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ON THE ACCELERATION OF HIGH-ENERGY PARTICLES IN SOLAR FLARES

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On the Acceleration of High-Energy Particles in Solar Flares

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Abstract

This paper discusses the relationship between some characteristics of microwave type IV radio bursts and solar cosmic ray protons of Mev energy. It is shown that the peak flux intensity of those bursts is almost linearly correlated with the Mev proton peak flux observed by satellites near the earth and that protons and electrons would be accelerated simultaneously by a similar mechanism during the explosive phase of solar flares.

Brief discussion is given on the propagation of solar comsic rays in the solar envelope after ejection from the flare regions.

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1. Introduction

It is well known that solar cosmic rays are generally produced from solar flares which accompany the intense emission of type IV radio bursts of wide frequency band. In fact, the acceleration of protons and heavier nuclei which constitute solar cosmic rays is closely connected with that of high-energy electrons responsible for the microwave component of Type IV radio bursts (e.g., Kundu and Haddock, 1960; Sakurai and Maeda, 1961). Intense emission of microwave type IV radio bursts is usually observed in association with solar proton flares (e.g., Castelli, Aaron and Michael, 1967, 1968).

In this paper, we shall, therefore, consider some problems related to the acceleration of solar cosmic rays by using observational data on solar cosmic rays and type IV radio bursts.

2. Relation of Solar Protons to Type IV Radio Bursts

During May, 1967 to December, 1969, thirty six solar cosmic ray events were observed by the Explorer 33 and 35 satellites. They have been published in the Solar Geophysical Data. By using solar flare data published in this Journal and the Quarterly Bulletin of Solar Activity, the position and importance of associated flares have been identified. In this paper, we shall use the data of both > 10 Mev and > 30 Mev solar protons.

In order to examine the relationship between the peak flux values of solar cosmic ray protons and the peak flux intensities of the microwave component of type IV radio bursts, we have picked up the data on the peak flux intensity for ~ 3,000 MHz (2,800 - 3,000 MHz) emissions associated with proton flares. For the first time, we aimed to use the observational data for ~9,000 - 10,000 MHz emissions, but enough data were not available for our investigation.*

As is well known, the propagation of solar cosmic rays is highly controlled by the magnetic fields ambient in the interplanetary space. Thus we need consider the variation of the peak-flux of solar protons with respect to the position of associated flares on the solar disk. We have plotted the peak flux values of > 10 Mev solar protons as a function of the angular distance from the central meridian of the sun and obtained the result as shown in Fig. 1. This figure shows that the peak flux of > 10 Mev solar protons decreases with going eastward on the eastern hemisphere. On the other hand, these fluxes are distributed at random on the western hemisphere. Similar tendency is also seen for > 30 Mev solar protons. In the later discussion, we shall thus use only the data of solar protons produced from the flares which occurred on the western hemisphere because the data of solar protons from the flares on the eastern hemisphere include the propagation effect of solar protons.

*The peak flux for these frequencies is known to be more useful to study proton flares (Castelli et al., 1967).

It is known that the peak flux intensity of the microwave component of type IV radio bursts does not show well-defined center-to-limib variation (Takakura, 1963; Sakurai, 1964, 1971a). If we use the data on solar protons and radio emissions associated with the flares which occurred on the western hemisphere, we are, therefore, able to examine the relationship between the peak flux solar protons observed at the earth's orbit and the peak flux intensity of the microwave component of type IV radio bursts. The result thus obtained is shown in Fig. 2. This indicates that the peak flux of > 10 Mev solar protons increase almost in proportion with the peak flux intensity of ~ 3,000 MHz emissions. This result seems to give us some physical insight for the study of solar cosmic ray phenomena since it indicates that the emission process of these microwave emissions is closely related to the acceleration of solar protons.

3. Characteristics of Solar Proton Fluxes

Solar proton fluxes were measured by the Explorer 33 and 35 satellites with respect to three different energy ranges (> 10, > 30 and > 60 Mev). In this paper, we have used the first two energy ranges to study the characteristics of solar proton fluxes.

At first, we have examined the relation between two peak fluxes of > 10 Mev and > 30 Mev solar protons. As shown in Fig. 3, the result indicates that the peak flux of > 30 Mev solar protons tends to increase proportionately with that of > 10 Mev solar protons.

It is remarked that this relation reflects the situation for the production of solar protons in flares. For the observed peak flux of solar protons at the earth's orbit is always proportional to the original proton flux ejected from flares (e.g., Webber, 1964; Burlaga, 1970; Feit, 1969, 1971). In fact, this nature is preserved independent of the propagation mechanism of solar protons in the interplanetary space. By taking this result into consideration, we obtain a view that the production rate of > 30 Mev protons is well proportional to that of > 10 Mev protons in solar flares. This is schematically expressed in Fig. 4. Namely, the ratio of the production rate of > 30 Mev protons to that of > 10 Mev protons is independent and constant for every solar flare.

Since the peak flux intensity of the microwave component of type IV bursts is also proportional to the peak flux of > 10 Mev solar protons, the production rate of high energy electrons responsible for this emission also changes by the same order of magnitude as that of > 30 Mev solar protons. This situation is also schematically shown in Fig. 4. The result as shown in this figure suggests that the spectral shapes of both solar protons and high energy electrons remain constant, being independent of the production rate and the properties of solar flares.

In order to find the dependence of the ratio between two peak fluxes for > 10 Mev and > 30 Mev solar protons on the position of associated flares, we have calculated these ratios as a function of the positions of these flares and obtained the result as shown in Fig. 5. This shows that these ratios are independent of the position of associated flares. Furthermore, this means that the result as shown in Fig. 3 is not dependent on the position of solar flares. Hence we would say that the propagation process of solar particles near the sun and in the interplanetary space does not alter the properties which solar protons are given while being accelerated.

4. Acceleration of High-Energy Particles in Solar Flares

As shown in Fig. 2, the peak flux intensity of the microwave component of type IV radio bursts increases with the peak flux of > 10 Mev solar protons. If we refer to the result of Fig. 3, a similar relation is also seen for > 30 Mev solar protons.

At present, it is believed that the microwave component of type IV radio burst is emitted from electrons of 100 Kev - 10 Mev energy by gyro-synchrotron mechanism due to interaction with sunspot magnetic fields in or near the flare regions. This component begins to be emitted during the explosive phase of flares and reaches the peak in intensity just after this phase (e.g., Svestka, 1970; Sakurai, 1971 b). It thus seems reasonable to conclude that such high energy electrons are accelerated in the explosive phase. It is thought of that the main part of solar cosmic ray protons and heavier nuclei are accelerated during the explosive phase of flares (e.g., Ellison, McKenna and Reid, 1961; Svestka, 1970). Thus we can say that both protons and electrons are simultaneously accelerated during the explosive phase of flares.

The result of Fig. 2 suggests that the total number of accelerated solar protons is proportional to that of high energy electrons responsible for the emission of the microwave component of type IV radio bursts, although we cannot comment quantitatively about it. Furthermore, these results as obtained in this paper further suggest that the acceleration mechanisms of protons and electrons in solar flares are the same or very similar to each other. If this is not the case, it seems difficult to obtain a linear correlation between the peak flux of solar protons and the peak flux intensity of microwave type IV emissions.

It has been theoretically inferred that the Fermi acceleration well explains the observed properties of solar cosmic rays such as rigidity spectra and nuclear abundances (e.g., Hayakawa et al., 1964; Wentzel, 1965; Sakurai, 1965 a, b, 1971c). Thus the acceleration of electrons would be associated with that of protons and heavier nuclei (Sakurai, 1971d).

5. Behavior of Solar Protons in the Solar Envelope

As is evident from Fig. 5, the ratios between the peak flux of both > 10 Mev and > 30 Mev solar protons do not show systematic variation with respect to the position of associated flares. This fact suggests that the diffusion mechanism of solar protons in the envelope of the sun is independent of the energy of solar protons. Since the peak flux of solar protons tends to decrease with going eastward on the eastern hemisphere (Fig. 1), this also suggests that the diffusion coefficient in the east-west direction near the sun is small compared with that in the radial direction. However, this coefficient must be independent of the energy of solar protons.

6. Summary

We have shown in this paper that the peak flux of solar protons increases with the peak flux intensity of the microwave component of type IV radio bursts and that the spectral shape of solar protons does not seem to change greatly from one event to another. Based on these results, we have considered the acceleration of solar protons and electrons which are responsible for the emission of type IV radio bursts. Solar protons are accelerated simultaneously with these electrons during the explosive phase, and the acceleration mechanisms of those protons and electrons are almost the same or very similar to each other.

It seems that the propagation mechanism of solar cosmic rays of Mev energy as discussed in this paper is independent of the kinetic energy of particles in the envelope of the sun.

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Caption of Figures

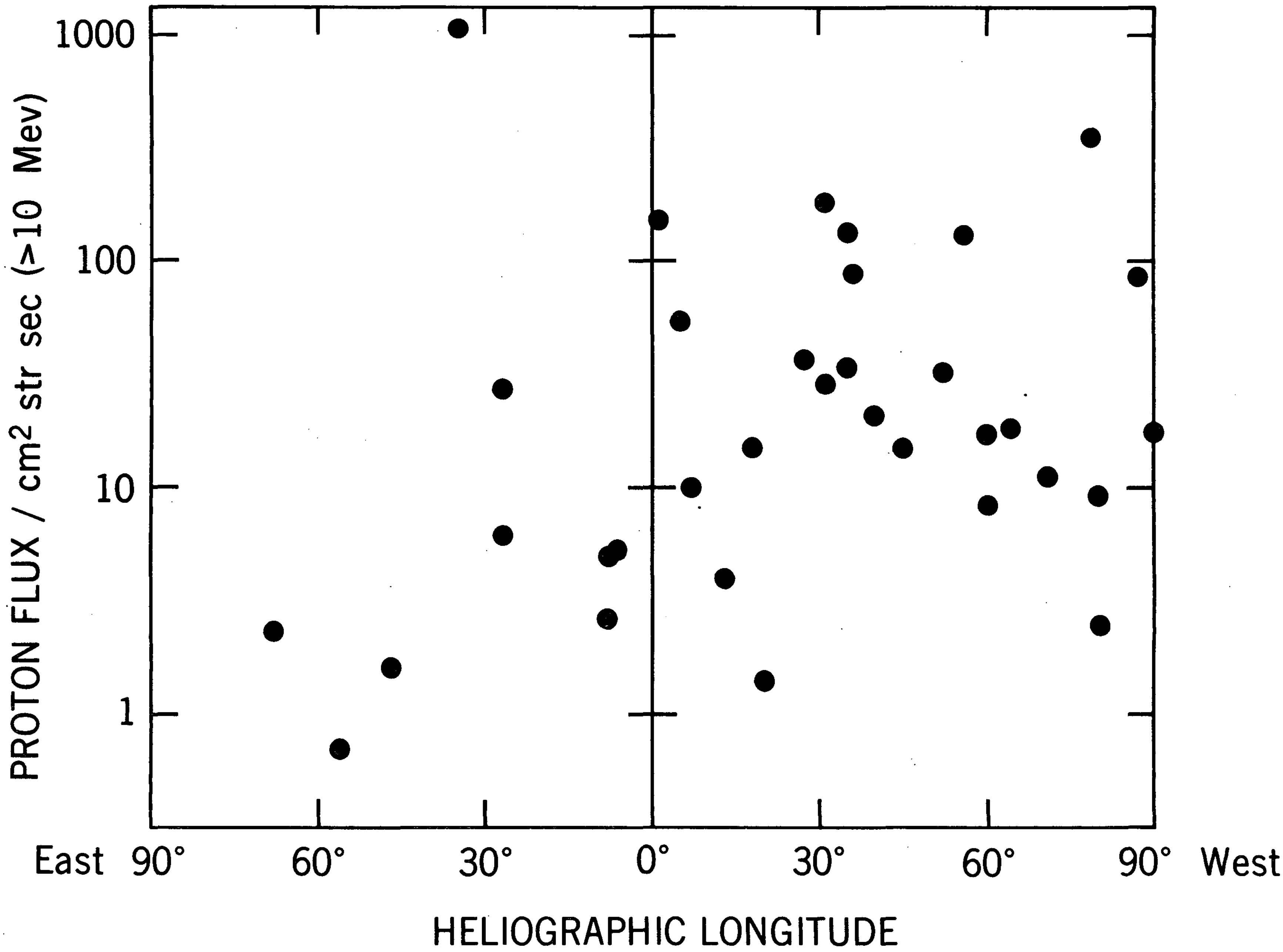
Fig. 1 Dependence of the peak flux of > 10 Mev solar protons on the angular distance of associated flares from the central meridian of the sun.

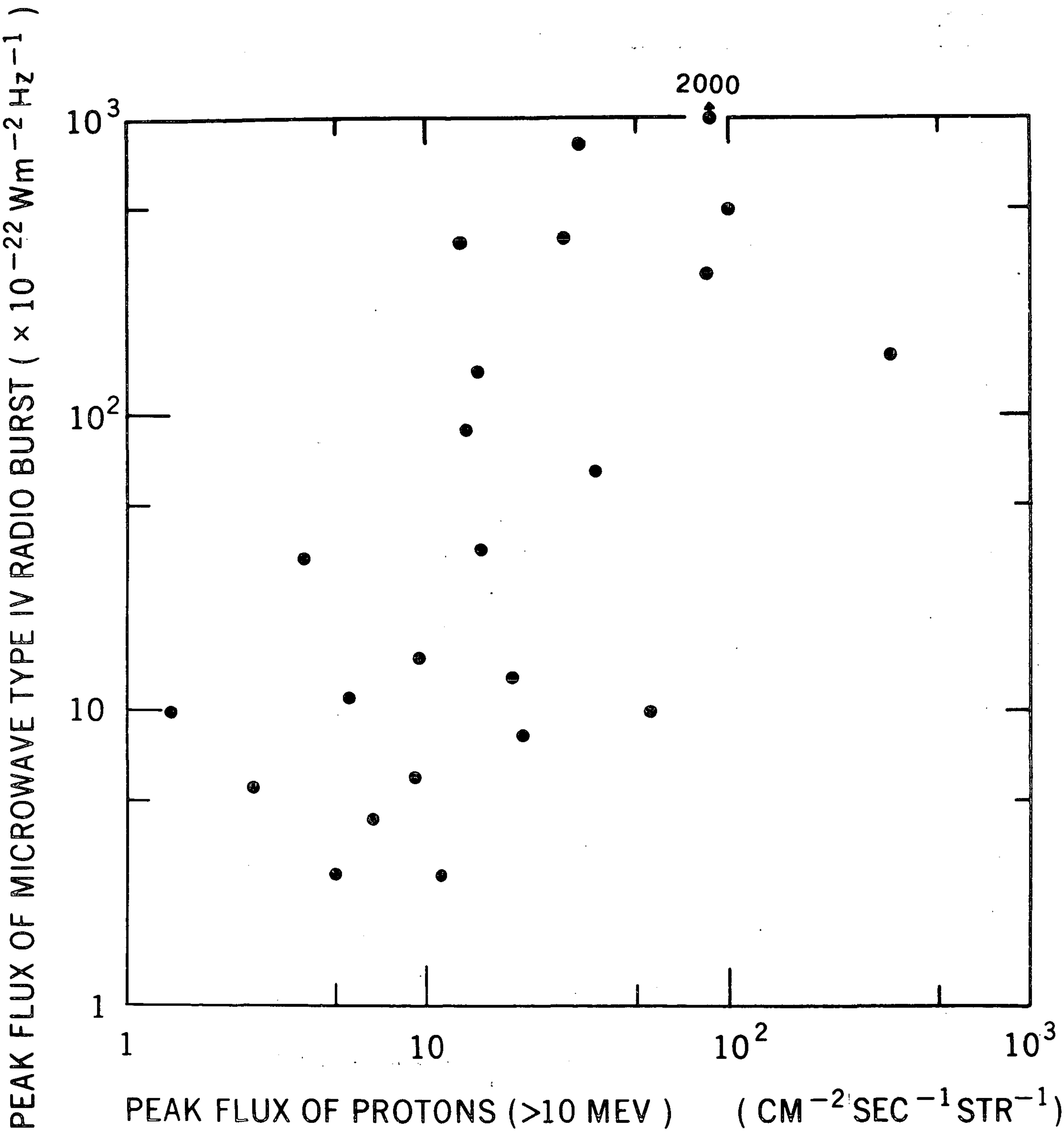
Fig. 2 Relation between the peak flux of > 10 Mev solar protons and the peak flux intensity of the microwave emission of type IV radio bursts.

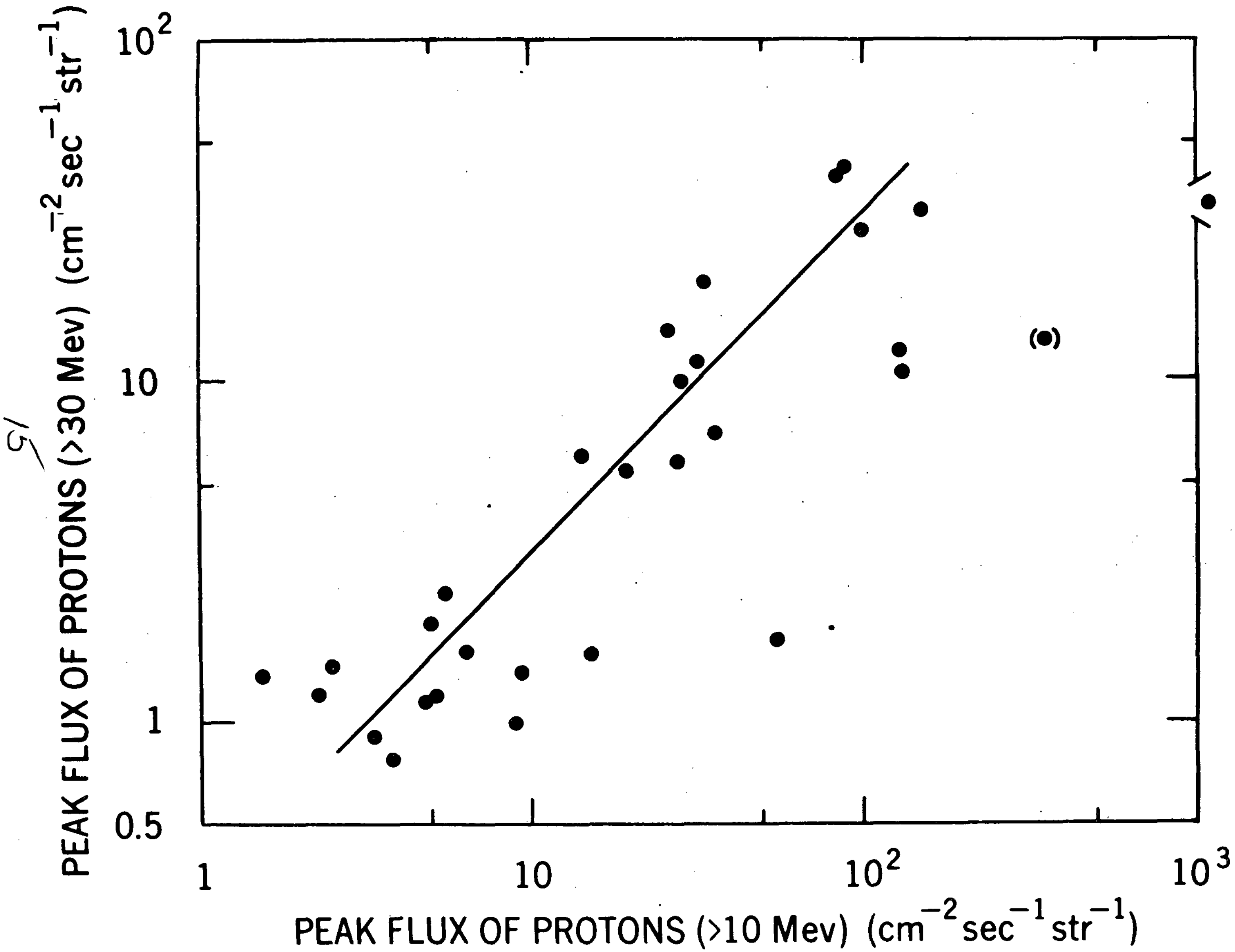
Fig. 3 Relation between the > 10 Mev solar proton flux and the > 30 Mev solar proton flux.

Fig. 4 Schematical illustration of the proton and electron flux variations as a function of particle energy.

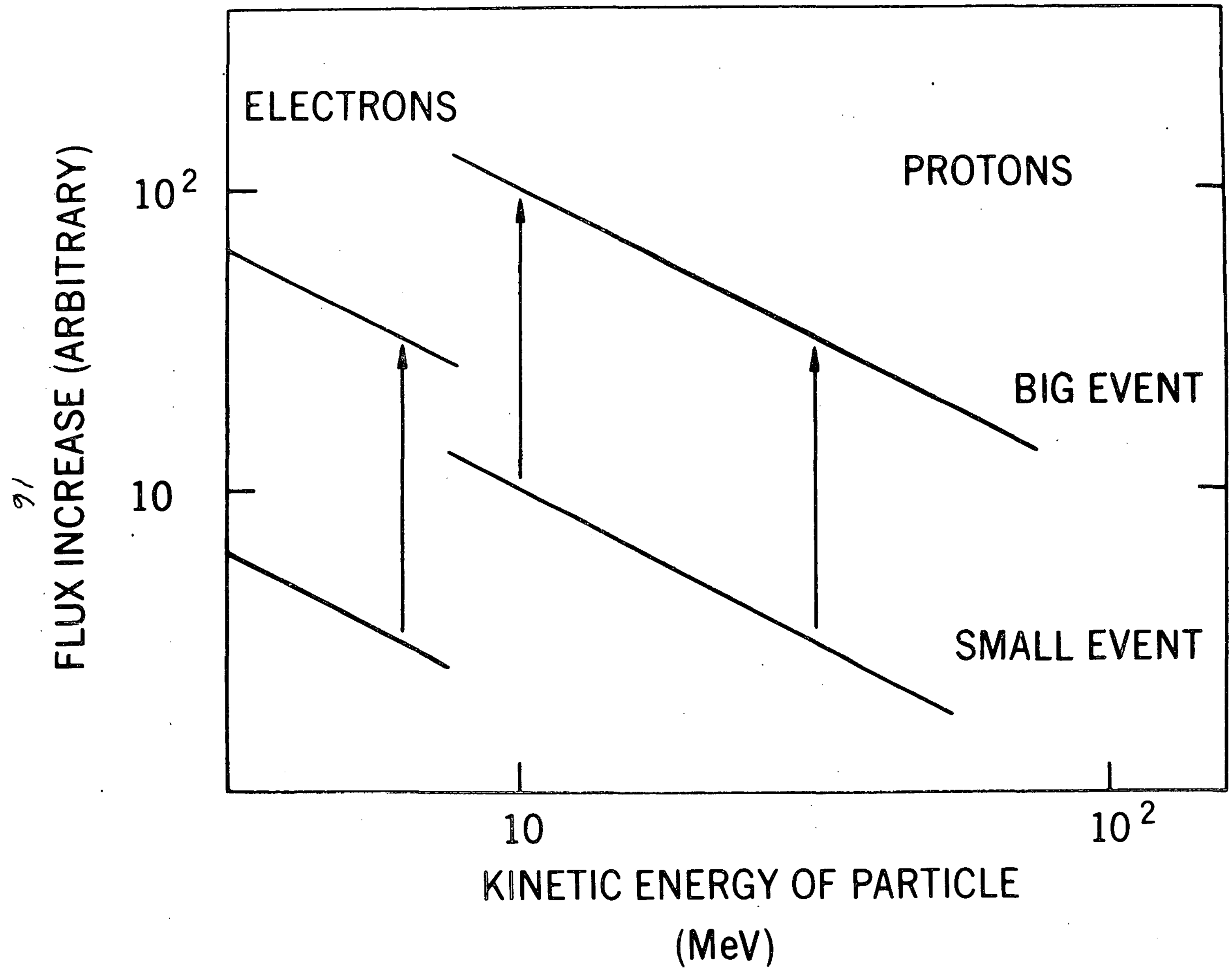
Fig. 5 Distribution of the ratio of the > 30 Mev proton flux to the > 10 Mev proton flux as a function of the angular distance from the central meridian of the sun.

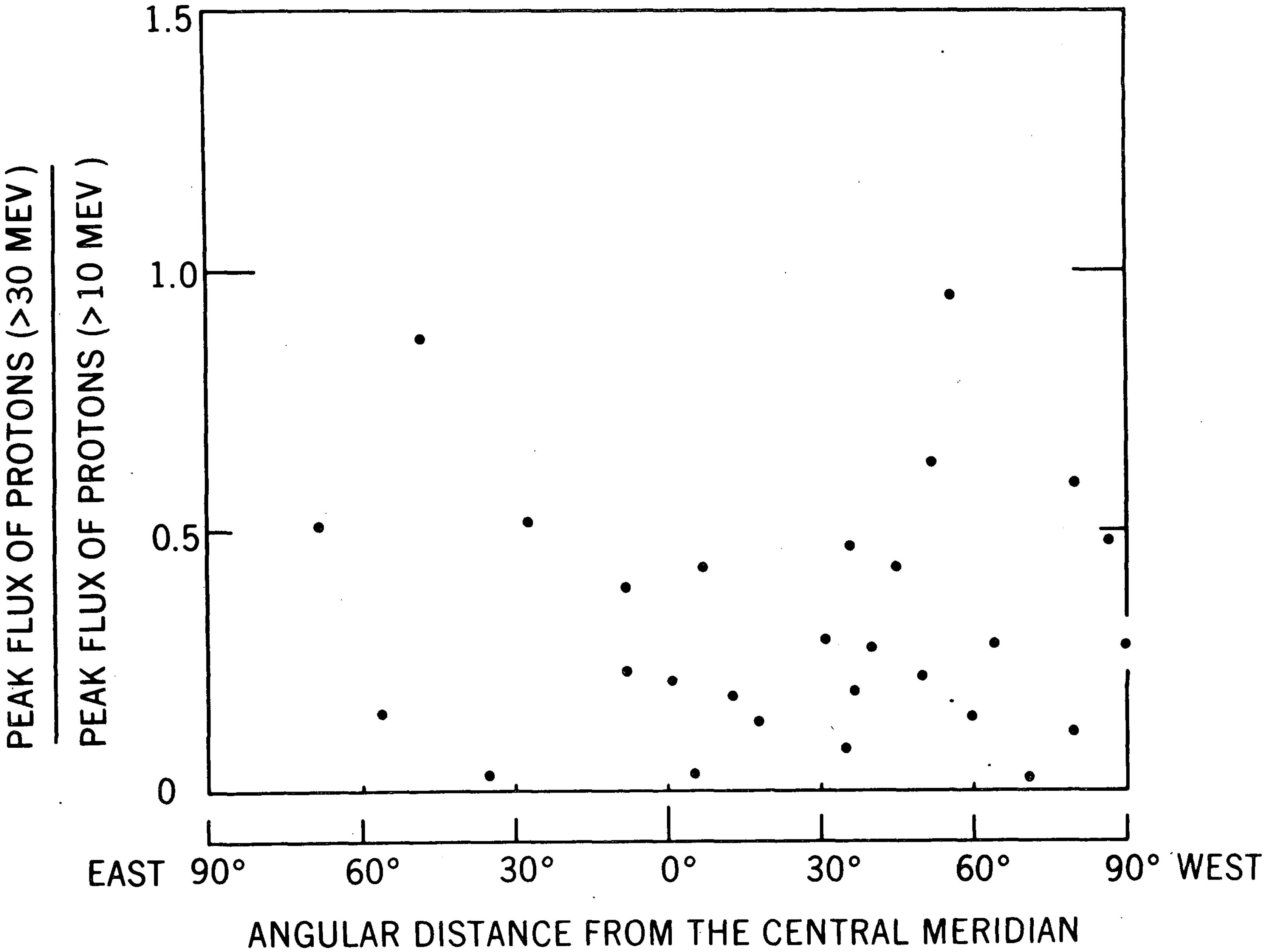

1000
100
10
1
PROTON FLUX / cm² str sec (>10 Mev)
East 90°
60°
30°
0°
30°
60°
90° West
HELIOGRAPHIC LONGITUDE


PEAK FLUX OF MICROWAVE TYPE IV RADIO BURST (× 10 −22 Wm −2 Hz −1)
2000
10^3
10^2
10
1
1
10
10^2
10^3
PEAK FLUX OF PROTONS (>10 MEV) (CM −2 SEC −1 STR −1)



15
PEAK FLUX OF PROTONS (>30 Mev) (cm⁻² sec⁻¹ str⁻¹)
10²
10
1
0.5
1
10
10²
10³
PEAK FLUX OF PROTONS (>10 Mev) (cm⁻² sec⁻¹ str⁻¹)


ELECTRONS
PROTONS
BIG EVENT
SMALL EVENT
FLUX INCREASE (ARBITRARY)
10²
10
10
10²
KINETIC ENERGY OF PARTICLE
(MeV)


1.5
1.0
0.5
0
PEAK FLUX OF PROTONS (>30 MEV)
PEAK FLUX OF PROTONS (>10 MEV)
EAST 90°
60°
30°
0°
30°
60°
90° WEST
ANGULAR DISTANCE FROM THE CENTRAL MERIDIAN

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