the emulsion to the darkroom humidity since both weight and emulsion thickness depend on the water content of the emulsion.

We therefore investigated another possibility for mass determination based on x-ray transmission, especially useful for the experiments on stratified emulsions.

The x-ray beam used for this purpose should be monochromatic or at least not change its quality within the range of the absorption measurements which generally comprises plates with 50 to 600μ emulsion thickness. Furthermore it is important that the penetrating power of the x-radiation should be appropriate in order to obtain appreciable changes in transmission for only small changes in emulsion thickness. As silver and bromine are the main constituents (per weight) of the emulsion, it is advisable to work near the short-wave edge of the K line of silver.

In the experiments a Norelco x-ray diffraction unit and an x-ray tube with Cu or Fe cathode was used and operated at 40 kev and 20 ma. The unit has four symmetrically located exit windows; two of these windows were used, one for the actual measurement and the other for monitoring the beam. In front of both windows diaphragms were placed with $\frac{1}{3}$-mm opening diameter in order to limit the size of the x-ray spot in the emulsion. The measurements were made with ionization chambers and the actual measurement always related to the monitoring beam and a carefully weighed standard emulsion and standard glass.

Figure 9 shows the transmission curve for a series of pellicles (NTB Eastman-Kodak emulsion) measured individually and then in groups of 2, 3, and 4 together. In this semilogarithmic curve, the weights of the emulsions per cm^2 (weighed at the same relative humidity) is plotted *versus* the transmitted radiation. The linearity of this curve proves the applicability of the method. The method is sensitive, since the radiation is dimished by a factor 30 while the weight per cm^2 of the combined emulsions varies only by a factor of 4.75.

Figure 10 gives the results obtained with Ilford $G5$ emulsions of about 200, 300, 400, and 600 microns. The abscissas are the weights of the plates per cm^2 after subtracting the weights of the corresponding glass slides. The ordinates correspond to the product $\mu_{em}d$ calculated from the expression

$$l^{-\mu_{em}d-\mu_{ge}}/l^{-\mu_{ge}}.$$

It was found that the attenuation of glass slides (same batch) does not vary more than ±3 percent. Since in a 300-micron emulsion five times more radiation is absorbed in the emulsion than in the corresponding glass slide, the error introduced is negligible. This fact has an advantage over the weighing method, where the weight of the glass slide—in the case of the 300μ emulsion—is about 3 times greater than the emulsion weight.

The point of the curve 2a with the letter L refers to the laminated emulsion plate having alternate layers of about 7μ and emulsion layers of about 35μ. These emulsions were weighed before development, after soaking in cold water and after processing. After each step the emulsion was conditioned to the same value of humidity. The thickness of emulsion and gelatin layers after processing was measured microscopically at various degrees of humidity before and after incorporating glycerin. Finally the emulsion was dissolved and weight and x-ray transmission of the glass slide were determined. From these measurements and the known composition of the emulsion and gelatin, we obtained the weight of the gelatin layers. The point L, weight of laminated emulsion minus weight of the gelatin layers, fits the transmission curve quite well. In the case of the stratified emulsions used in the neutron experiment and in one set of meson exposures, the ratio of light elements in emulsion to light elements in the gelatin layers in the dry plate (the emulsions were kept in the refrigerator before exposure) was determined to 2.95×0.3.

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The Cosmic-Ray Albedo*

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The fraction of splash albedo radiation leaving the earth which goes into (bound) orbits leading back to the earth is discussed in the Stoermer approximation. It is shown that the returning particles arrive at latitudes very close to the latitudes from which they leave the earth. A qualitative argument indicates that the returning radiation should be roughly isotropic.

I. INTRODUCTION

ROCKET[1,2] and balloon[3] measurements carried out in recent years suggest that at the top of the atmosphere an appreciable flux of cosmic radiation is directed toward the upper hemisphere. This *albedo* radiation presumably consists of secondary particles produced in the interactions initiated in the atmosphere by primary cosmic radiation; and as would be expected on the basis of such an interpretation, the albedo appears to be most intense at large zenith angles.[1]

Some of the albedo particles which emerge from the atmosphere can be expected to escape the earth's magnetic field; but some of them may be trapped in bound orbits, in which case they must eventually return to the earth in the "primary" radiation. We shall distinguish between two kinds of albedo radiation at the top of the atmosphere: *splash albedo* (particles whose direction of motion lies in the upper hemisphere); and *albedo primaries* (returning albedo particles, whose direction of motion lies in the lower hemisphere). This distinction is based only on direction of motion at the top of the atmosphere. A third class of particles at the top of the atmosphere consists of true primary radiation. The splash albedo can be distinguished experimentally by means of Cerenkov counters, for example.[4]

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

[1] J. A. Van Allen and A. V. Ganges, Phys. Rev. **78**, 50 (1950); **79**, 51 (1950).

[2] S. F. Singer, Phys. Rev. **77**, 729 (1950); **80**, 47 (1950).

[3] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[4] J. R. Winckler, Phys. Rev. **85**, 1053–1054 (1952).

On the other hand, the experimental distinction between albedo and true primaries is more difficult and must depend, as we shall see, on the fact that the forbidden Stoermer cones for true primary radiation are allowed for albedo primaries. For example, albedo primaries can arrive at the magnetic equator from the vertical direction with Stoermer energies below 0.5, which is the approximate lower limit for true primaries.

The existence of an appreciable flux of albedo primaries arriving at the top of the atmosphere would of course create difficulties in the present-day interpretation of cosmic-ray geomagnetic effects and would obscure attempts to determine the true primary cosmic-ray spectrum. This effect would be expected to be more serious for protons than for heavy nuclei: the possibility that the splash albedo contains an appreciable number of heavy nuclei can probably be ruled out. These particles, which would result from the breakup in the atmosphere of heavier primary nuclei, are known to preserve very closely the direction of motion of the parent nuclei. On the other hand, it is possible that low-energy electrons constitute a large fraction of the splash albedo. Perlow *et al.*[5] find an appreciable number of low-energy electrons in the "primary" radiation at $\lambda=41°$, and they interpret these as albedo primaries. At the same time, it is known that energetic electrons ($\gtrsim 1$ Bev) are at most very rare in the incoming radiation at the top of the atmosphere.[6] This, however, is consistent with Singer's observation[2] that energetic electrons ($\gtrsim 30$ Mev) do not contribute significantly to the splash albedo.

The purpose of the present work is to provide a preliminary discussion of the following questions: (1) What fraction of the splash albedo radiation emerging from the atmosphere returns to the earth, i.e., reappears at the top of the atmosphere as albedo primary radiation? (2) How do these returning particles distribute themselves with respect to latitude and direction of arrival?

II. RELATION BETWEEN SPLASH AND PRIMARY ALBEDO INTENSITIES

The detailed behavior of charged particles emerging from the atmosphere can be obtained only by numerical computation of the orbits in the earth's magnetic field. For the orbits of interest in the present discussion, i.e., those which return to the earth, the quadrupole term of the earth's field is not of negligible importance.[7] Nevertheless, if one considers only the dominant, dipole term, several interesting and semiquantitative results can be obtained. The Stoermer integral of motion for a particle of charge e and momentum p, in the field of the earth's dipole, is given by

$$\alpha=-R\cos\lambda\cos x+\cos^2\lambda/R, \tag{1}$$

where

$$R=r(cp/eM)^{\frac{1}{2}}. \tag{2}$$

The position of the particle is specified by the magnetic latitude λ and the radial distance r from the dipole M; x is the angle between the velocity vector and a reference vector directed toward the east. The Stoermer energy R_e is the value of R at the earth's surface ($r=r_e$).

It is known from Stoermer theory, which is based on Eq. (1), that particles for which $\alpha\geq 2$ and $R_e\leq 1$ cannot reach the earth from infinity. These conditions define the forbidden Stoermer cones. Conversely, the same Stoermer cones are easily seen to define the directions within which particles leaving the earth (splash albedo) cannot escape to infinity. Thus, the familiar Stoermer expression for the cutoff energy $\bar{R}_e$ as a function of latitude and direction of motion represents a limit below which particles leaving the earth (at latitude λ and with direction of motion x) cannot escape the earth's field,

$$\bar{R}_e=\cos^2\lambda/[1+(1+\cos x\cos^3\lambda)^{\frac{1}{2}}]. \tag{3}$$

Even of those particles which go into unbounded orbits $[R_e(\lambda,x)>\bar{R}_e(\lambda,x)]$, some may be led back to the earth —although the trajectories would in principle go off to infinity if the earth were transparent. The calculation of this effect requires detailed study of individual trajectories. We shall instead use the simple Stoermer approximation and therefore obtain a *lower* limit for the number of albedo particles that return to the earth.

A second consequence of Eq. (1) is the following. Consider a particle which leaves the earth with a given value of the parameter α [as determined, from Eq. (1), by the energy R_e and the latitude and direction of motion upon leaving the earth]. The range of latitude within which the particle can return to the earth is determined by setting $R=R_e$ and allowing $\cos x$ to vary between 1 and -1. We are considering only the case where $\alpha>2$. If we assume, further, that $R_e\ll 1$, we see that the second term on the right-hand side of Eq. (1) is dominant; i.e., the particle returns very closely to the same latitude from which it left the earth—although the longitude and direction of arrival may be very much changed. For example, a particle of Stoermer energy 0.2 (proton kinetic energy ≈ 1.6 Bev) which leaves the earth in the vertical direction at $\lambda=45°$ must return to the earth within $\sim 1.5°$ of $\lambda=45°$.

In summary then, if we know the energy and angular distribution of the splash albedo at a given latitude, we can obtain from Eq. (3) a lower limit on the number of particles which must return to the earth; and from the discussion of the preceding paragraph, we conclude that these particles return essentially to the original latitude. Thus, in the Stoermer approximation, the number of particles which return within an element of latitude is proportional to the number which leave from the same element.

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[5] Perlow, Davis, Kissinger, and Shipman, Phys. Rev. 88, 321 (1952). See also G. J. Perlow and J. D. Shipman, Phys. Rev. 71, 325 (1947); S. E. Golian and E. H. Krause, Phys. Rev. 71, 918 (1947).

[6] Critchfield, Ney, and Oleska, Phys. Rev. 85, 461 (1952).

[7] The author wishes to thank Professor M. S. Vallarta for an interesting discussion on the role of the quadrupole term.

The only question which now remains is how do the returning particles (albedo primaries) distribute themselves with respect to direction of arrival x? The answer to this requires a detailed study of individual orbits. However, we shall again content ourselves with a qualitative discussion. It is known experimentally that the splash albedo is most intense at large zenith angles; but after the particles leave the earth, the complicated bending in the earth's magnetic field might well be expected to wash out this strong angular dependence, so that upon returning to the earth the radiation is more nearly isotropic. One might attempt to justify this assertion with the following argument, which is based on ideas contained in the paper of Kane, Shanley, and Wheeler.[8]

Imagine that the earth emits splash albedo radiation but is otherwise transparent to cosmic radiation. Particles which are emitted in bound orbits and whose energy and parameter of motion lie within specified intervals ΔR_e and $\Delta\alpha$ will wander about in more or less complicated paths and eventually, by a kind of quasi-ergodic hypothesis, approach indefinitely closely to all points in phase space consistent with Eq. (1). An application of Liouville's theorem then shows that the intensity will be constant throughout the allowed volume. Since the parameter α depends only very little on x at the surface of the earth (for the case $R_e \ll 1$ and $\alpha > 2$ which we are considering), it follows that the intensity of returning radiation at the surface of the earth is virtually independent of x.

As a first approximation it may be reasonable to assume that the above situation prevails even in the presence of the opaque earth.

III. DISCUSSION OF EXPERIMENTAL EVIDENCE

As we have seen, splash albedo radiation which leaves the earth with energies below the cutoff [see Eq. (3)] must necessarily return to the earth. Conversely, any experimental evidence for particles with energies below the cutoff in the "primary" radiation at the top of the atmosphere would most easily be explained in terms of returning albedo.

Van Allen and Ganges,[1] by means of counter telescopes, have measured the cosmic-ray intensity as a function of zenith angle θ (averaged over azimuth) at rocket altitudes above the magnetic equator. The zenith-angle dependence is given by

$$I(\theta) = K(1+0.6\sin\theta), \tag{4}$$

where $K = 0.028$ particles/cm^2-sec-sterad. The counter telescope which was employed does not distinguish between downward-moving and upward-moving (splash albedo) radiation. But for any reasonable choice of spectrum, it turns out that the true primary radiation should if anything show a slight decrease with increasing zenith angle. The expression $0.6K\sin\theta$ may therefore be taken to represent the zenith angle dependence of splash albedo—if we assume, conservatively, that the intensity of splash albedo is zero in the precisely vertical direction. Singer[2] has likewise found a large zenith angle dependence (at $\lambda = 41°$), which he interprets in terms of the contribution of splash albedo. If the above expression is accepted, and if the assumption is made that the bulk of the splash albedo particles have energies below the lowest cutoff value at the equator ($\sim$10 Bev for protons), then one finds that as many as 40 percent of the incoming particles at the equator are albedo primaries; and in accordance with our previous arguments, one would expect these particles to be distributed isotropically over the upper hemisphere.

The experimental information on splash albedo intensities is, of course, far from complete, and it may be that the figures adopted here are too large. Nevertheless, the possibility that so large a fraction of the primary radiation at the equator consists of returning albedo particles would seem to merit further investigation. For latitudes increasingly far removed from the equator, the cutoff energies are decreasing and the fraction of splash albedo radiation which returns to the earth becomes of smaller importance. At the poles, in the limit of the Stoermer approximation, the intensity of albedo primaries vanishes.

Experimental information on albedo primary radiation is at present rather limited. However, Perlow and co-workers[5] have recently published the results of measurements carried out above the atmosphere at $\lambda = 41°$. They find that some 15 percent of the incoming charged-particle radiation consists of low-energy particles, which they interpret as returning albedo radiation. The intensity appears to be insensitive to zenith angle.

The author wishes to express his thanks to Professor Vallarta, Professor Winckler, and Professor Van Allen for valuable discussion.

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[8] Kane, Shanley, and Wheeler, Revs. Modern Phys. **21**, 51 (1949).