a maximum near 22 hours local sidereal time, but this was too close to the statistical variation to be reported as definitely significant.

Observations in the Shimizu tunnel. Beginning in 1939, underground cosmic ray observations have been made in the Shimizu railroad tunnel in Japan at 2000 feet above sea level and at different depths of water equivalent.[15] Eight

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[15] Y. Nishina, Y. Sekido, Y. Miyazake, and T. Masuda, "Cosmic Rays at a Depth Equivalent to 1400 Meters of Water," The Physical Review, 59:401, February 15, 1941.

months' data taken at a depth of 1200 meters of water equivalent on a three-fold coincidence telescope shielded by 50 cm. of lead were analyzed according to solar and sidereal time.[16] Only 1720 coincidences occurred during that time and the expected standard deviation for the hourly averages was 12%. No solar diurnal variation was found, but a sidereal variation with amplitude 10% and maximum at 6 hours local sidereal time was reported. Within the rather wide angle of over four hours subtended by their telescope this is the direction of the Crab nebula, and the authors suggest that this well-known source of cosmic noise may also be a point source of cosmic rays. A sidereal variation of this large magnitude should be easily detected, but the results of the other two experiments done at comparable depth, which will be discussed next, are negative.

Observations of the Cornell group. A very extensive series of measurements and calculations on cosmic rays underground in a salt mine near Ithaca, N. Y. at a depth of 1574 meters of water equivalent has been carried out over the past few years by a group at Cornell University.[17]

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[16] Y. Sekido, T. Masuda, S. Yoshida, and M. Wada, "The Crab Nebula as an Observed Point Source of Cosmic Rays," The Physical Review, 83:658-659, August 1, 1951.

[17] Paul H. Barrett, Lowell M. Bollinger, Guiseppe Cocconi, Yehuda Eisenberg, and Kenneth Greisen, "Interpretation of Cosmic-Ray Measurements Far Underground," Reviews of Modern Physics, 24:133-178, July, 1952.

Included in these observations were two studies of the solar and sidereal time variations, each carried on for about three months.

In the first of these, the results of which were reported by Cocconi in 1951,[18] a total of 20,450 four-fold coincidences, at an average rate of 4.92 per hour, were collected from a vertical telescope shielded by 14 inches of lead. The trays were each 30 in. by 30 in. and the separation between the top and bottom trays was 22 in. It was estimated that the coincidences were due to atmospheric mesons of average energy of about 1000 Bev. The data were analyzed by solar and sidereal time, with an expected standard error for the hourly means of 2.3%. The actual deviations of the average hourly rates from the mean for both solar and sidereal time were so close to the standard deviation expected for no variation at all that a solar or sidereal daily wave with amplitude of more than 3% was considered incompatible with the data.

The second series of measurements was made with five two-fold coincidence telescopes consisting of two trays of counters 30 in. by 36 in. separated by four inches of lead and one-half inch of iron with two inches of lead shielding

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[18] Cocconi, _op. cit._, p. 1193.

above and below.[19] An average hourly rate of 10.46 coincidences per hour for each telescope was obtained and a total of 90,702 coincidences was collected, leading to an expected standard deviation of 1.7% in the average hourly counting rates. The data were analyzed according to solar and sidereal time. The actual standard deviation of the hourly means for both sidereal and solar time was little larger than that expected for no variation at all, and the authors concluded that a solar or sidereal variation larger than about 1% did not exist.

Observations of Sherman. Operating in a salt mine near Detroit, Michigan at a depth of 846 meters of water equivalent, Sherman collected two-fold coincidences over the year ending March 21, 1952.[20] The trays of Geiger counters were each 24 in. by 24 in. and were separated with an inch of lead to eliminate coincidences due to local radioactivity. The arrangement was thus sensitive to cosmic rays over virtually the entire solid angle, a counting rate of 107.8 per hour being observed. An average energy of 200 Bev. was estimated for the mesons observed at this

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[19] Paul H. Barrett and Y. Eisenberg, "Diurnal Variations in High Energy Cosmic-Ray Intensities," The Physical Review, 85:674-675, February 15, 1952.

[20] Noah Sherman, "Diurnal Variations in the Intensity of Cosmic Rays Underground," The Physical Review, 89:25-26, January 1, 1953.

depth. The data were analyzed by calculating the average counting rate for each solar and each sidereal hour. A total number of 7.4×10^5 counts was recorded giving an expected standard deviation of .63% for hourly counts over the whole year. An actual standard deviation of .74% and .64% was found for the solar and sidereal hour values respectively. A first harmonic of .5% for the solar and .2% for the sidereal variation was found, both of which are well inside the standard errors. From a comparison of the expected and actual standard deviations Sherman concluded that no variation larger than about .5% in either sidereal or solar time could exist.

Observations of MacAnuff. Apparently the statistically most accurate observations of diurnal variations of cosmic rays underground so far have been made by J. W. MacAnuff in London at a depth of 60 meters water equivalent.[21] Unfortunately, since information on this work is only available at second-hand, many details are unknown.

Two three-fold counter telescopes, each tray of which was 60 cm. by 51 cm., were used; the height of the telescopes

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[21] J. W. MacAnuff, unpublished Ph. D. thesis, University of London, 1951 as reported by E. P. George, "Observations of Cosmic Rays Underground and their Interpretation," Progress in Cosmic Ray Physics (J. G. Wilson, editor; New York: Interscience Publishers, Inc., 1952), pp. 395-451.

was not mentioned. The counting rate of each telescope was about 7000 per hour. The combined data for the two telescopes were analyzed by solar and sidereal time and a small solar diurnal variation of .05% with a maximum at 1600 hours local time was found. The standard error on the two-hourly averages was about .03% or .04% on the one-hourly average. It was concluded that any semi-diurnal variation present must be less than .03% while any sidereal variation must be smaller than .02%. A barometric coefficient of -.47% per cm. Hg was found.

<u>Summary of results.</u> Many of the cited workers found no definitely significant solar and sidereal time variations. Of the three significant variations reported, two were contradicted by the results of other workers. The .05% twenty-four hourly solar wave with maximum at 1600 hours local time found by MacAnuff is not contradicted by the results of any of the other experiments, but cannot be confirmed, either, because of their statistical accuracy. The .2%, twelve hourly solar wave found by Rau was not found by MacAnuff who reports any variation of more than .03% incompatible with his data. Possibly this discrepancy is due to the difference in the average properties of particles triggering a three-fold coincidence telescope and those collected by an ion chamber. The 10% sidereal variation

found by Sekido et al. is contradicted by the results of all the other workers. It seems likely, therefore, that this variation is due to statistical fluctuations rather than a real variation of the cosmic rays.

CHAPTER IV

THE EXPERIMENTAL ARRANGEMENT

The equipment used in collecting the data for this experiment consisted of two three-fold coincidence Geiger tube telescopes with 8" of lead shielding, mounted in a framework such that one pointed east and the other west, both at a zenith angle of 45°. The framework was mounted on a cut-down searchlight base which was turned by an electric motor each hour until it was stopped after 180°. The telescopes thus exchanged directions with each other at the beginning of each hour. This rotation took ninety seconds for completion. A cross-section of the arrangement is given in Figure 2, p. 28.

<u>The shaft</u>. This equipment was operated at the bottom of a shaft 46" in diameter and 48' 7" in depth which was sunk in the sandy earth about one-half mile northwest of the Physics Department of the University of New Mexico. Samples of this earth taken during the excavation of the hole were found to have an average density of 2.0 gm. per cm.^{3}. The shaft was floored with cement and lined with steel boiler plate which extended 13" above the cement floor of the small house built over the entrance. A cross-section of the shaft and its protective house is shown in

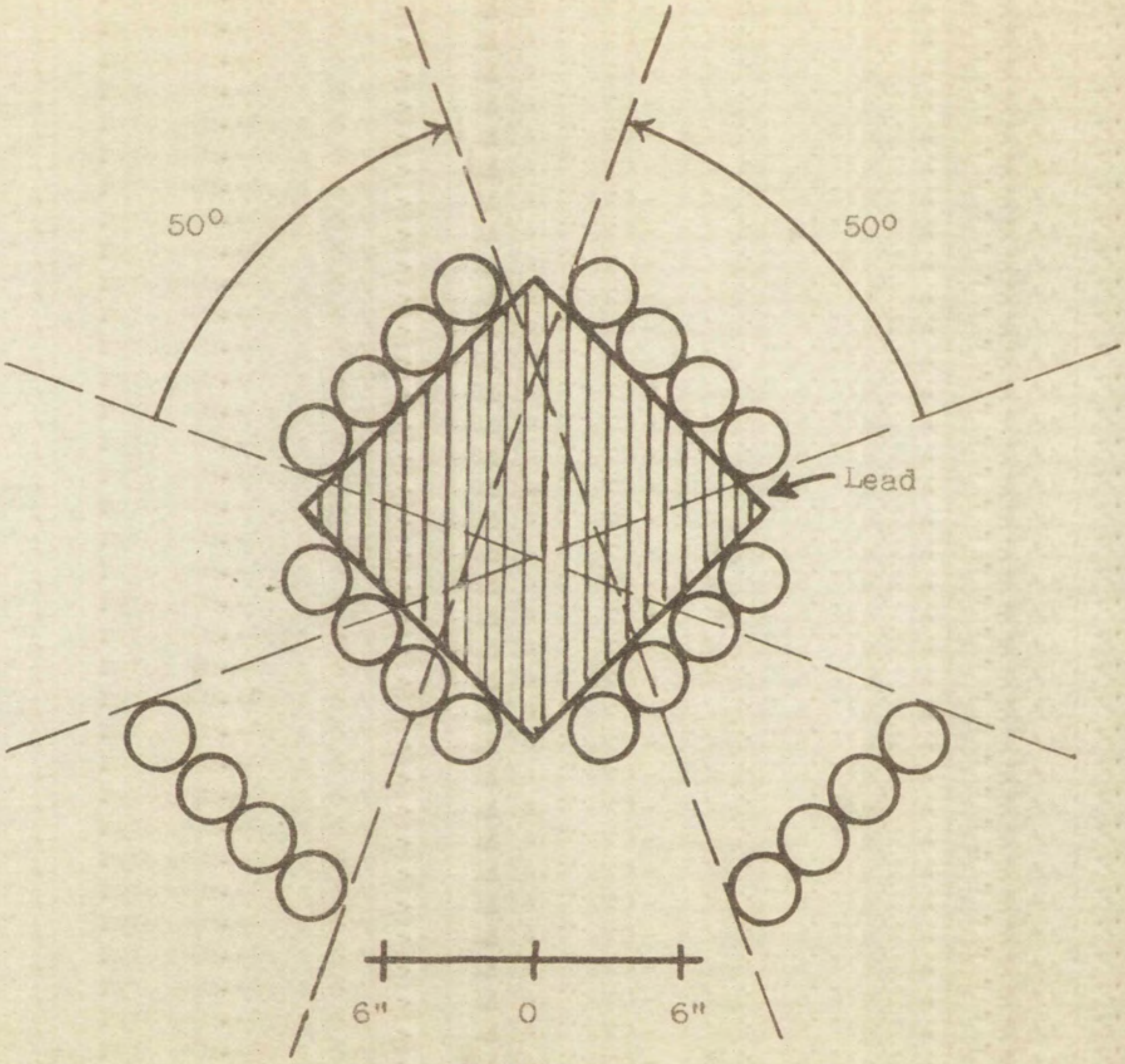

FIGURE 2

DIAGRAM OF EXPERIMENTAL ARRANGEMENT

Figure 3.

Electrical connection between the equipment and the surface was provided by two sixty-foot, four-wire cables wound on a revolving drum so that they could be let down with the framework as it was lowered. Eight separate electrical channels, four to the stationary base and four to the revolving framework carrying the telescopes and their associated circuits, were thus available. The complete apparatus weighed about three-quarters of a ton and could be lowered or raised in twelve minutes for servicing by means of an electrically-driven winch and steel cable. Two permanently mounted guide cables on the north and south sides of the shaft kept the equipment in line during its descent so that it would always come to rest in the same position at the bottom.

The telescopes. Figure 2 shows the arrangement of the two telescopes and and their lead absorber. Each consisted of three trays of four brass Geiger counters, the two top trays being separated by 8" of lead. Each counter was 2" in diameter and 24" in length; each tray thus had a sensitive area of 8" by about 22". A three-fold coincidence rate of about 1600 per hour was found for each telescope. The counters were filled with a mixture of argon and ethyl alcohol and operated near 1250 volts with a

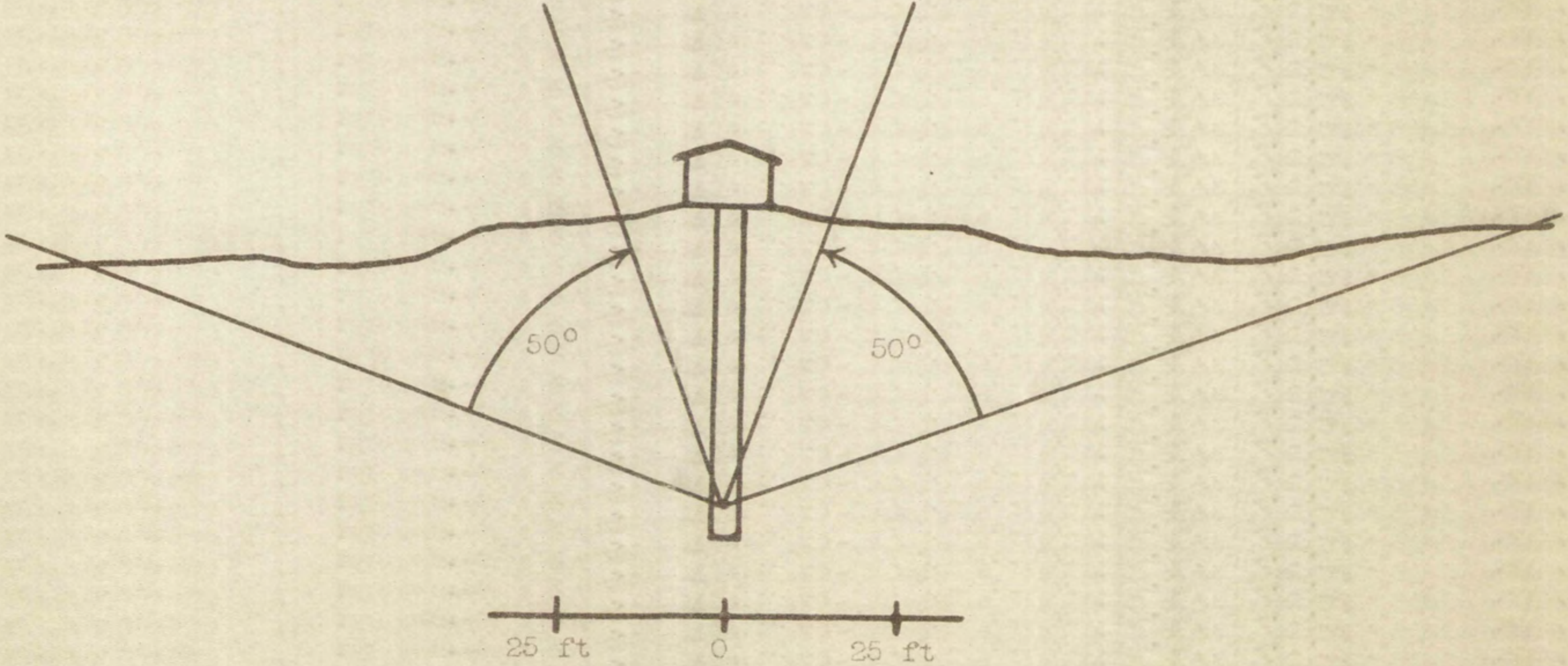

FIGURE 3

CROSS-SECTION OF SHAFT

plateau of about 300 volts. The counters were tested periodically and replacements made when necessary. Each counter was replaced once, on the average, during the year's run.

The distance between the centers of the top and bottom trays was 17". Each telescope subtended an angle about its axis of 50° in a vertical plane, and 104° in a plane at right angles to this vertical plane and passing through the 45° telescope axis. The maximum zenith angle with which a particle could enter either telescope was 70°, and the minimum was 20°. The east and west telescopes were separated by an angle of 45° or six hours. A daily time variation large enough to be detected should thus have reached a maximum in the west about six hours later than in the east. The two telescopes were interchanged each hour to equalize the effects on the results for the east and the west of any peculiarities of operation of the two telescopes and their associated circuits.

The electrical circuits. Both telescopes had a common power supply but separate coincidence, scaling, and recording circuits. A block diagram of the arrangement is given in Figure 4. Power for everything but the turntable motor was brought in through a constant voltage transformer. About 3.5 amperes was required. The high-voltage power

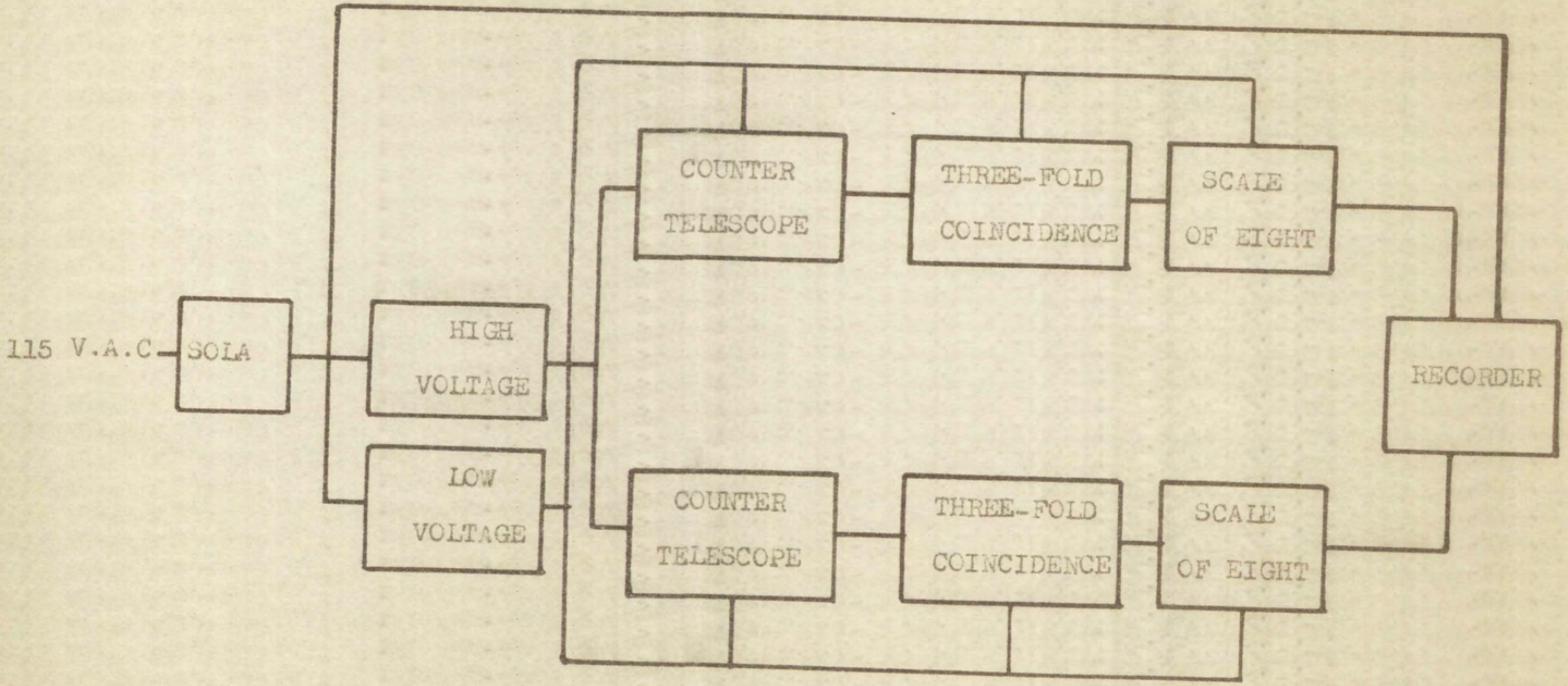

FIGURE 4

BLOCK DIAGRAM

supply was adjustable from 1175 to 1450 volts and was provided with a compensating circuit to assure constant voltage. The low-voltage power supply provided a B≁ voltage of 285 volts and an adjustable bias voltage. This was not a constant voltage supply, but tests showed that no difference in counting rate could be detected over a much wider range of deviation than could ever be expected to occur in actual use. A separate chassis and transformer was used for the filament supply. Each telescope had its own standard Rossi-type three-fold coincidence circuit, Figure 5, and a scaling circuit containing three scale-of-two stages producing a scale factor of eight.

The chassis containing all these circuits were mounted on the same framework which held the Geiger counters. Pulses from the scaling circuit were transmitted up through the sixty-foot cables to the mechanical counters of the automatic recorder at the surface. Each hour the reading of these counters was printed on a continuous tape. The printing mechanism was operated every hour by an electric clock and micro-switch system. In case of a power failure, power to the equipment underground and the recorder at the surface was cut off until reset. Six power failures occurred during the year's run.

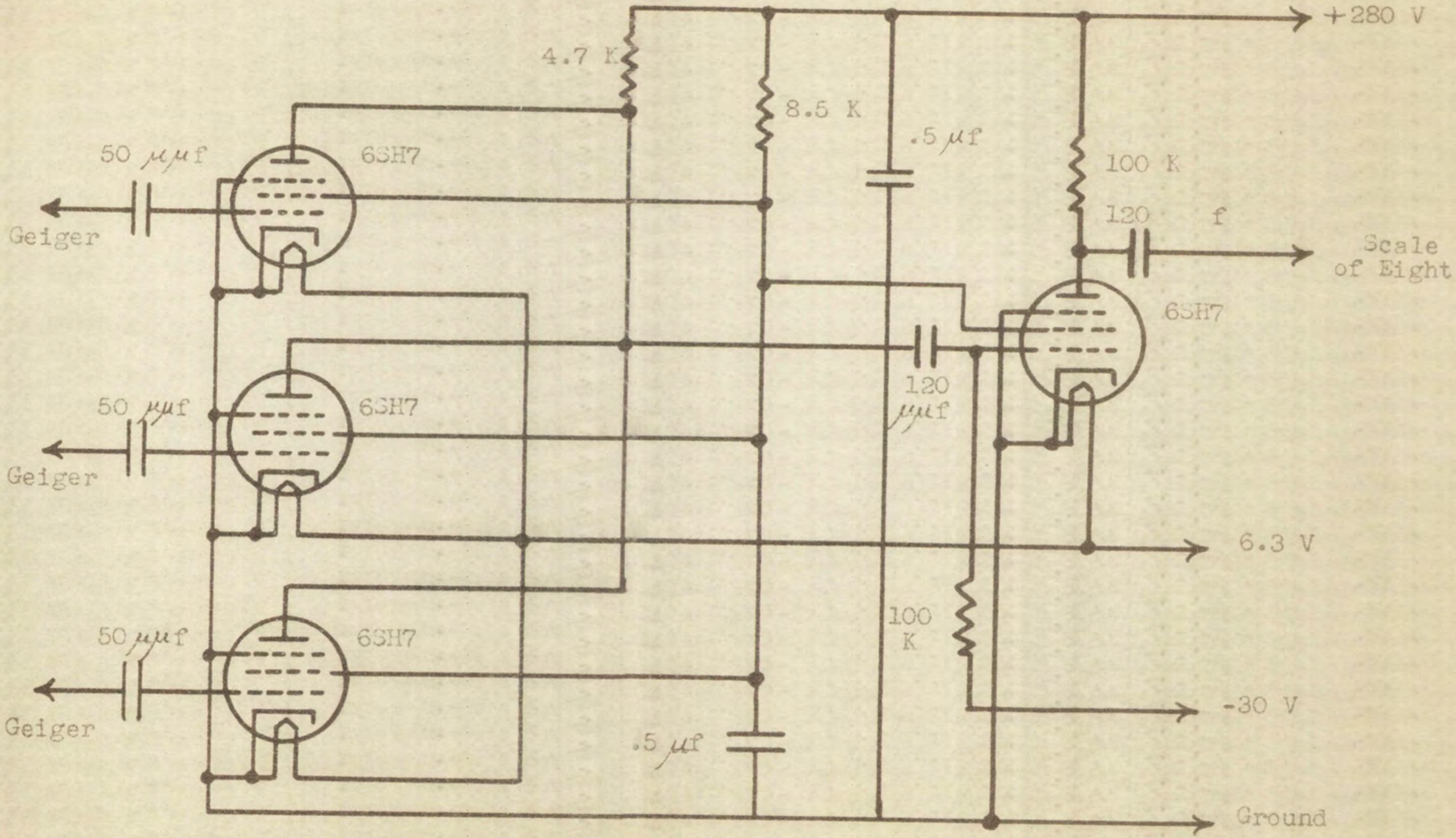

FIGURE 5

THREE-FOLD COINCIDENCE CIRCUIT

CHAPTER V

ANALYSIS OF THE DATA

The equipment was kept operating underground from March 21, 1953 to March 21, 1954. Only the 255 days for which the entire day's record was available were used in the final analysis. A record of all repairs and replacements made on the equipment was kept, and it was assumed that the mean counting rate remained constant during the times when the apparatus was operating undisturbed. These periods varied from five to thirty days.

The data were removed from the recorder usually once a week. The accumulated coincidences for each telescope were printed on the tape for the beginning of each solar hour (Mountain Standard Time). To obtain any hour's counts, it was thus necessary to subtract from each value that of the preceding hour. This was done for all the data and each day's values were recorded. If only one hour was missing from a day's record, the day was still used. The average of the preceding and following hour's counts for that direction and that telescope was substituted for the missing value.

Table I is a typical data sheet showing two day's values. It will be noticed that each channel (T-1 and T-2)

TABLE I

SAMPLE DATA SHEET

Period Ia Date	Solar Hour	Sidereal Hour	Barometric Pressure (inches Hg)	Scaled Counting Rates			
				East		West	
				T-1 R	T-2 G	T-1 G	T-2 R
4/4/53 Sat.	12:30 A.M.	13:00	24.8		191	201	
			24.8	204			199
			24.8		190	207	
			24.8	200			207
			24.8		186	204	
			24.8	193			198
	6:30 A.M.	19:00	24.9		189	201	
			24.9	185			204
			24.9		184	199	
			24.8	195			195
			24.8		188	202	
			24.8	194			205
	12:30 P.M.	1:00	24.8		193	206	
			24.8	194			206
			24.7		186	202	
			24.7	188			206
			24.7		189	202	
			24.7	194			194
	6:30 P.M.	7:00	24.7		195	198	
			24.7	198			203
			24.7		188	199	
			24.7	197			202
			24.7		200	204	
			24.7	193			212
4/5/53 Sun.	12:30 A.M.	13:00	24.7		190	206	
			24.7	199			205
			24.7		198	206	
			24.7	187			204
			24.7		195	198	
			24.8	202			208
	6:30 A.M.	19:00	24.8		199	202	
			24.8	199			193
			24.8		192	192	
			24.8	199			197
			24.8		191	210	
			24.8	210			197

Period Ia Date	Solar Hour	Sidereal Hour	Barometric Pressure (inches Hg)	Scaled Counting Rates			
				East		West	
				T-1 R	T-2 G	T-1 G	T-2 R
	12:30 P.M.	1:00	24.8		187	208	
			24.7	186			199
			24.7		188	211	
			24.7	195			200
			24.7		185	202	
			24.7	200			192
	6:30 P.M.	7:00	24.7		196	200	
			24.7	192			198
			24.7		188	204	
			24.7	201			199
			24.7		187	215	
			24.7	203			200

counted alternately east and west. The R and G refer to the red and green lights which indicated to an observer at the surface the position of the equipment at the bottom of the shaft. West was always recorded on green by channel 1 and on red by channel 2. The numbers refer to the scaled counts. Under "solar time" is given the mid-point of the mean solar hour (M.S.T.) over which the counts were collected. The equation of time as well as the six minute difference between Albuquerque local time and Mountain Standard Time was ignored. Under "sidereal time" is given the sidereal time, to the nearest hour, corresponding to that particular solar time. This was taken from The American Ephemeris and Nautical Almanac.[22] Again the equation of time and the six minute time difference was ignored. Under "barometric pressure" is given the average pressure to the nearest tenth of an inch of Hg for that hour as taken from the weekly microbarograph records at the Physics Department.

Before going on to describe the method used to evaluate the data, the properties of the cosmic rays whose intensity was being measured and the effect of the pressure and temperature of the atmosphere on this intensity must be considered.

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[22] The American Ephemeris and Nautical Almanac for the Year 1953 (Washington, D.C.: United States Government Printing Office, 1951), pp. 2-18.

Character of the cosmic radiation underground. The ionizing radiation underground has been shown to be composed almost entirely of μ-mesons[23] accompanied by a soft secondary component locally generated by these mesons plus that due to radioactivity. Only the μ-mesons are capable of passing through 8" of lead and discharging three trays of counter tubes. Thus, the three-fold coincidences measured in this experiment can be considered for all practical purposes as due entirely to μ-mesons.

This penetrating μ-meson component has a differential energy spectrum proportional to $E^{-2.8}$. That is

$$dn(E) = AE^{-2.8}dE$$

where $dn(E)$ is the number of particles between E and $E + dE$, and A is a constant of proportionality. Then the average energy, $\overline{E}$, for a low energy cut-off of E_m is given by

$$\overline{E} = \frac{\int_{E_m}^{\infty} EAE^{-2.8}dE}{\int_{E_m}^{\infty} AE^{-2.8}dE} = \frac{1.8}{.8} E_m$$

For μ-mesons under 100 Bev., the energy loss in earth, $\frac{dE}{dx}$, is due primarily to ionization and may be considered constant at 2.2 Mev./gm. cm.^{2}.[24] Then if x is the thickness

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[23] E. P. George, "Observations of Cosmic Rays Underground and Their Interpretation," Progress in Cosmic Ray Physics (J. G. Wilson, editor, New York: Interscience Publishers, Inc., 1952), p. 398.

[24] Ibid., p. 409.

Character of the cosmic radiation underground. The ionizing radiation underground has been shown to be composed almost entirely of μ-mesons,[1] accompanied by a small secondary component largely generated by these mesons plus that due to radioactivity. Only the μ-mesons are capable of passing through [illegible] of lead and discharging three trays of counter tubes. Thus, the three-fold coincidences measured in this experiment can be considered for all practical purposes as due entirely to μ-mesons.

This penetrating μ-meson component has a differential energy spectrum proportional to $E^{-2.4}$.[2] That is

$$dn(E) = AE^{-2.4}dE$$

where dn(E) is the number of particles between E and E + dE, and A is a constant of proportionality. Thus the average energy, $\bar{E}$, for a lower energy cut-off of E_0 is given by

$$\bar{E} = \frac{\int_{E_0}^{\infty} EAE^{-2.4}dE}{\int_{E_0}^{\infty} AE^{-2.4}dE} = \frac{1.4}{.4}E_0$$

For μ-mesons under 100 Bev., the energy loss in earth, $\frac{dE}{dx}$, is due primarily to ionization and may be considered constant at 2.2 Mev./gm. cm.$^{-2}$.[4] Then if x is the thickness

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[2] E. P. George, "Observations of Cosmic Rays Underground and Their Interpretation," Progress in Cosmic Ray Physics (J. G. Wilson, Editor, New York: Interscience Publishers, Inc., 1952), p. 230-231.

[4] Ibid., p. 190.

of absorber that the mesons have penetrated in gm. per cm.^{2} and E_m the minimum energy with which they could have started, their average energy (before passing through the absorber) is

$$\overline{E} = 2.25\ E_m = 2.25\ \frac{dE}{dx}\ dx \cong 5x.$$

In this experiment, the minimum zenith angle of a particle detected by the telescopes was 20° and the maximum was 70°. The maximum telescope sensitivity was at 45°. The average energy of mesons coming in at these angles was 18 Bev. at 20°, 23 Bev. at 45°, and 48 Bev. at 70°. These values were calculated using a density of 2.0 gm./cm.^{3} for the earth and a vertical thickness of the atmosphere at Albuquerque of 800 gm./cm.^{2}.

The number of particles of energy above E_m is proportional to $(E/E_m)^{-1.8}$. Since

$$E_m = \frac{dE}{dx}\ x = 2.2\ \frac{h}{\cos\theta}$$

where h is the vertical depth in gm./cm.^{2} and θ is the zenith angle at which the particles are incident, this means that the number of particles at a depth h and zenith angle θ is proportional to $(\cos\theta)^{1.8}$ or approximately $\cos^2\theta$. Therefore, in this experiment the average energy should lie somewhere between that for 45° and 20° zenith angle or between 23 Bev. and 18 Bev. Taking 20 Bev. as a rough estimate of the average energy near the top of the atmosphere of the of absorber that the mesons have penetrated in gm. per cm.^{2} and E_m the minimum energy with which they could have arrived, their average energy (before passing through the absorber) is

$$\overline{E} = 2.5\ E_m = 2.5\ \frac{dE}{dx}\ x \cong 5x.$$

In this experiment, the minimum zenith angle of a particle detected by the telescope was 20° and the maximum was 70°. The maximum telescope sensitivity was at 45°. The average energy of mesons coming in at these angles was 18 Bev. at 20°, 23 Bev. at 45°, and 55 Bev. at 70°. These values were calculated using a density of 2.9 gm./cm.^{3} for the earth and a vertical thickness of the atmosphere at Albuquerque of 800 gm./cm.^{2}.

The number of particles of energy above E is proportional to $(E/E_1)^{-1.8}$. Since

$$E_m = \frac{dE}{dx}\ x = 2.2\ \frac{h}{\cos \theta}$$

where h is the vertical depth in gm./cm.^{2} and θ is the zenith angle at which the particles are incident, this means that the number of particles at a depth h and zenith angle θ is proportional to $(\cos \theta)^{1.8}$ or approximately $\cos^2\theta$. Therefore, in this experiment the average energy should lie somewhere between that for 45° and 20° zenith angle or between 23 Bev. and 18 Bev. Taking 20 Bev. as a rough estimate of the average energy near the top of the atmosphere at the mesons whose intensity was measured in this experiment, and assuming a multiplicity of the production process of forty to fifty,[25] gives 800-1000 Bev. as the average energy of the primaries.

From the curves published by Vallarta et al.,[26] the maximum deflection of a 240 Bev. particle detected by the east telescope is 9° (entering at a zenith angle of 20°) and the minimum deflection is 7° (entering at a zenith angle of 70°). For the west telescope the corresponding deflections are 6° and 5°. These values have been calculated for particles incident in the plane of the geomagnetic equator and would be expected to be lower for higher latitudes. The fact that the average energy increases with increasing zenith angle should tend to equalize the deflections suffered by particles incident at different zenith angles. Therefore, in this experiment a directional effect of the primaries should not be obliterated by the action of the earth's magnetic field, which at most should place the time of maximum slightly sooner (assuming positive primaries).

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[25] U. Camerini, W. O. Lock, and D. H. Perkins, "The Analysis of Energetic Nuclear Encounters Occurring in Photographic Emulsions", Progress in Cosmic Ray Physics (J. G. Wilson, editor; New York: Interscience Publishers, Inc., 1952), p. 11-12.

[26] Vallarta et al., op. cit., p. 2.

Barometric pressure affect. The pressure effects the cosmic ray intensity at the earth's surface in two ways. First, a higher pressure means a greater amount of matter for the particles to penetrate so that more of the μ-mesons are absorbed. Second, a change in pressure is usually associated with a change in the height of the pressure layer in the upper atmosphere in which a majority of the μ-mesons are produced. A greater number of mesons decay before reaching the ground if the average height of the production layer rises. For measurements at the earth's surface these two effects must be separated, but at moderate depths underground the average meson energy is so large that the decay effect becomes negligible.[27] The barometer effect is thus considered as entirely due to absorption, and the change of intensity, ΔI, is set proportional to the change in pressure, ΔP. Thus

$$\Delta I = \beta_B \Delta P,$$

where the constant of proportionality, β_B, is called the barometric coefficient.

Measurements of the barometric coefficient made at depths comparable to that of this experiment are -.47% per cm. Hg at 60 meters of water equivalent[28] and -.04% per cm. Hg

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[27] Elliot, op. cit., p. 465.

[28] MacAnuff, op. cit., p. 421.

at 40 meters of water.[29] At these moderate depths the exponent of the integral energy spectrum is approximately 2,[30] so that the intensity N_1 at a depth d_1 and the intensity N_2 at a depth d_2 are related approximately by the expression

$$N_2 = N_1 \left(\frac{d_2}{d_1}\right)^{-2} .$$

Therefore, since a pressure change of 1 cm. Hg corresponds to a change in depth of 13.5 gm./cm.^{2}, β_B, the barometric coefficient at 60 meters of water, which is just the per cent change in counting rate at that depth per cm. Hg change in pressure, is given by

$$100 \left[1 - \frac{6000 + 13.5}{6000}\right]^{-2} = -.45\% \text{ per cm. Hg}$$

which agrees well with MacAnuff's observed value of -.47% per dm. Hg. Rau's value of zero (within his statistical error) is difficult to understand. With 60 feet of earth at a density of 2 gm. per cm.^{3} plus 8 in. of Pb at 11.3 gm. per cm.^{3} as the average path to be traversed by a cosmic ray in the present experiment, a value of -.69% per cm. Hg would be expected. The actual barometric coefficient observed was -.61% ± .13% per cm. Hg which agrees satisfactorily with the theoretical value.

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[29] Rau, <u>op. cit.</u>, p. 278.

[30] George, <u>op. cit.</u>, p. 414.

This coefficient was calculated from the data of the two longest individual runs, of 30 and 35 days respectively. The counts were combined into four-hour intervals to simplify the calculations. The corresponding average pressure for each four-hour interval was determined and the counting rates ordered by pressure and time of day. For each time of day, for instance 2-6 A.M., both counting rate and pressure were reduced to per cent deviation from their respective means. The results from the same time of day for the two periods could then be combined giving six sets of per cent change in intensity vs. per cent change in pressure.

The separation according to time of day was done so that a false barometric coefficient would not be obtained due to a simultaneous periodic variation in pressure and cosmic ray intensity. To see this more clearly, suppose a strong solar variation existed in the primary radiation giving a twenty-four hour period to the counting rate. Then suppose that the barometric pressure also varied with the same period and phase. Now even if no true causal relationship between the pressure and the counting rate existed, a comparison of intensity vs. pressure would show an apparent relationship. Since it is well-known that the pressure does have a definite diurnal variation, the possible effects of this on the barometer coefficient were eliminated by considering the

intensity vs. pressure relationship with the time of day held constant (at least within four hours).

Having obtained the six sets of intensity vs. pressure values with the solar time held approximately constant, they were fitted by least squares to the above-mentioned relationship

$$\Delta I = \beta_B \Delta P.$$

The weighted average value of the barometric coefficient thus obtained was, as stated above, .61% ± .13% per cm. Hg. Figure 6 shows the six sets of intensity vs. pressure points together with the least-squares straight line fitted to them.

In view of the small amplitude of the diurnal variations which were being investigated, it was decided that the barometer coefficient was large enough to warrant correction of the data for pressure. However, as will be discussed later, the final corrections turned out to be quite small.

Temperature effect. Besides the effect of the pressure, there is a change in intensity due to the temperature variations of the upper atmosphere. This has been investigated at sea level by Duperier[31] who found a coefficient of +.12% per °C change in the temperature of the 200-100 millibar

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[31] A. Duperier, "The Meson Intensity at the Surface of the Earth and the Temperature at the Production Level," Proceedings of the Physical Society, London, A 62:684-696, November, 1949.

intensity vs. pressure relationship with the time of day held constant (at least within four hours).

Having obtained the six sets of intensity vs. pressure values with the solar time held approximately constant, they were fitted by least squares to the above-mentioned relationship

$$\Delta I = \beta_B \Delta P.$$

The weighted average value of the barometric coefficient thus obtained was, as stated above, .01% ± .1% per cm. Hg. Figure 6 shows the six sets of intensity vs. pressure points together with the least-squares straight line fitted to each.

In view of the small amplitude of the diurnal variations which were being investigated, it was decided that the barometer coefficient was large enough to warrant correction of the data for pressure. However, as will be discussed later, the final corrections turned out to be quite small.

Temperature effect. Besides the effect of the pressure, there is a change in intensity due to the temperature variations of the upper atmosphere. This has been investigated at sea level by Duperier[31] who found a coefficient of -.12% per °C change in the temperature of the 200-100 millibar

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[31] A. Duperier, "The Meson Intensity at the Surface of the Earth and the Temperature at the Production Level," Proceedings of the Physical Society, London, A 57:468-484, November, 1945.

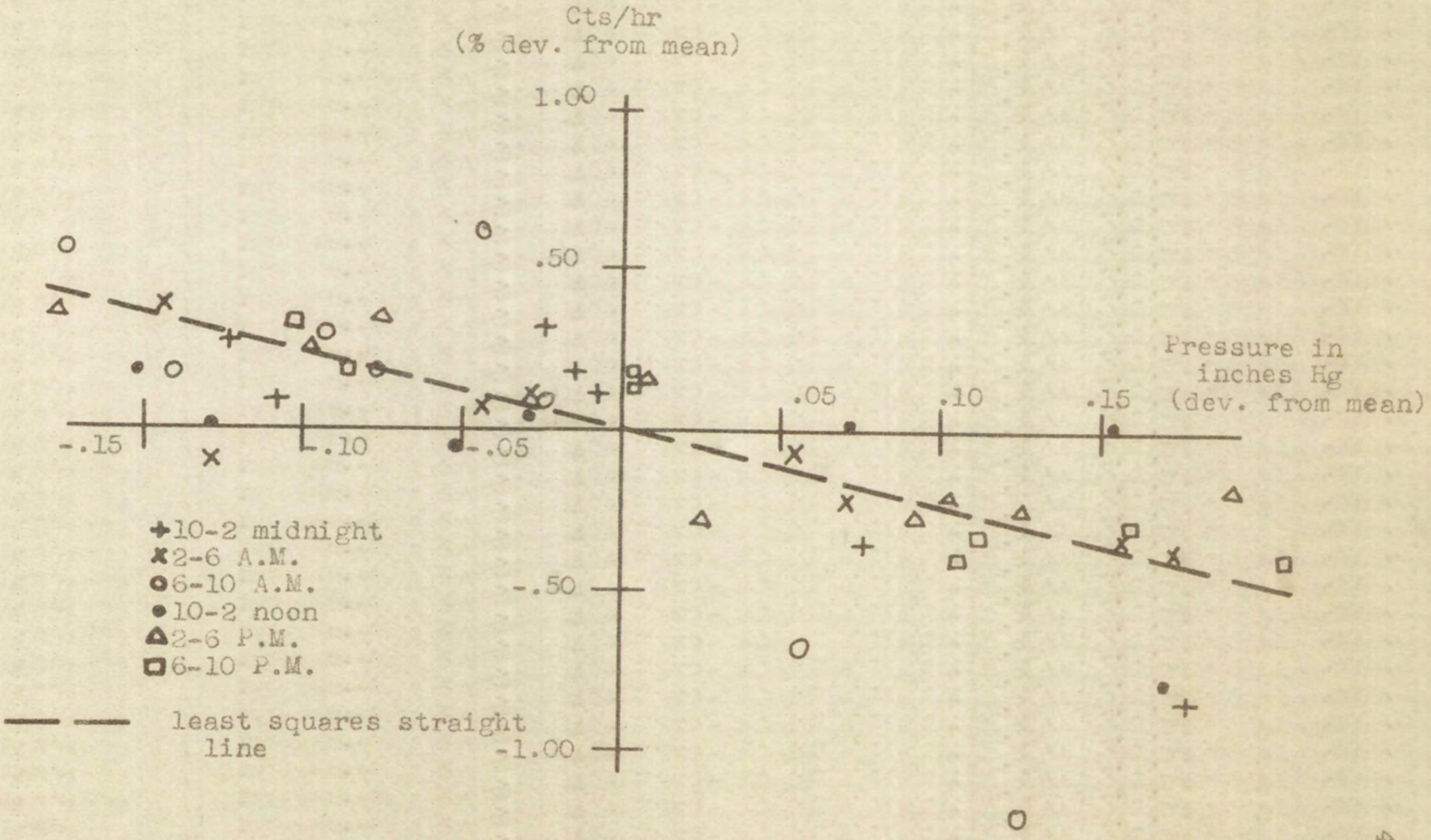

FIGURE 6

ATMOSPHERIC PRESSURE VS. COSMIC RAY INTENSITY

layer after elimination of the effect due to change in height of the μ-meson producing layer. He suggested that this was due to the competing processes of π-meson decay and π-meson collision with nuclei in the upper atmosphere. At a high temperature and thus low density, fewer π-mesons would interact with nuclei and more would be left to decay into μ-mesons. However, Cotton and Curtis,[32] also working at the surface, found a zero coefficient. Underground at 60 meters of water equivalent, MacAnuff[33] found a coefficient of +.05% per °C, also for temperatures in the 200-100 millibar level. Barrett *et al.*,[34] at 1574 meters of water equivalent, found a coefficient of +.79% per °C using an average temperature for the whole atmosphere in which layers above the 100 millibar level were weighted most heavily. On the other hand, Sherman,[35] working at 850 meters of water equivalent, found a zero coefficient, although his work is reported to be still under revision.

In view of this contradictory evidence, together with

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[32] E. S. Cotton and H. O. Curtis, "Effects on the Penetrating Component of the Cosmic Radiation," *The Physical Review*, 84:840, November 15, 1951.

[33] MacAnuff, *op. cit.*, p. 421.

[34] Barrett *et al.*, *op. cit.*, p. 146.

[35] Noah Sherman, "Atmospheric Temperature Effect for μ-mesons Observed at a Depth of 846 M.W.E.," *The Physical Review*, 93:208-211, January 1, 1954.

layer after elimination of the effect due to change in height of the μ-meson producing layer. He suggested that this was due to the competing processes of π-meson decay and π-meson collision with nuclei in the upper atmosphere. At a high temperature and thus low density, fewer π-mesons would interact with nuclei and more would be left to decay into μ-mesons. However, Cotton and Curtis,[32] also working at the surface, found a zero coefficient. Underground at 60 meters of water equivalent, Neuhauff[33] found a coefficient of +.05% per °C, also for temperatures in the 200-100 millibar level. Barrett et al.,[34] at 1574 meters of water equivalent, found a coefficient of +[illegible]% per °C using an average temperature for the whole atmosphere in which layers above the 100 millibar level were weighted most heavily. On the other hand, Sherman,[35] working at 850 meters of water equivalent, found a zero coefficient, although his work is reported to be still under revision.

In view of this contradictory evidence, together with

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[32] E. S. Cotton and H. O. Curtis, "Effects of the Penetrating Component of the Cosmic Radiation," The Physical Review, 84:840, November 15, 1951.

[33] Neuhauff, op. cit., p. 621.

[34] Barrett et al., op. cit., p. 115.

[35] Noah Sherman, "Atmospheric Temperature Effect for μ-mesons Observed at a Depth of 846 M.W.E.," The Physical Review, 93:208-211, January 1, 1954.

the apparent lack of a diurnal period in the temperature variation of the upper atmosphere,[36] and the lack of consistent data at Albuquerque regarding the important levels above 100 millibars, no attempt was made to correct the data of this experiment for upper-atmospheric temperature.

Calculation of the solar and sidereal time variations. The data for the whole year were ordered by pressure and solar and sidereal hour without regard to the particular period, that is, the interval of several weeks during which the instrumental counting rate could be expected to remain constant, from which they came. The validity of this procedure will be discussed later. The total counts for each pressure for each hour were then reduced to the common pressure of 25.0 in. Hg using the calculated barometric coefficient of -.61% ± .13 per cm. Hg. or -2.4% ± .5 per in. Hg. The corrected values were then added up for each hour. It was found that the largest barometric correction was .12% ± .02 for any solar hour and .05% ± .01 for any sidereal hour.

Since only complete days were used, each hour's sum contained the same number of contributions from any given period and, thus, could be expected to have the same means

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[36] Barrett *et al.*, *op. cit.*, p. 147.

in this respect. However, due to the rotation of the equipment, successive hours differed in the number of contributions from channels 1 and 2 (which ordinarily had different means due to slight differences in the counters), but alternate hours were equal in this respect. Thus, the mean for the odd hours and the mean for the even hours was calculated and the hour values were reduced to per cent deviations from their respective means. This put the twenty-four hour values on a comparable basis.

It was mentioned above that the period from which the data came was ignored in calculating the hourly per cent deviations from the mean. The obvious method of calculating these values would be to find the hourly deviation from the mean for each period for each hour and then combine them, weighting each according to the total number of counts in its respective period. To see that this leads to exactly the same result as the simpler method used above, consider the case of the hour H for the two periods A and B of number of days N_A and N_B respectively. Then for period A the per cent deviation from the mean of the intensity during hour H is given by

$$100\left[\frac{N_A\overline{R}_A - \sum R_{AH}}{N_A\overline{R}_A}\right]$$

where R_{AH} is one hour's count at the hour H and $\overline{R}_A$ is the mean hourly counting rate for the whole period which is

equal to $\frac{\sum R_A}{24\ N_A}$ or the sum of all the counts over the whole period divided by the number of hours in the period. Since the standard deviation for the period is inversely proportional to the square root of the total number of counts, then if the deviations from the mean are weighted as usual according to the reciprocal of the square of their standard deviation, the weighting factor for combining A's per cent deviation from the mean will be

$$\frac{N_A\overline{R}_A}{N_A\overline{R}_A + N_B\overline{R}_B} .$$

Similar expressions hold for period B. Thus, the weighted average hourly deviation from the mean for hour H, periods A and B, will be

$$\left[\frac{N_A\overline{R}_A}{N_A\overline{R}_A + N_B\overline{R}_B}\right] 100 \left[\frac{N_A\overline{R}_A - \sum R_{AH}}{N_A\overline{R}_A}\right] + \left[\frac{N_B\overline{R}_B}{N_B\overline{R}_B + N_A\overline{R}_A}\right] 100 \left[\frac{N_B\overline{R}_B - \sum R_{BH}}{N_B\overline{R}_B}\right]$$

$$= 100 \left[\frac{N_A\overline{R}_A + N_B\overline{R}_B - \sum R_{AH} - \sum R_{BH}}{N_A\overline{R}_A + N_B\overline{R}_B}\right]$$

which is just the per cent deviation from the mean of the average intensity during hour H if A and B are not separated but considered as a whole.

<u>Harmonic dial analysis</u>. In addition to the direct calculation of the hourly means described above, the

twenty-four hour solar and sidereal Fourier coefficients were calculated for each day. (These calculations were done at an early stage of the analysis of the experiment, and no barometric correction was applied.) This method is usually called harmonic dial analysis because the results for each day may be conveniently represented by a vector with length proportional to the amplitude of the sine wave present on that day and pointing toward the angle at which the maximum occurs (Figure 7). If the angle scale is labeled with the corresponding time of day (for a twenty-four hour wave), the diagram resembles a clock dial, hence the name. This method has been extensively discussed in theory and application by Chapman and Bartels in Geomagnetism.[37]

The data were grouped into four-hour intervals to simplify the calculations. The solar Fourier coefficients were found in the usual way by harmonic analysis, but the sidereal coefficients were obtained by rotating the solar results by the amount that the sidereal time had changed against solar time as measured from the beginning date of the experiment to the midpoint of each day.

The Fourier coefficients found in this way were divided by the mean counting rate for their particular period and their average and root mean square deviation was calculated.

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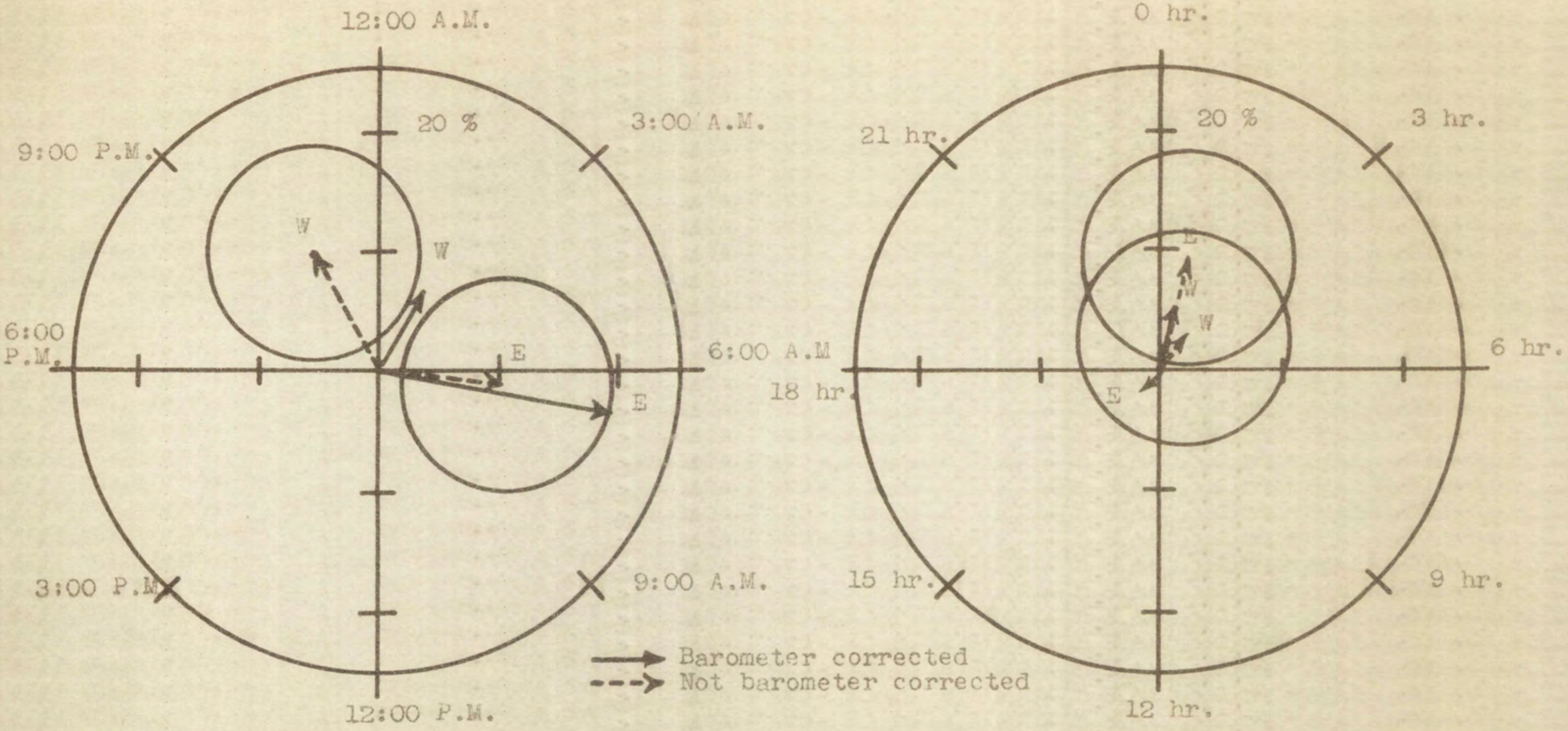
[37] Sydney Chapman and Julius Bartels, Geomagnetism, Volume II (Oxford: The Clarendon Press, 1940), pp. 545-594.



SOLAR HARMONIC DIAL

SIDEREAL HARMONIC DIAL

FIGURE 7

SOLAR AND SIDEREAL HARMONIC DIALS

CHAPTER VI

RESULTS OF THE EXPERIMENT

The solar variation. The cosmic ray intensity variation with a period of one solar day yielded by the first method of analysis is shown in Figure 8 and in Table II. These results have been corrected for the barometer effect. Harmonic analysis of the values for the east gives an amplitude for the twenty-four hour wave of .21% ± .05 with a maximum at 6:30 A.M. Harmonic analysis of the west values gives a wave with amplitude .08% ± .05 and maximum at 1:30 A.M. In view of the standard errors, these two results are difficult to reconcile, especially since the west wave would be expected to lag the east wave in phase by about 90° or six hours, not lead it by five hours.

Each hourly value has an expected standard deviation from the mean, based on the total number of counts, of .17% for the east and .16% for the west, leading to the standard deviation of .05% for the amplitudes quoted above. The root-mean-square deviation of the hour values about the mean is .24% for the east and .16% for the west. The root-mean-square deviation of the hour values about the fitted sine curve is .13% for the east and .15% for the west. The amplitudes and standard deviations found for the solar variations are listed in Table III.

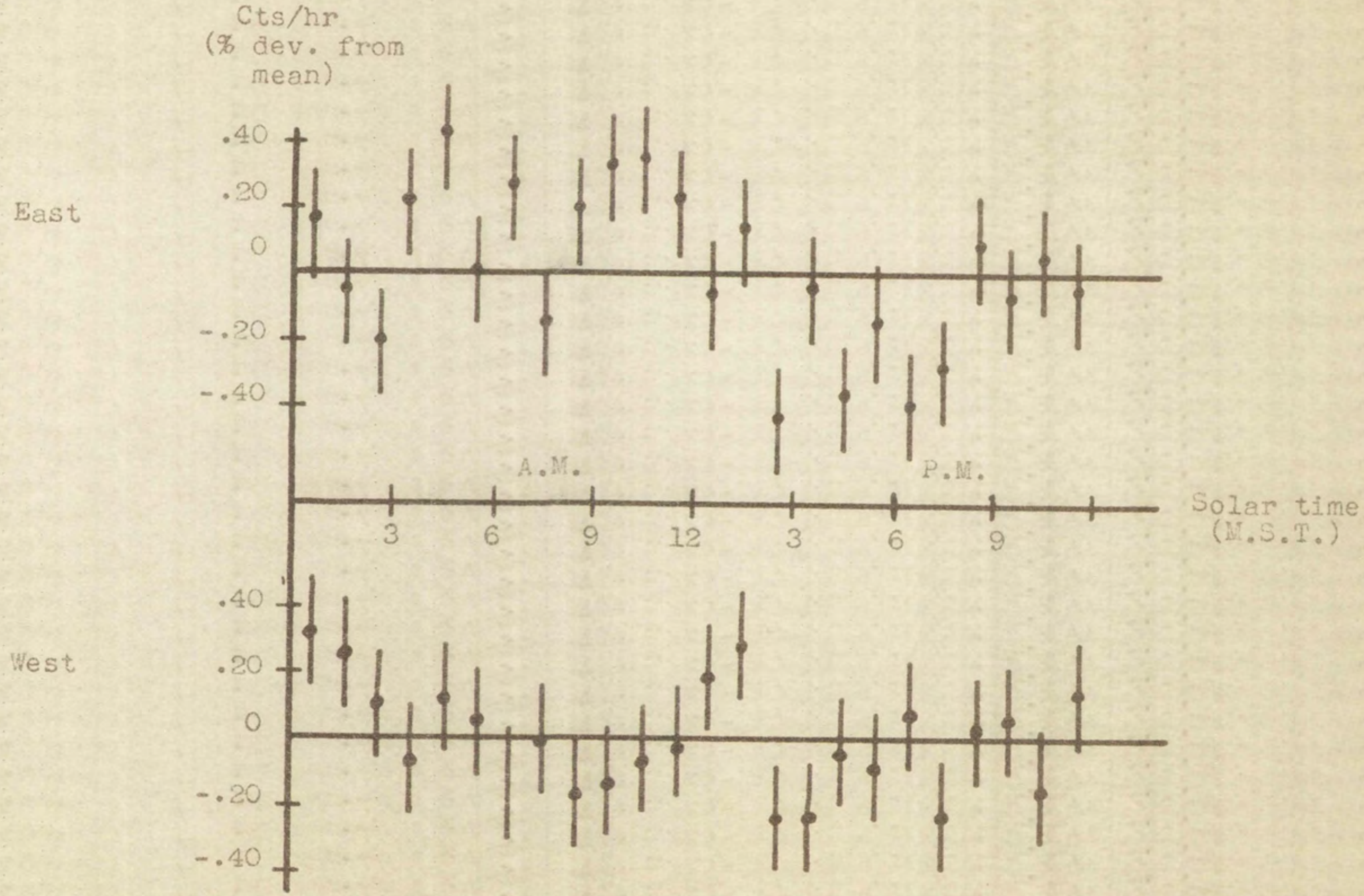


FIGURE 8

SOLAR TIME VARIATIONS

TABLE II

SOLAR HOURLY MEANS

Solar hour	Counts per hour (% deviation from the mean) East	West
0-1	.15	.32
1-2	-.06	.27
2-3	-.21	.10
3-4	.22	-.05
4-5	.42	.13
5-6	-.01	.06
6-7	.26	-.13
7-8	-.15	-.01
8-9	.19	-.18
9-10	.32	-.12
10-11	.34	-.06
11-12	.21	-.01
12-13	-.07	.18
13-14	.13	.26
14-15	-.44	-.25
15-16	-.05	-.25
16-17	-.38	-.04
17-18	-.16	-.09
18-19	-.40	.07
19-20	-.30	-.24
20-21	.07	.02
21-22	-.08	.05
22-23	.04	-.16
23-24	-.07	.14
Mean total scaled counts per hour..........	44726	46641

TABLE III

TWENTY-FOUR HOUR SOLAR WAVE

	East	West	Average
Amplitude	.21% ±.05	.08% ±.05	.08% ±.04
Time of Maximum	6:30 A.M.	1:30 A.M.	7:30 A.M.
Theoretical standard deviation	.17%	.16%	.12%
Root-mean-square deviation about mean	.24%	.16%	.13%
Root-mean-square deviation about sine curve	.13%	.15%	.11%

At a given hour, the west telescope was directed to a part of the sky that had been overhead three hours previously, and the east telescope was directed to a part of the sky that would be overhead three hours later. Therefore, to obtain a combined result from both sets of data, the west values should be combined with the east values for six hours earlier. An amplitude of .08% ± .04 with a maximum at 7:30 A.M. is obtained in this way. The standard deviation expected from the total number of counts is .12%, the root-mean-square deviation of the one-hour values about the mean is .13%, and the root-mean-square deviation of the hour values about the fitted sine curve is .11%.

The results of the harmonic dial analysis for the twenty-four hour solar wave are shown in Figure 7 and Table IV. These results have not been corrected for the barometer effect. An amplitude of .11% ± .05 with maximum at 6:30 A.M. is found for the east, and an amplitude of .11% ± .05 with maximum at 10:30 P.M. is found for the west.

The root-mean-square deviations of the Fourier coefficients for the 255 days are .80% and .72% for the east, and .67% and .76% for the west. Since the standard deviations for the two Fourier coefficients are nearly the same, the ellipses of equal probability should be nearly circular.[38]

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[38] J. Bartels, "Statistical Methods for Research on Diurnal Variations," *Terrestrial Magnetism and Atmospheric Electricity*. 37:291-302, September, 1932.

TABLE IV

RESULTS OF HARMONIC DIAL ANALYSIS

	East	West
Solar daily wave:		
Amplitude	.11% ± .05	.11% ± .05
Time of maximum	6:30 A.M.	10:30 P.M.
Sidereal daily wave:		
Amplitude	.10% ± .05	.03% ± .05
Time of maximum	1 hr.	1.5 hr.

Thus, if a circle with radius 1.18 times the average standard deviation of the Fourier coefficients is drawn with the head of the average amplitude vector as center, half the amplitude vectors for the individual days should fall inside the circle. The average standard deviation of the Fourier coefficients for the east is .76% and for the west .73%. The expected standard deviation of the mean coefficients should be equal to these values divided by the square root of the total number of days represented. This gives .05% for the standard deviation of the mean for both the east and the west. In Figure 7, page 52, the circle with radius equal to 1.18 times the standard deviation has been drawn about the heads of the vectors representing the mean amplitudes. This circle has the meaning that if another determination of this vector were to be made, using another 255 days' data, the resultant vector would have a fifty per cent probability of ending within this circle.

The barometer-corrected results yielded by the other method of analysis are also shown in Figure 7 for comparison with the non-corrected harmonic dial results. The differences in the results of the two methods seem reasonable in view of the standard errors and the .12% maximum barometric correction made for one hour. A random variation of .12% in each hour would give an expected error of .03% in the calculated sine-wave amplitude.

Thus, if a circle with radius 2.15 times the average standard deviation of the Fourier coefficients is drawn about the end of the average amplitude [illegible] half the amplitude vectors for the 1936 and [illegible] will fall within the circle. The average standard deviation of the [illegible] for the east is .196 and [illegible] for the west [illegible]. The expected standard deviation of the mean [illegible] which corresponds to these values divided by the square root of the number of days represented. This gives [illegible] for the standard deviation of the mean. In both the [illegible] In Figure 7, page [illegible], the circle with radius 2.15 times the standard deviation has been drawn about the ends of the vectors representing the mean amplitude. This circle has the meaning that if another [illegible] were to be made, using [illegible] data, the calculated vector would have a fifty per cent probability of [illegible] within this circle.

The barometer-corrected results [illegible] for the same method of analysis are also shown in Figure 7 [illegible] with the non-corrected [illegible] results. The differences in the results of the two [illegible] in view of the standard errors and the [illegible] correction made for each hour. A [illegible] in each hour would give no [illegible] calculated [illegible] values.

When the solar values are analyzed for a twelve-hour wave, an amplitude of .11% ± .05 is found for both directions, but the phases, 10:30 A.M. and P.M. and 1:00 A.M. and P.M., do not show the east leading the west by about six hours as would be expected for a real effect. The expected standard deviation of a one-hour value calculated from the total number of counts is .12% for the east and .14% for the west. The root-mean-square deviation about the fitted sine curve is .13% for the east and .12% for the west. These values for the twelve-hour solar wave are shown in Table V.

Combining the results for the two directions in the same manner as before gives a twelve-hour solar wave with amplitude .05% ± .04 and maximum at 11:30 A.M. and P.M. The theoretical standard deviation of the one-hour values is .08%, the root-mean-square deviation about the mean is .19%, and the root-mean-square deviation about the sine wave is .12%.

No harmonic dial analysis has been made for the twelve-hour solar wave.

The sidereal variation. The results of the analysis of the data for sidereal variation by the first method are shown in Figure 9 and in Table VI. The amplitude of the twenty-four hour wave for the east is .02% ± .05 with a maximum at 15 hours. The west wave has an amplitude of

When the [illegible] [illegible] [illegible] [illegible] wave, an amplitude of [illegible] is [illegible] [illegible] [illegible], but the phase, [illegible] [illegible] [illegible] [illegible] [illegible] do not show the same [illegible] [illegible] [illegible] would be expected for a [illegible] effect. The [illegible] standard deviation [illegible] [illegible] [illegible] [illegible] the total number of points [illegible] [illegible] [illegible] [illegible] the 100-meter [illegible] [illegible] [illegible] is .15% for [illegible] [illegible] [illegible] [illegible] for the twelve-hour [illegible] wave [illegible] [illegible].

Combining the [illegible] [illegible] [illegible] the same manner as [illegible] [illegible] eight-hour [illegible] have amplitudes [illegible] [illegible] shown in Table 4.5. The theoretical [illegible] [illegible] [illegible] is .09%, the [illegible] [illegible] [illegible] is .19%, and the [illegible] [illegible] wave is .12%.

So [illegible] [illegible] [illegible] the twelve-hour solar wave.

The [illegible] [illegible]. The results of the analysis of the data for [illegible] [illegible] are shown in Figure [illegible]. The amplitude [illegible] twenty-four hour wave for [illegible] [illegible] maximum at [illegible] hours. [illegible] [illegible]

TABLE V

TWELVE-HOUR SOLAR WAVE

	East	West	Average
Amplitude	.11% ± .05	.11% ± .05	.05% ± .04
Time of maximum	10:30 A.M. and P.M.	1:00 A.M. and P.M.	11:30 A.M. and P.M.
Theoretical standard deviation	.12%	.11%	.08%
Root-mean-square deviation about mean	.15%	.14%	.19%
Root-mean-square deviation about sine curve	.13%	.11%	.12%

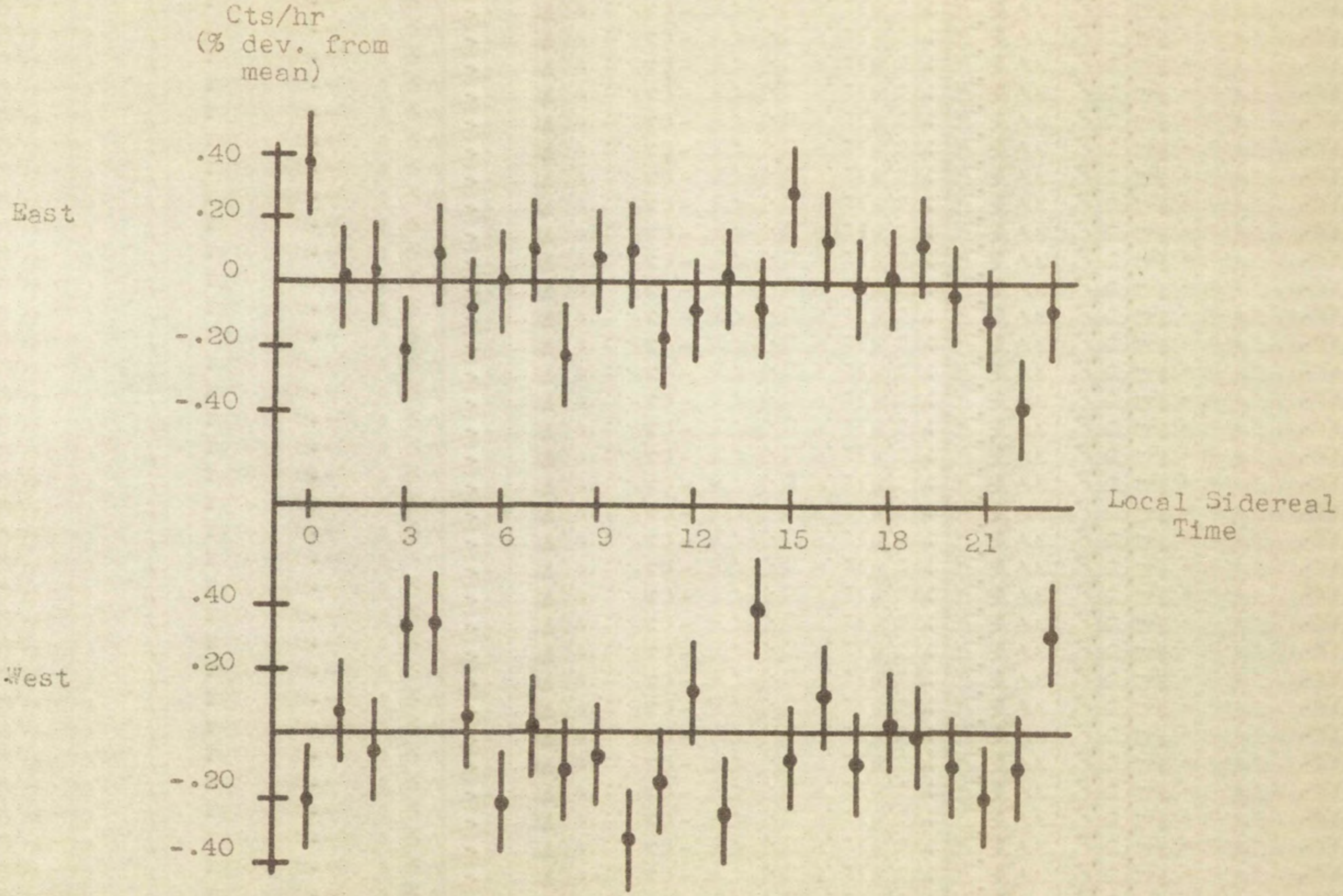

FIGURE 9

SIDEREAL TIME VARIATIONS

TABLE VI

SIDEREAL HOURLY MEANS

Sidereal hour	Counts per hour (% deviation from the mean)	
	East	West
0	.38	-.19
1	.03	.07
2	.04	-.04
3	-.20	.33
4	.09	.34
5	-.07	.06
6	.02	-.20
7	.11	.03
8	-.21	-.11
9	.08	-.06
10	.10	-.33
11	-.17	-.15
12	-.08	.14
13	.02	-.23
14	-.07	.40
15	.28	-.07
16	.13	.12
17	-.01	-.09
18	.02	.04
19	.12	.01
20	-.04	-.09
21	-.11	-.19
22	-.39	-.09
23	-.08	.31
Mean total scaled counts per hour.........	45727	46641

.05% ± .05 with a maximum at 1 hour. Thus, no sidereal wave was found with amplitude greater than the standard error.

The theoretical standard deviation for the one-hour values, calculated from the total number of counts, is .17% for the east and .16% for the west. The root-mean-square deviation from the mean is .16% for the east and .19% for the west. The root-mean-square deviation from the fitted sine curve is .16% for the east and .19% for the west.

Combining the results for the east and west in the same manner as before gives a wave with amplitude .03% ± .04 with a maximum at 21 hours. The theoretical standard deviation for the one-hour values is .12%; the root-mean-square deviation from the mean is .12%; and the root-mean-square deviation from the fitted sine curve is also .12%. The amplitudes and standard deviations for east, west, and the average of both are given in Table VII.

The harmonic dial analysis yields a twenty-four hour sidereal wave for the east with amplitude .10% ± .05 and maximum at 1 hour. The west wave has an amplitude of .03% ± .05 with maximum at 1.5 hours. These results have been obtained with no correction for the barometer effect. They are shown in Figure 7, page 52, along with the pressure-corrected results of the other method for comparison. Again the circle with radius equal to 1.18 times the standard

.05% ± .05 with a maximum at 1 hour. Thus, no sidereal wave was found which would be greater than the standard error.

The theoretical standard deviations for the two-hour values, calculated from the total number of counts, is .03% for the east and .03% for the west. The root-mean-square deviation from the mean is .04% for the east and .04% for the west. The root-mean-square deviation from the fitted sine curve is .03% for the east and .03% for the west.

Combining the results for the east and west in the same manner as before gives a wave with amplitude .03% ± .03% with a maximum of 21 hours. The theoretical standard deviation for the averaged values is .02%; the root-mean-square deviation from the mean is .04%; and the root-mean-square deviation from the fitted sine curve is also .03%. The amplitudes and standard deviations for east, west, and the average of both are given in Table VII.

The harmonic dial analysis yields a twenty-four hour sidereal wave for the east with amplitude .02% ± .05% and maximum at 2 hours. The west wave has an amplitude of .03% ± .05 with maximum at 1.5 hours. These results have been obtained with no correction for the barometer effect. They are shown in Figure 7, page 57, along with the [illegible] corrected length of the dial vector for [illegible]. Again, the circle with radius equal to 1.96 times this [illegible]

TABLE VII

TWENTY-FOUR HOUR SIDEREAL WAVE

	East	West	Average
Amplitude	.02% ± .05	.05% ± .05	.03% ± .04
Time of maximum	15 hr.	1 hr.	21 hr.
Theoretical standard deviation	.17%	.16%	.12%
Root-mean-square deviation about mean	.16%	.19%	.12%
Root-mean-square deviation about sine curve	.16%	.19%	.12%

deviation has been drawn about the tip of the resultant amplitude vector obtained by harmonic analysis.

Analysis of the data for a twelve-hour sidereal wave gives an amplitude of .07% ± .05 with maximum at 5 and 17 hours for the east, and an amplitude of .13% ± .05 with maximum at 6 and 18 hours for the west. The theoretical standard deviation for the one-hour values is .12% for the east and .11% for the west; the root-mean-square deviation from the mean is .10% for the east and .13% for the west; and the root-mean-square deviation from the fitted sine curve is .09% for the east and .10% for the west.

Combining the data for the east and west yields an average twelve-hour wave with amplitude .07% ± .04 and maximum at 11 and 23 hours. The theoretical standard deviation is .08%; the root-mean-square deviation from the mean is .12%; and the root-mean-square deviation from the fitted sine curve is .12%. The results for the twelve-hour wave are summarized in Table VIII.

TABLE VIII

TWELVE-HOUR SIDEREAL WAVE

	East	West	Average
Amplitude	.07% ± .05	.13% ± .05	.07% ± .04
Time of maximum	5 and 17 hrs.	6 and 18 hrs.	11 and 23 hrs.
Theoretical standard deviation	.12%	.11%	.08%
Root-mean-square deviation about mean	.10%	.13%	.12%
Root-mean-square deviation about sine curve	.09%	.10%	.12%

CHAPTER VII

CONCLUSIONS

This experiment was planned to yield information on very small solar and sidereal time variations. The cosmic ray intensity was measured by means of two counter-tube telescopes directed east and west, both at a zenith angle of 45°. This gave them a separation of about six hours in hour angle so that if any solar or sidereal time variation were present, it would be expected to appear with a maximum in the west telescope six hours later than in the east telescope.

The amplitudes, phases, and standard deviations found for the twenty-four hour and twelve-hour solar and sidereal waves have been discussed and tabulated in the preceding chapter. Some of these variations have amplitudes greater than the standard errors, but the lack of the expected six-hour phase difference between the results for the east and the west makes it difficult to decide whether they represent true intensity variations or merely statistical fluctuations.

The combined results for the east and west data give a twenty-four hour solar wave with amplitude .08 ± .04 and maximum at 7:30 P.M., a twelve-hour solar wave with amplitude

.05% ± .04 and maximum at 11:30 A.M. and P.M., a twenty-four sidereal wave with amplitude .03% ± .04 and maximum at 21 hours, and a twelve-hour sidereal wave with amplitude .07% ± .04 and maximum at 11 and 23 hours.

These results do not conflict with the work of Sherman[39] or Barrett and Eisenberg,[40] who had a much larger statistical error and also obtained negative results. They neither confirm nor contradict the work of Rau[41] and MacAnuff[42] who had a somewhat smaller statistical error. They are definitely incompatible with the 10% sidereal variation found by Sekido *et al*.[43]

As calculated earlier (see p. 16), a Compton-Getting effect of .3% is predicted for this particular latitude and telescope angle. The data seem, therefore, to be incompatible with a variation this large; and it must be concluded that the cosmic rays originate inside our own galaxy, or possibly that bending by galactic magnetic fields has distorted the original distribution. Bending in the magnetic fields of the earth or sun would not be sufficient to destroy the effect to this extent.

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[39] Sherman, *op*. *cit*., p. 26.

[40] Barrett and Eisenberg, *op*. *cit*., p. 675.

[41] Rau, *op*. *cit*., p. 286.

[42] MacAnuff, *op*. *cit*., pp. 423-24.

[43] Sekido *et al*., *op*. *cit*., p. 658.

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