II-3B-14. The Propagation of Cosmic Rays through Interplanetary Space on May 4, 1960, and during November 1960*

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This is a brief summary of some recent studies of the solar flare effect. Owing to space limitations, only the more important results will be reported. A more adequate report of these studies has been submitted for publication elsewhere.

Part 1

This first section deals with the use of neutron monitor data to establish the manner in which the unidirectional flux of flare radiation depends upon direction.

The term "asymptotic direction of approach" will be used to specify the direction in which a cosmic ray of given rigidity must be moving in the region outside the geomagnetic field in order that it shall arrive at a specified point on the earth's surface from specific azimuth and zenith angles. The asymptotic directions may be calculated using any desired approximation to the real geomagnetic field. In this work, the Finch and Leaton (1957) approximation, employing surface spherical harmonics up to and including the sixth degree, has been used (see the paper by McCracken and Freon, II-4-19)

The asymptotic direction are specified by an asymptotic latitude (with respect to the geographic equator), and an asymptotic longitude (with respect to the Greenwich meridian). The asymptotic directions of approach to Deep River, and Churchill, Canada, are plotted in Fig. 1 for various rigidities in the range 1.0–10.5 BV. Arrival from the vertical (open circles) and at 32° to the vertical from geomagnetic north, south, east and west is indicated. The Churchill points are all shifted 30° to the west for clarity.

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Consideration of the variation in flare enhancement with change in observing latitude shows that cosmic rays of rigidity <1 BV do not contribute to the flare effect seen by a sea level neutron monitor. That is, the atmosphere imposes at cut-off at 1 BV, and lesser rigidities may be neglected in what follows. We shall call the solid angle containing all the asymptotic directions of approach which contribute to the counting rate of a cosmic ray detector the asymptotic cone of acceptance of the detector. Referring to Fig. 1., it can be seen that the asymptotic

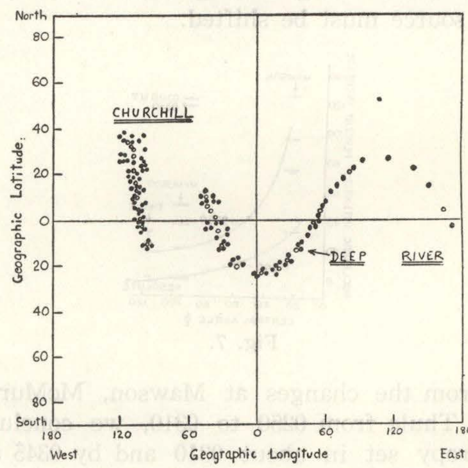

Fig. 1.

directions for Deep River extend over a large range of latitude and longitude, that is the cone of acceptance is large, and consequently a neutron monitor at this station does not "look" in a single direction in space. Considering Churchill, however, it is clear that the cone of acceptance is relatively small ($\ll 4\pi$), and therefore the neutron monitor at that station samples the cosmic ray intensity from essentially a single direction in space. A moments reflection shows that the difference between the two stations may be stated alternatively in that the Deep River neutron monitor can see the 9.00, 4.00 and

Table I. Listing the W values applicable on November 12, 1960.

UNIVERSAL TIME	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22
W	0.392	0.183	0.216	0.231	0.138	0.101	0.011	0.017

20.00 o'clock impact zones, while the Churchill monitor can only see the 9.00 o'clock zone.

A careful analysis has identified those neutron monitors which have small cones of acceptance, details of the cones being given in Fig. 2. A mean direction of viewing, being a weighted mean of the asymptotic directions (the weight for each rigidity being proportional to the fraction of the total counting rate which it contributes), is shown for each station.

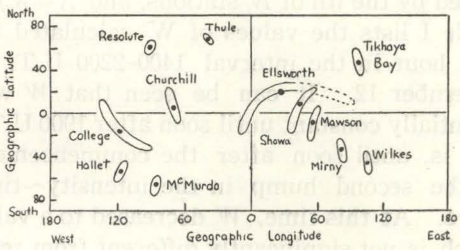

Fig. 2.

Part 2

The preceding concepts will now be used to investigate the flare effect of May 4, 1960. Fig. 3 displays the counting rate enhancements observed by seven neutron monitors whose cones of acceptance are small. It has been shown that standard neutron monitors of the type employed at these stations will record identical percentage enhancements when an isotropic flux of solar origin is incident upon the earth, and it must therefore be concluded that the differences in event amplitude which are evident in Fig. 3 must have been due to a marked anisotropy in the cosmic radiation. To investigate this anisotropy quantitatively, a "map" of the cosmic radiation flux as a function of direction has been prepared by assigning the observed percentage enhancements to the mean directions of viewing of each of the stations. (Fig. 4). It can be seen that the greatest flux of radiation came from a direction considerably to the west of the earth-sun line.

In principle it would be desirable to use Fig. 4 to determine the "contour lines" of constant cosmic ray intensity upon the celestial sphere at various times during the flare effect, however, in practice, eight observations do not permit this to be done with any precision. Instead, we test the specific hy-

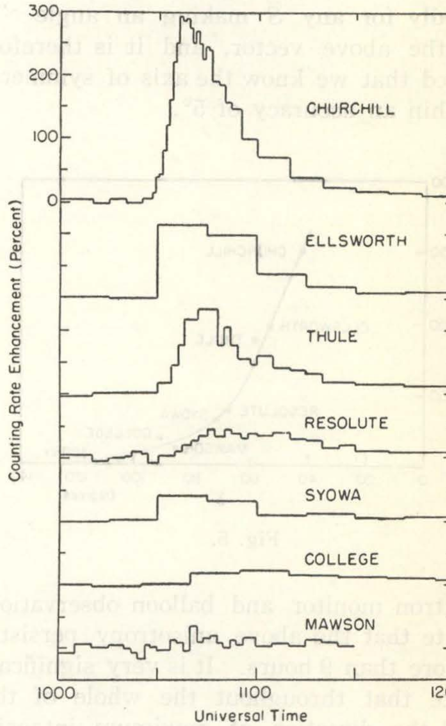

Fig. 3.

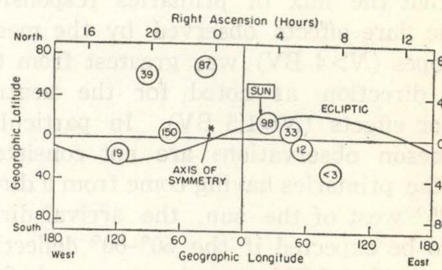

Fig. 4.

pothesis that the radiation fluxes were symmetrical about some direction, $\vec{S}$. Assuming a vector $\vec{S}$, computing the angles δ_i between this and the mean direction of viewing of the ith station, and plotting the observed enhancements against δ_i it is possible to find whether an "axis of symmetry" existed for the interval under discussion. For the interval 1045–1100 U.T. on May 4, a direction $\vec{S}$ which was 57° west of the sun, and 10° north of the ecliptic yielded Fig. 5. The ability to fit a smooth curve to the observed points is indicative that the fluxes were symmetrical about the above direction. The ability to fit a smooth curve deteriorated markedly for any $\vec{S}$ making an angle >5° with the above vector, and it is therefore believed that we know the axis of symmetry to within an accuracy of 5°.

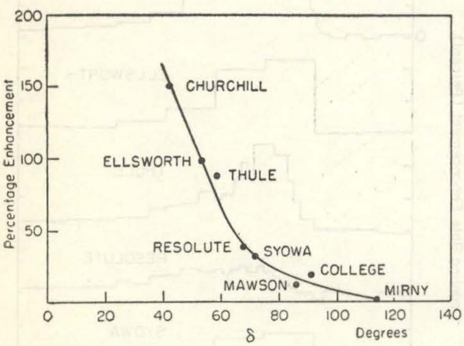

Fig. 5.

Neutron monitor and balloon observations indicate that the above anisotropy persisted for more than 9 hours. It is very significant to note that throughout the whole of this period the direction of maximum intensity always remained inclined about 50–60° to the west of the sun. Also of significance is the fact that the flux of primaries responsible for the flare effects observed by the meson telescopes (N>4 BV) was greatest from the same direction as noted for the neutron monitor effects ($N\approx$1.5 BV). In particular, the meson observations are not consistent with the primaries having come from a direction 25° west of the sun, the arrival direction to be expected if the 50°–60° deflection noted at $N\approx$1.5 BV were due to a weak field roughly normal to the plane of the ecliptic.

Part 3

Maps of the cosmic ray flux can be easily prepared for any flare effect. The more important results of such studies of the November 12, and November 15, 1960 flare effects follow.

A. November 12, 1960 (Fig. 6)

During the period 1400–1900 U.T., that is, during the first "hump" in the intensity$\sim$time curve, the radiation was anisotropic, the maximum flux arriving from a direction 50°±10° to the west of the earth-sun line. A quantitative measure of the degree of anisotropy can be defined as follows:

$$W=\left[\frac{1}{N-1}\Sigma(X_i-\bar{X}_i)^2\right]^{1/2}/\bar{X}_i$$

where X_i is the percentage enhancement observed by the ith of N stations, and $\bar{X}=X_i/N$. Table I lists the values of W calculated for each hour in the interval 1400–2200 U.T. on November 12. It can be seen that W was essentially constant until soon after 1900 U.T., that is, until soon after the commencement of the second hump in the intensity$\sim$time curve. At this time, W decreased to a value which is not significantly different from zero.

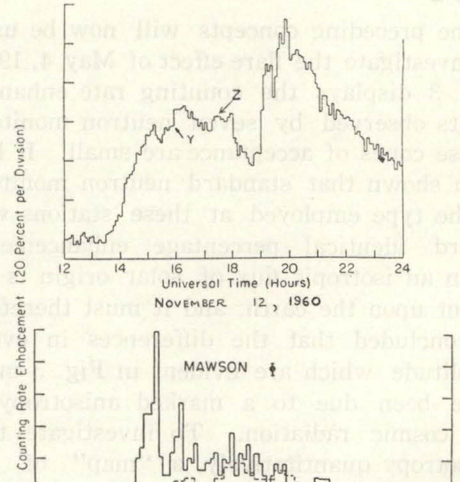

Fig. 6.

That is, during the first "hump", the cosmic radiation maintained a constant (and relatively large) degree of anisotropy, the radiation becoming isotropic soon after the commencement of the second "hump". It is believed that the second "hump" was the result of the earth being enveloped by a magnetic regime into which solar cosmic rays had been ejected at the time of the flare (1320 U.T.) (Steljes, Carmichael, and McCracken, 1961), and the forgoing observation regarding the time variation of the anisotropy is of considerable significance in determining the nature of the magnetic regime which was trapping the cosmic rays.

The fluctuation Y (Fig. 6) has been shown to be due to an anisotropic flux of radiation arriving from the general direction of the sun, while fluctuation Z was due to an anisotropic flux from the general direction of the anti-sun.

B. November 15, 1960.

On this occasion the cosmic radiation attained isotropy very rapidly after an initial phase of very great anisotropy (Fig. 6). Calculation of W (as defined above) shows that the radiation was essentially isotropic (to within 2% of the mean enhancement) by 0400 U.T. During the anisotropic phase, the maximum flux came from a direction which must have been $>20°$ west of the sun (Lockwood and Shea report elsewhere in this volume that the maximum flux came from a direction about 50° west of the sun).

Solar cosmic rays were first observed by Mawson at 0240 U.T., the maximum flux being observed prior to 0300 U.T. By way of comparison, Churchill, which was looking in the opposite direction to Mawson, did not see any significant increase in cosmic ray intensity until after 0310 U.T. However, once Churchill did start to see solar cosmic radiation, the intensity rose very rapidly, the intensity becoming comparable to that being observed by Mawson by 0330 U.T. That is, initially, there was complete exclusion of solar cosmic rays from some directions of arrival, and then, once solar cosmic rays did start to come from those directions, the flux very quickly established isotropy. This experimental observation places severe limitations on the magnetic configuration which existed in interplanetary space at the time.

Part 4

The above facts, and others, have led to the following conclusions:—

(i) The facts that the radius of gyration of a solar cosmic ray in the known interplanetary magnetic field is <0.05 AU, and that the time of flight for cosmic rays when generated on the western portion of the solar disc is short, and long when generated near the centre of the disc, indicates that magnetic lines of force connect the earth to an active solar region when it is near the western limb. No such direct connection exists when the active region is near the centre of the solar disc.

(ii) The axes of symmetry of the cosmic ray fluxes are identified as being paralleled to the lines of force of the interplanetary magnetic field. That is, the lines of force during the three events considered here were inclined about 50° to the west of the earth-sun line.

(iii) The presence of particles arriving at the earth with pitch angles of 80° (Fig. 5) is *not* consistent with spiralling from the sun to the earth along *highly ordered* lines of force. Small scale irregularities in the lines will provide both the large pitch angles, and the isotropy observed at late times for flares occurring on the western portion of the solar disc (e.g. November 15, 1960).

(iv) The lateness of the onset for a station looking in the (roughly) anti-sun direction on November 15, and the rapidity of the subsequent increase in intensity speaks in favour of particles either spiralling along the lines of the interplanetary field until they suffer coherent reflection at a well defined point in space, or arriving at the earth along the returning loop of the line of force which led the early particles to Mawson.

(v) The double hump structure of the November 12 flare effect, and the slow initial rise have been interpreted elsewhere as being due to the earth first being outside, and then entering the region of space which has direct magnetic connection to the sunspot group in which the parent flare occurred. The long persisting anisotropy observed during the first hump is shown to be consistent with the particles diffusing away from the lines of force onto which they were initially injected, and ultimately reaching the line connecting to the earth. The anistropy persists since the diffusion is most effective near to the sun, and so the cosmic ray population on the line of force which connects with the earth is continually being replenished at a point near the sun.

References

Stelies J. F., H. Carmichael and K. G. McCracken, J. Geophys. Res. **66** (1961) 1363.

Discussion

Chasson, R. L.: For the Nov. 15 event the delayed rises seen at Churchill and Thule are markedly different in shape. Do you attribute this to a difference of cut-off rigidity?

McCracken, K. G.: The difference must be interpreted as being due to the detectors sampling the radiation from different directions in space. I believe that the flux of radiation observed by Mawson at 0240 U.T. was wide enough in angular extend to be observed at Thule. Then at 0316 U.T. Thule also saw the flux observed by Churchill. That is, Thule saw both fluxes of radiation.

Bailey, D. K.: From the observations of polar cap absorption we know that the energy spectrum of the solar cosmic rays for the May 4, 1960 event could not have extended very far into the subrelativistic region. The magnitude and duration of the PCA event was uniquely small among all the PCA's observed from late 1951 to the present 46 events, the low-energy extension can hardly have extended below 100 Mev with any significant intensity.

Roederer, J. G.: Your angle of 50° corresponds to a twisted field line belonging to a solar wind of approx 500 Km/sec. However, during May 4 and Nov. 15 events, the earth was sitting in a Forbush Decrease belonging to a cloud emitted at higher speed. Shouldn't then the guiding field lines be less twisted than 50° with respect to the sun-earth line?

McCracken: The explanation of the 50° westward shift is neither simple nor unambiguous. It may be that the plasma carrying the field in the vicinity of the earth on May 4 and Nov. 15 had been emitted after the flare responsible for the onset of the Forbush decrease, and with a velocity lower than the 1500 km sec^{-1} required to explain a transit time of 24 hours.

Davis, L.: Is not the point at issue in this discussion whether or not the gas is emitted from the sun in a constant direction as seen by an observer rotating with the sun? If the gas were shot out of a nozzel which were stationary, one would get an inclination as indicated.

But if the nozzle were swung with an angular velocity of one degree per hour, the direction of an entrained magnecic field as seen at the earth could be deflected by as much as about 60°. If the gas were shot out in bursts, each ending gas into a considerable range of angles, the entrained field should be quite irregular. Only with Parker's smooth radial wind does a regular spiral appear natural to me.