PHYSICAL REVIEW VOLUME 92, NUMBER 2 OCTOBER 15, 1953

The Time Variation of Cosmic-Ray Heavy Nuclei*

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(Received June 30, 1953)

Two 4×4 Ilford G-5 photographic emulsions in contact were exposed to the cosmic radiation in such a way that one plate was moved slowly and uniformly with respect to the other. By this technique it is possible to determine the time at which heavy nuclei pass through the plates. The plates were exposed above 90 000 feet on June 4, 1952, for 8 hours during the day. A reliable altitude record was available and was used to correct for the altitude changes during the 8 hours. 947 heavy nuclei with more than 10 delta rays per 100 microns, corresponding to Z greater than about 10, were traced through and their time of passage measured. This was done by new techniques which are described in detail. The data have been divided into three time intervals. The intensity during the middle interval between noon and 2 P.M. is greater by 25±8.5 percent than the average of the other two. It is concluded that this is due to a real fluctuation in the intensity of of cosmic-ray heavy nuclei at the top of the atmosphere. The possibility that this may be due to a dipole magnetic field of the sun is discussed.

I. INTRODUCTION

THE problem of the origin of cosmic rays has been a subject of speculation ever since their discovery in 1912 by Hess. Recently, theoretical approaches to this problem have been proposed by Fermi, Alfvén, Teller, and others. A great deal of experimental effort has gone into the study of the cosmic radiation and a great deal has been learned, but the problem of the origin has not been completely solved. The study of time variations probably will be important in the future if this problem is to be solved. The reason that time variation information is valuable is that by this means there is the possibility of deducing something about the direction from which the particles come and thus of obtaining information on the position and perhaps the nature of the source.

In order to deduce the original direction of the particles from observations of the direction and time of their arrival at the earth, one has to take into account the diurnal rotation of the earth and the effect of the earth's magnetic field in bending the paths of the cosmic-ray particles, a problem[1] which has been studied intensively for many years by Störmer, Vallarta, and others, and is still not completely solved in all detail. Then too, there are the effects of other magnetic fields which are less well known, such as a possible magnetic field of the sun. It may turn out that important additional evidence for the existence and nature of such fields will come from cosmic-ray measurements, principally from time variation work on the primaries.

The study of time variations is complicated by a number of disturbing factors. Work at low altitude is plagued by the well-known problems due to the presence of the atmosphere. Besides temperature and barometric effects, there is the effect of the lateral spread of the secondaries away from the original direction of the primary. But perhaps most serious is the complicated nature of the cascade of events through the atmosphere, so that measurement of any one component cannot easily be related to a given primary, but represents some sort of averaged out effect. Thus it is a great advantage in studies on time variations to carry them out at the top of the atmosphere on the primaries themselves.

This paper reports work on the heavy nucleus primaries with charge, $Z \geqslant 10$. For this range of charge, the method of delta-ray counting allows one to identify a group of particles which includes mostly primaries. Secondaries from nuclear events contribute only a very small amount.

Time variations at the top of the atmosphere which might be connected with a diurnal effect have been looked for and not found in the total ionizing component and in the gamma rays by Bergstralh and Schroeder[2]; in bursts and low Z heavy nuclei using a pulse ionization chamber by Pomerantz and McClure[3]; and in the heavy nuclei using photographic emulsions by Freier, Anderson, Naugle, and Ney[4] and by Anderson, Freier, and Naugle,[5] who quote an upper limit of ±20 percent for time variations. Lal, Pal, Kaplon, and Peters[6] have given an upper limit of 10 percent for time variations in the high-energy heavy nuclei.

Changes have been observed, however, by Neher, Peterson, and Stern[7] in the total ionizing component on one out of several flights; by Swetnick, Neuburg, and Korff,[8] who found a 17±7 percent change in the neutrons at high altitude; by Ney and Thon[9] who

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* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

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[2] T. A. Bergstralh and C. A. Schroeder, Phys. Rev. **81**, 244 (1951).

[3] M. A. Pomerantz and G. W. McClure, Phys. Rev. **86**, 536 (1952).

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[5] Anderson, Freier, and Naugle, Bull. Am. Phys. Soc. **28**, No. 3, 7 (1953).

[6] Lal, Pal, Kaplon, and Peters, Phys. Rev. **86**, 569 (1952).

[7] Neher, Peterson, and Stern, Phys. Rev. **90**, 655 (1953).

[8] Swetnick, Neuburg, and Korff, Phys. Rev. **86**, 589 (1952).

[9] E. P. Ney and D. M. Thon, Phys. Rev. **81**, 1069 (1951).

found a change in alpha particles and heavy nuclei using scintillation counters; and by Lord and Schein.[10,11]

In their first investigation, Lord and Schein compared the intensity of heavy nuclei of $Z \geqslant 10$ on two day balloon flights and two night balloon flights. The intensity during the day was found to be about twice the nighttime intensity. However, there are difficulties in comparing the intensities on different flights, and so in order to overcome these, the drop-load technique was used. In this technique, two gondolas are carried aloft on the same balloon and after a certain time one is dropped, the other continuing at altitude. An experiment of this type, carried out on May 22, 1950, gave a day-night ratio of about 2.5. The zenith angle dependence of the heavy nuclei found in the plates was studied, and it was concluded that the effect could not have been due to error in the altitude measurement.[12]

It became clear that the development of a new technique was desirable because of the poor time resolution inherent in both previously used techniques and because of the uncertainties introduced in comparisons between different plates. Work was carried out in this laboratory[11] to develop an apparatus which moves one plate slowly in contact with another fixed plate. The time of traversal of a heavy nucleus can be deduced by measuring the relative positions of the tracks of the heavy nucleus in the two plates. It was found that a rate of motion of about $\frac{1}{4}$ mm per hour was sufficient to determine the time of a particle traversing the plates to within a few minutes. Similar work has been carried out at other laboratories. A description of the moving plate method of studying time variations follows, together with the results of the analysis by this method of one flight.

II. NEW DEVELOPMENTS IN MOVING PLATE TECHNIQUE—EXPERIMENTAL PROCEDURE

The plates selected for analysis had been exposed on a Skyhook balloon flight at Minneapolis, June 4, 1952. The flight was launched at 5:50 A.M. and reached an altitude of 91 000 ft at 9:45. It then spent 8 hours between 91 000 and 96 000 ft. It was released at 4:56 P.M., descended by parachute and reached the ground at 5:35 P.M. The altitude record was obtained by a barograph. The plates were 4×4 inches with 400-micron G-5 electron sensitive emulsions.

The relative orientation of the plates during the flight is shown in Fig. 1. The moving plate holder was driven against a spring by a screw and train of gears. The motor was a tuned reed controlled dc motor of constant speed. The rate of motion was 282 microns per hour. The whole apparatus was enclosed in an aluminum can so as to be made water and airtight.

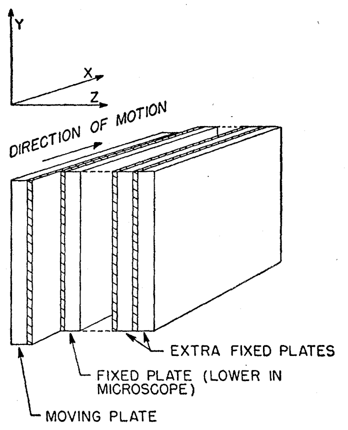

FIG. 1. The way in which the plates were oriented during the flight. The directions of the axes referred to in the text are shown.

The Microscope

The microscope that was used for determining the times of traversal of the heavy nuclei by measuring the relative position of their tracks in the two plates had been fitted with a special stage. This stage consists of two very accurate slides and screws. It is possible with this stage to reproducibly measure the relative position of two objects under the microscope, such as the ends of heavy nucleus tracks, to within about 3 microns. The availability of this precision stage made possible the refined techniques to be described. The stage is actually much more stable than the microscope nose piece. Changes in the position of the objective cause considerable difficulty in attempts to measure the absolute position of an object under the microscope, but relative positions can be measured quite accurately if care is taken not to touch the objective or its mounting between the two measurements involved. The procedures developed thus never rely upon absolute positions but only on relative positions.

Location of the Heavy Nuclei

In order to locate the heavy nuclei, the plate which had been fixed was scanned under a relatively low power, that is with a field of view of 1 mm. Tracks with greater than 10 delta rays per 100 microns were recorded. A delta ray was counted if it had three or more grains. Ten such delta rays per hundred microns corresponds to a Z of about 10 at minimum ionization. Slower particles with lower Z will contribute only a small fraction of the tracks. All delta-ray counts were made by one observer. Even if there is a systematic change of the delta-ray criterion during the course of the scanning, this is likely to have no effect on the final time distribution determined, because first all heavy nuclei were located, and then afterwards the times of traversal of these previously located tracks were determined.

No effects are to be expected from temperature changes during the flight since the flight was made

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[10] J. J. Lord and M. Schein, Phys. Rev. **78**, 484 (1950).

[11] J. J. Lord and M. Schein, Phys. Rev. **80**, 304 (1950).

[12] Marcel Schein (private communication).

during daylight hours, and the equipment was enclosed in a Cellophane-covered gondola of the type which we have used often in the past. Temperature changes during a day flight in such a gondola are known to be small. The temperature of the barograph was constant to within ±6°C.

Alignment of the Plates

In order to determine the times of traversal of the heavy nuclei by the procedure to be described, it is necessary to place the plates in the microscope in the same relative position that they had at some one time during the flight. It is strongly recommended that future experiments use a mechanical method of alignment so that the relative y positions (Fig. 1) of the plates will be the same in the microscope as during the flight. This can be done easily by having the bottom edges of the two plates rest against a flat surface along which one plate can slide during the flight. Then when the plates are placed in the microscope against a stop, they will be in the same relative orientation with respect to the y direction. In this experiment, the y alignment had to be determined from tracks in the emulsions.

A special plate holder was added to the microscope stage so that the lower plate was held in place as bebefore, and the upper plate could be placed on top with the emulsion in contact and adjusted in the y direction by two screws, one at each end, and in the x direction by a cam-shaped stop.

After much experimentation, the plates were aligned using large cosmic-ray stars. It was found that large stars near the surface of the emulsion frequently had several prongs which could be traced through into the the other emulsion even though there was a variable air gap between the plates probably caused by warping due to humidity changes during the flight. The limitations of this method are the shear distortions in the emulsion which cause events near the surface of the emulsion to be moved from their original positions.

Shear Distortions

In these plates the shear distortion amounted to about 25 microns displacement of the surface of the emulsion from its original position. It causes tracks which were originally straight to appear curved. An examination of such curved tracks in both emulsions revealed the fact that the direction of the projection of the tangent to the track at the air intercept in one emulsion closely matched the direction of the tangent at the air intercept in the other emulsion. In fact this direction was the same in the two plates to as close as the measurements could be made with a cross hair in a rotating eyepiece—about 0.01 radian. This result is reasonable since there can be no shear stress across a free surface, but there can be a large one at the emulsion glass interface. The stress curve can be expected to be smoothly varying through the thickness of the emulsion between these two extremes. It was thus assumed that the projection on the emulsion surface of the original *direction* of the tracks was closely given by the direction of the tangent at the air interface in either emulsion. It was also assumed that there was a good bond between the glass and the emulsion so that the *position* of the intercept of the track with the emulsion-glass surface was not affected by these distortions.

Procedure for Measuring the Time

In order to make sure that the plates remained in the same relative alignment throughout the measurements, two heavy nucleus tracks were chosen as standards, one at each end. Frequently during the measurements these tracks were returned to and remeasured. The relative positions of the emulsion-glass intercepts of the two tracks of each heavy nucleus in the two emulsions was reproducibly measured to within ±2 microns.

To measure the time of a heavy nucleus, the low-power (10×) objective was used which has a long enough working distance that it can see through the glass backing of the upper plate and into either of the two emulsions. In the procedure, a heavy nucleus is located in the lower emulsion by its previously determined coordinates. The cross hair in one of the occulars is turned so as to appear to line up exactly with the direction of the track. In the cases of those tracks which appear curved due to emulsion distortion, the cross hair is lined up so as to be tangent to the track at the emulsion-air intercept (see Fig. 2). The assumption is that this tangent is undistorted as to direction. The microscope is then focused up into the upper emulsion, and a search is made for the same track in the upper emulsion. After the track is found in the upper emulsion, a check is made of the direction of the tangent: it should be in line with the cross hair to within the accuracy of setting, which is about 0.01 radian. A check is also made to see that the density of the track is about the same as in the other emulsion, that the projected length is about the same, and that the apparent y distance between the air intercepts is reasonable considering the variable air gap between the emulsions. With all of these criteria, the traced-through track can be identified with considerable certainty. Then, with the precision screw, the x distance is measured between the two positions of the stage where the cross hair intersects the emulsion-glass intercepts of the track in the two emulsions. This x distance is proportional to the time of traversal of the heavy nucleus relative to an arbitrary zero.

In the case of tracks so long that the glass intercepts in the two plates cannot be seen without adjusting the y axis of the stage, this adjustment is made by moving the stage obliquely with the two screws together in the direction of the track as given by the cross hair. This is done by moving some large grain or other landmark in the emulsion from one end of the cross hair to the other the required number of times to produce a sufficient motion in the y direction.

This procedure eliminates, in first approximation, the effects of the shear distortion in the emulsions and the variable air gap during the flight. Shear distortion does not affect the direction of setting of the cross hair which is determined by the direction of the track at the air intercepts, and it does not affect the x distance which is measured to the undistorted glass intercepts. The variable air gap has no effect because it only moves the tracks farther apart along the direction of the cross hair.

Reproducibility of the Measurements

The cross hair can be set to the end of the track or to a landmark to within ±2 microns for each setting. The cross hair can be set tangent to the track to within about 0.01 radian. It can be shown that this gives an error

$$\Delta x = y\Delta\theta \sec^2\theta,$$

where y is the component of the distance between the two emulsion-glass ends of the track and θ is the cross hair angle, that is the angle between the y axis and the projection of the track in the x-y plane.

In order to check these estimates of precision, some of the tracks were remeasured. Over half of the measurements were reproducible to within 15 microns or three minutes of time. If all of this error is attributed to the setting of the angle of the cross hair, over $\frac{2}{3}$ of the measurements are reproducible to within 0.01 radian. In other words, the largest errors in the measurement of the time come from the tracks which are long, or from those which make a large angle with the vertical or y axis. Emulsion distortion contributes to the reproducibility error only through the fact that it is more difficult to set the cross hair tangent to the track if the track has a large curvature due to distortion. The variable air gap between the plates during the flight only contributes through increasing y in the above expression and sometimes by requiring more settings of the cross hair.

Effects of Misalignment

There are three possible sources of error which could be caused by misalignment of the plates.

The first type of alignment error could be caused by a difference between the direction of motion of the plate during the flight and the direction of the x axis of the microscope stage. If φ is the angle between these two directions, then there is an error introduced into the time

$$\Delta t = t \tan\theta \tan\varphi,$$

where θ is the eyepiece angle as before. It can be seen that this error is 0 for all vertical tracks. The effect on tracks with eye-piece angle θ is to expand or contract the time scale slightly depending on the relative sign of θ and φ. It is estimated that this error is less than 1 percent in this experiment and thus is negligible.

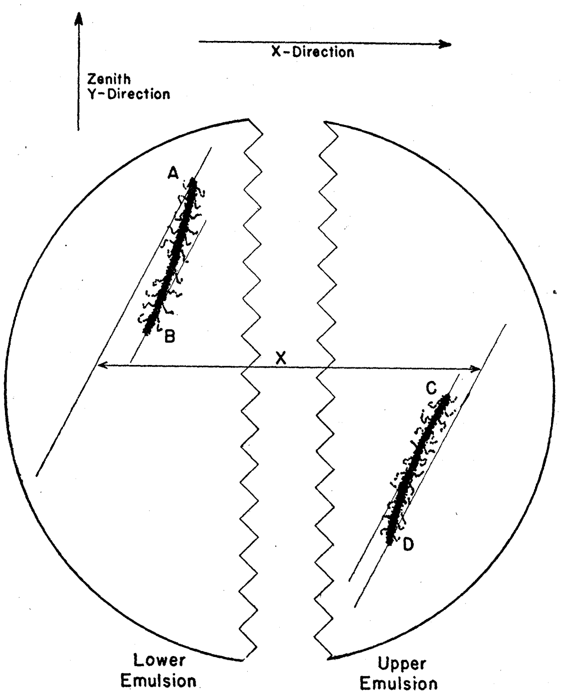

FIG. 2. The method of determining the time. B and C represent the intercepts of the track with the emulsion-air surface of the lower and upper emulsions. The cross hair is set parallel to the track at these two points. The distance x is measured with the precision screw by setting the cross hair to points A and D which are the intercepts of the track with the emulsion-glass surfaces.

The second type of error to consider could be caused by misalignment of the plates in the vertical or y direction. The error in x due to this cause is

$$\Delta x = \Delta y \tan\theta,$$

and again is 0 for vertical tracks. In this experiment it is estimated that Δy is of the order of ±15 microns. This comes about because the emulsions were aligned using stars which are on the surface and are thus subject to translation errors due to distortions in the emulsion. Also it is possible that the plates did not follow exactly a straight line in the original motion.

The third type of error, which could be of the same order of magnitude but is probably less, could be caused by plates out of alignment by a small rotation about an axis perpendicular to the plane of the emulsion. At the ends of the plates this reduces to an error of the second type above, but at the top and bottom it becomes an error in the y alignment which will add to or subtract from the time measurement depending upon whether the track is at the top or bottom of the plate.

These errors can be reduced by using mechanical

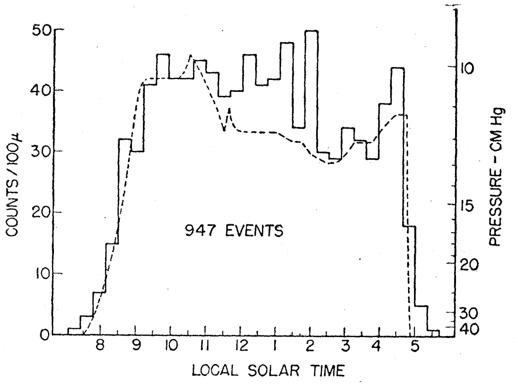

FIG. 3. The histogram is the number of tracks found in each interval of 100 microns of plate motion. The dotted curve is the calculated counting rate as a function of time assuming no changes in the flux with time at the top of the atmosphere and using the given altitude changes.

methods of alignment, but even with good mechanical methods one would probably want to check the alignment using traced-through star tracks.

In this experiment both the second and third type of error could have been accurately determined and corrected, if it had been found necessary. This could have been done by tracing through more than the 9 stars, and measuring the distortion in the emulsion at the star positions. It was decided that this was unnecessary, as these errors were found to be small.

III. ANALYSIS OF DATA AND EXPERIMENTAL RESULTS

The time was measured on 947 tracks. All of the time determinations were made by one person. Then all of the time measurements were repeated by another person, but readings were made to one less significant figure. All large discrepancies (greater than 50 microns) were carefully investigated by the original investigator, carefully remeasured if necessary, and the source of each discrepancy found. Thus it is probable that the 947 separate time measurements contain no more than one or two gross errors.

The raw data obtained are plotted in Fig. 3 in the form of a histogram of the number of events found per 100 micron interval of plate motion. 100 microns of plate motion is equivalent to 21.3 minutes of time. The observed variations with time can be caused by changes with time of the flux at the top of the atmosphere and by changes in the altitude of the balloon. In order to separate these two effects, the altitude curve provided by the barograph was used to correct for altitude changes.

To calculate what effect a change in altitude of the balloon will have on the flux of heavy nuclei through the plates, it is necessary to know how the particles are absorbed in the atmosphere. For nuclei of $Z \geqslant 10$, there seems to be agreement in the literature that the nuclear mean free path in air is 21 grams per cm^2. There is also the effect of ionization loss. The flux of particles per unit area through a vertical plate at depth D in the atmosphere is given by

$$\Phi(D)=\Phi_0-\frac{4}{\pi}\int_0^{\pi/2}\sin^2\theta f(D\sec\theta)d\theta,$$

where θ is the angle between the direction of the track and the vertical, and Φ_0 is the flux at the top of the atmosphere. The function $f(D\sec\theta)$, which is the measured linear attenuation function, was obtained from the curve given by the Minnesota group[4] on the basis of a number of flights. A curve for the altitude effect assuming a constant Φ_0 was obtained by numerical integration. It is shown in Fig. 3, superimposed on the cosmic-ray histogram.

It can be seen in Fig. 3 that there is a good fit between the two curves in the region of the slow rise of the balloon at the beginning of the flight and the rapid descent at the end. The total elapsed time of the flight, as measured by the moving plate mechanism and the heavy nuclei, agrees remarkably well with the total time as measured by the barograph clock. This is a very good indication that the moving plate mechanism was operating correctly. Since the local time of these altitude changes at the ends of the flight is known from visual observations of the launching and release time of the balloon, this excellent fit makes possible an absolute determination of the time of the cosmic-ray events. This has been done and the local solar time is given.

An examination of the portion of the curves between the initial rise and the final descent reveals that there is agreement between the two curves for the first and last thirds of the time at altitude, even to the detail of the small rise in the last third. In the center third, however, there is a large increase of the cosmic-ray histogram over the dotted altitude effect curve during the middle of the flight. In order to show this, the cosmic-ray histogram for the 21 intervals between the rise and descent has been corrected for altitude changes using the result of the numerical integration, and normalized to the flux per cm^2 per second through a vertical plane at a pressure of 1.1 cm Hg. This is shown in the histogram of Fig. 4. The increase of the center bar over the average of the other two amounts to 25 percent. If we use statistical errors which represent the square root of the number of counts, it could be as low as 17.5 percent or as high as 32.5 percent. The application of the chi square test gives a probability of 0.007 that a random sample will give no better fit to a straight line. The statistical error on each of the three points amounts to about 6 percent. The reproducibility of ±3 minutes amounts to only 2 percent of these 150-minute time intervals. It is estimated that the alignment errors are also about 2 percent. These errors are not negligible, but they are smaller than the statistical errors. These errors are much too small to account for the observed increase.

Altitude records can usually be relied upon to within about ½ mm Hg pressure according to our previous experience. The record itself shows changes recognized and marked on the graph of about ¼ mm. In principle the altitude can be accurately determined from observed zenith angle distributions. For this purpose one would need to measure a much greater number of heavy nuclei. Also one would need better information on the attenuation of the heavy nuclei in the atmosphere and the zenith angle distribution averaged over all directions at the top of the atmosphere. Due to the fact that the absorption of heavy nuclei in the atmosphere is approximately exponential, the zenith angle distribution becomes much more peaked toward the vertical at lower altitudes. In other words, the altitude effect is much greater at the larger zenith angles than it is at the smaller zenith angles.

An examination of the zenith angle distribution of the heavy nuclei in this experiment yields a valuable qualitative check on the barometer record. The eyepiece angle and the y component of the length of each track in the emulsion was measured, and from these the zenith angle for each heavy nucleus was calculated. The 947 heavy nuclei were divided into four approximately equal groups according to the magnitude of the zenith angles. These zenith angle intervals turned out to be 0°–38½°, 38½°–50½°, 50½°–60½°, 60½°–90°. The heavy nuclei in these four groups were then plotted against time in the four histograms shown in Fig. 5.

An examination of Fig. 5 shows that the intensity during the first time interval increases relatively to the intensity during the last time interval as the zenith angle is increased. This clearly shows that during the first time interval the apparatus had a higher average altitude than during the second. There is a smaller difference between the intensities during the second and third time intervals which indicates that they represent more nearly equal altitudes. The third interval is perhaps higher than the second. Thus the altitude during the second interval was certainly lower than during the first interval and perhaps lower than the last interval too. This is in perfect agreement with the barograph record and in disagreement with what one would have to assume in order to explain the results in terms of an altitude change instead of a fluctuation in the primary flux. The observed increase cannot be attributed to errors in the barograph record.

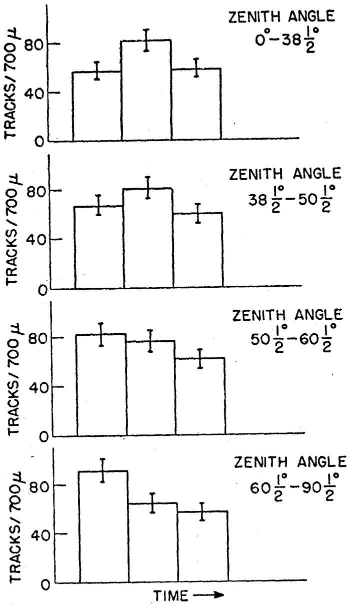

FIG. 5. The heavy nuclei have been divided into four nearly equal groups according to zenith angle. Each group is plotted in the same three time intervals used in Fig. 4.

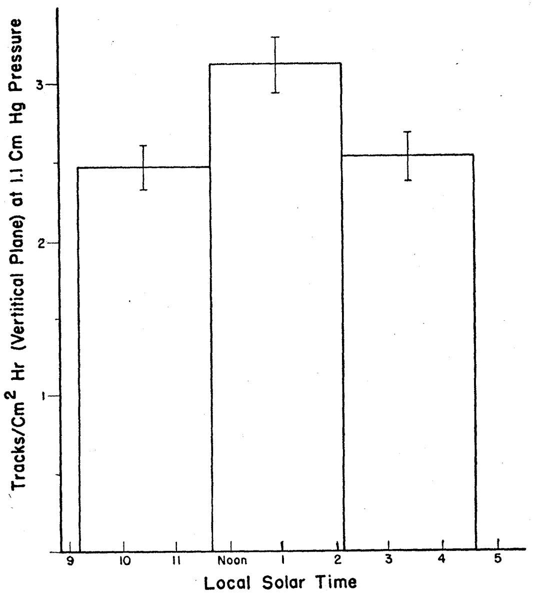

FIG. 4. The flux of heavy nuclei through the plates corrected to a constant altitude and plotted in three intervals of 700 microns each. This represents all of the data except the sections during the ascent and descent of the balloon.

The data at small zenith angles show that the center interval has an increase of 41±18 percent over the average of the other two. This is without altitude correction which would make it an even greater increase. Though this is perhaps not statistically different from the 25±8.5 percent deduced from all the data with the altitude correction, it possibly represents a first indication that the time changes observed here are confined to the low-energy heavy nuclei. It will be important to investigate this possibility in future experiments.

A large azimuthal asymmetry of the heavy nuclei coupled with a very slow rotation of the apparatus was looked for as a possible explanation for the effect. Because the photographic plates were flown with the emulsions in a vertical plane, they did not present the same projected area for the detection of particles in different directions. Now if the balloon had rotated very slowly and there had been a large directional asymmetry in the flux of the heavy nuclei, the flux observed in the plates would fluctuate as the balloon turned. In order to investigate this possibility, the 947 heavy nuclei were divided into four groups depending upon which quadrant they were in with respect to the apparatus. An effect of the type postulated would show up as some sort of periodicity in each of these four quadrants. Careful examinations, comparison with a random separation of the data into four parts, and application of statistical tests revealed no evident periodicity. It is concluded that either there was no measurable azimuthal asymmetry in the heavy nuclei, or that the period of the rotation was sufficiently rapid to prevent its being resolved with 21.3-minute intervals. The observed increase cannot be attributed to a directional asymmetry and rotation effect.

However, there is one feature about the separation of the data into four quadrants that seems to be outside of experimental error, and that is that the number of heavy nuclei in quadrants 2 and 3 is 434 and the number in quadrants 1 and 4 is 513. Although there was a slight difference in the geometry of the apparatus between these two sides, in particular there were two other plates on the side of quadrants 2 and 3 which might have introduced some detectable absorption, it was found that the explanation was rather to be found in a small tilt of the apparatus by about 3°. This was discovered by plotting the distribution of the angles of the tracks with the vertical projected in the y-z plane. This distribution rises at small angles as the sine of the angle due to the vertical orientation of the plates. But at large angles it falls again becaue of absorption in the atmosphere. The fact that the difference between the number in quadrants 1 and 4 and the number in quandrants 2 and 3 appears mostly at the larger angles speaks strongly in favor of the tilt explanation rather than the local geometry explanation. There is no way in which such a tilt could affect the apparent time distribution, since there are no effects due to rotation.

The data were also divided up in other ways in an effort to detect discrepancies. For instance, the data at large eyepiece angles were divided into two groups, with angles of a given sign in each group. Since most of the plate orientation type of errors have a sign which depends systematically on the eyepiece angle, such errors might be expected to show up. They did not to within the statistical precision of the test.

In conclusion, these data show that there was a real increase in the flux of the heavy nuclei with $Z \geqslant 10$ at the top of the atmosphere around noon of June 4, 1952 in the vicinity of Minneapolis. No imaginable systematic error could have caused such an apparent increase, and the probability that it is a statistical fluctuation is low.

IV. DISCUSSION

The results of this experiment constitute strong evidence that the heavy nuclei do fluctuate with time. The average flux of heavy nuclei with $Z \geqslant 10$ measured here agrees remarkably well with the daytime flux obtained by Lord and Schein,[11] even though the delta-ray counts were made by different observers and the acceptance criterion may have been slightly different.

There have been large changes in cosmic-ray intensity at low altitude which have been attributed to charged particles accelerated by some mechanism on the sun.[13–15] On November 19, 1949, the ionization chamber at Climax, Colorado, recorded an extraordinary increase in the cosmic radiation at about 11 A.M. G.M.T. Forbush, Stinchcomb, and Schein[16] report that the increase amounted to 180 percent. Increases were observed at other stations around the world, but none at the equator. From the absorption in the atmosphere of the radiation responsible for the increase, it was deduced that the increase was due to the nucleonic component which is responsible for the production of stars in photographic emulsions. This increase coincided with a solar flare, as have similar smaller increases observed by Clay, Ehmert, Simpson, and others. It was concluded that nucleons are at times accelerated by some mechanism on the sun to cosmic-ray energies.

Changes correlated with solar flares have also been observed at balloon altitudes in the star rate but not in the heavy nuclei. Lord, Elston, and Schein[17] reported a 50 percent increase in the rate of star production during a small solar flare which produced no detectable increase at sea level. The flux of heavy nuclei showed no detectable increase. Freier, Anderson, Naugle, and Ney[4] also were not able to detect any increase in the heavy nuclei during solar activity. Thus we have some direct evidence that protons and possibly alpha particles are accelerated by the sun, but we have no direct evidence for the acceleration of heavy nuclei.

The steady emission of heavy nuclei coming directly from the vicinity of the sun would be expected to give a peak in the intensity in the morning due to the deflection of the particles in the earth's field. The fact that the observed peak is in the afternoon makes this explanation unlikely.

A peak in the flux of heavy nuclei near noon does not necessarily have to be interpreted as direct emission of heavy nuclei of cosmic-ray energy from the sun. One can postulate that the heavy nuclei arrive isotropically from all directions and still explain a diurnal effect, if one postulates a magnetic dipole field of the

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[17] Lord, Elston, and Schein, Phys. Rev. **79**, 540 (1950).

sun. The effect that a solar magnetic dipole would have in producing diurnal variations has been considered by Janossy, Epstein, Vallarta and Godart, and Rossi. Such a dipole field would prevent particles with less than a certain energy from reaching the region of the earth's orbit. Particles with slightly higher energies would be able to reach the earth only from certain allowed directions. These directions would be such as to produce a maximum at 6:00 P.M. in the absence of a terrestial magnetic field and if the solar dipole were pointed in the same direction as the earth's. The effect of the earth's field is to deflect further the particles so that the maximum would be earlier in the afternoon. The precise shape of the intensity curve depends upon the strength and orientation of the solar dipole; upon the energy spectrum of the cosmic-ray particles detected; and upon the geomagnetic latitude of the point of observation. Alfvén[18] has suggested that such effects may be greatly reduced by the scattering of particles into trapped orbits around the sun by the earth's magnetic field. The theory has been investigated in detail by Kane, Shanley, and Wheeler,[19] and by Dwight.[20]

Neher, Peterson, and Stern[7] who used balloons and also Van Allen[21] who used rockets have shown that there are no additional primary particles arriving north of 58° geomagnetic latitude. It is postulated that this is probably due to a solar magnetic moment of 0.65×10^{34} gauss-cm^3. That the sun may have a magnetic field in spite of the apparently negative spectroscopic evidence is discussed by Alfvén.[22] He states on the basis of magnetohydrodynamic arguments that the observed turbulence on the surface of the sun would make it impossible to measure equatorial fields of the order of 20 gauss by the Zeeman effect method.

The observed peak in the early afternoon agrees qualitatively with the solar magnetic field effect calculated by Kane, Shanley, and Wheeler, and by Dwight. If the peak is present every day, it would constitute evidence for a solar magnetic dipole field of the same order of magnitude as deduced from the latitude cutoff. Observations of the changes of the effect with solar rotation and geomagnetic latitude would provide a new method for calculating the magnitude and orientation of a solar dipole. The effect should be largest near the knee of the latitude effect curve where these measurements were made.

The author wishes to express his sincere thanks to Professor Marcel Schein who suggested the experiment and gave much valuable help and advice. He also wishes to thank Dr. Jere J. Lord for help in the early stages of the experiment and Mr. David B. Williams for checking the time measurements and assisting with the angular distribution. The moving plate apparatus was developed in the Physical Sciences Central Development Shop with the help of Mr. T. J. O'Donnell and Mr. Walter Norlander. The precision stage was designed and made in the Physics Department Machine Shop by Mr. Ivar Kalberg.

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[20] K. Dwight, Phys. Rev. **78**, 40 (1950).

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