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The Nature of the Cosmic Radiation

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On a view which regards the primary cosmic radiation as of charged corpuscular nature, it seems quite customary to regard the situation as one in which rays of a wide range of energy enter the atmosphere, pass through losing energy continually until they have completed their range, when they stop. If cosmic-ray intensity is measured by the number of rays per square centimeter per second per unit solid angle, or by something proportional thereto, the increase of cosmic-ray intensity with altitude is then ascribed to a situation in which the softer rays are more numerous in amount and describe shorter ranges. It is the custom to conclude, therefore, that the average radiation gets softer with increase of altitude. The purpose of this paper is to show that the foregoing view is completely erroneous and that if the distribution of energy of the incoming rays is adjusted so as to give an exponential law, then the quality of the radiation is independent of altitude. In other words, the radiation at some altitude above sea level is obtainable from that at sea level by simply increasing in the same proportion the numbers of all of the rays of varying energies. The situation is, therefore, one which seems quite incapable of accounting for the fact that nuclear bursts in lead produced by the primary radiation increase in number with altitude far more rapidly than the intensity of the cosmic radiation itself.

A VIEW which maintains that the primary cosmic radiation is of a charged corpuscular nature has to face the experimental existence of an approximately exponential absorption law and at the same time a state of affairs in which each ray has a definite range. Over this range it produces ionization at a more or less constant rate which is of the same order of magnitude for an energy of 10^9 volts as for an energy of 10^6, at which latter energy it has only a meter or so of its range left. It is only in this last meter, and indeed in the last part of that meter, that the ionization per centimeter amounts appreciably, and the total amount of ionization in this richly ionizing region is relatively small. On such a view the increase of cosmic-ray intensity with altitude is to be attributed to the softer, that is smaller energy rays, ending their paths at altitudes which are greater the less the energy. If we define the cosmic-ray intensity I_θ for the zenith angle θ as the number of rays passing per second per unit solid angle per square centimeter of area with plane perpendicular to the direction defined by θ, then the exponential law demands that $I_\theta = Ae^{-\mu R}$, where R is the effective path length corresponding to the direction θ. The number of the above rays which are absorbed in the range R to $R+dR$ is the number which *enter the atmosphere* within the limits specified with energies between E_0 and E_0+dE_0 determined by R and $R+dR$. This conclusion holds whatever may be the nature of the loss of energy by the rays provided only that it is sufficiently continuous along the path that rays of the same energy do not have a statistical distribution of ranges varying over limits which are appreciable compared with the effective thickness of the atmosphere. If R is proportional to E_0, say

$R=\beta E_0$, as would be the case where the energy loss occurred by a uniform ionization per centimeter of path, the exponential nature of I_θ would involve an exponential law of the form $\beta A e^{-\mu\beta E_0} dE_0$ for the number of rays entering the atmosphere within the prescribed limits and having energies between E_0 and E_0+dE_0. The existence of such a state of affairs would be rather remarkable, and even though the energy loss were more complicated than that corresponding to uniform ionization, so that R might not be proportional to E_0, the exponential nature of I_θ would necessitate a peculiar law of energy distribution for which there would seem to be no obvious reason. It would be strange, indeed, if such law as existed should conspire in form to produce the relatively simple exponential law for I_θ.

However, the most significant feature is that, as we shall show, regardless of the nature of the energy loss, provided only that we measure intensity by the corresponding number of primary rays, or something proportional thereto, *the existence of an exponential law for intensity necessitates that the quality of the radiation shall be the same at all altitudes.* In contrast to what seems to be usually implied there is no such thing as the soft rays being found in proportional excess of the hard rays at high altitudes. Rays which are hard at high altitudes are rays which are softer (in the sense of smaller energy) at sea level.

The reason for the foregoing statement is as follows: Let I_θ be the intensity for the direction θ as above defined, so that after path lengths R_1 and R_2 through the atmosphere in the direction θ, we have, respectively,

$$I_{\theta_1}=Ae^{-\mu R_1}; \quad I_{\theta_2}=Ae^{-\mu R_2}. \tag{1}$$

Thus

$$(I_{\theta 1}-I_{\theta 2})/I_{\theta 1}=1-e^{-\mu(R_2-R_1)}. \tag{2}$$

The exponential nature of (1) has resulted in $(I_{\theta_1}-I_{\theta_2})/I_{\theta_1}$, depending only upon R_2-R_1. Now $I_{\theta_1}-I_{\theta_2}$ is the number of rays which, within the prescribed limits of angle, etc., disappear in the distance R_2-R_1. These are the rays which are within R_2-R_1 of the end of their range; and this fact *characterizes* their energy range and the upper limit of that range. Eq. (2) tells us that, for the prescribed limits of angle, etc., *the number of rays below a certain assigned energy bears to the total number of rays a ratio which is independent of everything but the energy range specified and in particular a ratio which is independent of the altitude.* In other words the *quality* of the radiation is independent of altitude. *The only affect of increased altitude is to increase the numbers of rays of all energies in the same proportion.*

Since on the foregoing views the quality of the radiation would be independent of altitude, all phenomena produced by the radiation should increase with altitude simply in proportion to the intensity as measured by the number of primary rays. The numbers of secondaries of all classes should increase with altitude in proportion to the primaries, and so, if the secondaries represent the things measured for the most part by our counter and ionization apparatus, the measured intensities should follow an exponential law. Moreover, the number of bursts (Hoffmann Stösse) of all sizes in lead for example, should increase exponentially with altitude in the *same proportion as the cosmic-ray intensity itself.* The last-named conclusion is drastically in opposition to the experiments of the Montgomerys[1] who found a twenty-five-fold increase of Stoss production in lead at the altitude of Pike's Peak as compared with a fivefold increase of the apparent radiation itself. It is similarly in opposition to analogous experiments of R. D. Bennett, G. S. Brown and H. A. Rahmel,[2] to the experiments of T. H. Johnson,[3] and of B. Rossi and S. de Benedetti,[4] for showers of smaller numbers of rays. On the other hand, these experiments on increase of shower and Stoss production with altitude are in harmony with the idea that all the primary rays come for the most part right through the atmosphere, losing energy on the way and having a secondary or shower-producing efficiency proportional to the energy in the case of air, and to a higher power of the energy in the case of lead.[5] This view leads, as the writer

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[1] C. G. and D. D. Montgomery, Phys. Rev. **47**, 429 (1935).

[2] R. D. Bennett, G. S. Brown and H. A. Rahmel, in a paper presented at the Pittsburgh meeting of the Am. Phys. Soc., Dec. 27–29, 1934; Phys. Rev. **47**, 339A (1935).

[3] T. H. Johnson, Phys. Rev. **45**, 569 (1934).

[4] B. Rossi and S. de Benedetti, Ricerca Scient. **5**, 1 (1934).

[5] W. F. G. Swann, Phys. Rev. **46**, 828 (1934).

has shown, to an exponential law with altitude for the intensity of secondary or shower-production in air; so that, provided that our apparatus measures these secondaries for the most part, an exponential law is to be expected for the measured intensity. While in the paper cited, the case considered was that of a single-energy ray entering the atmosphere, this restriction is not necessary. It may be worth while to explain this matter in detail, and to this end we shall restate the argument.

Let n be the number of secondary rays produced per centimeter of path of the primary of energy E. Let us then assume $n=\alpha E$ where α is a constant. Since the rays lose energy by producing secondary rays,

$$dE/dx=-\beta n=-\beta\alpha E,$$

where dx is an element of length of path, and β is a constant. Thus

$$E=Be^{-\beta\alpha x};\quad \text{and}\quad n=\alpha Be^{-\beta\alpha x}.$$

It is easy to see that the number of secondary rays per unit solid angle per square centimeter per second is proportional to n, so that the intensity I_θ in the direction θ is given by

$$I_\theta=Ae^{-\beta\alpha x},$$

where x is the path length through the homogeneous atmosphere for the direction θ.

It will be noticed that the apparent absorption coefficient $\beta\alpha$ is independent of the kind of ray which enters the atmosphere. There may be a mixture of all kinds of energies entering, and so a mixture of all kinds of energies at any altitude; but all have the same apparent absorption coefficient at whatever part of their energy range they may be. This conclusion depends upon the constancy of β, and so implies that the *kind* of secondaries produced is independent of the energies of the primaries for all of the energies concerned. This must be regarded as an approximation which will be discussed in a subsequent communication. The essential thing is that, to this approximation, the law is exponential, and the existence of this law and the magnitude of the apparent absorption coefficient is independent of the existence of a wide range of energy entering the atmosphere. However, even a single energy, or narrow groups of energies, in the entering rays implies a resulting situation in which the quality of the primary radiation changes with altitude, and so provides for the creation of a natural explanation of the rapid increase of Stoss production in lead with altitude. A sufficiently wide range of entering energies, while still giving an exponential law for measured intensity, would tend to iron out the quality variation with altitude, and so would impair the effectiveness of the theory in accounting for an increase of Stoss production in lead, with altitude, which is more rapid than the increase with altitude of the radiation itself.

If we consider photons as the main agencies in the primary cosmic radiation, the story of the exponential law becomes, of course, rather definite. In its simplest form it involves the assumption of photons of one frequency, so that the quality of the radiation would again be independent of altitude and the same difficulties with regard to variation of Stoss production with altitude would occur. The story becomes complicated by the degradation of photon energy through Compton collisions, etc., but this is a feature which it is not the purpose of this paper to pursue.