Dr. Chuck Berry

A MACHINE CALCULATION OF RADIATION BELT FLUXES

By

W. N. Hess
Goddard Space Flight Center
Greenbelt, Maryland

Abstract

This report describes in some detail how one evaluates the total flux of high-energy protons and electrons encountered in transiting the radiation belts. If one knows this flux, then a knowledge of the shielding involved enables one to calculate the total radiation dose received. The determination of the total flux can be done for any orbit through the belts.

To evaluate the total dosage, the particles in the radiation belt are divided into four groups. The intensity of each particle group is determined at all positions in space and is given in particles/cm^2-sec-Mev. Then, by integrating in time along a vehicle orbit, one can get the total flux encountered by the vehicle in particles/cm^2-Mev. The final information is given in the form of energy spectra because, in performing the dose calculations, it is necessary to consider particles of different energy independetly.

Part I will deal with the high-energy protons in the radiation belt. Part II will consider all other particles in the belt. Part III will try to predict the time variations to be expected in the high-energy proton population.

I: HIGH ENERGY PROTONS

Introduction

In connection with the radiation hazard problem associated with men in space, the Theoretical Division at the Goddard Space Flight Center has developed a method for determining the total flux and spectrum of particles that would be encountered by a space vehicle intersecting the radiation belts.

This report describes the method of analysis. The problem has been coded for a 7090 computer. The central problem is to write a description of the radiation belt at all positions of space. Then, this can be used to determine total particle flux encountered by a space vehicle. The first step is to translate geographic coordinates to magnetic coordinates. This is necessary because a vehicle trajectory is normally given in geographic coordinates, and the only reasonable description of the radiation belt is in terms of magnetic coordinates. Secondly, the fluxes of particles in the radiation belt must be written in terms of magnetic coordinates. The best coordinate system is the BL system where B is the magnetic field intensity and L is the magnetic shell parameter.[1] McIlwain started the radiation belt analysis in BL coordinates by studying the high-energy protons detected in Explorer IV. This analysis will be extended here to cover all particles in the radiation belt.

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[1] McIlwain, Journal of Geophysical Research, 66, 3681 (1961)

TRANSFORMATION FROM GEOGRAPHIC TO MAGNETIC COORDINATES

A Code was written at Iowa by McIlwain to describe the magnetic field of the earth in terms of the 48-term expansion of Finch and Leaton. The code calculates the field strength B at all positions in space and from this calculates L. The code was written for a 7070 computer and has been modified for our 7090 computer. A general description of the code is given in Appendix I and a listing of the code is also appended.

DESCRIPTION OF THE RADIATION BELT

We will somewhat arbitrarily divide the radiation belt into four types of particles and treat these types of particles separately in determining the flux encountered by the vehicle.

In this report we will study only high-energy protons ($E > 30$ Mev). The other components of the belt will be considered in Part II of this report. These high-energy protons will probably contribute most of the dose for any particular flight because of their large penetrability. The information we will use to write a description of the spacial distribution of $E > 30$ Mev protons is determined by the geiger counter on Explorer IV[1, 2] and also some information [3] from Pioneer III. The energy spectrum of these protons was measured by Freden and White and others.[4] The spatial distribution of $E > 30$ Mev protons has been

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[2] Van Allen, et al., J. Geophys. Res., 64, 271 (1959)

[3] Van Allen and Frank, Nature, 183, 430 (1959)

[4] Freden and White, J. Geophys. Res., 67, 25; 65, 1377
Freden and White, Phys. Rev. Lts., 3, 9 (1959)
Armstrong, Harrison, Heckmann, and Rosen, J. Geophys. Res., 66, 351
Naugle and Kniffen, Kyoto Papers

translated into B and L coordinates by McIlwain.[1] Amplification and extensions of this work are under way now at the State University of Iowa, and Dr. Ernest Ray will help us incorporate them into this program. The range of fluxes of B and L covered by Explorer IV is not adequate to cover the total range of interest. Because of this, some extrapolations have been necessary. Figure 1 shows the values of the fluxes of E > 30 Mev protons as measured by Explorer IV and extrapolated for this current work. The extrapolations have involved assuming that the flux of protons was highest at the magnetic equator. The variation of intensity along the magnetic line has been taken to go inversely as the atmospheric density using the model atmosphere given by Hanson.[5] This extrapolation process has been checked for the ranges of values measured by Explorer IV and turns out to work quite well up to L = 1.8. Beyond L = 1.8 the extrapolation process relied on data[3] from Pioneer III which gave the proton flux for E > 30 Mev roughly along the equator. This was used with a modified version of the inverse density rule given above. For L > 2.2 the extrapolation is not well based, and there may be moderately sized errors on Figure 1 in this range. More information will be available later for this region, and this report will be updated when appropriate.

The information provided by Figure 1 is the integral of the spectrum of particles of energies greater than 30 Mev. We must now take information about the proton-energy spectrum and translate the information

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[5] Hanson, J. Geophys. Res., 67, 183 (1962)

in Figure 1 into a differential spectrum for all values of B and L. To do this we will assume that the energy spectrum as measured by Freden and White[4/] is independent of position. This is only approximately true. Theoretically, we expect that there will be fewer high-energy particles at the outer edge of the radiation belt. Experimentally, there is some small amount of information which tends to agree with this, but it is inconclusive. The Naugle-Kniffen proton-energy spectrum[4/] at $L \sim 1.65$ seems very similar to the Freden-White spectrum. In assuming the spectrum does not vary with position, we are being conservative as far as dosages are concerned. We will, therefore, take the Freden and White spectrum shown in Figure 2 to be characteristic of all protons above 30 Mev. We have fitted the spectrum in two pieces in order to handle this problem conveniently. From 30 Mev to 200 Mev the spectrum in Figure 2 is given by $\Phi = 333\ E^{-1.1}$. From 200 to 700 Mev the flux is given as $\Phi = 5.8 \times 10^{6}\ E^{-2.94}$. These values are for about 1150 km at a position of 9° N and 40° W. This position, according to the BL code, corresponds to B = .201 L = 1.354. Comparison of this information with other emulsion flights shows the spectrum has changed little, if any, over a year and a half.

For an arbitrary position we can write

$$\Phi(B, L) = k(B, L)\ E^{-1.1} \quad \text{for} \quad 30 < E < 200 \text{ Mev} \qquad (1)$$

and

$$\Phi(B, L) = 1.72 \times 10^{4}\ k(B, L)\ E^{-2.94} \quad \text{for} \quad E > 200 \text{ Mev} \qquad (2)$$

Using this spectral shape, we can integrate to get the total flux about 30 Mev as given in Figure 1. The total flux in particles C(B, L), of energy $E > 30$ Mev per cm^2-sec is given by

$$C(B, L) = \int_{30}^{\infty} \Phi \, dE \qquad (3)$$

$$C(B, L) = k(L, B) \int_{30}^{200} E^{-1.1} \, dE + 1.72 \times 10^4 \, k(L, B) \int_{200}^{\infty} E^{-2.94} \, dE \qquad (4)$$

$$C(B, L) = 1.55 \, k(L, B) \qquad (5)$$

For $L = 1.354$, $B = .201$ we have $k = 333$ which gives $C(L = 1.354, B = .201) = 516$. From Figure 1 we get $C(L = 1.354, B = .201) = 3000$. The agreement of these two evaluations is not good, but at least part of the difference is understandable. The Freden-White flux is an average value for the altitude range 1000-1180 km. Changing this into a flux at the position of maximum count rate will increase it about x3. The rest of the difference in the values of k might be attributed to uncertainties in the vehicle position. Anyway, the Atlas rocket experiment is not as good a way to evaluate flux as Explorer IV, so we will use the expression $C(B, L) = 1.55 \, k(B, L)$ and data from Figure 1 to evaluate $k(B, L)$.

This process gives us the absolute value of the Freden and White energy spectrum for particles above 30 Mev at all positions in the inner radiation belt.

One measurement gives quite different values for inner-zone proton fluxes than those shown in Figure 1. Instruments flown on

Midas III gave[1] a total flux of 3×10^5 protons/cm^2-sec of E > 60 Mev and also indicated a steep energy spectrum in this energy range. This flux is considerably higher than most other values for inner belt fluxes. This value was at 3450 km altitude. A later Midas flight[2] with similar instrumentation gave a total flux of 2.5×10^4 protons/cm^2-sec of E > 25 Mev at an altitude of 3640 km. This second measurement is in quite good agreement with other data. If the high flux from the first flight is real it must cover only a quite limited range in latitude and of altitude. This seems quite unlikely. It seems more likely that there was some instrumental problem and that the fluxes are not as high as determined on the first flight, but this is not certain. This reported high flux should be considered when studying possible radiation doses. In this report we are not using the high fluxes reported on Midas III because they are hard to rationalize with other values.

There are time variations of this high-energy proton flux which we expect to take place. They have not been measured experimentally, but they are fairly well based theoretically. The flux of these protons should increase by perhaps a factor of x10 or even more from solar maximum to solar minimum at the lower edge of the inner belt. Above 2000 km only small changes should occur. The flux at solar minimum should be larger for two reasons. First, the galactic cosmic-ray proton flux which produces the neutrons which populate the radiation belt is a maximum at solar minimum and is about twice as large as at solar minimum. Secondly, the exospheric densities will be less at solar minimum. Secondly, the exospheric densities will be less at solar minimum because there is less solar heating and, therefore, lower temperatures and, therefore, smaller scale heights. The density may be less by x 10 or more[6], but we must wait for definite information on this. Both of these effects increase the particle fluxes at solar minimum and a reasonable working estimate of the magnitude of these effects is that an increase of x10 may occur at 1000 km altitude. This is a quite large and important change. It will increase the dose received from these protons especially for rendezvous missions just below the inner belt. More work is being done on this subject now and Part III of this report will deal with these time variations in detail.

Some time variations have been seen in the inner belt. An increase in the total proton flux of E > 18 Mev of x2 was seen[7] on Injun for the period March 1959 to December 1960. This might well be the solar cycle variation that is expected. Also, some short time variations were seen by the Injun experiment, but they were more pronounced near the outer edge of the inner belt and may be in the electron component rather than the protons.

We probably know the proton spectrum to a factor of x2 now at most positions in the inner belt, but there is a possibility that

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6/ Harris and Priester, Journal of Atmospheric Sciences (July 1962)

7/ Pizzella, "Time Variations of Intensity in the Earth's Inner Radiation Zone - October 1959 through December 1960," State University of Iowa, 62-1 time variations may occur that are not expected. We should gather data on the variation of proton flux for the next several years to help answer this question.

DISCUSSION OF FIGURE 1

We have converted the count rates shown[1/] in McIlwain's Figure 5 to omnidirectional fluxes by using $G_o = .42\ cm^2$. The values of G_o listed[2/] in the literature are $G_o = .14$ for a stopping power of 1.2 gm/cm^2 (or a range of 30 Mev) and a G_o of .70 cm^2 for a range of 60 Mev. We have made an equivalent G_o for 30 Mev particles by using $.14 + (.70 - .14)F$ where F is the ratio of protons of $E > 30$ Mev as determined by integrating equation 3. This method of getting an equivalent total G_o for $E > 30$ Mev protons is probably good to 20 percent. The Pioneer III data used was taken from reference 3 and a value of $G_o = .62$ was used. The fluxes shown in Figure 1 are omnidirectional fluxes in $\frac{\text{protons}}{\text{cm}^2\text{-sec}}$ of $E > 30$ Mev for the period 1958. They may not be correct for 1962 or other times because of solar cycle changes. Part III of this report will deal with this problem.

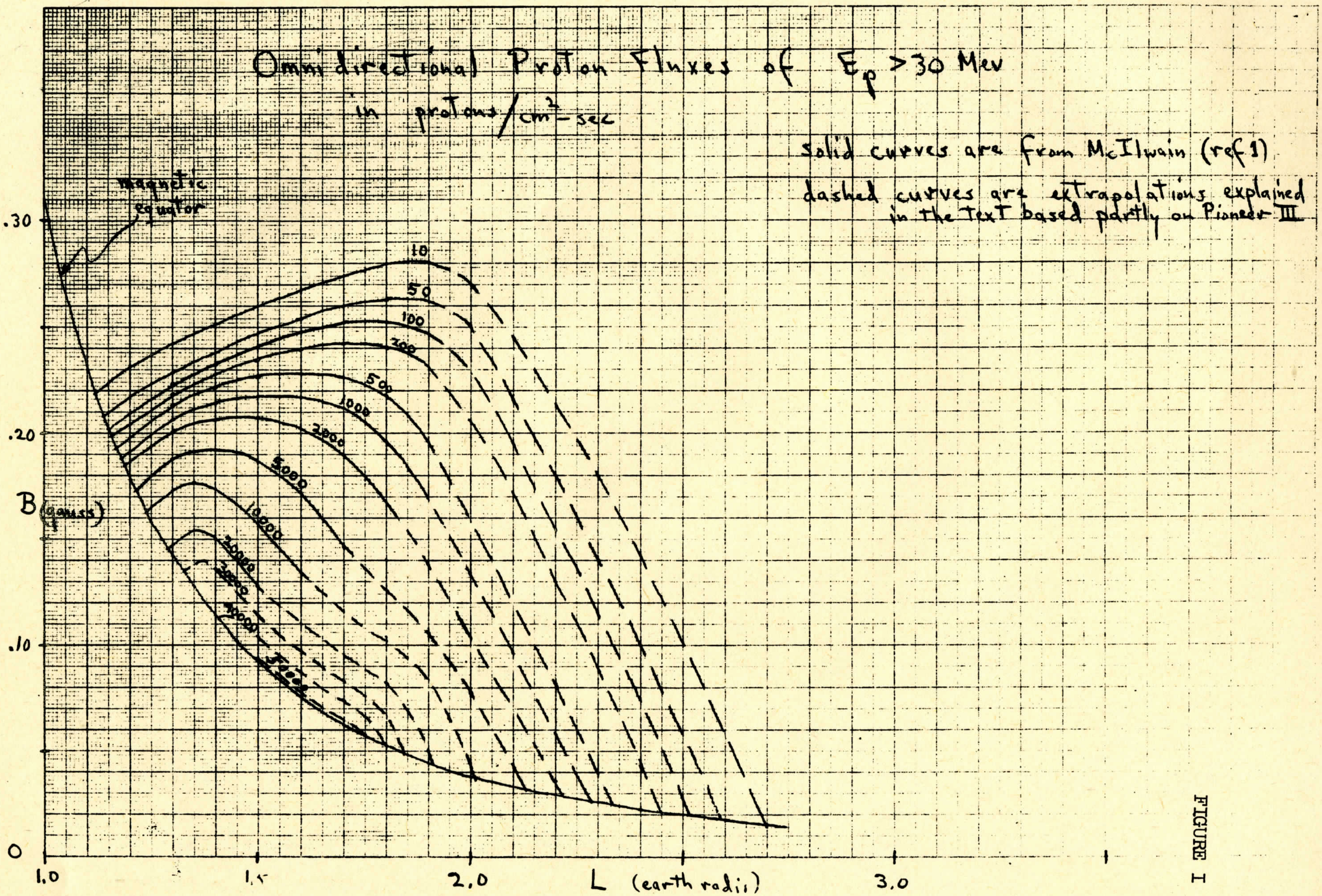
Omnidirectional Proton Fluxes of E_p > 30 Mev
in protons/cm^2-sec
solid curves are from McIlwain (ref 1)
dashed curves are extrapolations explained in the text based partly on Pioneer III
magnetic equator
.30
.20
.10
0
B (gauss)
1.0
1.5
2.0
L (earth radii)
3.0
10
50
100
200
500
1000
2000
5000
10000

FIGURE I