ON THE THEORETICALLY PREDICTED FLUX PROFILES OVER POLAR CAPS AND THEIR COMPARISON WITH OBSERVATIONS

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RESUMEN

Se propone un método para construir perfiles latitudinales teóricos del flujo de protones solares sobre los casquetes polares. El método se basa en funciones de transferencia del medio interplanetario a los detectores a bordo de satélites polares y en la información obtenida de la simulación de trayectorias en modelos magnetosféricos de protones de 2 a 500 MeV. En el método se ha tomado en cuenta la dependencia del perfil latitudinal con el tiempo local de observación, con la época del año y con los cambios en la topología magnetosférica debida a perturbaciones. Asimismo, se ha considerado todo el espectro de energías que registra el detector en vez de la energía media. La comparación de perfiles teóricos con los observados permite un análisis más riguroso que el basado en métodos previamente usados y permite una identificación más detallada de las regiones de penetración, así como la interpretación de la estructura fina de los perfiles observados. Los perfiles teóricos construidos para canales de energías más altas, para la fase anisotrópica de los eventos solares de febrero 25, 1968 y de noviembre 18 de 1969, concuerda satisfactoriamente con las observaciones y con nuestro modelo de iluminación desigual. Este acuerdo conduce a postular un mecanismo que opera en la región fronteriza de la cola magnetosférica que hace girar las partículas incidentes hacia la Tierra. La comparación entre los perfiles teóricos y los observados, para bajas energías, muestra la influencia de fuertes mecanismos de modulación. El método, aplicado a un gran número de observaciones seleccionadas y realizadas en diferentes canales de energía, permite mejorar la sensibilidad de la técnica que emplea los protones solares como trazadores de la topología de la cavidad geomagnética y su región fronteriza.

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ABSTRACT

A method for constructing theoretical latitudinal profiles of solar proton fluxes over polar caps is proposed. It is based on transfer functions between the interplanetarv medium and the detector in polar orbiting satellite and on information obtained from simulation of 2 to 500 MeV proton orbits in magnetospheric models. The method takes into account the dependence of flux profiles on local time of observation, on seasonal or storm changes in tail topology and on the whole spectrum of energies registered by detector's channel. Comparison with observations allow a more rigorous analysis than the one achieved by methods used in the past, permits a more detailed identification of regions of entry and an interpretation of some fine features of the observed flux structures. Theoretical profiles for higher energy channels constructed for th anisotropic phase of February 25, 1968 and November 18, 1969 events agree satisfactorily with the observations and with our model of uneven illumination and leads to postulate a turning mechanism that operates in the tail boundary region. For lower energies the comparison between predicted and observed structures indicates the influence of strong modulating mechanisms. The method when applied to a large number of selected observations in different energy channels allows an improved sensitivity of the technique of tracing the topology of the geomagnetic cavity and of its boundary region by means of solar protons.

INTRODUCTION

Since 1965, the uneven illumination of polar caps by solar protons has been used for tracing the topology of distant regions of the earth magnetic domain. The tracing technique depends on the comparison of the observed latitudinal flux profiles with the ones theoretically derived. However an important handicap in using this technique is its low sensitivity (see Paulikas, 1974). It is the purpose of this article to describe a more rigorous method of constructing theoretical profiles than the ones used in the past. The new method, as will be shown, leads to more a precise and detailed identification of regions of entry of the illuminating flux and to an improvement of the resolution of the tracing technique.

The method is based on transfer functions between the interplanetary medium and the detector on board polar orbiting satellites. In principle the choice of adequate transfer functions should be guided by: a) the characteristics of the flux and of the field in the interplanetary medium; b) changes in the flux induced during its passage across the boundary region between the interplanetary medium and the geomagnetic cavity, that is across the magnetosheath and the magnetopause; c) de regions and modes of entry into the cavity and d) the modes of propagation of protons across the tail, the outer and inner magnetosphere.

The difficult task of defining the transfer functions is simplified for the case of particles propagating by the direct mode across the tail and the magnetosphere. In this case the information about the propagation, the regions of entry and the directions of approach, is obtained from simulation of trajectories by numerical integration of differential equation of motion in a magnetospheric model (see for example Gall et al, 1972).

In order to improve the sensitivity of the tracing technique *all* of the information obtained by trajectory simulation should be contained in the construction of the theoretical flux profiles. Indeed the computed points of entry and the directions of approach exhibit a strong dependence on particle energy and a remarkable dependence on local time and on the seasonal variation of the tail topology (Gall and Bravo, 1974). On the other hand, the observations are usually made in wide energy channels of detectors on board polar orbiting satellites, that sweep, during one pass, many local time meridians. Hence in the method proposed here the theoretical flux profiles are constructed by integrating the monoenergetic fluxes over the energy interval of the detectors channel, taking into account the changing local times of observations and the season during which the proton event takes place.

Methods used in the past for comparison of theory with observation (Morfill and Quenby, 1971; Durney et al, 1972, Morfill and Scholer, 1973) do not take into account all of the variables mentioned. In the present work 3000 orbits for protons of energies ranging from 2 to 500 MeV were computed using Mead and Fairfield model (1972). This magnetospheric model is deduced from magnetic field measurements and consenquently includes all of the external field sources and contains the transversal field component (B_Z) in the plasma sheet. Moreover the model represents the field for both quiet and perturbed times and for all seasons of the year. The orbits computed with the help of this model represent an improvement over the ones obtain with the Williams and Mead model (Morfill and Quenby, 1971; Gall et al, 1972).

In the first part of this article the method for constructing theoretical flux profiles is described in detail; in the second, the method is applied to selected observations made during the anisotropic phase of two solar proton events; the third part contains a discussion on the method proposed and conclusions.

METHOD FOR CONSTRUCTING THEORETICAL LATITUDINAL FLUX PROFILES

Consider a detector that registers at time t protons in a channel of energies bounded between ϵ_{min} and ϵ_{max} along the satellite pass given in invariant latitude (λ) and the magnetic local time (τ) coordinates. Let P (λ' τ) be a point along the pass. If D(ϵ, t) is the energy spectrum of the interplanetary flux, the intensity detected in any direction by the channel is given by:

$$I\ (\lambda,\ \tau,\ t) = \int_{\epsilon_{min}}^{\epsilon_{max}} D\ (\epsilon,\ t)\ F\ (\epsilon,\ \lambda,\ \tau,\ t)\ d\epsilon \qquad (1)$$

here F are transfer functions between the interplanetary medium and the detector. Obviously F = 0 for all latitudes lying below the cutoff latitude of ϵ. Strictly speaking F is also a function of arrival direction, but the focussing effect of the geomagnetic field makes this dependence so weak that it can be neglected for all energies, except those near the cutoff. The expression (1) is of general nature and is valid for both the diffusive and the direct mode of propagation of protons across the geomagnetic cavity and its boundaries and for any effect modulating the flux and the spectrum. The dependence on time, t accounts for temporal changes of interplanetary flux and of the magnetospheric configuration.

In this paper we shall limit ourselves exclusively to the effect of interplanetary anisotropy and to solar protons that propagate by direct mode across the cavity. Moreover, of the temporal variations we shall only consider the seasonal variation of the cavity topology and the perturbed geomagnetic field configuration ($Kp > 2$). In this case, the uneven illumination is due to the anisotropy of the incoming flux, modulated however by the topology of the tail and the boundary region between the geomagnetic cavity and the interplanetary medium.

To define the transfer functions we assume an anisotropic interplanetary flux along the Parker spiral with a square distribution of pitch angles, the interplanetary field may also contain a northern or southern component. For this case the spectrum D in expression (1) is replaced by $D(\epsilon, \alpha)$ equal to $i_{max}(\epsilon)$ for $\alpha < \alpha_o$. The transfer functions postulated and used in the analysis of some observed profiles, are listed in Table 1. For entry across the near magnetopause ($R < R_o$) the exact points of entry and directions of approach are given by orbit computation. For this case we assume the intensity transmitted to the interior of the cavity to be I_{max} for flux impinging with $\alpha < \alpha_o$ and I_{min} for flux impinging with $\alpha > \alpha_o$. R_o is the maximum distance, within which the magnetospheric model used in the computations represents satisfactorily the field configuration; $R_o = 17\ R_E$ for the Mead and Fairfield model used. If any shielding takes place during the passage across the front boundary region, that is across magnetosheath and magnetopause, the transfer function is multiplied by a shielding factor $K(\epsilon, \alpha)$. For particles entering at more distant ($R \geqslant R_o$) regions of the tail only approximate directions of approach are known and the intensity of the flux transmitted is assumed to be I_{max} for approach directions at the magnetopause from dawn and I_{min} for directions from dusk. Again, if any shielding occurs by the tail transition region the transfer functions includes a shielding factor $k(\epsilon, \alpha)$. Due to differences in the characteristics of the front and tail transition regions, two different shielding factors are postulated.

Transfer Functions and Monoenergetic Flux Profiles

In order to assign to $F(\epsilon, \lambda, \tau)$ a value from Table 1, we compute the orbit along which the flux protons of energy reach the point of detection at given local time. The computation is made in the conventional way starting from the detector (as described for example Gall and Bravo, 1970). In the case when the orbit extends into the tail ($R > R_o$), the integration is continued further with the help of a simple field tail model, (Gall and Bravo, 1973) and the approximate directions and regions of entry are thus determined.

There exist no analytical expressions for F as functions of particle energy ϵ and coordinates λ and τ of the point of detection. These transfer functions can however be conveniently described by a large set of monoenergetic latitudinal flux profiles along different local time meridians. A number of profiles computed with Mead and Fairfield model are plotted in figures 1, 6 and 7. The profiles are constructed for the case when the boundary region excerts no shielding effect on the incident flux.

As the topology of the outer magnetosphere of the tail and plasma sheet changes with the tilt between the geomagnetic axis and the direction of the solar wind, the regions of entry for the interplanetary flux illuminating any of the polar cap latitudes will change with season and with geomagnetic perturbation. Using Mead and Fairfield model, for quiet times and different tilt angles as well as for $K_p > 2$ we have computed a large number of orbits along which protons reach polar caps at different magnetospheric conditions. Some monoenergetic flux profiles for summer, winter, equinoxes and $K_p > 2$ are plotted in figure 1. For the construction of these profiles the transfer functions F were again taken from Table 1, as their values depend exclusively on the region and direction of entry.

Due to limitations of magnetospheric models used, the computed cutoffs do not coincide with the observed ones. Discrepancies between computed cutoffs (Smart et al, 1969), and the ones observed in satellites (Stone, 1964; Imhof et al, 1971; Luhmann and Carl, 1973) and balloons (see for example Israel and Vogt, 1969) have been reported.Consequently when comparing the computed with the observed flux profiles it is necessary to apply a latitudinal correction. In the present study we have introduced a simple linear correction $\Delta(\epsilon)$ and compared the flux observed at the invariant latitude of the point of detection (λ_{obs}) with the flux computed using equation (1) for $\lambda = \lambda_{obs} + \Delta(\epsilon)$; here $\Delta(\epsilon)$ is the difference in degrees between the computed and the observed latitudinal cutoff for protons of energy ϵ.

Sumarizing, the instructions for the application of the method are the following:

1. Plot the orbit of the satellite in invariant latitude vs magnetic local time coordinates.
2. Select the proper season and geomagnetic conditions to be considered.
3. Using the appropriate magnetospheric model compute the trajectories for a large number of selected proton energies of the detector channel and obtain the regions and directions of approach at the entry.
4. Select the transfer functions from Table 1.
5. Construct the flux profiles with the help of equation (1) using the measured (or assumed) ratio of anisotropy and the energy spectrum and taking into account the latitudinal cutoff correction.

COMPARISON OF THEORETICAL FLUX PROFILES WITH OBSERVATIONS DURING FEBRUARY 1969 AND NOVEMBER, 1968 EVENTS

We shall now apply the method previously described to construct some theoretical flux profiles and compare them with observations. The latitudinal profiles selected for comparison and analysis were observed by ESRO II polar orbiting satellite during two different proton events. Our choice was guided by the fact that they present some typical structures and were made in high and low energy channels. Moreover their analysis, made using less rigorous methods, is available and has been largely quoted (Durney et al, 1972; Morfill and Scholer, 1973).

Jakeways et al, (1970) and Engelman et al, (1971) have reported observations of latitudinal flux structures during February 25th, 1969 event along 10.48-11.00 UT pass by channels $\epsilon > 250$ MeV and 90-350 MeV aboard ESRO II; Morfill and Quenby (1971) and Durney et al, (1972) report structures observed by the same satellite, during the November 18, 1968 in channel 90-350 MeV, during the

11.02-11.28 UT pass. Structures over polar caps illuminated by fluxes of lower energies protons, detected by ESRO II channel 2-17 MeV along the 23.47-24.02 UT pass during the February, 1969 event were reported by Haskell and Hynds (1972) and Engelman et al, (1971). The three passes of ESRO II are plotted in figure 2 and the observed flux profiles in figures 3a, b, 4 and 5.

The construction of the theoretical flux profiles was based on computations –with the help of Mead and Fairfield model– of a larger number of monoenergetic latitudinal profiles along local time meridians swept by the satellite, for five or more energies of each channel. The profiles, constructed for the case of no shielding by the boundary region between interplanetary and cavity are illustrated in figures 6a, b and c. For observations during the November event the winter (tilt angle = $-30°$) and for the February event the equinox monoenergetic profiles were used. For observations studied, we used the exponent 2.5 for the interplanetary energy spectrum and a square distribution of pitch angle with $\alpha_0 = 50°$. Based on observations in the interplanetary medium (Engel, 1970; Balogh and Hynds, 1970), the values of 0.45 and 0.36 were assigned to the ratio I_{min}/I_{max} for $\epsilon > 90$ MeV and $\epsilon < 17$ MeV respectively for observations during the February event and 0 for the highly anisotropic November event (Durney et al, 1972).For all energies $\epsilon < 100$ MeV a cutoff correction Δ of $2°$ was introduced. I_{max} was asigned to the maximum intensity observed over polar caps as assumptions were made that neither shielding nor local acceleration takes place. The anisotropy of the interplanetary flux exhibits for the February event a strong southern component (Engel, 1970) specially intense during the reported low channel observations.

The computed flux profiles are plotted in figures 3a and b, 4 and 5, where they can be compared directly with observations.

Analysis of Flux Profiles

The comparison of the observations with profiles constructed by the method here described leads to the following results.

High Energies ($\epsilon \geqslant 90$ MeV).

The auroral peaks (A) in figures 3a, b and 4 at around 03.00 and 17.00 MLT are illuminate during both events by fluxes of *all energies* of the channel that enter from dawn directions via plasma scheet. The flux entering via the front magnetopause contributes little and only to the 03.00 MLT auroral peak. The peaks over high polar latitudes (B) observed around 24.00 and 22.00 MLT are due to flux of *all energies* of the channel arriving via north tail lobe, from dawn. As the detector sweeps across these high latitudes, it registers the polar peaks and the outer edges of the polar plateaux (see figures 6a and c). The deep valleys (V), that lie between the auroral and polar peaks and extends from 66° to 78° is observed during both events. As the detector sweeps the valley latitudes at 18.30 and 21.00 MLT it detects low flux as for all energies of the channel it scans exclusively the dusk directions of approach. The intensity minima (V_1, V_2, V_3) observed during the November event along the slopes of auroral peaks are detected due to the wide energy range of the channel and the fact that while sweeping over the polar caps across these latitudes, the satellite scans simultaneously for different energies different regions of entry and different directions of approach.

The deeper minimum (V_2) is illuminated mainly by higher energies (lower flux) arriving from the dawn side of the plasma sheet boundary, while lower energies protons arrive from the dusk side of the tail lobe boundary. The inverse situation prevails for the smaller minima (V_1, V_3). The regions "a" in figure 4 lie below the vertical cutoff of the highest energies of the channel; these latitudes are illuminated by flux reaching the detector under other than vertical directions of incidence. The observations show a very satisfactory accord with predictions of our model of uneven illumination (Gall et al, 1972).

A theoretical analysis of higher energy profiles was previously made by Morfill and Quenby (1971) Durney et al, (1972) and Morfill and Scholer (1973). The conclusions reached by these authors differ from the ones presented here. This is due to the less rigorous method used by the authors as they do not introduce either the seasonal effect or the latitudional cutoff correction and do not take into account the energy width of the channel. Indeed their analysis and conclusions about the entry into the magnetosphere are based on computations made for the mean energy of the channel alone.

Low Energies ($2 \leqslant \epsilon \leqslant 17$ MeV)

The theoretical profile for the low energy channel, of $2 \leqslant \epsilon \leqslant 17$ MeV illustrated in figure 5, accounts only for the general characteristics of the observed flux structure, namely it predicts extended valleys along 3.20 and 15.30 MLT semimeridians and a plateau over higher latitudes. The predicted morning valley being illuminated by flux entering the cavity under large pitch angles ($\alpha > 50^\circ$) from dawn while the 15.30 MLT valley, by flux arriving from the dusk side. The higher latitude plateau is illuminated by flux arriving via the dawn tail.

The fact that the theoretical profiles fail to exhibit the fine features observed is a clear indication that fluxes of lower energies are modulated by mechanisms not considered in the simple transfer functions used.

Previous attempts by Morfill and Scholer (1973) to analyse low energy flux profiles over polar caps by assuming the direct mode of propagation and the sole effect of interplanetary anisotropy, have also failed to account for their complex structure.

DISCUSSION

The latitudinal flux profiles over the polar caps contain much information about the topology and the dynamics of the magnetosheath, the magnetopause, the tail and the outer magnetosphere as well as about the modes of entry and the modulating mechanisms that operate on the flux of solar protons in the cavity. However its interpretation is complex and still a challenging problem to the researcher.

The method of analysis proposed in this paper is of "trial and error" type. The postulated modes of propagation and transfer functions are fed into equation (1) and the theoretical flux profiles thus derived. The discrepancies with observations serve as a guide to improve the assumptions on modes and transfer functions. In the construction of profiles in previous sections we have assumed a full, unshielded transmission of interplanetary anisotropic flux into the cavity and the direct mode of propagation in the cavity. We shall discuss the implications of these assumptions and their relations to the field topology. We shall do so first for higher energy particles.

Higher energies

One possible mode of entry that provides full unimpeded transmission of flux into the cavity is the "direct impact". The concept of direct impact first introduced for relativistic cosmic rays must however be redefined when applied to non-relativistic solar protons. The entry by direct impact applies only to the case when the direction of the interplanetary flux impinging on the shock wave is the same as the direction of approach at the point of entry into the cavity, upon crossing the magnetopause. The direct impact will not hold if any deviation from the original direction occurs in the boundary region. The deviation can be caused by irregularities in the magnetosheath or by changes in the magnetic field directions due to reconnection or draping around the geomagnetic cavity. The entry by direct impact tells us of course nothing about the topology of the boundary region, the flux being affected only by its passage across the outer and inner magnetosphere. The profiles computation show that illumination by direct impact of anisotropic flux along Parker spiral can for example be conveniently observed during equinoxes, by a 50 or 90 MeV detector at 900 and 600 MLT (see figure 7) when a wide plateau type illumination over the polar caps is expected. To our knowledge, no such observations have so far been reported. Deviations from these profiles would indicate a violation of direct impact, and would serve as a tool for the study of field irregularities, for reconnection of field lines across the front magnetosheath or draping of lines around it.

The latitudinal profiles of higher energy fluxes analysed previously, seem to be associated with another mode of entry that also provides full transmission of the flux into the cavity. We have seen that the profiles of higher energy flux observed by ESRO II agree remarkably well with the theoretical profiles computed for full transmission of the interplanetary anisotropic flux into the cavity. However the computed directions of approach show that the flux illuminating the observed peaks enter the tail across the dawn magnetopause under directions forming large pitch angles ($\alpha > 50^{\circ}$) with the interplanetary magnetic field and large angles (30°-100°) with the tail lines. One is then lead to conclude that a very efficient mechanism must operate in the boundary region that induces a rotation of the anisotropic flux by large angles. The mechanism must operate in addition to turning excerted by the B_z component in the neutral sheet.

Two modes that involve a turning mechanism and preserve the intensity of the flux has recently been proposed for an open field topology: 1) entry along well defined tail windows (Evans, 1972) where the turning is provided by non-adiabatic motion across a soft "elbow" of the interplanetary field lines merging with the tail lines and 2) entry along lines merging across all of the tail magnetopause (Morfill and Quenby, 1971) the turning being provided by the field discontinuity across the magnetopause, that causes the particles to perform multiple crossing of the boundary with abrupt changes in the original direction. Both mechanisms of rotation were studied by these authors for the restricted case when the particles emerge into the tail, under a zero pitch angle with the tail lines. Obviously this case corresponds to adiabatic motion in the tail for particles that reach the polar cap. Our trajectory simulation show however that higher energy ($\epsilon \gtrsim 10$ MeV) particles do not move adiabatically along the tail and that instead must enter the tail under large pitch angles and cross many tail lines on its way to polar orbiting satellites (see Gall and Bravo, 1973 Fig 4). The modes of entry proposed by Evans, Morfill and Quenby, based on field merging, could provide the necessary turning mechanism if they would hold without the restrictive condition imposed. Study of delay in the appearance of flux enhencement over polar caps with respect to the enhencement in the planetary medium (Evans 1972) could allow to discriminate between the two modes of entry proposed for open field topology.

However the turning mechanism need not be limited to the open field topology. The flux entering the magnetosheath could as well undergo a change to earthward direction at the "elbow" of the interplanetary lines that drape around the body of the tail. If the turning mechanism is equally efficient for the "closed" and "open" lines, and induces equal illumination over polar caps then one is lead to conclude that the higher energy particles cannot serve as adequate tools to discriminate between the open and closed field topology. This differs from the conclusion of Morfill and Scholer (1973) that interpret the polar peaks of higher observed by ESRO II as a definite proof of field lines reconnection across the tail magnetopause.

Low Energy

A clear discrepancy exists between the observed low energy flux profiles and those predicted theoretically on the basis of full transmission of the interplanetary flux and the direct mode. Many factors that affect the entry and propagation of these particles are not included in the simple transmission functions used. Acceleration and diffusion many well operate in the tail and in the boundary region. Indeed, isotropisation of 1 MeV proton by the magnetopause have been observed (Montgomery and Singer, 1969; Cooper and Haskell, 1972) and bursts at 35 R_E in the tail of locally accelerated protons of energies up to 4 MeV have been reported (Kohl et al, 1974).

Diffusive entry and propagation into closed tail field due to field irregularities (Michel and Dessler, 1970) and entry by wave-particle scattering in region where the tail lines and interplanetary field lines intermingle (Paulikas 1974) have been proposed.

The variety and variability with time of low energy flux profiles demonstrate the high sensitivity of these protons to the changes in the outer regions of the earth cavity and to changes in the interplanetary magnetic field configuration.

The deviation of the observed from the computed profiles can again serve as a tool in the search of mechanisms affecting the entry and propagation and of regions of the earth cavity and its boundary region where they operate, although the problem is now more complexe. A proper selection of local time of observations, in different energy channels should help to discriminate between different modes of entry and different field topologies.

CONCLUSIONS

1. The method proposed here, based on assumed transmission functions provides a useful tool for analysis of solar protons flux structures over polar caps and their relation to the topology and dynamics of earth's magnetic cavity.

2. Deviation of observed from theoretically derived flux serves as a guide to improve transmission functions and to study characteristics of the cavity that induce flux modulation.

3. Satisfactory agreement between observed and theoretically derived flux structures exists for higher energies ($90 < \epsilon < 350$ MeV). This leads to postule a turning mechanism that must operate in the magnetosheath or/and magnetopause.

4. Higher energy fluxes cannot help to resolve between reconnection or draping of field lines around the tail, that is between open or closed field models.

5. Deviations of observed and theoretically derived flux structures for low energies ($\sim$ 2 Mev) suggests that a large number of modulating effects such as scattering at entry or in the tail, local acceleration, etc., are operating in the tail in the magnetosheath or magnetopause. For these particles time delays between flux enhencement in the interplanetary medium and over polar cap is a necessary additional tool of analysis.

6. Fluxes of solar protons of intermediate energies, say 10-30 MeV may well prove to be the best tracers to resolve between open and closed field topology.

TABLE I

Entry through tail lobes and plasma sheet at $R > R_o$	$F = 1$ for directions from dawn $F = \frac{I_{min}}{I_{max}}$ for directions for dusk $K(\epsilon, \alpha)$ modulating factor in case of shielding
Entry through magnetopause at $R \leqslant R_o$	$F = 1$ for entry with $\alpha < \alpha_o$ $F = \frac{I_{min}}{I_{max}}$ for entry with $\alpha > \alpha_o$ $k(\epsilon, \alpha)$ modulating factor in case of shielding

Transfer functions for the anisotropic phase of solar proton events. Anisotropy is assumed with a square pitch angle distribution along Parker spiral, with or without N or S component. I_{max} and I_{min} are the intensities in the interplanetary medium along solar and antisolar directions respectively, integrated over all energies of the channel R_o is the maximum distance within which the magnetospheric model represents satisfactorily the field configuration.

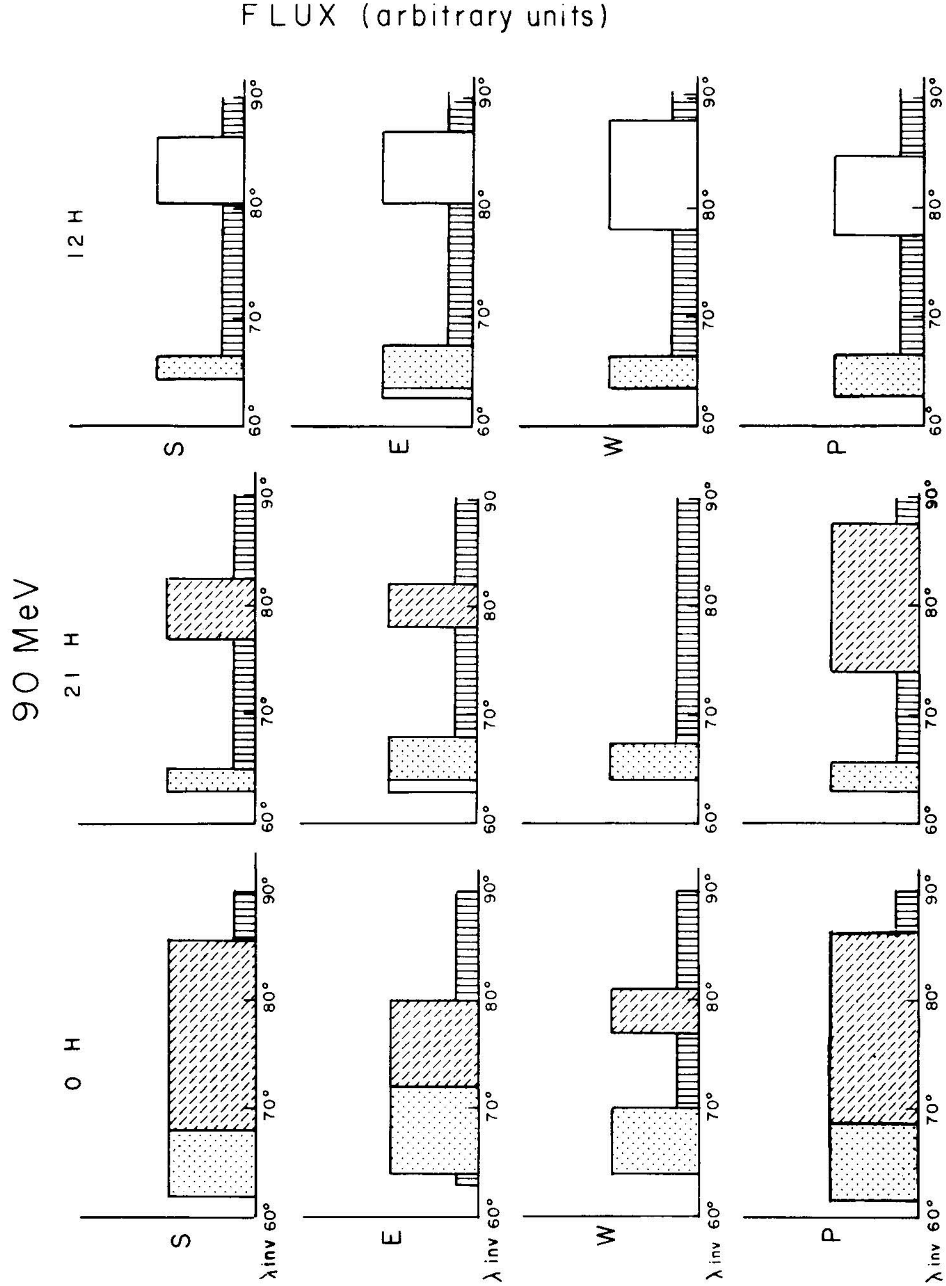


Figure 1. Changes in uneven illumination of polar caps induced by seasonal variation and magnetic perturbation of the geomagnetic cavity. Latitudinal flux profiles of 90 MeV protons along three different magnetic local times meridians for S, summer; E, equinoxes; W, winter and P, ($K_p > 2$). Pointed, dashed and white latitudinal zones are illuminated by flux entering from dawn via plasma sheet, via dawn tail and via front magnetopause, respectively. Striped zones, are illuminated from dusk.

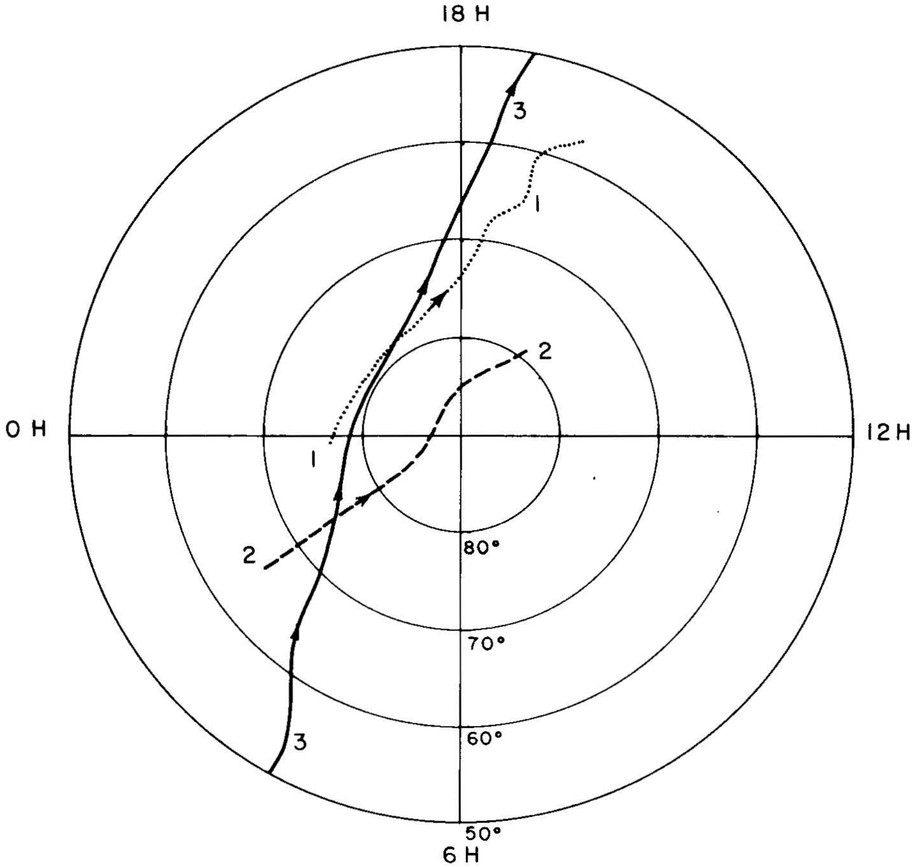


Figure 2. Passes of ESRO II polar orbiting satellite plotted in invariant latitude vs magnetic local time coordinates. Passes (1) and (2) correspond to February 25th, 1969, 10.48-11.00 UT and 23.47-24.02 UT respectively, and (3) to November 18, 1968, 11.02-11.28 UT.

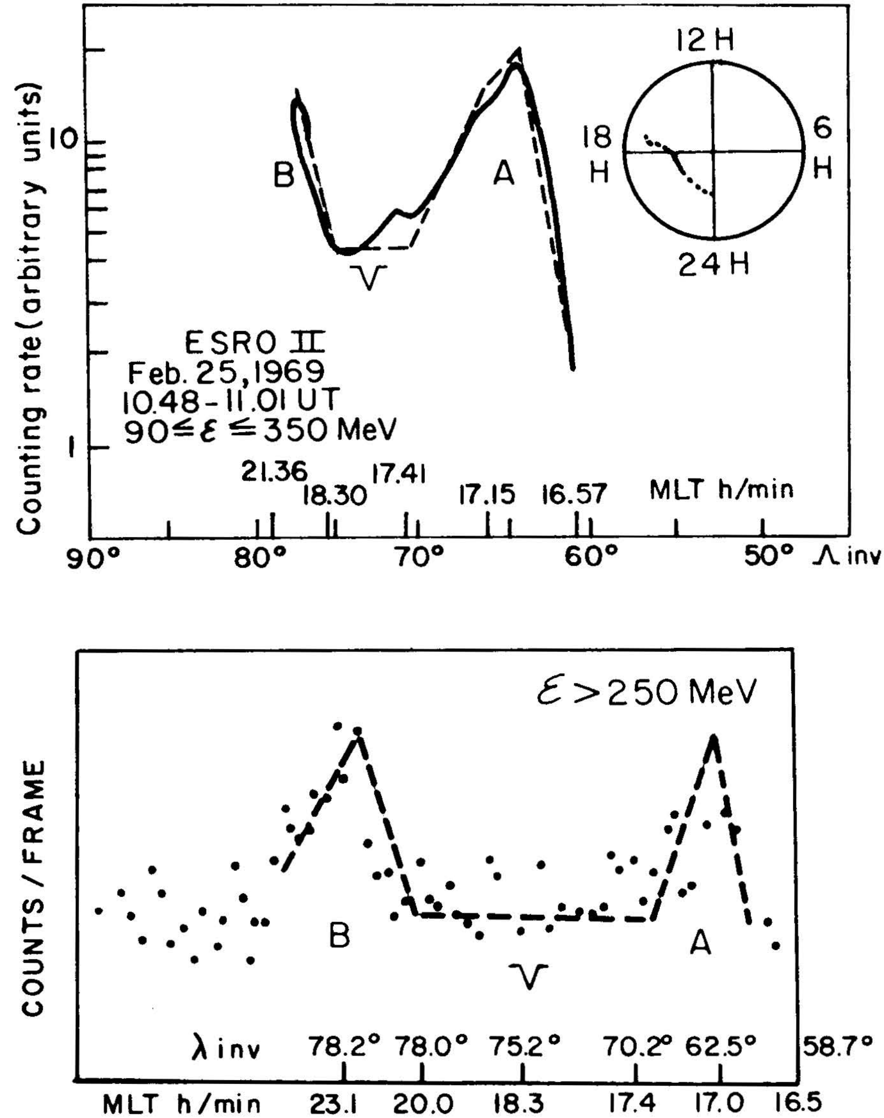


Figure 3. (a) and (b). Comparison of theoretical flux profiles (dashed lines) with the profiles observed by two high energy channels (solid line in (a) and points in (b)) along an ESRO II pass, during February 25th, 1969 event. The observed profiles are reproduced from Engelmann et al, 1971 and Jakeways et al, 1970. The satellite pass is shown in the circle attached.

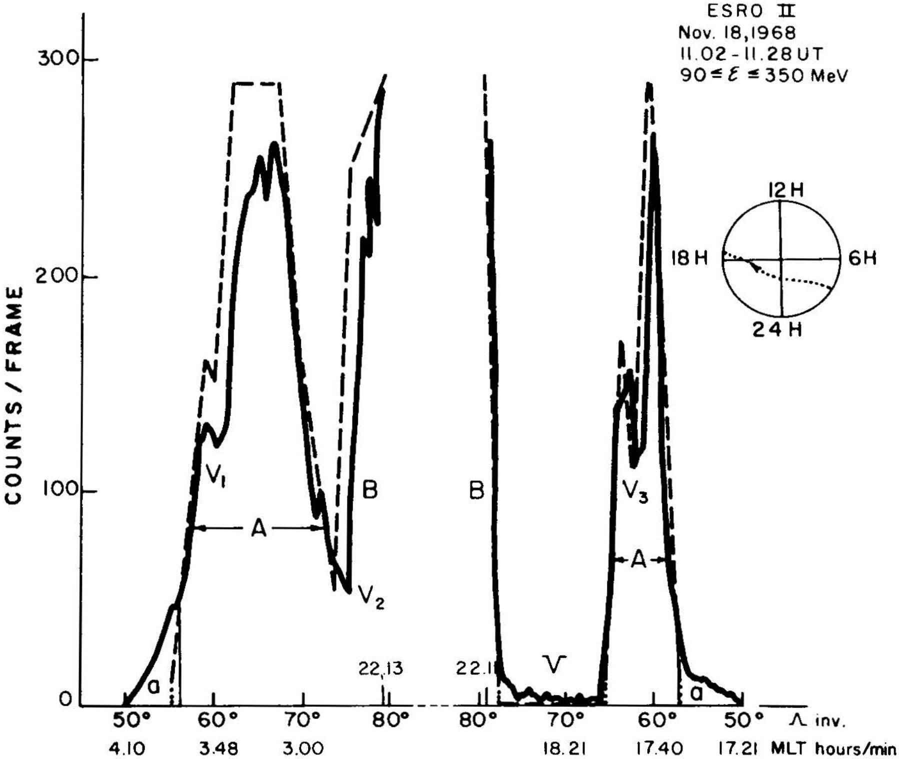


Figure 4. Comparison of theoretical (dashed line) are observed high energy flux profile (solid line) along an ESRO II pass during November 18th, 1968 event. The observed profile is reproduced from Morfill and Quenby, 1972. The satellite pass is shown in the circle attached.

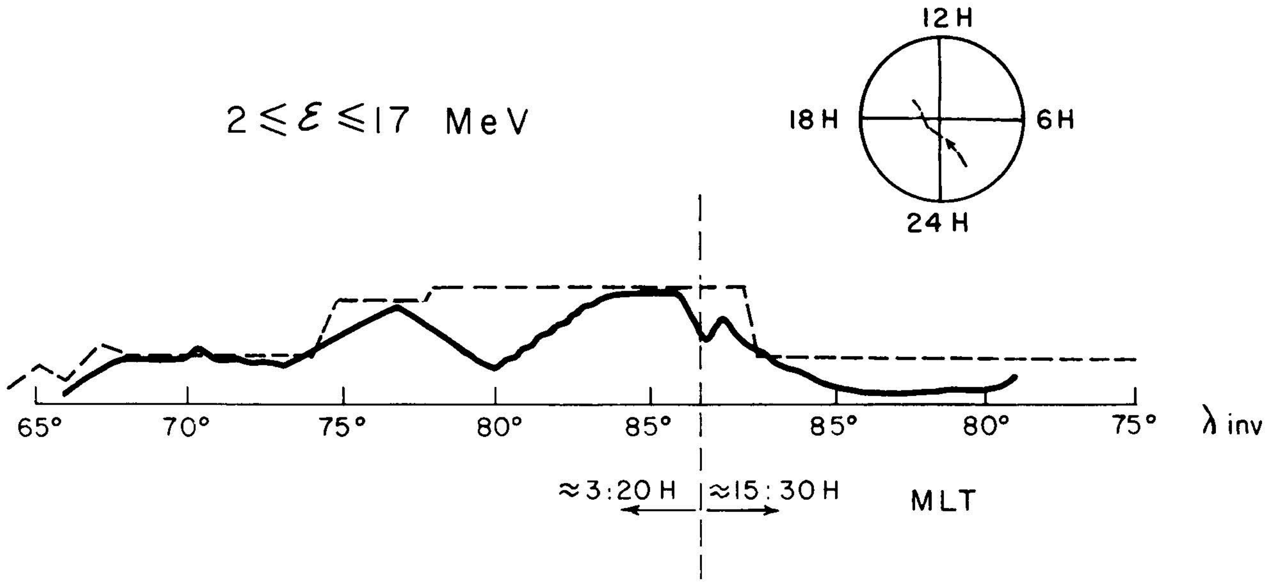


Figure 5. Comparison of theoretical (dashed line) and observed low energy flux profile (solid line) along an ESRO II pass during February 25th, 1969 event. The observed profile is schematically reproduced from Morfill and Scholer, 1973. The satellite pass is shown in the circle attached.

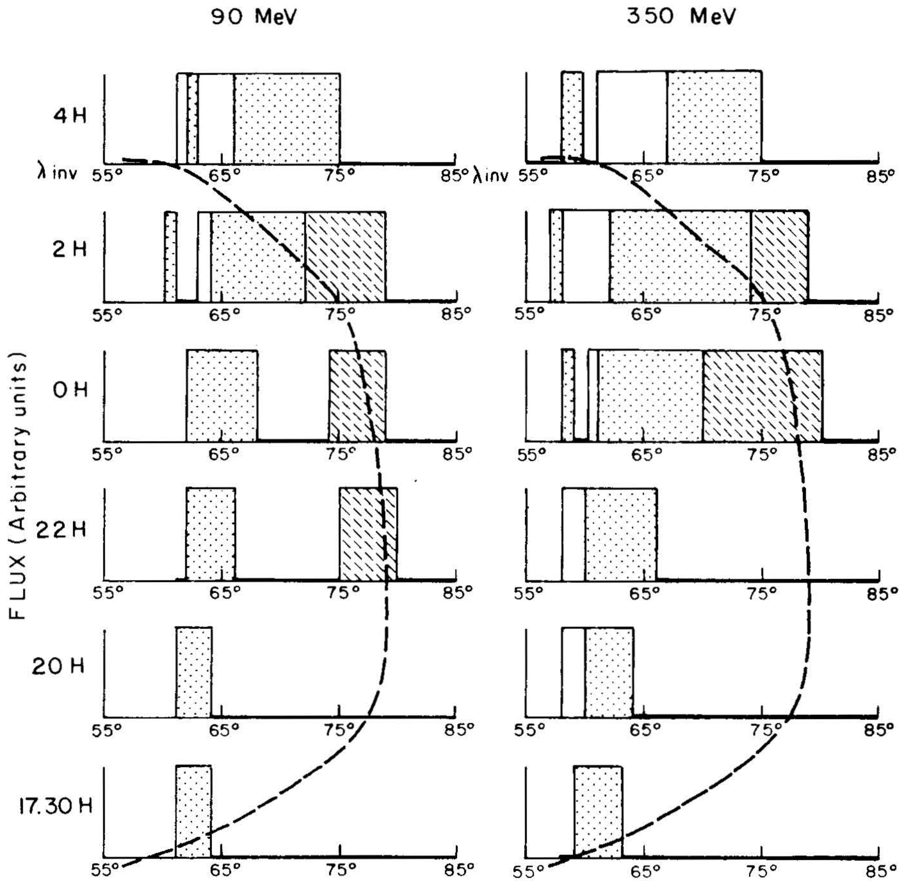
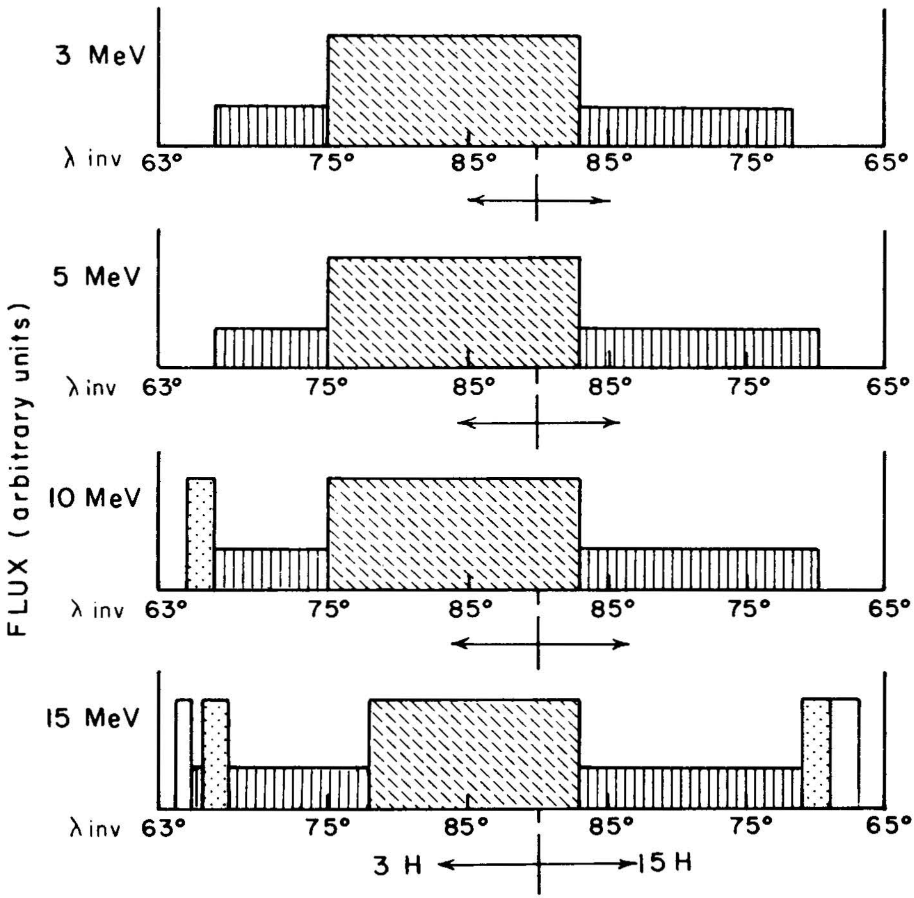
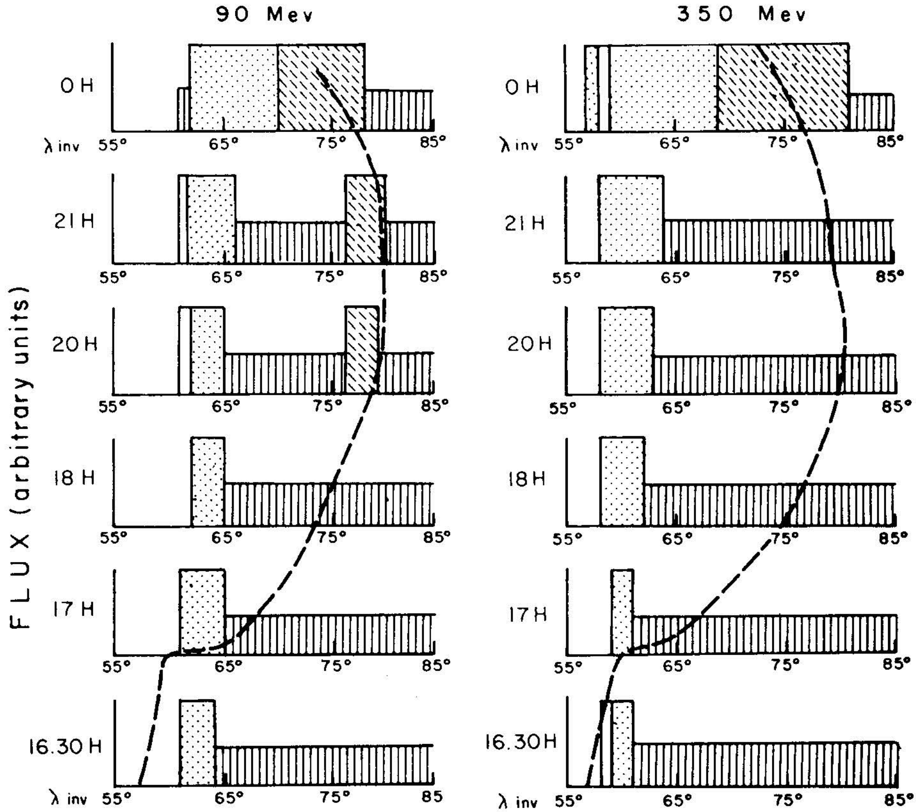


Figure 6. a, b and c. Theoretical latitudinal profiles along different magnetic local time meridians illuminated by monoenergetic protons fluxes, during equinoxes (a) and (b) and (c) during winter (TILT = −30°). The dashed lines represent the ESRO II passes: (a) 10.48-11.00 UT February 25th, 1969, and (c) 11.02-11.20 UT November 18th, 1968. During the pass (b) 23.47-24.02 UT of February 25th, 1969, the satellite swept approximately across the 3 and 15 hours local time meridian. For simplicity equal intensity was considered for all energies. Different regions of entry of the illuminating flux are marked as in Fig. 1.


3 MeV
λ inv 63° 75° 85° 85° 75° 65°
5 MeV
λ inv 63° 75° 85° 85° 75° 65°
10 MeV
λ inv 63° 75° 85° 85° 75° 65°
15 MeV
λ inv 63° 75° 85° 85° 75° 65°
3 H
15 H
FLUX (arbitrary units)

b



90 Mev
350 Mev
FLUX (arbitrary units)
0 H
21 H
20 H
18 H
17 H
16.30 H
λ inv
55°
65°
75°
85°

c

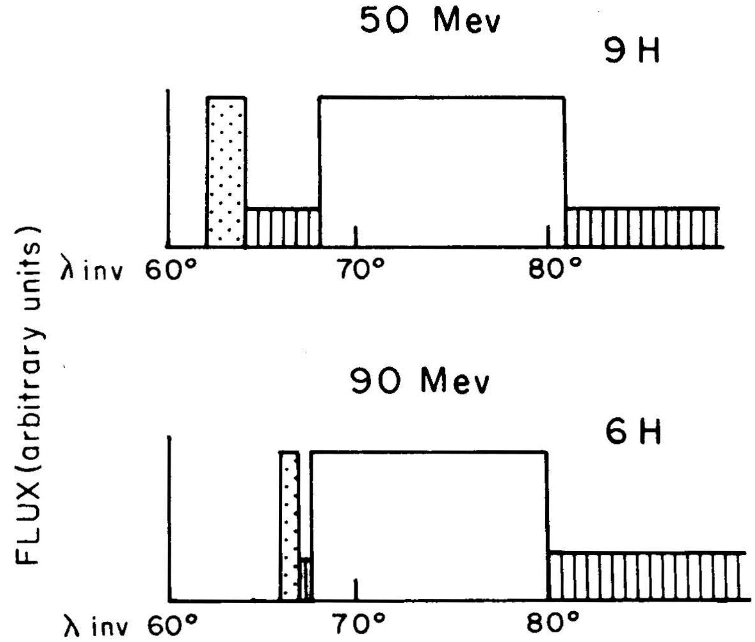


Figure 7. Theoretical monoenergetic flux profiles along two local time meridians. Illumination in absence of shielding by direct impact through front magnetopause is indicated by white areas; the pointed and stripped latitudinal zones are illuminated respectively from dawn plasma sheet and by flux impinging under large pitch angles.

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BIBLIOGRAPHY

BALOGH, A., and R. J. HYNDS, 1970. "Low Energy Proton Measurements in Interplanetary Space on Board the Heos-1 Satellite", (eds.), V Manno and D. E. Page, in *Intercorrelated Satellite Observations Related to Solar Events,* D. Reidel Publ. Co. Dordrecht, Holland. p. 471.

COOPER, W. A., and G. P. HASKELL, 1962. Anistropy of Low-Energy Solar Protons at the Boundary of the Magnetotail, *J. Geophys. Res.* 77, 6849.

DURNEY, A. C., G. MORFILL and J. J. QUENBY, 1972, Entry of High-Energy Solar Protons into the Distant Geomagnetic Tail, *J. Geophys. Res.,* 77, (19): 3345-3360.

ENGEL, A. R., 1970 "The Solar Particle Event of 25 February, 1969", (eds.), V. Manno and D. E. Page, in *Intercorrelated Satellite Observations Related to Solar Events,* D. Reidel Publ. Co. Dordrecht, Holland. p. 478.

ENGELMANN, J., R. J. HYNDS, G. MORFILL, F. AXISA, A. BEWICK, A. C. DURNEY, and L. KOCH, 1971. Penetration of Solar Protons over the Polar Cap during the February 25, 1969, Event, *J. Geophys. Res.,* 76, (19): 4245-4261.

EVANS, L. C., 1972. Magnetospheric Access of Solar Particles and Configuration of the Distant Geomagnetic field, Ph. D. Thesis. Calif. Inst. of Tech., Pasadena.

GALL, R., and S. BRAVO, 1970. Geostationary Satellites and the Anisotropies of Cosmic-Ray Propagation in the Interplanetary Medium, *J. Geophys. Res.* 75, 7284.

GALL, R., S. BRAVO, and A. OROZCO, 1972. Model for the Uneven Illumination of Polar Caps by Solar Protons, *J. Geophys. Res.,* 77, (28): 5360-5373.

GALL, R., S. BRAVO, 1973. The Role of the Neutral Sheet in the Illumination of Polar Caps by Solar Protons, *J. Geophys. Res.,* 78, 6773.

GALL, R., and A. OROZCO, 1974. Review on the Usage of Magnetospheric Model, *J. Geophys. Res.,* 79, 293.

GALL, R., S. BRAVO, 1974. "On a Model of Propagation of 5-300 MeV Protons in the Earth Magnetic Cavity" in *Corrolated Interplanetary and Magnetospheric Observations* (ed.) D. E. Page, D. Reidel Publ. Co. Dordrecht, Holland.

HASKEL, G. P., and R. J. HYNDS, 1972. Mechanism for the Injection of Protons into the Magnetosphere, *Earth's Magnetospheric Processes,* Edited by B. M. McCormac., D. Reidel Publ. Co. Dordrecht, Holland, 81.

IMHOF, W. L., J. B. REAGAN, and E. E. GAINES, 1971. Solar Particle Cutoffs as Observed at Low Altitudes, *J. Geophys. Res.,* 76, 4276.

ISRAEL, M. H., and R. E. VOGT, 1969. Characteristics of the Diurnally Varying Electron Flux near the Polar Cap, *J. Geophys, Res.,* 74, 4714.

JAKEWAYS, R., P. L. MARSDEN, and J. R. CALDER, 1970. Observations recorded by the Leeds University Cosmic Ray Detector on Board the ESRO II Spacecraft during the Solar Flare of February 25th, 1969, in *Intercorrelated*

Satellite Observations Related to Solar Events, (eds.), V. Manno and D. E. Page, D. Reidel Publ. Co. Dordrecht, Holland p. 486.

KOHL, W., S. M. KRIMIGIS and E. T. SARRIS (AGU 1974 San Francisco) Energy Spectra and Comparation of Proton Bursts at 35 R_E.

LUHMANN, G. J., and G. A. CARL, 1973. Solar and Geomagnetic Modulation of Low Energy Secondary Cosmic Ray Electrons, *J. Geophys. Res.,* 78, 1502.

MEAD, D. G., and D. H. FAIRFIELD, 1972. Two Quantitative Magnetospheric Models Derived from Satellite Magnetometer Data, Transactions, American Geophysical Union, Volume 53, Number 11, p. 1099.

MICHELL, F. C., and A.J. DESSLER, 1970. Diffusive Entry of Solar-Flare Particles into Geomagnetic Tail, *J. Geophys. Res.,* 75, 6061.

MONTGOMERY, M. D., and S. SINGER, 1969. Penetration of Solar Energetic Protons into the Magnetotail, *J. Geophys. Res.,* 74, 2869.

MORFILL, G., and J. J. QUENBY, 1971. The Entry of Solar Protons over the Polar Caps, *Planet. Space Scie.,* 19, 1541-1577.

MORFILL, G., and M. SCHOLER, 1973. Uneven Illumination of the Polar Caps by Solar Protons: Comparison of Different Particle Entry Models, *J. Geophys. Res.,* 78, (25): 5449-5462.

PAULIKAS, G. A., 1974. Tracing of High-Latitude Magnetic Field Lines by Solar Particles, *Reviews of Geophysics and Space Physics,* 12, 117-128.

SMART, D. F., M. A. SHEA and R. GALL, 1969. The Daily Variation of Trajectory-Derived High-Latitude Cutoff Rigidities in a Model Magnetosphere. *J. Geophys. Res.,* 74, 4731.

STONE, E. C., 1964. Local Time Dependence of Non-Stormer Cutoff of 1.5 MeV Protons in Quiet Geomagnetic Field, *J. Geophys. Res.,* 69, 3577.

THOMAS, G. R., D. M. WILLIS, and R. J. PRATT, 1974. Comparison of Solar Proton Trajectory Computations Using Model Magnetospheres. (ed.) D. E. Page in *Corrolated Interplanetary and Magnetospheric Observations,* B. Reidel Publ. Co. Dordrecht, Holland. pp. 449-461.

WILLIAMS, D. J., and G. D. MEAD, 1965. Night Side Magnetosphere Configurations as Obtained from Trapped Electrons at 1100 Kilometers, *J. Geophys. Res.,* 70, 3017.