Effective Geomagnetic Equator for Cosmic Radiation*†

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The distribution of the geomagnetic field extending far from the surface of the earth is investigated by using cosmic-ray particles as probes. Since for any longitude the cosmic-ray intensity reaches a minimum at the effective geomagnetic equator of this outer field, a series of determinations of the minimum intensity at several longitudes defines its effective equatorial plane. Measurements using the neutron intensity from the nucleonic component prove that large discrepancies exist between experimental observations and the presently accepted geomagnetic coordinates derived from surface magnetic field measurements. It is also found that meson intensity data from the past 20 years or more may be used to determine minima at other longitudes.

The results indicate that the effective geomagnetic equator for cosmic rays is simulated by a westward shift of the inclined magnetic dipole of the earth by about 40°–45°, without requiring an appreciable change in the angle of inclination.

Several anomalous results which have been reported at intermediate and equatorial latitudes for primary alpha particles and heavy stripped nuclei detected in photoemulsions are readily explained by this shift in coordinates, supporting the view that the discrepancies are world-wide in character.

Since the surface magnetic field measurements do not account for this large-scale effect, it is suggested that the explanation may be found from the interaction of the rotating and inclined magnetic dipole field with a highly ionized interplanetary medium.

I.

AT present, the geomagnetic coordinates used to describe the spatial intensity distribution of the cosmic radiation are derived from world-wide surface measurements of vector field intensity. However, since the cosmic-ray particles begin to interact with the external field of the earth throughout a large volume extending a considerable distance from the earth, these particles may be utilized as "probes" to explore the otherwise inaccessible magnetic field around the earth. The fundamental question then arises: is the description of the outer magnetic field required to account for the terrestrial distribution of cosmic-ray particles the same as the field distribution computed from surface magnetic measurements?

For 25 years, the application of cosmic-ray observations to the description of the earth's field has been occasionally discussed, but apparently anomalous results led to the conclusion that the differences in distribution from the expected geomagnetic field were probably of meteorological origin, or due to local magnetic field anomalies. We have been interested in reexamining this problem since we now have the means for measuring cosmic-ray intensity which are strongly dependent on geomagnetic latitude and are free from temperature effects in the atmosphere. The theory and the method of measurement for relating cosmic-ray intensity observations to the coordinates of the geomagnetic equator and for measuring the eccentricity of the magnetic dipole have been discussed recently.[1]

In this paper we shall only consider the location of the geomagnetic equatorial plane derived from cosmic-ray observations and the implications of these results for a world-wide system of cosmic-ray geomagnetic coordinates effective for cosmic-ray particles. We shall not be concerned here with the longitude effects of cosmic-ray intensity which is strongly influenced by quadrupole terms in the geomagnetic field, but instead, we shall examine the location of cosmic-ray intensity minima (derived from latitude curves) around the earth—we define the equatorial plane as the plane passing through these intensity minima.

II.

The change in nucleonic component intensity was measured by a neutron intensity monitor carried across the geomagnetic equator at three different longitudes. Two of the measurements were made possible this past year (1954–1955) by the antarctic expedition of the *U.S.S. ATKA* which crossed the equator at 30° W and 100° W longitude. Complete details on the instrumentation, pressure correction and two-hemisphere sea-level latitude curve will be published.[2] In addition, neutron intensity observations in aircraft at 78° W longitude have been available since 1948.[3] These three equatorial crossings have provided us with intensity minima free of atmospheric influence and primary intensity variations. The results for December, 1954 and March–April, 1955 are plotted in Figs. 1 and 2. In Fig. 3, the positions of these minima are plotted on geographic coordinates. The positions of the centered and eccentric geomagnetic dipole field equators derived from surface magnetic field measurements are shown as a common curve in Fig. 3 because of the small differences between them. The discrepancies between the cosmic-ray and magnetic-field observations are obvious.

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† Work assisted in part by the Office of Scientific Research and the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, U. S. Air Force.

[1] Simpson, Jory, and Pyka, J. Geophys. Research 61, 11 (1956).

[2] See D. C. Rose *et al.* Can. J. Research (to be published).

[3] J. A. Simpson, Phys. Rev. 83, 1175 (1951).

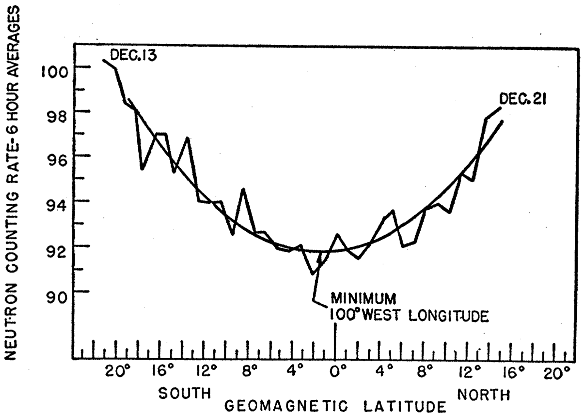

FIG. 1. Sea-level neutron intensity measured December, 1954 near the geomagnetic equator. The smooth curve is the least squares fit to 36 points from the data: $Y=91.85+0.0597X+0.0216X^2$.

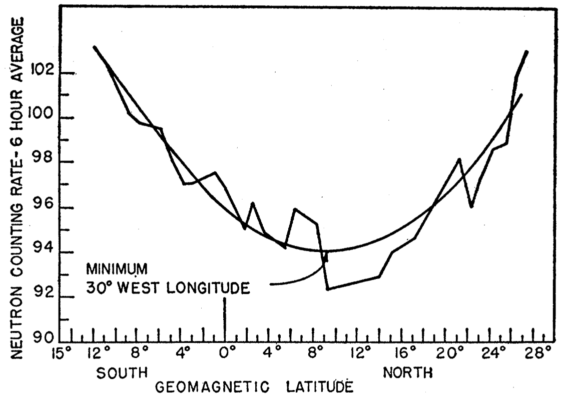

FIG. 2. Sea-level neutron intensity measured March-April, 1955 near the geomagnetic equator. The smooth curve is the least squares fit to the data: $Y=95.95-0.409X+0.022X^2$.

The meson intensity from the vertical was also measured with a threefold vertical counter telescope located in the same cabin as the neutron pile on board the *U.S.S. ATKA*. The absorber was 12.5 cm of lead. The data were corrected for pressure but not for the changes in atmospheric temperature, with the results shown in Fig. 4. It is clear that the positions of the minima are in agreement with the nucleonic component measurements even though the intensity minima are less well defined because of the small latitude dependence of the meson intensity. Consequently, we conclude that even for charged particle detectors the upper atmosphere temperature distributions do not conceal the position of the minima.

Since we now know that meteorological effects and primary intensity variations do not account for these major discrepancies, we have re-examined the ion chamber and counter telescope observations available to us between 1933 and the present for the purpose of accepting valid data at different longitudes from those measured with neutron detectors. Acceptance of the additional charged-particle (meson-intensity) data is based upon satisfying one or both of the following criteria: (a) The data were obtained at times of solar cycle minimum, or (b) there were two or more traversals over the same equatorial longitude.

The deviations $\Delta\lambda$ of the observed cosmic-ray intensity minima from the geomagnetic dipole equator are shown in Table I. The errors in the charged-particle data are larger than for the neutron intensity observations, and since they are influenced by atmospheric temperature effects, we have weighted the neutron measurements more heavily than the charged particle measurements. The vertical telescope data obtained by Law *et al.*[4] are particularly important, and we have obtained a least squares fit to their data which indicates that $\Delta\lambda$ is probably $-6°$ instead of $-8°$ as implied from the solid line drawing in the published paper. The points from Table I are shown in Fig. 3.

If we assume that these data prescribe the equatorial plane for the external magnetic field of an eccentric and tilted dipole, then they should define an almost perfect sine curve when plotted on geographic coordinates. We have fitted the sine curve by the method of least squares under two different assumptions. In one case we have fitted a sine curve to the data, assuming that the amplitude is the same as that given by the geomagnetic field data and have adjusted the phase of the curve. For the second curve, we have fitted both the amplitude and phase of the sine curve to the data. These results imply that the location of the dipole magnetic field vector required to satisfy the deflection of cosmic-ray particles is to be rotated westward by 40°–45° without necessarily changing the inclination or eccentricity. This is in disagreement with the established position of the dipole based upon surface magnetic field measurements, and we shall return to this discrepancy later in our discussion.

Our assumption that the effective magnetic field is described by an eccentric dipole has been based upon the evidence that the residual two quadrupole terms in the description of the earth's field (the first three quadrupole terms produce the eccentricity) do not interfere with the determination of the position for minimum intensity of a latitude curve. Since these residual quadrupole terms form a sectorial quadrupole, their effect in shifting the position of the minima is negligible ($<0.6°$) at the equator[5] for detectors that select incoming radiation preferentially from the vertical as is the case for detectors deep in the atmosphere.[1]

In Fig. 5, for comparison we have added the equator defined by 0° inclination measurements of the earth's magnetic field. Also, we have attempted to define the

[4] Law, McKenzie, and Rathgeber, Australian J. Sci. Research **A2**, 493 (1949).

[5] F. Jory, Phys. Rev. **102**, 1167 (1956).

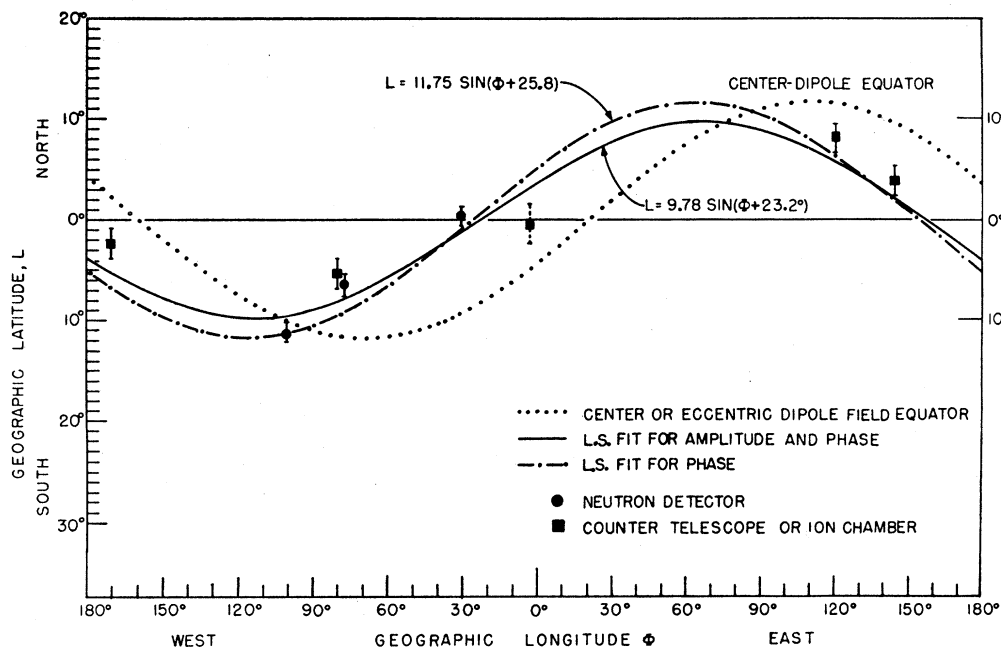

FIG. 3. The geographic coordinates for the minima of cosmic-ray intensity are shown both for neutron and meson intensity data. The presently accepted position of the geomagnetic equator for both magnetic and cosmic-ray studies is shown as a dotted line curve. The effective cosmic-ray equator derived from measurements is shown as the broken line curve, or the solid curve. The inclined equatorial plane appears to be shifted *westward* approximately 40°–45°.

most likely line for the geomagnetic equator, using the ionization chamber data of Millikan and Neher.[6]

III.

If our results define the effective geomagnetic equator for charged particles approaching the earth from great distances in the field of an eccentric or distorted dipole, then the world-wide geomagnetic coordinates to be used in explaining cosmic-ray effects will be different from those in current use. We tentatively define the equator derived from the positions of intensity minima as the

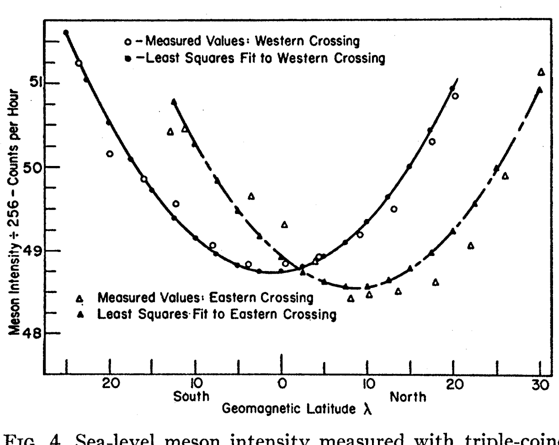

FIG. 4. Sea-level meson intensity measured with triple-coincidence detectors at the same time as the neutron intensity measurements shown in Figs. 1 and 2.

[6] R. Millikan and H. V. Neher, Phys. Rev. **50**, 15 (1936).

geomagnetic *cosmic-ray* equator. It should then be possible to account for some of the anomalous cosmic-ray results not understood at present on the basis of the geomagnetic coordinates. We shall consider some examples here.

There is evidence that the changes in geomagnetic coordinates are to be found at intermediate latitudes. Recently, Waddington[7] at Bristol has directly observed the energies of alpha particles which can arrive at geomagnetic latitude 55° N (center dipole field coordinates). He finds that, contrary to theory, no alpha particles are present below approximately 0.7 Bev/nucleon and the total intensity is 40% less than expected at 55°. We believe that his measurements are partly explained by the assumption that the actual geomagnetic latitude is appreciably less than 55° N. The flux of heavy primaries ($Z>3$) was also determined and is consistent with a change of latitude. On the other hand, measurements made by Ney[8] indicate that the alpha particle cutoff at ~107° W longitude and 61° geomagnetic latitude corresponds to a geomagnetic cutoff for a latitude not *less* than 61° N. From Fig. 3, it is clear that the shift in magnetic dipole suggested by the equator measurements will produce only a small change in geomagnetic coordinates over north

[7] C. J. Waddington (private communication); see also Proceedings of the Guanajuato Conference (unpublished). Waddington has recently compared his earlier measurements at Minnesota with his Bristol observations and finds that the geomagnetic cutoff at Minnesota may be slightly less than the value given by geomagnetic theory.

[8] E. P. Ney (private communication); see also Ney and Thon, Phys. Rev. **81**, 1069 (1951).

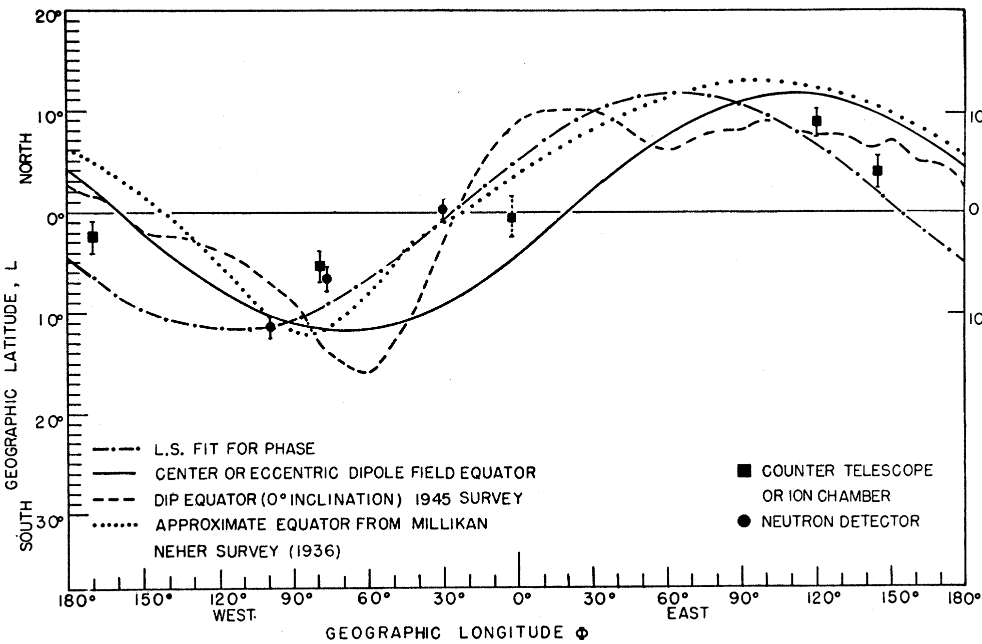

FIG. 5. Comparison of equators for surface magnetic field, ion chamber intensity, and the data from Fig. 3.

central America, but will produce a change of 6°–7° over England and western Europe, bringing all these measurements into substantial agreement.

There is, however, an alternative explanation for these alpha-particle intensity discrepancies between Europe and the United States where the measurements are made above 50° geomagnetic latitude. The coordinates reported by both observers were derived from a centered dipole which introduces a vertical cutoff rigidity $pc/Ze=N$. If the cutoff corresponding to the eccentric dipole is N' at the same position on the earth, then the predicted fractional change in cutoff between the centered and eccentric dipole is $(N'-N)/N$. Jory has calculated this function at all longitudes for the selected latitudes reproduced in Fig. 6.[5] We note that the difference in vertical cutoff expected between 0° and 90° W longitude, although smaller than the observed effect, is of the correct magnitude and sign to account for the alpha-particle discrepancies in the latitude range of 55°. Consequently, a decision in the interpretation of the alpha-particle observations will rest heavily upon observations at much lower geomagnetic latitudes, namely 35°–42° north, where $(N'-N)/N \approx 0$.

Flux values for alpha particles and heavy nuclei have already been published for measurements at $\lambda=41°$ geomagnetic latitude at both ~10° E longitude (Sardinia) by Fay[9] and ~105° W longitude (White

TABLE I. Location of minimum cosmic-ray intensity. The difference between the positions of the geomagnetic equator and the effective cosmic-ray equator is $\Delta\lambda$, with $+\Delta\lambda$ placing the cosmic ray equator north of the geomagnetic equator.

Reference	Longitude	$\Delta\lambda$	Date
Clay *et al.*[a,b]	3° W	+4°	1933
U.S.S. ATKA[c]	30° W	+9°	1955
Simpson[d]	77° W	+4°	1948
Johnson and Reed[e]	80° W	+5°	1935
U.S.S. ATKA[c]	100° W	−1°	1954
Compton and Turner[f]	170° W	−4°	1936
Law, McKenzie, and Rathgeber[g]	145° E	−6°	1948
Sekido, Asano, and Masuda[h]	121° E	−3°	1937

[a] J. Clay *et al.*, Physica **1**, 369 (1934).
[b] This point is somewhat uncertain.
[c] See reference 2.
[d] See reference 3.
[e] T. H. Johnson and D. N. Reed, Phys. Rev. **51**, 557 (1937).
[f] A. H. Compton and R. Turner, Phys. Rev. **52**, 799 (1937).
[g] See reference 4.
[h] Sekido, Asano, and Masuda, Sci. Papers Inst. Phys. Chem. Research (Tokyo) **40**, 439 (1943).

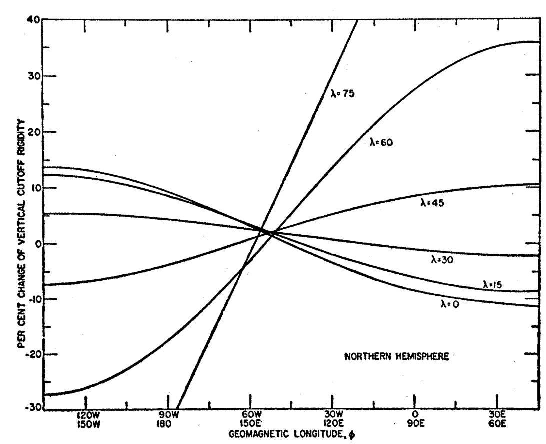

FIG. 6. The fractional change in cut-off rigidity from the vertical due to the introduction of the eccentric dipole.[5]

[9] H. Fay, Z. Naturforsch. **10a**, 572 (1955).

TABLE II. Comparison of flux values (in m^{-2} sec^{-1} $sterad^{-1}$) for alpha particles and heavy nuclei. All measurements of alpha particles and heavy nuclei are free from large scale albedo effects. Note the discrepancies between 100° west and 10° east longitude at $\lambda = 41°$ for all nuclei intensities. By changing the geomagnetic coordinates to follow the effective cosmic-ray equator (Fig. 3), all these data are brought into agreement.

Centered dipole geomagnetic coordinates	90°–105° W longitude α	$6 \leq Z \leq 10$	$Z < 10$	0°–10° E longitude α	$6 \leq Z \leq 10$	$Z < 10$	
55°	280–320[a–e]			170[a]			Two effects present
41°	90–110[c]	5.8–7.1[d]	2.5[d]	53±13[e]	2.8[f]	1.2[f]	Unique effect

[a] See reference 7.
[b] See reference 8.
[c] N. Horwitz, Phys. Rev. **98**, 165 (1955) and references therein.
[d] See reference 10.
[e] M. Reinharz (private communication).
[f] See reference 9.

Sands, U. S. A.) by several investigators.[10] A comparison of the published values appears in Table II; this disagreement was noted by Fay.[9] The intensity at 10° E longitude is a factor of two lower than the intensity at 105° W longitude. These measurements are not open to the criticism we have presented for the measurements at 55°. Hence, we interpret this difference in flux at "$\lambda = 41°$" to a difference in geomagnetic cutoff consistent with the difference predicted from our equator measurements, Fig. 3.

Also free from the difficulties outlined above are the recent observations of Danielson *et al.*[11] using nuclear emulsion plates to measure the angular distribution and azimuthal asymmetry of incoming heavy nuclei at geomagnetic latitude 10° N (center dipole coordinates) and approximately 90° W longitude. They find that, contrary to predictions of geomagnetic theory based upon center or eccentric dipole coordinates, the azimuthal asymmetry is not oriented east-west, but rather northeast and southwest with the excess flux appearing from the southwest as shown in Fig. 7. We believe that this effect is evidence for the geomagnetic cosmic-ray equator since the "east-west" effect for the primary cosmic rays is aligned with the cosmic-ray equator in Fig. 3.

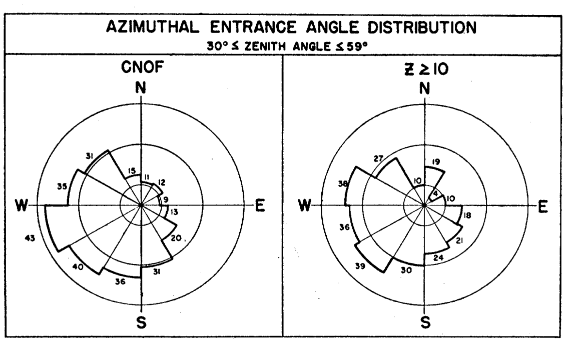

FIG. 7. The intensity of heavy, stripped nuclei as a function of azimuthal angle. This should appear as an excess of particles coming from the geomagnetic west over the number of particles coming from the geomagnetic east. The measurements were at ~90° W longitude and ~10° N geomagnetic latitude. These measurements were reported by Danielson, *et al.*[11]

All these results obtained with photographic emulsions at intermediate and equatorial latitudes strongly support, but do not yet prove, the view that a completely new world-wide coordinate system, following the cosmic-ray equator in Fig. 3, is required to describe the effective magnetic field distribution for cosmic rays.

IV.

If we assume that the discrepancy just described arises from the earth's magnetic field of internal origin, then the discrepancy can only be taken into account by changing the Gauss coefficients already well established for the dipole terms of the potential function. But this leads to a disagreement with the already known[12] surface magnetic field distribution. On the other hand, it is clear from the large scale of the effect upon high-energy charged particles that the earth's main field extending far from the surface is involved. Consequently, we are led to a tentative interpretation of the phenomenon by which the outer field distribution converges to the already established magnetic field distribution at the earth's surface.

These measurements provide evidence that the earth is immersed in a highly conducting interplanetary medium, and, because of the rotation of the inclined field, this outer field (of internal origin) interacts with the ionized medium. The dynamics of this outer region are not understood at present. Only recently has there been serious consideration given to the astrophysical problem of a rotating and magnetized body immersed in a conducting gaseous medium.[13] Though this is a likely direction in which to search for the explanation of the effective cosmic-ray equator, there is already one point of difficulty—Lüst[14] has computed that,

[10] Kaplon, Noon, and Racette, Phys. Rev. **96**, 1408 (1954).
[11] Danielson, Freier, Naugle and Ney, Phys. Rev. (to be published).

[12] E. H. Vestine *et al.*, Carnegie Institution of Washington Publications 578 and 580, 1947, (unpublished) and references therein.
[13] R. Lüst and A. Schlüter, Z. Astrophys. **34**, 263 (1954).
[14] R. Lüst (private communication).

assuming infinite conductivity for the medium and a 45° westward shift of the equatorial magnetic field, the earth's rotation velocity would be reduced from its present value to zero in a time much smaller than the lifetime of the earth.

The classical longitude effect for cosmic-ray intensity also displays a westward shift.[2,15] We wish only to mention here that the explanation to account for the longitude shift proposed by Lemaitre,[16] namely a parallactic effect on the cosmic-ray particle trajectories, cannot account for the observed cosmic-ray equator and, indeed, is too small an effect to account for the observed longitude effect.

The distortions of the earth's outer field in the interplanetary medium and the possible existence of an outer ring current make it unlikely that the charged particles experience the field distribution of a perfect magnetic dipole. Therefore, further measurements at many longitudes are required before we can consider our representation of the effective cosmic-ray equator by a sine curve as a reasonably good approximation. We do not at present know the difficulties which may be encountered by extrapolating to high magnetic latitudes these equatorial results; preliminary measurements in the Arctic and Antarctic indicate that serious difficulties may arise.[2] However, it appears unlikely that the main features of this striking discrepancy at low latitudes will be appreciably different from those in Fig. 3.

[15] H. Hoerlin, Z. Physik **102**, 666 (1936).
[16] G. Lemaitre, Nature **140**, 23 (1937).

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Bubble Counting for the Determination of the Velocities of Charged Particles in Bubble Chambers*

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The density of bubbles along tracks in a liquid propane bubble chamber has been measured as a function of particle velocity for positive pions and protons with velocities $\beta=v/c>0.4$. For temperatures from 55°C to 59.5°C the bubble density, b, is described by $b=(A/\beta^2)+B(T)$, where $A=9.2\pm0.2$ bubbles/cm and B is a function of temperature only. Velocities can be determined by bubble counting, using fast comparison tracks of known velocity, with a final average error in velocity of 5% for proton tracks 10 cm long. Accurate temperature control is not required to obtain this accuracy by using this method.

I. INTRODUCTION

An important feature of the cloud chamber and nuclear emulsion for interpretation of nuclear processes is their ability to furnish information concerning particle velocities by measurement of the relative ionization. Together with other data, this ionization measurement permits the identification of particles, the determination of particle masses, and the calculation of characteristics of nuclear events.

The usefulness of the bubble chamber as a research instrument in nuclear physics is similarly much enhanced by the experimental finding that the density of bubbles along a track is a quantitative measure of the velocity of charged particles. Previously published bubble chamber photographs demonstrated this possibility qualitatively,[1] but now we have completed a systematic series of measurements which establishes the quantitative reliability of bubble counting as a technique analogous to grain counting in a nuclear emulsion or droplet counting in a cloud chamber. The bubble density measured in propane did not turn out to be proportional to the relative ionization, but rather is a linear function of $1/\beta^2$, where $\beta=v/c$ is the relativistic velocity of the particle. This result makes

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† Fulbright Research Scholar, University of Michigan, Fall, 1955.

[1] D. A. Glaser and D. C. Rahm, Phys. Rev. **97**, 474 (1955).