Biermann: In order to improve the statistics, it might be useful to take into account the distinction, (introduced first, I believe, by Denisse) between radio-active regions and others. Only in the former group (×1/5 of all) flares may be accompanied by acceleration processes which produce relativistic electrons or energetic protons.

Noyes: 21-cm scans from Sydney were examined for the period July 1957 — December 1958. These data showed the same general trend stated in the conclusions previously given: that many of the cosmic ray producing groups were characterized by high brightness temperatures at 21 cm, but not all high temperature groups produced cosmic rays. Since such data were not available to me after 1958, for consistency I used none of the data.

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II-3B-6. Intensity of Solar Proton Emissions

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The intensity of proton emissions associated with solar flares has been studied over the period of maximum activity for solar cycle 19. During this period, from 23 February 1956 to 3 September 1960, there were 43 events in which there was experimental evidence for solar proton emission. Using the published data for these events we have estimated the *time integrated free space proton flux* for several of the events. For those events observed only by riometers the integrated flux was determined by taking the proton intensity to depend quadratically on the riometer absorption and assuming that the time history for all events is similar.

A summary is given of the estimated integrated flux (size) for 36 of the events. This data is then used to determine the integral size-frequency distribution, giving the average rate of occurrence, during solar maximum, of events larger than any specified size. The relatively flat size spectrum and the corresponding intensity spectrum have a shape approximating an inverse power law. It is suggested that this observation may be interpreted as defining a general property that any theory must possess which attempts to explain the acceleration of energetic protons during flares. The size distribution may also be used for estimating the hazard for a manned space system.

Introduction

The discovery, during the IGY, of the relatively frequent low energy solar proton emissions following solar flares has been followed by many investigations to elucidate the basic phenomena of cosmic ray production by the sun. The intensity of these events is of fundamental interest for cosmic-ray and solar physicists and also now of considerable practical interest.

The purpose of this study has been to use the available experimental data on the flare associated proton production by the sun over the period of solar maximum (cycle 19) to deduce the total integrated proton flux (protons/cm^2) received near the earth. During the period chosen for study, from 23 February 1956 to 3 September 1960, there were 43 events in which there was evidence for solar flare proton emission either by direct observation with ionizing particle detectors or indirectly from riometer or ionosonde observations.

The analysis method discussed here provides a means of studying the partition of solar flare energy into energetic particles and may aid in the development of an understanding of the processes leading to acceleration of these particles.

Size Analysis

The empirical study discussed here, using the presently available data, is only a first step and is illustrative of the procedure to be adopted for analyzing data from future experiments. In order to estimate the total time integrated proton flux for the excess radiation associated with a flare it is necessary to know completely the spectral intensity versus time. Generally this has not been measured directly but has been inferred from a combination of sea level neutron monitor data, riometer data and balloon data; however, during an event beginning on 3 September 1960 Winckler and his collaborators[1] and a NASA group[2] measured directly with balloons and rockets the spectral time history of the protons over most of the event. By use of their published data, integral time history curves may be constructed as shown in Fig. 1 in which each curve gives the integral intensity of protons in space above a given energy and as a function of time. By integration under each curve and combining the results, an average differential spectrum is obtained for all the particles emitted during the event and the result is shown in Fig. 2. In this analysis the "size" of an event is defined as the total time integrated flux for protons of energy greater than 100 Mev.

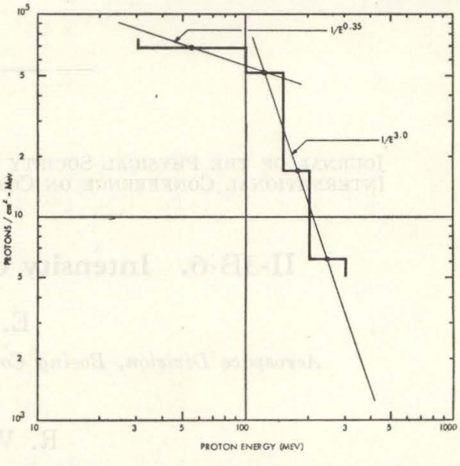

Fig. 2. The average differential energy spectrum is shown for the excess radiation received near the earth following the class 3 flare of 3 September 1960.

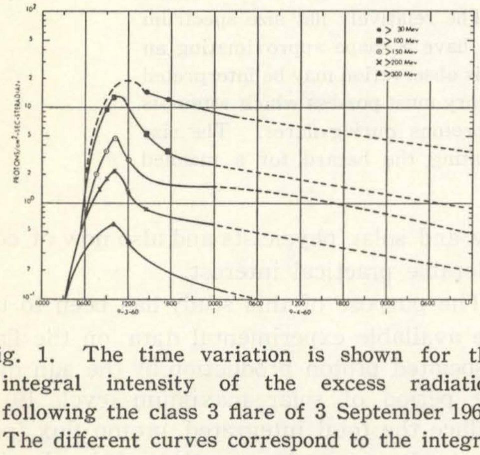

Fig. 1. The time variation is shown for the integral intensity of the excess radiation following the class 3 flare of 3 September 1960. The different curves correspond to the integral flux above different energy thresholds.

This same procedure cannot be used for other events because the data are less complete. In eight cases though we have made an estimate of the size of the proton event by combining the fragmentary particle intensity data with riometer records. A detailed analysis of the time history of several events has been made by Webber[3] and using his results we obtain agreement on event sizes to within a factor of three. Since his work represents a more complete collection of available observations we based our final results on his work whenever there were differences.

In 30 other cases we have used data obtained from riometers. From the observed maximum cosmic noise absorption and its time duration it is possible to make an estimate of the size of the event using the relation

$$S_i = S_o\left(\frac{A_i}{A_o}\right)^2 \times \frac{\tau_i}{\tau_o}(\text{Protons/cm}^2) \qquad (1)$$

where the symbols S, A and τ refer to the size, maximum riometer absorption (db), and the time duration of the event, respectively. The subscript (τ_i) refers to the event in question and (τ_o) to one of a known size as determined by reference to balloon data.

This relation can be justified as follows: the observed riometer effect (absorption of cosmic radio noise) can be shown to depend on the square root of the intensity of the protons bombarding the upper atmosphere of the earth. This follows from the theory of the absorption of high frequency radio waves as developed by Chapman and Little[4] and Bailey[5]. If it is assumed in addition that the proton events have the same differential energy spectrum and this remains constant throughout a given event then the proton intensity, I, at high latitude may be expressed as

$$I(t)=CA^2 f(t/\tau) \qquad (2)$$

at any time t, for protons above a given threshold. In this expression C is a proportionality constant, A the observed maximum cosmic noise absorption for a given riometer location and $f(t/\tau)$ a function which describes the time variation of intensity. We assume that the time history has the same functional shape for all events and is characterized by the event duration τ. It therefore follows that the size of the event is given by

$$S=\int I(t)dt=CA^2\tau\int f(t/\tau)d(t/\tau) \qquad (3)$$

If the integral is assumed to be the same for all events then expression (1) follows.

Results

Table I shows a summary of the sizes for the 36 events for which it was possible to make an estimate. It should be noted that the sizes given represent only the total flux of particles over 100 Mev. Spectral distributions are also available for the largest events, and from these one finds considerable differences in spectral shape; in particular the great event of 23 February 1956 was relatively poor in low energy (<100 Mev) protons. In most cases the data do not justify more than a single number to characterize an event, and the spectral shape below 100 Mev are much less certain than those above.

In Fig. 3 we give a histogram of the data of Table I, expressed as an average rate of occurrence of events of at least a given size (integral size-frequency distribution). There is definite evidence that flares do not occur at random because more than one solar proton event has been associated with the same solar active region. Also there is weak statistical evidence for a seasonal variation[6].

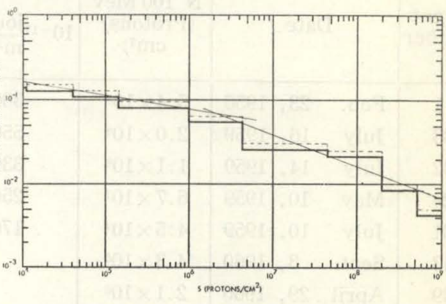

Fig. 3. The frequency is shown of solar proton emissions of size greater than indicated on the abcissa. The size is defined as the number of protons/cm² of energy greater than 100 Mev. This curve corresponds to the maximum of solar cycle 19. The dotted curve represents the data corrected for missing events.

As mentioned above, of the 43 events which occurred over the period chosen, only 36 were observed by techniques which gave data for making a size estimate and the simplest manner of treating the 7 missing events is to assume they are distributed in size in the same manner as the ones shown in Fig. 3. The dotted boxes correspond to the distribution after correction for this missing information.

Discussion

The integral distribution shown in Fig. 3 is strikingly flat in its fall off with increasing size. The two straight lines shown which fit the dotted histogram (on this logarithmic plot) over different size ranges may be expressed as

$$N(>S)=0.64/S^{0.15} \qquad 10^4<S<2\times10^6$$

$$N(>S)=16.1/S^{0.37} \qquad 2\times10^6<S<10^9$$

where $N\ (>S)$ is the number of events per week (at solar maximum) with a size greater than S (protons/cm²).

If one plots, instead of size on the abscissa, the estimated or observed maximum intensity for the event then the resulting intensity distribution has very nearly the same shape

Table I. The time integrated flux (protons/cm²) of protons with energy greater than 100 Mev are shown in columns 3 and 7 arranged in order of decreasing size. Columns 4 and 8 show the corresponding total energy flux for the Type IV radio burst measured in joules/ m^{2}-Hz.

Event Number	Date	N 100 Mev (Protons/ cm²)	R. F. Flux $10^{-17}\frac{\text{joules}}{m^2-Hz}$
1	Feb. 23, 1956	5.4×10^{8}	300
33	July 16, 1959	2.0×10^{8}	550
32	July 14, 1959	1.1×10^{8}	330
29	May 10, 1959	6.7×10^{7}	250
31	July 10, 1959	4.5×10^{7}	170
43	Sept. 3, 1960	4.3×10^{6}	
39	April 29, 1960	2.1×10^{6}	
20	March 23, 1958	1.9×10^{6}	75
41	May 6, 1960	1.6×10^{6}	
26	Aug. 22, 1958	1.4×10^{6}	160
12	Aug. 29, 1957	1.1×10^{6}	22
24	Aug. 16, 1958	1.1×10^{6}	80
27	Aug. 26, 1958	1.0×10^{6}	160
19	Feb. 9, 1958	5.0×10^{5}	26
14	Sept. 2, 1957	4.5×10^{5}	3
9	July 3, 1957	2.9×10^{5}	12
13	Aug. 31, 1957	2.0×10^{5}	180
16	Sept. 21, 1957	1.4×10^{5}	7.5
Event Number	Date	N 100 Mev (Protons/ cm²)	R. F. Flux $10^{-17}\frac{\text{joules}}{m^2-Hz}$
28	Sept. 22, 1958	1.4×10^{5}	2.8
42	May 13, 1960	8.8×10^{4}	
40	May 4, 1960	8.7×10^{4}	
18	Oct. 20, 1957	5.7×10^{4}	
21	April 10, 1958	4.7×10^{4}	
36	April 1, 1960	4.3×10^{4}	
35	March 30, 1960	3.9×10^{4}	
11	Aug. 9, 1957	2.6×10^{4}	
17	Sept. 26, 1957	2.0×10^{4}	
25	Aug. 21, 1958	1.9×10^{4}	
37	April 5, 1960	1.8×10^{4}	
38	April 28, 1960	1.1×10^{4}	
10	July 24, 1957	7.7×10^{3}	90
30	June 13, 1959	7.6×10^{3}	
34	Aug. 18, 1959	4.3×10^{3}	
7	May 19, 1957	1.1×10^{3}	
15	Sept. 12, 1957	5.3×10^{2}	30
23	July 29, 1958	3.4×10^{2}	26

as the size distribution. This observation is of interest because it shows that the frequency of events does not increase rapidly as one lowers the detection threshold. This may explain why recent efforts[7] to detect a sea level intensity increase from the frequent small flares (small flare effect) was unsuccessful however in a specific event the spectral shape may also be as important. The development of observational methods which *greatly* reduced the threshold intensity for observing the solar flare effect are represented by the development of the riometer and the high altitude balloon technique.

Since it is now well established that there is a high degree of correlation between Type IV radio bursts and solar proton emissions, it is of interest to compare the total r.f. energy emitted with the number of protons released. Pick[8] has studied the relation of Type IV radio emissions to other solar and geophysical phenomena and gives the total r.f. energy emitted during the time of the burst per cycle/sec at 10 cm wavelength. These "radiosizes" are also tabulated in Table I and it is readily seen that there is little (if any) correspondence between radio size and proton size. Webber's study[3] reaches a similar conclusion when *peak* r.f. intensity is compared with *peak* proton flux. It would be preferable if the data were available to integrate the r.f. flux over the total frequency band emitted rather than use the total energy emitted at just one frequency.

Proton emissions are generally all associated with flares of optical class 2 and larger and therefore the events studied here represent an assembly of flares whose total energy releases are thought to lie within one or two orders of magnitude (10^{31}–10^{33} ergs) and which give rise to particle emissions of enormous variability (over about 6 orders of magnitude). The resulting broad and flat frequency distribution shown in Fig. 3, which approximates an inverse power law, is a striking fact which any theory of flare emissions must cope with. The distribution of intensities (also similar to Fig. 3) is related, at least in a general way, with the total energy of the proton emission. If this distribution is representative of a statistical process then a power law distribution follows directly. This argument envisions an exponential growth in total energy of all particles. Such a growth law terminated at a random time, leads to a simple power law.

If the size of the flare is related to the free space radiation dose[9], and if one neglects the non-random occurrence of flares, then the size frequency distribution represents the frequency of encounters which would give an unshielded man in space a radiation dosage larger than a given value. This is shown in Fig. 4.

In the region of interest, the ordinate can be thought of as the probability to receive

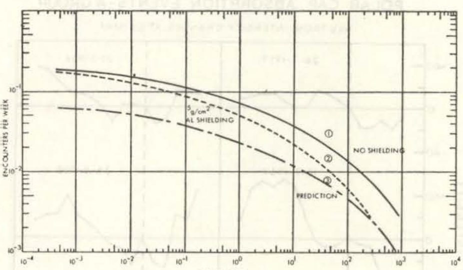

Fig. 4. The ordinate gives the frequency of encounters which will give a radiation dosage larger than a given value. The curve labeled (1) corresponds to that expected for an unshielded astronaut, (2) the case with a 5 gm/cm² shield and (3) to the modification expected using a solar flare prediction technique.

more than a specified dose during a one week mission. On this logarithmic plot the effect of shielding is to shift the entire curve left, as shown. If flares can be avoided to some extent by use of a prediction technique, this would shift the curve downward. For a one-week exposure a reduction in encounter probability by a factor of three seems practical, according to a recent study[6]. This is shown as curve 3) in the figure.

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Discussion

Ney, E. P.: A statement was made implying that the total number of particles in the flare was related to the neutron monitor response. However the slope of the energy spectrum seems to be at least as important as the total number of particles.

Chupp, E. L.: I agree that a flatter spectrum in a given event may determine whether the small flare effect can be seen in a neutron monitor provided the intensity is sufficiently high.