On the Fine Structure Pattern of Directional Cosmic-Ray Intensity

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1. INTRODUCTION

IN 1934–35 one of us developed a theory[1] predicting a fine structure pattern in the directional intensity distribution of cosmic rays. During the same period rather promising indications of this fine structure were found[1] in Johnson's directional intensity data.[2, 3] In the past year two independent experiments[4, 5] were undertaken specifically to test this fine structure, with results which leave little doubt that it exists. The combined evidence at the present time supports our view that such fine structure patterns offer a direct method of analysis of the primary cosmic rays, their energy spectra, and their absorptive properties. The present paper briefly summarizes the theoretical and experimental investigations in this field.

2. THEORY

Because the above-mentioned theory involves a combined analysis of geomagnetic and absorptive effects upon the primary energy spectra at infinity, it has been built upon the concept of a directional energy spectrum. In the absence of absorption this spectrum is derivable from, and equivalent to, the allowed cone.[6] Thus, without absorption, the directional energy spectrum of a given particle species j is a function $f_j(\epsilon; r, \lambda; \eta, \theta)$ involving the two positional parameters[7] (r, λ) and two directional parameters[7] (η, θ) of the Lemaître-Vallarta theory. Above a certain critical energy ϵ_1 the spectrum coincides with the spectrum $f_j(\epsilon)$ at infinity. Below this energy it consists in general of alternate allowed and forbidden energy bands, the edges of which are at critical energies ϵ_i $(i=2, 3, 4, \cdots)$. Energies above ϵ_1 correspond to the interior of the main cone,[6] and the allowed low energy bands correspond to the penumbra.[6, 8] The complete set of critical energies, including ϵ_1, are functions of the form

$$\epsilon_i = \epsilon_i(r, \lambda; \eta, \theta) \quad (i=1, 2, 3, \cdots); \tag{1}$$

and this set of functions, together with the spectrum $f_j(\epsilon)$ at infinity, completely determines $f_j(\epsilon; r, \lambda; \eta, \theta)$.

For rays traversing a path length h in the earth's atmosphere, through the point (r, λ) in the direction (η, θ), the spectrum $f_j(\epsilon; r, \lambda; \eta, \theta)$ becomes transformed into an absorbed spectrum $f_j(\epsilon, h; r, \lambda; \eta, \theta)$. Any actually observed directional intensity must be a sum, over all species j of cosmic rays, of expressions of the form

$$I_j(h; r, \lambda; \eta, \theta) = \int_0^\infty f_j(\epsilon, h; r, \lambda; \eta, \theta) d\epsilon, \tag{2}$$

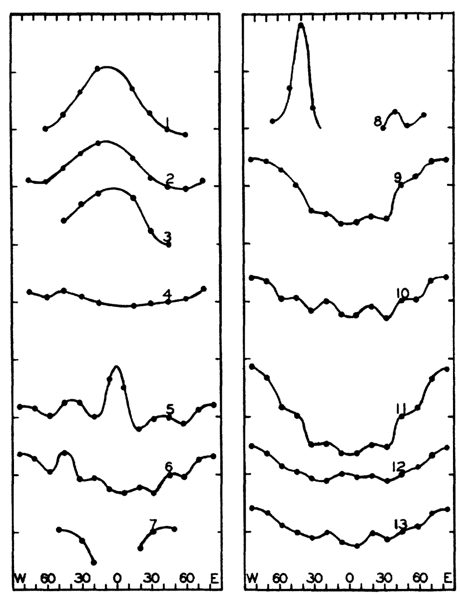

FIG. 1. Absolute deviations, reference 12, $\Delta(z)$ of observed directional intensities $I(z)$ from the $\cos^2 z$ distribution in the east-west plane at the stations listed in Table I (Johnson). Each vertical scale division represents a deviation of 25 percent of the vertical intensity. The abscissa is zenith angle z in degrees.

[1] Cf. E. J. Schremp, Phys. Rev. **53**, 915(A) (1938); **54**, 157 (1938).
[2] T. H. Johnson, Phys. Rev. **45**, 569 (1934).
[3] T. H. Johnson, Phys. Rev. **48**, 287 (1935).
[4] H. S. Ribner, Phys. Rev. **55**, 1271 (1939).
[5] D. M. Cooper, Phys. Rev. **55**, 1272 (1939).
[6] Cf. M. S. Vallarta, J. Frank. Inst. **227**, 1 (1939).
[7] For definitions, see G. Lemaître and M. S. Vallarta, Phys. Rev. **49**, 719 (1936), where a normalized r absorbing the energy ϵ is discussed.
[8] R. Albagli Hutner, Phys. Rev. **55**, 15 (1939); **55**, 614 (1939). The latter paper furnishes quantitative calculations of the critical energies ϵ_i for certain ranges of $(r, \lambda; \eta, \theta)$.

involving such absorbed directional energy spectra. The present theory includes a formulation of a phenomenological absorption law[9] embracing the most general spectral transformations possible under rectilinear absorption. In formulating this law the four geomagnetic parameters may be set aside, since they remain essentially constant during the absorption process and serve only to specify the initial forms $f_j(\epsilon, 0)$ of the absorbed spectra $f_j(\epsilon, h)$. If $\sigma_{jk}(\epsilon, \xi)d\xi$ is the probability for the production, in unit path length, of a particle k of energy ξ from a particle j of energy ϵ, then it may readily be shown that the spectra $f_j(\epsilon, h)$ obey the simultaneous set of integro-differential equations

$$\frac{\partial f_j(\epsilon, h)}{\partial h}=\sum_k\int_0^\infty \{\sigma_{kj}(\xi, \epsilon)f_k(\xi, h) -\sigma_{jk}(\epsilon, \xi)f_j(\epsilon, h)\}d\xi \quad (3a)$$

$$=\sum_k\int_0^\infty \sigma_{kj}(\xi, \epsilon)f_k(\xi, h)d\xi -\mu_j(\epsilon)f_j(\epsilon, h), \quad (3b)$$

where

$$\mu_j(\epsilon)=\sum_k\int_0^\infty \sigma_{jk}(\epsilon, \xi)d\xi \quad (4)$$

is the absorption coefficient for species j. For a wide class of transition probabilities $\sigma_{jk}(\epsilon, \xi)$, Eqs. (3) possess rapidly converging series solutions involving exponential functions, obtainable by the method of iteration. A qualitative study of such solutions has indicated that spectral lines or bands are only gradually deformed under absorption, and partake for the most part in a rigid translation toward lower energies. This latter behavior is characteristic of idealized range absorption. Range absorption, in a generalized sense, may thus be expected to occur for corpuscular cosmic rays of any energy, even though attended by secondary production and by large radiative energy losses.

According to these ideas a fine structure pattern may then manifest itself whenever variations in direction (η, θ) produce sharp changes either (1) in ϵ_i, or (2) in I_j through implicit variations in h. Of these two conditions, (1) is in general independent of absorption effects, whereas (2) universally postulates the traversal of an observable range limit of a primary spectral line or band. Such primary spectral prominences may be either (a) penumbral and main cone energy bands or (b) lines or bands inherent in the spectra at infinity. Patterns of types (1) and (2a) should consist of loci of intensity prominences with no symmetry, except when there exist primary rays of the same mass but opposite charge. Patterns of type (2b) should consist of circular loci of prominences concentric about the zenith. The theoretical consequences which would be indicated by the actual presence of one or more of these three conditions (1, 2a, 2b) may be decided by experiment.

3. Early Experimental Results

The first experimental indications of a fine structure pattern were found[10] in 1934 in the data of Johnson's earliest east-west directional surveys.[2] An analysis[1] of Johnson's complete data[3] in 1935 yielded the curves shown in Fig. 1, where we have plotted against zenith angle z in

TABLE I. *Latitude and altitude data for the curves in Fig. 1. λ is geomagnetic latitude in degrees, and h_0 is the vertical atmospheric depth in equivalent meters of water.*

Curve	λ	h_0	Station
1	0	6.24	Cerro de Pasco, Peru
2	0	7.03	Huancayo, Peru
3	0	10.3	Lima, Peru
4	20	10.3	Barro Colorado Island, Panama Canal Zone
5	29	6.25	El Pico Nevado de Toluca, Mexico
6*	29	6.25	El Pico Nevado de Toluca, Mexico
7	29	6.8	San Rafael, Mexico
8	29	7.5	Mexico City, Mexico
9	28	10.3	Vera Cruz, Mexico
10	36	8.45	Parral, Chihuahua, Mexico
11	49	6.25	Mt. Evans, Colorado
12	49	7.10	Echo Lake, Colorado
13	51	10.3	Swarthmore, Pennsylvania

* 8.6 cm of lead between counters.

[9] A general phenomenological treatment of absorption based on this law was developed in an unpublished work by one of us (E.J.S.) in 1935–36. Similar formulations of this law for various purposes have since been made by Bhabha and Heitler, Proc. Roy. Soc. **A159**, 432 (1937), Ornstein and Uhlenbeck, Physica **4**, 478 (1937), and others.

[10] By one of us (E.J.S.) in collaboration with M. S. Vallarta. Cf. G. Lemaître, M. S. Vallarta and L. Bouckaert, Phys. Rev. **47**, 435 (1935).

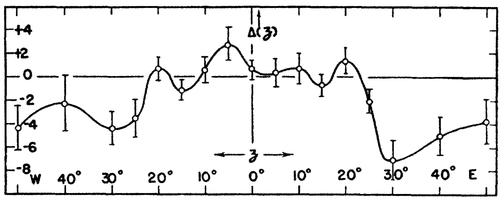

FIG. 2. Percent deviations, reference 12, $\Delta(z)$ of observed directional intensities $I(z)$ from the $\cos^2 z$ distribution in the east-west plane at St. Louis, Missouri (Ribner).

the east-west plane ($\eta=0$, $\theta=z$) the deviation $\Delta(z)$ defined by the following relation

$$I(z)=I(0)\cos^2 z+\Delta(z), \qquad (5)$$

in which the zenith intensity is normalized to a value near unity. The curves in this figure and their probable errors were computed from Johnson's published total counts,[3, 11] and are further explained in Table I. The prominences in these curves are in general several times as large as the probable errors. On the whole they show an east-west *positional symmetry*, which is a new result to be distinguished from the well-known east-west *intensity asymmetry* established by Johnson with the same data. The latter asymmetry is of course corroborated by these curves, but is here seen to be of somewhat smaller magnitude than this new effect. This positional symmetry indicates two possibilities: either the presence, in comparable numbers, of primaries of the same mass but opposite charge; or the presence of lines or bands inherent in the spectra at infinity. In view of the gradual deformation of the patterns with latitude and the apparent absence of fine structure at the equator, it appears that at least some of the symmetric prominences of Fig. 1 (of type 1 or 2a) reflect the presence of comparable numbers of primary positrons and negatrons, as one of us inferred[1] in 1935. It is however possible that other symmetric prominences, especially at the highest latitudes, may be of type 2b, and hence may reveal in addition the presence of lines or bands in the spectra in interstellar space. Moreover, in view of the gradual deformation of the patterns with altitude, condition (2a) or (2b) seems in general to prevail. Evidence of another kind for this conclusion is provided by curves (5) and (6) in the figure, which were obtained at the same station, without and with a lead shield, respectively. We see in the first curve a spectral prominence in the zenith direction, which in the second curve is completely absorbed.

[11] An analysis of Johnson's primary data by our method of Section 4 would more definitely eliminate possible counter sensitivity fluctuations. However, experience with our own data indicates that both methods are about equally reliable when, as in Johnson's case and in ours, all points of a given curve are cyclically re-explored.

4. Recent Experimental Results

Since all earlier directional data like Johnson's were taken for other purposes than are contemplated in the present theory, there has been a need for more specific tests of the theoretical predictions, requiring more closely spaced angles of exploration and apparatus of improved angular resolution. In the past year one of us[4] therefore undertook a new east-west survey at St. Louis, with results which are shown in Fig. 2,

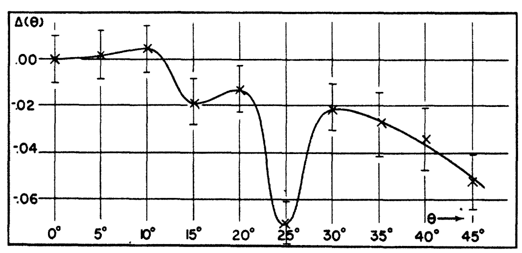

FIG. 3. Absolute deviations, reference 12, $\Delta(\theta)$ of observed directional intensities $I(\theta)$ from the $\cos^2\theta$ distribution in the eastern azimuthal plane at Columbia, Missouri (Cooper).

where there is plotted the deviation $\Delta(z)$ defined by the relation[12]

$$I(z)=I(0)\cos^2 z\{1+\Delta(z)\}. \qquad (6)$$

The points of this curve and their probable errors were obtained by cyclically re-exploring the angles indicated and by forming the average and residuals of $\Delta(z)$ over many repeated cycles of data. This method of exploration, like Johnson's, eliminated secular variations in counter sensitivity. A comparison of Fig. 2 with curve (13) of Fig. 1, at the same geomagnetic latitude and atmospheric depth, shows good agreement

[12] Eq. (6) defines $\Delta(z)$ essentially as a percent deviation of $I(z)$ from the $\cos^2 z$ distribution, while Eq. (5) defines $\Delta(z)$ as a corresponding absolute deviation. The two definitions yield $\Delta(z)$ curves of comparable form, except at very large angles.

between the two curves when the latter is corrected for its high background counting rate. Of the three approximately symmetrical pairs of prominences ($z \cong \pm 10°$, $20°$, $40°$) indicated by Fig. 2, two ($z \cong \pm 20°$, $40°$) appear in curve (13) of Fig. 1, the third ($z \cong \pm 10°$) being missed presumably because Johnson's points are considerably farther apart than ours.

An independent survey of eastern angles at the nearby location of Columbia, Missouri, undertaken by Cooper,[5] has led to results which are shown in Fig. 3. Cooper's prominences (at $\theta = z \cong 10°$, $20°$, $30°$) agree with ours except at large angles, where the two patterns show a small relative displacement. Similar displacements occurred at different times within our own data, and were interpreted as arising from magnetic and barometric disturbances. It seems, therefore, that the displacement between Cooper's 25° minimum and 30° prominence, and our own 30° minimum and 40° prominence, is due mainly to the fact that the total "exposure time" in one or both of our experiments was insufficient to average out such positional fluctuations in the pattern.

The experimental results to date thus appear to have securely established the existence of a fine structure pattern. Our arguments of Section 2, applied qualitatively to experimental data limited to the east-west plane, have shown quite conclusive evidence, of a new kind, for the presence of positrons and negatrons in the primary radiation. We believe, however, that a study of fine structure patterns at all azimuths can best provide evidence concerning questions of this sort.

One of us (E. J. S.) takes this opportunity to acknowledge his indebtedness to Professor M. S. Vallarta, who sponsored the research in which the foregoing theory was developed.