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THE MAGNETIC FIELDS IN INTERPLANETARY SPACE AS DERIVED FROM OBSERVATIONS OF COSMIC RAY SOLAR FLARE EFFECTS

by

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THE MAGNETIC FIELDS IN INTERPLANETARY SPACE AS DERIVED FROM OBSERVATIONS OF COSMIC RAY SOLAR FLARE EFFECTS*

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ABSTRACT. A study has been made of the manner in which the cosmic ray intensity observed at the earth varies with time subsequent to the production of cosmic radiation by a solar flare. It is shown that the time scales of any two flare effects can be markedly different. A quantitative comparison reveals that the flares responsible for the four flare increases exhibiting the shortest time

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** This author was at MIT when this work was performed.

scales occurred on the western solar limb, while the four responsible for the increases with the longest time scales occurred near the centre, or on the eastern portion of the solar disc. The above experimental facts are shown to be consistent with a well known theoretical model for the interplanetary magnetic fields.

The proposed model predicts that impact zones will be pronounced for a flare on the western limb, and poorly defined for one near the centre of the solar disc, predictions which are shown to be in accord with the observations. Considering the flare effect of May 4, 1960, it is shown that the apparent source of the cosmic radiation lay in a direction about 60° to the west of the earth-sun line. This is interpreted as indicating that in the vicinity of the earth, the lines of force of the interplanetary magnetic field were inclined to the earth-sun line by about 60° on May 4.

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INTRODUCTION

The motion of a cosmic ray generated in a solar flare will be greatly influenced by any magnetic fields which extend throughout the solar system. It is therefore possible to think of the flare produced cosmic radiation as a tool which is available for the investigation of the interplanetary magnetic fields. By considering the times of flight, and other experimantally determinable features of the cosmic radiation from solar flares, we shall use this tool to test one theoretical model for the interplanetary magnetic field regime.

The Time Scale of Cosmic Ray Flare Effects

In a recent paper (McCracken and Palmeira, 1960) it has been pointed out that there are very marked differences between the time scales of different cosmic ray flare effects. This is illustrated in Fig. 1, which reproduces the meson data observed during three different flare effects, and which leaves no doubt as to the great differences which do occur. To make a quantitative comparison of the time scales of the rising intensity phases, we have defined the rise time of the flare effect as the interval between the commencement of the intensity enhancement and the time at which maximum intensity was attained. Using this definition and making allowance for the fact that the time scale of a flare effect is dependent upon the type and location of the detector used to make the observation, Table I has been prepared to permit the intercomparison of the eight largest flare effects which have been observed to date. For each flare effect, the position on the solar disc at which the parent flare occurred has been listed. It is noticeable that the four flare effects exhibiting the shortest time scales were the result of the generation of cosmic rays by flares on or near the western solar limb. The foure remaining events, for which the time scales were long, correspond to flares which occurred near the centre or on the eastern portion of the solar disc.

Confirmation that the position of the parent flare on the solar disc has an influence upon the subsequent cosmic ray observations is given in Fig. 2, where the time delay between the occurrence of a flare, and the subsequent arrival of the cosmic rays at the earth (as indicated by ionospheric effects in polar regions) is plotted against the position on the solar disc at which the flare occurred (data derived from Reid and Leinbach, 1959, Leinbach, 1960). It can be seen that the delays tend to be least for flares near the western limb of the sun, and greatest for flares on the eastern half of the solar disc.

The Model

The model which we shall examine is essentially that discussed by Piddington (1959), Cocconi et al (1958), Gold (1959), and in part by Morrison (1956) and Parker (1958). It is suggested that the matter ejected by an active solar region, by virtue of its high electrical conductivity, carries part of the sun spot magnetic field with it, setting up a magnetic field in which the lines of force extend from the vicinity of the earth's orbit back to the active solar regions.

Now consider Fig. 3, that is, the case in which an active region has passed across the solar disc, and is situated near the western limb of the sun. The fields established by the plasma streaming from the active region envelope the earth, and magnetic lines of force connect the earth to the vicinity of the active region. In such a case, cosmic rays produced by a solar flare in the active region would gain immediate access to the earth by spiralling along the lines of force in the interplanetary field. The times of flight of the cosmic rays, and the interval of time required for the cosmic ray intensity to reach a maximum would be short.

By way of contrast Fig. 4 illustrates the case in which an active region is near the centre of the solar disc. A magnetic field has been established by the material streaming away from the active region, but, as yet, the earth is not within this field, and lines of force do not connect the earth to the active region. In this case, cosmic rays produced by a flare in the active region would have to diffuse across the lines of force of the field rooted in the active group, and through various remnants of the fields established by previous solar activity. As a result of this diffusion the time delay, and duration of the rising intensity phase would be longer than if direct access to the earth had been possible.

The models outlined in Figs. 3 and 4 are in agreement with the variable time scales, and variable delay times which are summarised in Table I and Fig. 2. Considering Fig. 3, it is clear that the magnetic induction (B) must fall off with increasing distance from the sun, and consequently the pitch angles (θ) of cosmic rays injected onto a line of force will decrease as they recede from the sun (on account of the constancy of $\sin^2\theta/B$). That is, the cosmic radiation arriving from a flare near the western limb should exhibit marked impact zones, and the direction of arrival should indicate the direction of the lines of force in the vicinity of the earth. By contrast, in the case of the situation depicted in Fig. 4, the diffusion process should result in there being no preferred direction for the arrival of cosmic rays at the earth. That is, impact zones should be poorly defined, or non existent for flares near the centre of the solar disc. Table I shows that the above predictions are in harmony with the observations. It can be concluded that the available evidence supports the model illustrated in Figs. 3 and 4.

The May 4, 1960 Flare Effect

Data obtained during this flare effect, the result of cosmic ray production by a flare on the western limb, are displayed in Fig. 5. One very noticeable feature of the data is that stations using identical instruments, and situated at similar geomagnetic latitudes, observed counting rate enhancements differing greatly in amplitude. This is strongly suggestive of there being pronounced impact zones.

To investigate this point, we have prepared the impact zone diagram given in Fig. 6 on the assumption of a cosmic ray source in the direction of the sun. This diagram differs from those prepared by Firor (1953) in that the calculations of Quenby and Webber (1959) have been used to make allowance for the fact that the geomagnetic field is not a dipole field. Details of the method used in the preparation of this diagram will be given elsewhere.

The predicted impact zones are not in agreement with the observations. The greatest deviations between the predictions and the observations are in that the predictions place Churchill and Syowa in the "forbidden" polar and main impact zones, respectively, while in actual fact Churchill observed the greatest, and Syowa one of the smallest enhancements recorded at sea level. Remembering that the cosmic radiation observed in the secondary and higher order impact zones has a rigidity close to the geomagnetic cut-off applicable to the station, and that the geomagnetic cut-off rigidity for Churchill is very low (o.11 Bv), it is clear that Churchill cannot observe a secondary impact zone increase as particles of rigidity <1 Bv do not contribute to the counting rate of a sea level neutron monitor. In order to explain the very great increase which was observed we must conclude that Churchill was in the main impact zone. A few minutes consideration will show that, if sources centred on the sun are considered, it is impossible to place Churchill in the main impact zone, without predicting that the European stations, and Mawson were in the main impact zones also, predictions which Fig. 5 shows are not consistent with the observations.

Consider Fig. 7, an impact zone diagram based on a source shifted 75° to the west of the sun and in the ecliptic plane. It can be seen that there is now a good agreement between the predictions and the observations. In particular, Churchill has now been placed in the main impact zone, and Soywa in the background zone. This rather crude analysis suggests that during the May 4 event the cosmic radiation approached the earth from a direction considerably to the west of the sun-earth direction, a conclusion fully substantiated by a more elaborate analysis. This latter analysis indicates that the source was actually centred about a direction 60° to the west of the sun, and 10° north of the ecliptic plane.

Returning now to the model which we have found to be applicable to the May 4 event (Fig. 3), we conclude that on May 4, 1960 the lines of force of the interplanetary magnetic field made an angle of about 60° with the earth-sun line. Such an angle is understandable in terms of the velocity of the plasma bearing the magnetic field being about 350 km sec^{-1}.

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TABLE I

Listing the rise times (measured relative to that of the May 4, 1960 event), the position on the sun where the parent flare occurred, and details of the impact zones observed on the earth. An asterisk indicates the events for which a large number of observations are available, and in which the greatest reliance can be placed.

Event	Time Scale	Position on Solar Disc	Impact Zones
May 4, 1960	1	90° W	* very marked
February 23, 1956	4	80° W	* marked
November 19, 1949	6	70° W	* very marked
March 7, 1942	7	90° W	marked
February 28, 1942	13	4° E	poorly defined
July 25, 1946	17	15° E	not noticeable
July 17, 1959	36	30° W	* none
September 3, 1960	50	90° E	none

* * *

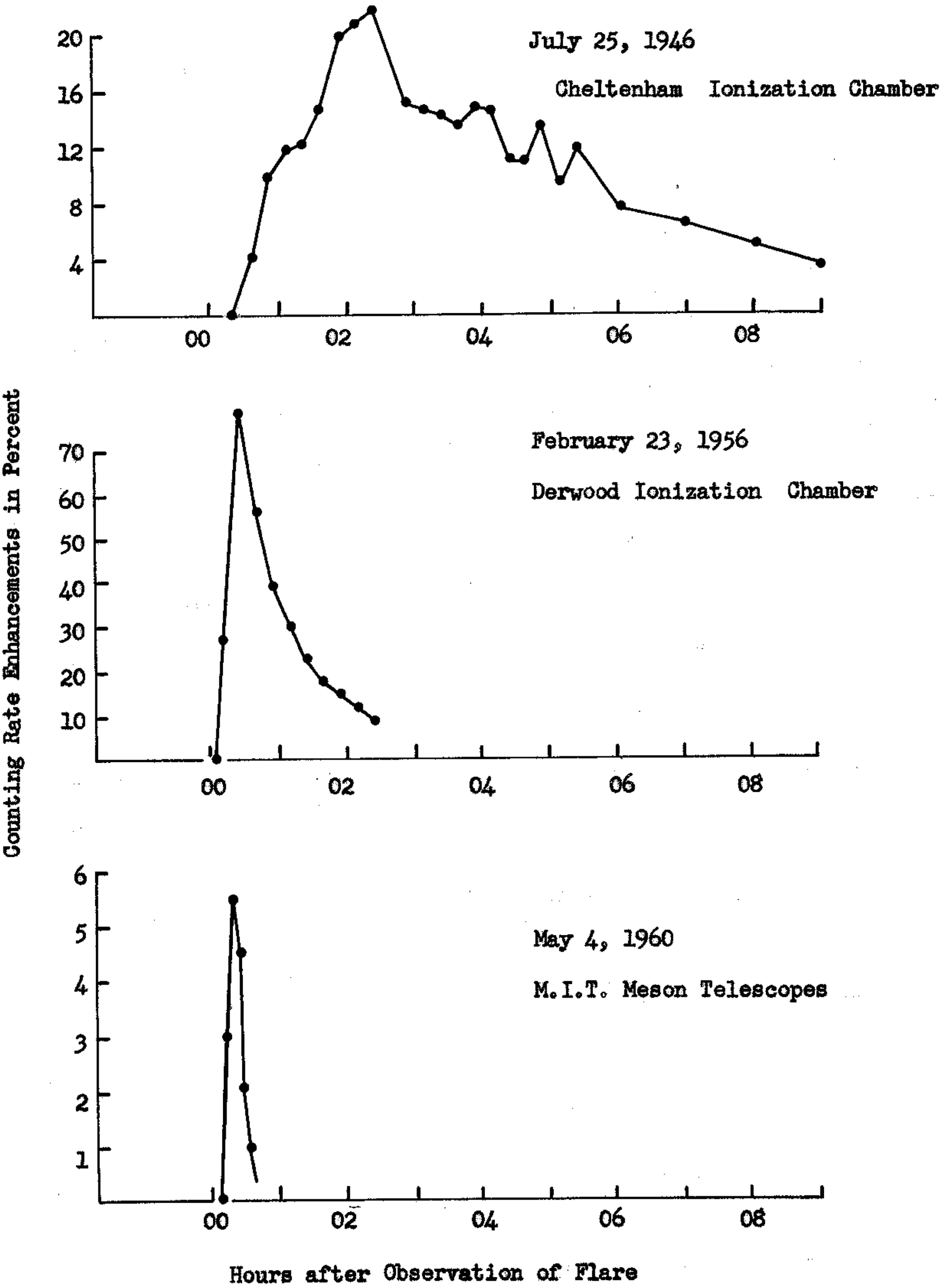
July 25, 1946
Cheltenham Ionization Chamber
20
16
12
8
4
00
02
04
06
08
February 23, 1956
Derwood Ionization Chamber
70
60
50
40
30
20
10
00
02
04
06
08
May 4, 1960
M.I.T. Meson Telescopes
6
5
4
3
2
1
00
02
04
06
08
Counting Rate Enhancements in Percent
Hours after Observation of Flare

Fig. 1

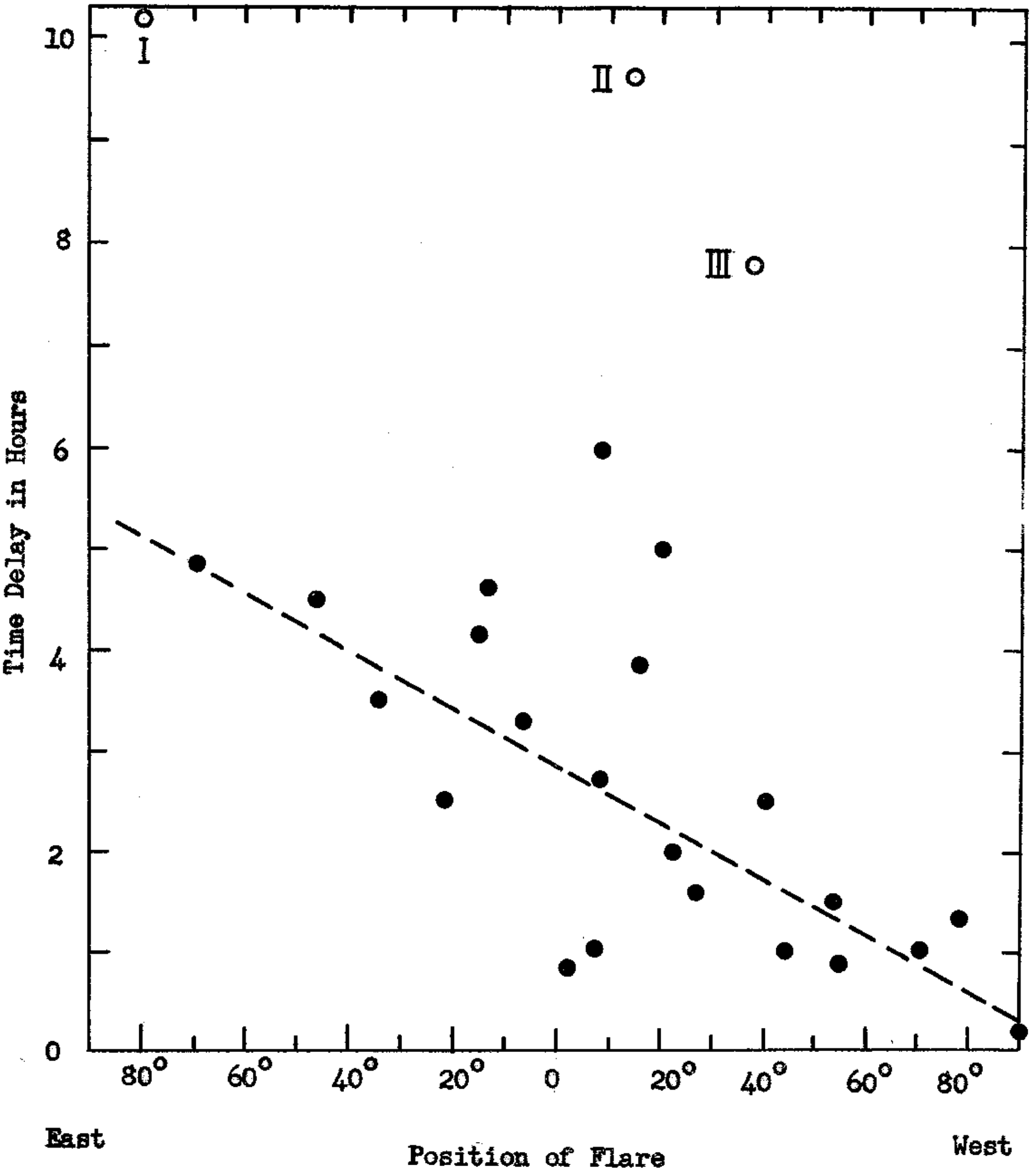
Time Delay in Hours
10
8
6
4
2
0
I
II
III
80°
60°
40°
20°
0
20°
40°
60°
80°
East
Position of Flare
West

Fig. 2

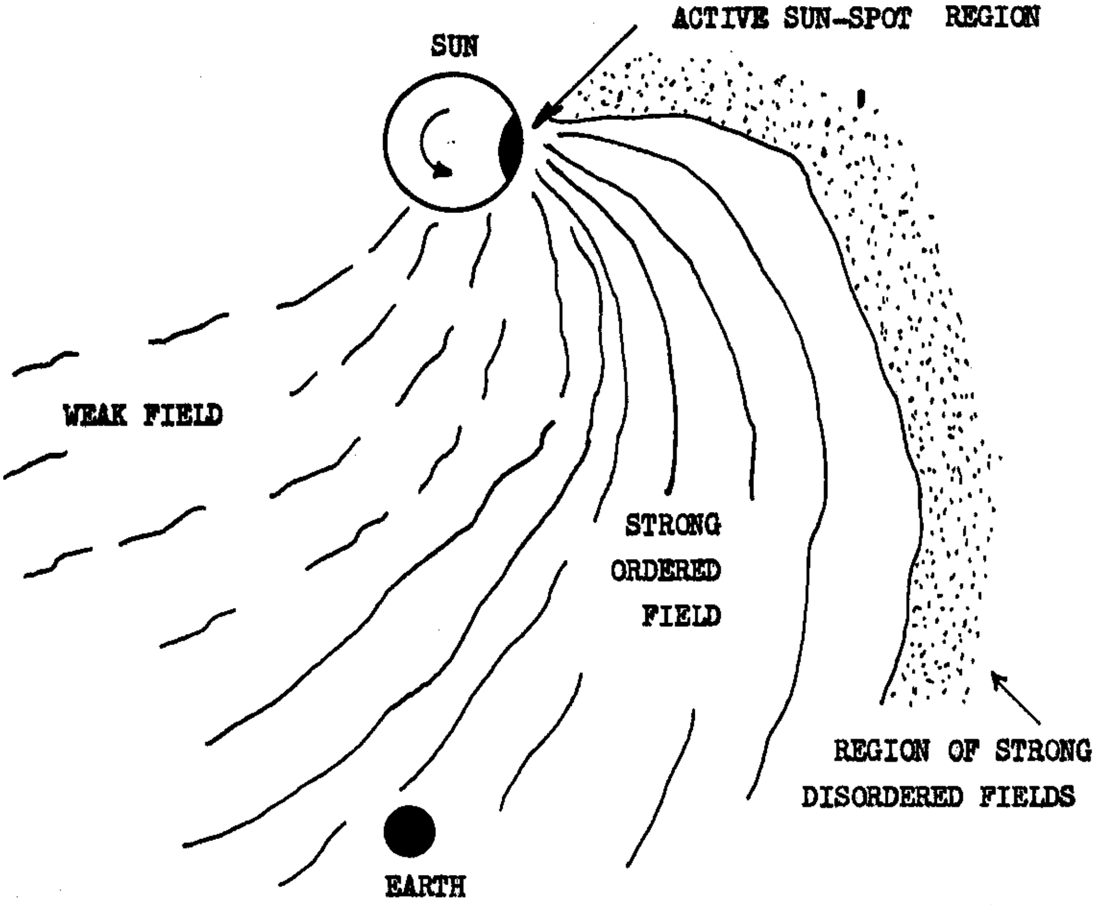
ACTIVE SUN-SPOT REGION
SUN
WEAK FIELD
STRONG ORDERED FIELD
REGION OF STRONG DISORDERED FIELDS
EARTH

Fig. 3

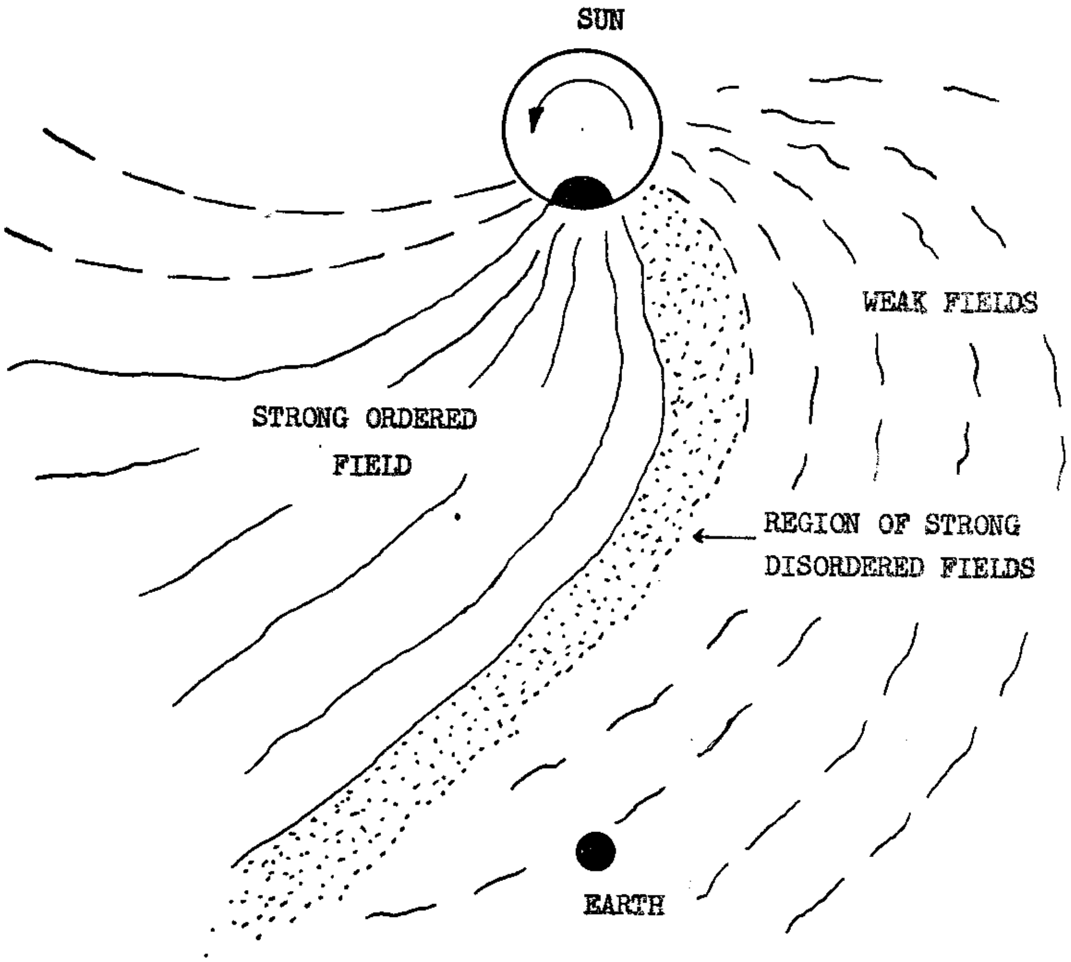
SUN
WEAK FIELDS
STRONG ORDERED FIELD
REGION OF STRONG DISORDERED FIELDS
EARTH

Fig. 4

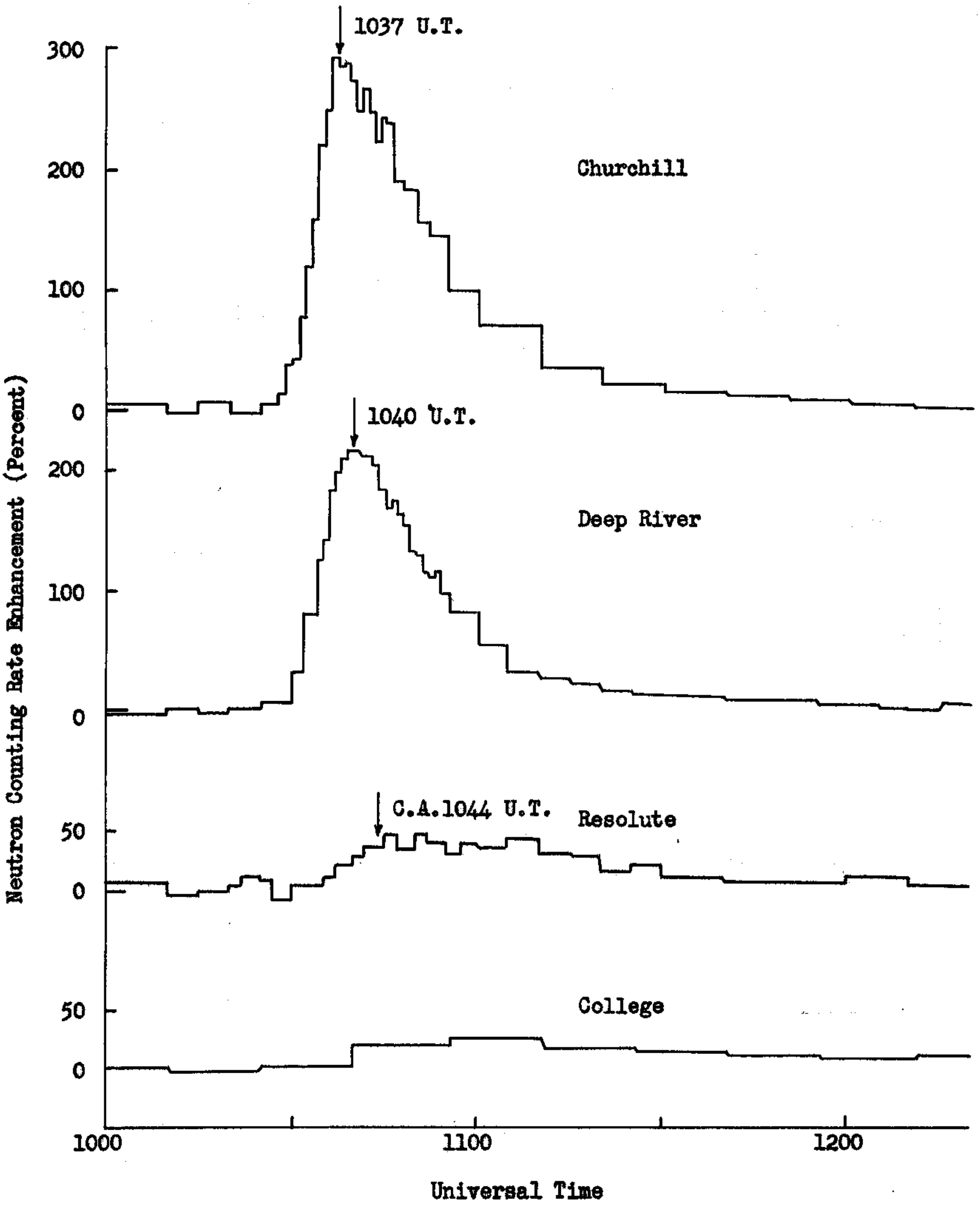
1037 U.T.
300
200
100
0
Churchill
1040 U.T.
200
100
0
Deep River
C.A.1044 U.T.
50
0
Resolute
50
0
College
Neutron Counting Rate Enhancement (Percent)
1000
1100
1200
Universal Time

Fig. 5

IMPACT ZONES, MAY 4, 1960

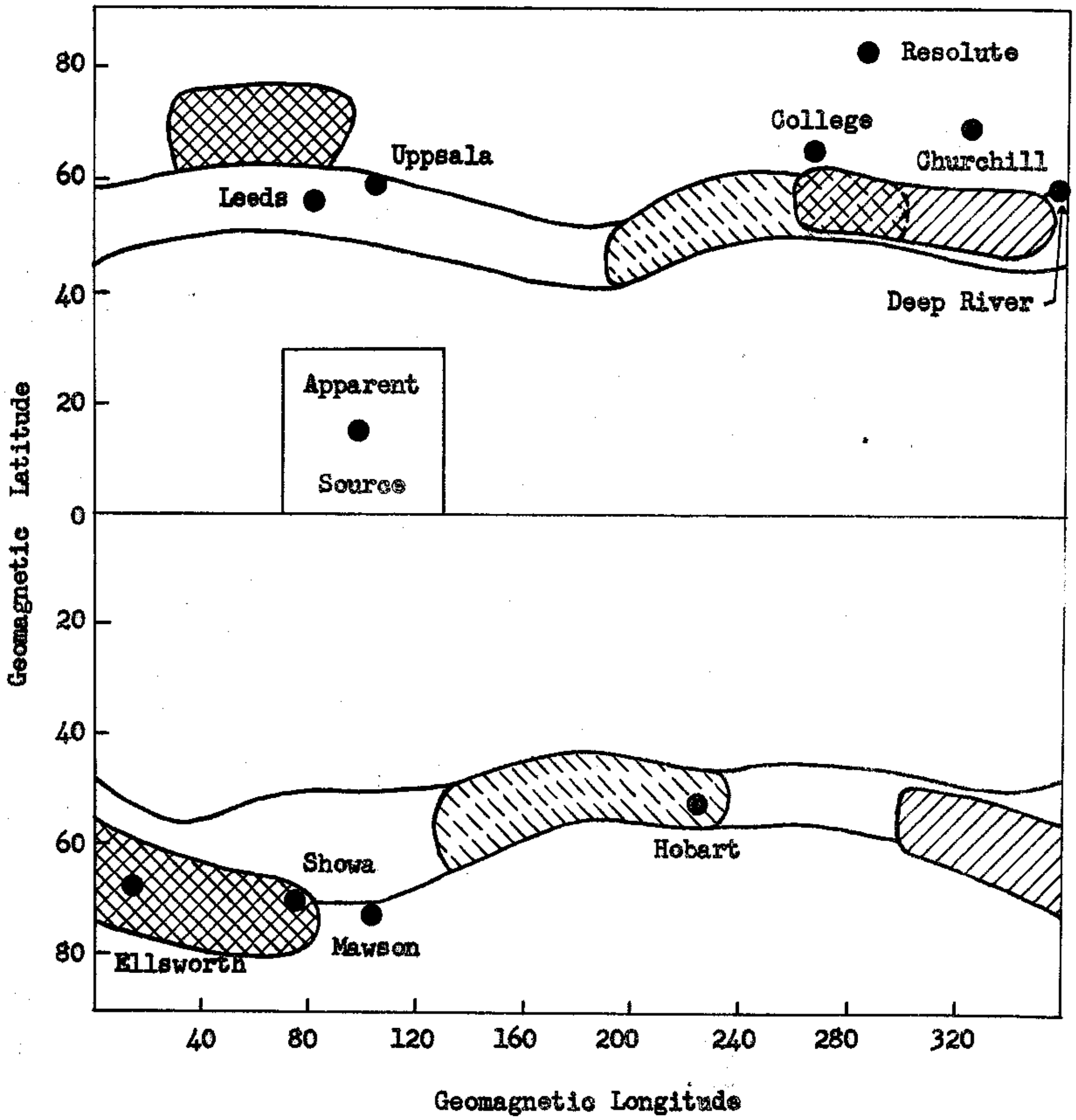

Fig. 6

IMPACT ZONES, MAY 4, 1960

SOURCE DIRECTION 75° WEST OF SUN 8 IN PLANE OF ECLIPTIC

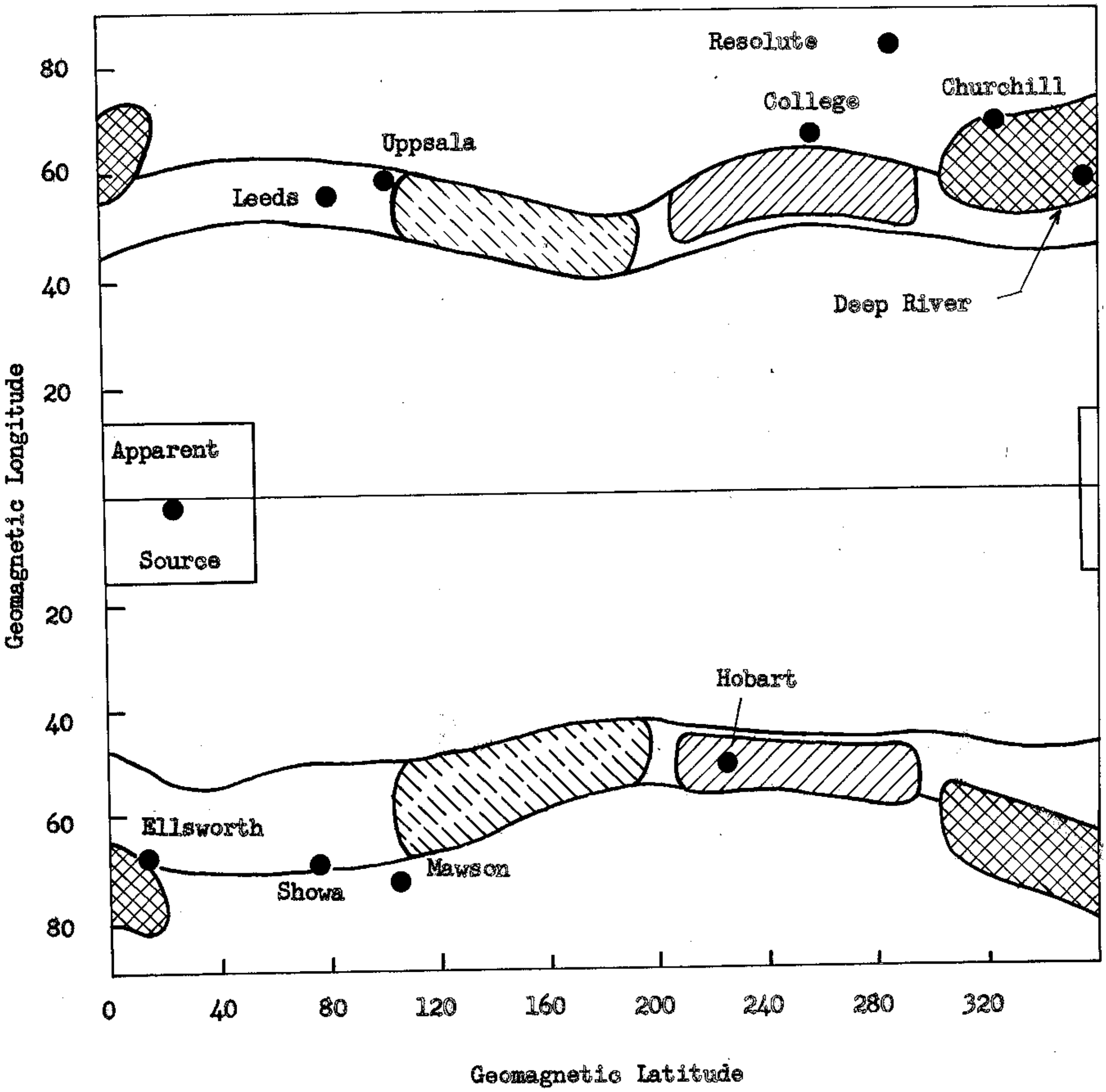

Fig. 7