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Evidence from Particle Precipitation of Two-Way-Convection in Auroral Latitudes*

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Abstract. Latitudinal distributions of keV proton and electron fluxes in the upper ionosphere are shown to display reminiscences of the characteristics in the noon sector even past dawn and dusk on the nightside. These observations support the proposal of Frank (1971a,b) that plasma is convected along the magnetospheric flanks from day to nightside. The keV particle data show, however, that in most of the auroral particle precipitation zone the transport of hot plasma is from night to day.

Key words: Magnetospheric Physics — Auroral Particles — Magnetospheric Convection.

1. Introduction

Although convection of magnetospheric hot plasma from the nightside to the dayside along the flanks of the magnetosphere has been inherent in physical models of the auroral phenomena since the dynamic morphology of auroral substorms became known some ten years ago (see e. g. the review by Akasofu, 1968), the idea that convection in the opposite direction at auroral latitudes may be even more important from the plasma source point of view was first forwarded by Frank (1971a,b) a few years ago. The basis for his suggestion was the discovery of the polar cusps which are a few latitude degrees wide and extend from about 0900 to 1500 magnetic local time (Heikkila and Winningham, 1971). Frank (1971a,b) proposed that the convection of the magnetic field lines, with associated plasma, from the polar cusps along the flanks into the plasma sheet in the tail is the most important source of hot plasma in the magnetosphere.

That plasma convects along the auroral oval as suggested by Frank (1971a,b) has been confirmed by means of electric field measurements (Frank and Gurnett, 1971). These measurements show, however, that there is an electric field so directed that it gives rise to convection in the antisunward direction, only poleward of a certain boundary, which coincides closely with the $>$ 40 keV electron trapping boundary under most conditions.

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* To Prof. G. Pfotzer in honor of his 65th birthday.

Equatorward of this boundary the convection has the opposite (sunward) direction.

The purpose of this note is to present some observations of latitudinal and local time distributions of keV proton and electron precipitation obtained by means of the polar orbiting low-altitude satellite ESRO 1 A, which provide some additional indirect evidence for the convection of the hot plasma to go from day to night poleward of a border latitude and in the opposite direction equatorward of it. The observational data discussed are of two kinds: the average precipitated flux as function of corrected geomagnetic latitude (practically identical with invariant latitude) and eccentric dipole time, and individual latitudinal profiles of keV electron and proton fluxes at 10° and 80° pitch angles measured at about 1000 km altitude (± 300 km).

2. *Instrumentation*

The satellite ESRO I A (Aurorae) was launched on October 3, 1968 into a near polar orbit (inclination 93.8°). The apogee was 1533 km after launch and the perigee was 258 km. The satellite with the auroral particle experiment was in operation until June 26, 1970. It was magnetically stabilised. The particle experiment, S 71 B, was operated only when the satellite was within the range of a telemetry station. This experiment which has been described in detail elsewhere (Riedler *et al.*, 1971) contained 10 sensor units, each consisting of an electrostatic analyser and channel multiplier detector measuring only protons or only electrons in a fixed energy interval and arranged at angles of 10° and 80° to the satellite axis.

This report is based entirely on 8 sec average values. These are, for low and medium fluxes, the average of measurements during two to three complete measuring cycles or, for very high fluxes, the average over more than 40 cycles. In 8 sec the satellite traveled about 60 km (half a latitude degree). Therefore, the spatial/temporal structure is smoothed out. Individual auroral arcs of a characteristic width of 1 to 10 km are generally strongly suppressed in the data.

3. *Observations and Discussion*

The average precipitation patterns for keV electrons and protons as measured by ESRO I A are illustrated in Fig. 1 for 6 keV, 10° pitch angle particles under quiescent to moderately disturbed conditions (after Riedler and Borg, 1972). A feature of Fig. 1 of interest to us here is that the local-time distribution of the precipitation intensity has broad maxima centered in late morning and late evening with minima in between at 0100—0200 EDT in the early morning and near noon (EDT) and that there is hardly any difference between the precipitation rate at dawn and at dusk neither

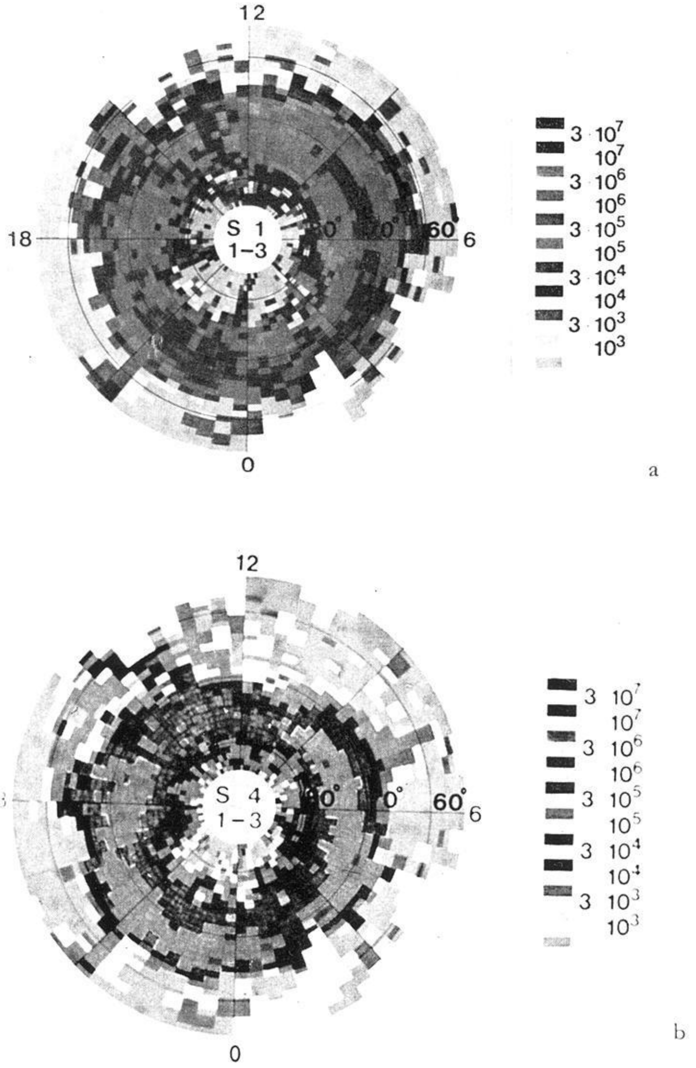


Fig. 1. Average fluxes of precipitated electrons (a) and protons (b) of 6 keV energy for fairly low activity level ($K_p = 1$—3) as measured during a 20-month period from October 1968 to June 1970 with the ESRO I A satellite. The coordinates are corrected geomagnetic latitude (practically identical with invariant latitude) and eccentric dipole time. Original is coloured. The highest intensities are found for the electrons (a) in the dark regions surrounded at higher and lower latitudes by lighter areas, whereas for the protons (b) the light regions indicate the highest precipitation fluxes. After Riedler and Borg (1972)

for keV electrons nor for keV protons. For still lower electron energies no dawn–dusk asymmetry at all can be seen. This absence of a significant dawn–dusk asymmetry is not only a statistical fact but is more or less regularly seen in individual passes. For energies above the keV range a dawn–dusk asymmetry is present.

The night-time minimum, which is the less pronounced one, is not our concern here. It can be found also in data for precipitation of electrons of higher energies and in the percentage hourly occurrence of aurora as function of the local time (Davis, 1962) and may be related to special features of the convection pattern or to the large scale distribution of the pitch angle diffusion rate.

The observed local time distribution shown in Fig. 1 clearly indicates that injection of keV particles on field lines reaching the auroral regions is extended over the entire width of the magnetotail. The distributions are consistent with a model in which hot plasma from the tail is convected towards the earth up to a forbidden region with strong pitchangle diffusion prevalent over the entire nightside in an L-range of 3—10 outside this boundary. The keV plasma is also convected past dawn and dusk into the dayside but the fluxes decrease there in the direction of the noon meridian.

The precipitation patterns in Fig. 1 show too that there is no, or only a slight, effect of the azimuthal magnetic drift motion of the keV electrons and protons on the distribution of the keV particle precipitation on the nightside. A significant dawn–dusk asymmetry seems unavoidable if the keV particles due to azimuthal drift moved over a large sector of local time angle before being precipitated. Such an asymmetry can be seen at higher energies and is significant already at 13 keV (Riedler and Borg, 1972; Riedler, 1972).

It appears to be most difficult to interpret the average precipitation patterns in Fig. 1 in terms of a convection from the dayside to the nightside. Quite peculiar field and/or wave distributions have to be advocated to explain the predominant nighttime precipitation in such terms. Even if such special configurations at the present time can not be definitely disproved on the basis of average, time-independent situations, a model with the injection on the dayside over the whole latitudinal width of the auroral particle precipitation zone with a subsequent convection toward midnight can be eliminated on the basis of the time-dependent behavior.

That the enhancement of precipitation during substorms generally starts in the midnight sector and subsequently expands in all directions from the initiation area was demonstrated on the basis of auroral observations already in the early sixties (see e.g. Akasofu, 1963). It has later been shown also in electron precipitation at energies above the keV range which does not produce much aurora but instead affects the D-layer electron den-

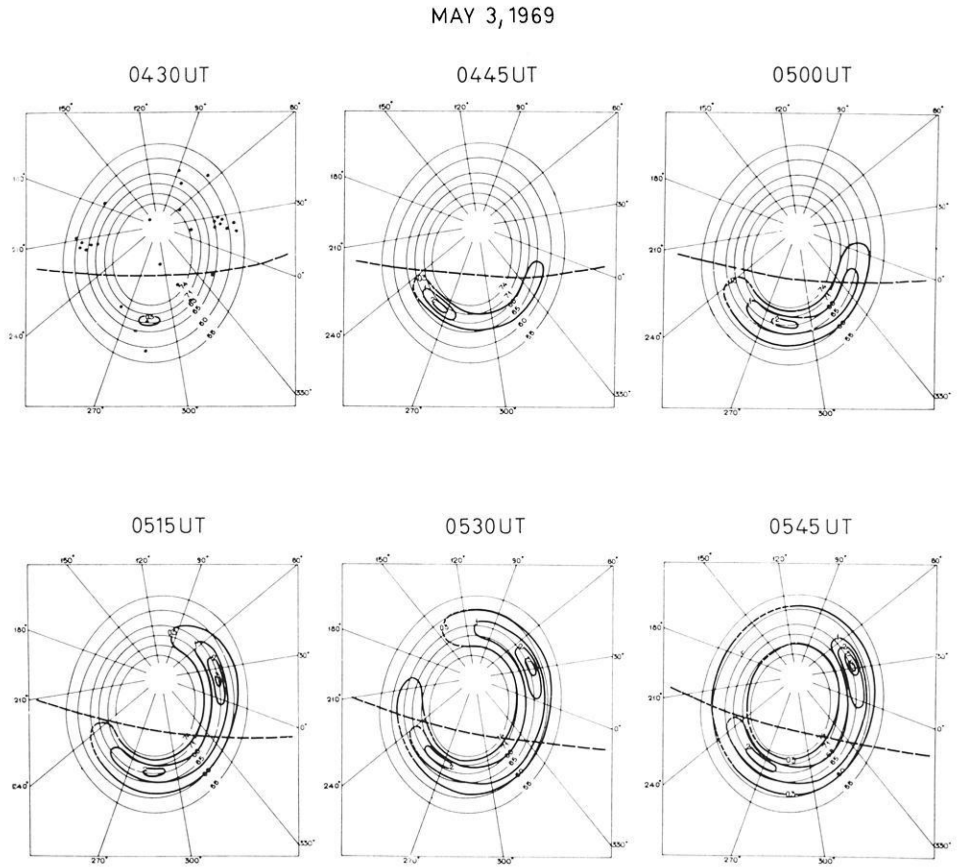
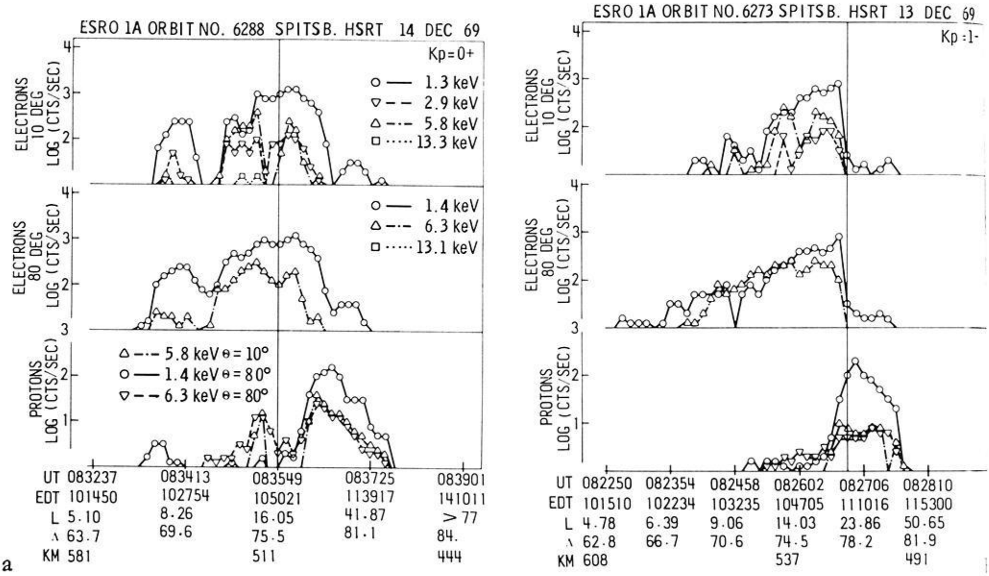
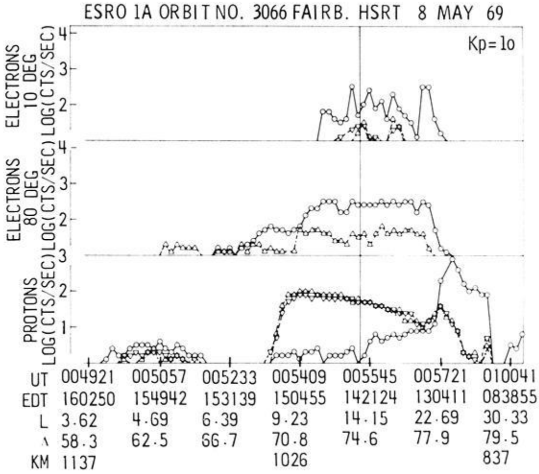


Fig. 2. Synoptic maps of auroral absorption for a substorm starting around 0430 UT on May 3, 1969 (after Berkey *et al*, 1971), for the first $1^1/_4$ hour after the start. The points in the first diagram shows the riometer stations on which the synoptic maps are based

sity (Berkey *et al.*, 1971, 1974). An example of the temporal development of the precipitation pattern during a substorm as measured by the increased D-layer electron density, which absorbs cosmic radio noise observed at the ground level, is shown in Fig. 2.

It seems very difficult to understand a time series as the one shown in Fig. 2 in terms of an injection of hot plasma from the dayside into the nightside, but such a temporal development is a natural consequence of the injection of hot plasma into the inner magnetosphere from the magnetotail over the whole width of the tail, with the precipitation setting in when the plasma has reached within a certain distance of the earth, which





c

Fig. 3a–e. KeV electron and proton data from ESRO 1 A passes through the noon sector. The straight line over the diagrams indicate the location of a trapping boundary for >40 keV electrons as determined on ESRO 1 A by Page and Shaw (1972)

naturally may be expected to happen first in the midnight sector. We thus conclude that the average precipitation pattern, as well as the substorm behaviour strongly support convection from the nightside towards the dayside being most important in the auroral regions.

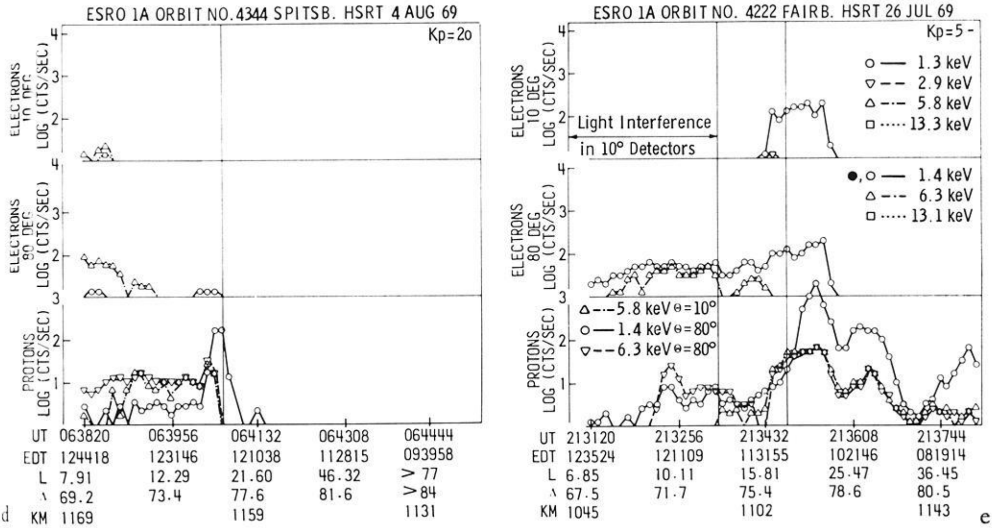


Fig. 3 d and e

None of the observations of auroral particle precipitation referred to above indicates that convection from day to night plays any important role at all. There is, however, some particle data that suggest that convection takes place from day to night at dawn and dusk in the most poleward part of the auroral particle precipitation zone, but they are of a different nature than the data discussed earlier: the latitudinal distributions of keV electrons and protons (with 8 sec time resolution) for individual satellite passes. These data are consistent with and suggestive of, although no definite proof of, an antisunward convection in what appears to be the continuation of the polar cusps on the morning and evening sides of the earth and sometimes into the night. This observational evidence will be described and exemplified here next. The situation in the central part of the dayside will first be illustrated as it constitutes the reference with which the latitudinal profiles in the morning and evening will be compared.

A number of latitude profiles on the dayside, crossing the cusp region between 1030 and 1330 EDT, are shown in Fig. 3. They are ordered according to increasing K_p between 0_+ and 5_-. Some of them show only part of the particle precipitation zone because the instrument was operated with real-time telemetry and frequently telemetry could be received for only part of the region where energetic electrons and protons occurred. The vertical line in each of the diagrams shows where the trapping boundary was located by Page and Shaw (1972) with the use of a Geiger Müller tube onboard the same satellite which measured electrons of energies above some 40 keV.

The latitude profiles shown in Fig. 3a—d were obtained during quiet conditions. Still they show quite large differences. One thing they all and Fig. 3e have in common is, however, that at the poleward boundary of the particle zone there is an intensification of the proton flux, particularly at low energy. The proton pitch-angle distribution approaches isotropy in this region, which is some 2 to 5° of latitude wide and has its center located at an invariant latitude between 78 and 80° in quiet conditions.

What is of particular interest is a common feature in all of Fig. 3a—3e: the 1 keV proton precipitation is displaced poleward in comparison with the 6 keV protons. This displacement is generally 0.5—1° of latitude.

Fig. 3 shows that there are usually no electron fluxes of energies greater than 1 or 2 keV in this region of fairly intense soft proton flux at the poleward edge of the particle zone. When electrons are observable they appear only in the lowest energy channel.

This high-latitude region in the noon sector is the polar cusp. The 1 keV proton channel of the ESRO-I instrument measures close to the peak in the cusp proton energy spectrum (see e.g. Winningham, 1972; Sckopke *et al.*, 1973). Fig. 3 shows that the proton spectrum within the cusp softens with increasing latitude. In most cases the cusp can be clearly identified, even in 6 keV proton data, from the intensification of the flux and isotropization of the pitch-angle distribution.

The peak proton flux within the cusp region may vary by a factor of more than 20 although the K_p index is almost identical. The rough estimates of the $H\beta$ peak intensity corresponding to the measurement shown in Fig. 3 vary between a few tens and several hundreds of Rayleighs.

Equatorward of the cusp the situation may be quite variable, as shown by Fig. 3. Whereas there are hardly any protons south of the cusp in Fig. 3b, the differential flux at 6 keV is as intense over many degrees equatorward of the cusp as it is in the cusp in Fig. 3c. The proton spectrum is much harder in this equatorward zone. In those cases where the 6 keV flux is significant, the pitch angle distribution is in general within a factor of two of isotropy. The protons give rise to Hβ emission of intensity between a few tens and a few hundreds of Rayleighs.

The electron population equatorward of the cusp has frequently a fairly hard spectrum (see Fig. 3d) but it sometimes is quite soft (see Fig. 3a and c).

The 4278 Å intensities corresponding to the highest electron flux values shown equatorward of the cusp in Fig. 3 vary between a few tens of Rayleighs and several hundred Rayleighs.

The polar cusp does not always stand out so clearly in the ESRO I data as shown in Fig. 3, but the poleward softening of proton energy spectrum and the isotropization of the 6 keV proton pitch-angle distribution can be seen practically all the time.

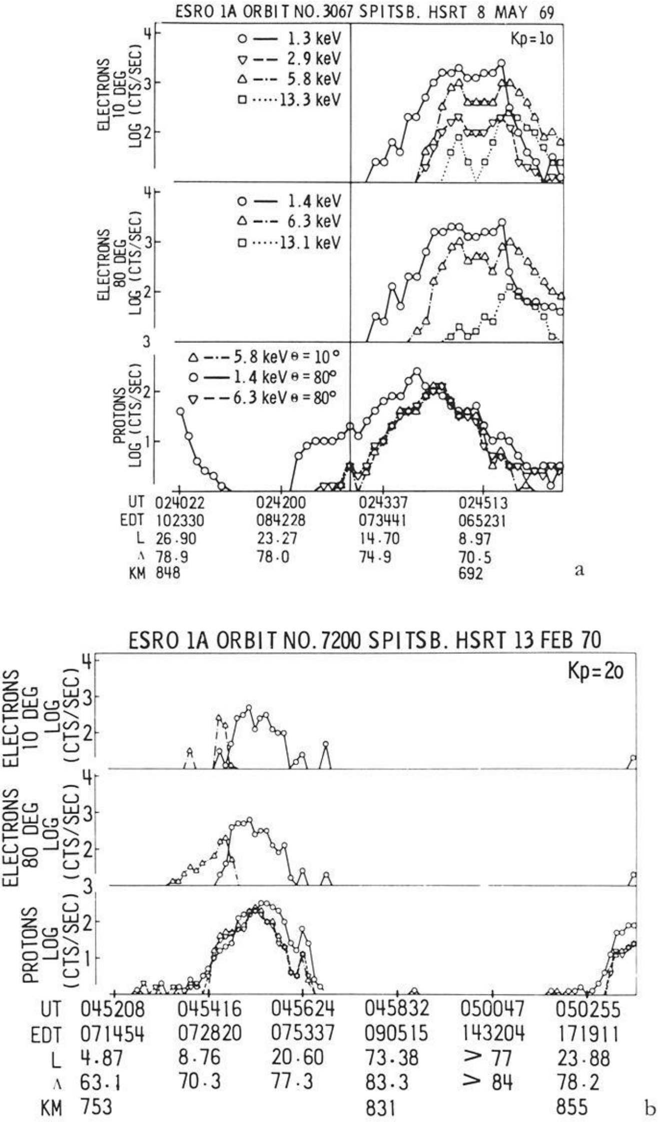


Fig. 4a–d. KeV electron and proton data from ESRO I A passes through the forenoon to dawn sector. Concerning the straight vertical lines in (a), (c) and (d) see caption of Fig. 3

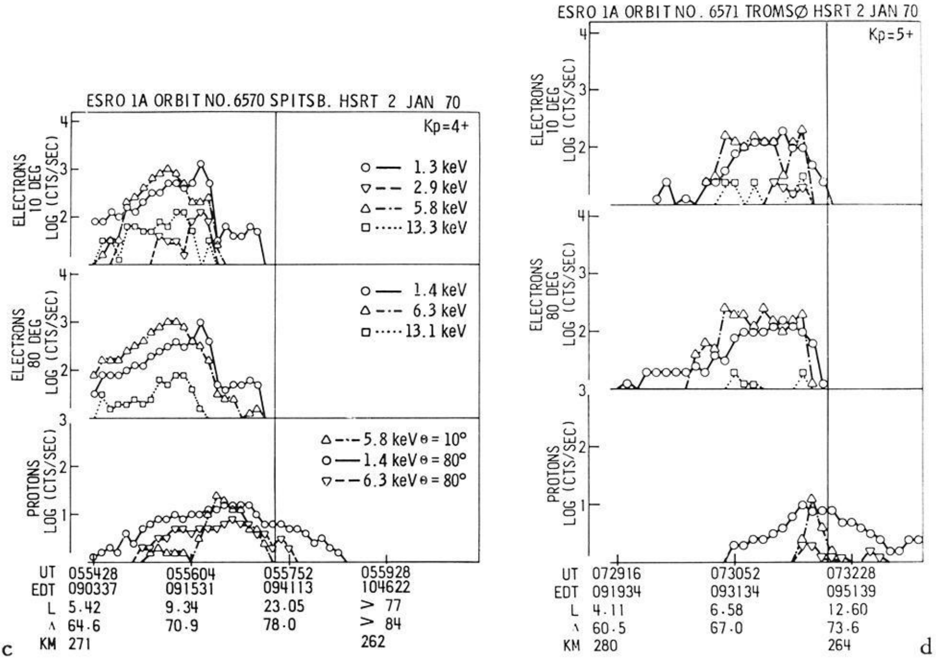


Fig. 4c and d

The characteristics of the latitude profiles of keV proton and electron fluxes illustrated for the noon sector in Fig. 3 extend without any significant changes to about 0900 EDT in the morning and 1500 in the afternoon. An interesting observation in the ESRO I data is that some of the characteristics of the latitude profiles shown in Fig. 3 are found somewhat modified also at much greater distances from noon, out to the dawn and dusk sectors. Sometimes this relation with the 3 and 6 keV electron distributions having their peak fluxes well south of the peak proton fluxes and reaching only to about the latitude of the peak of the proton profile, is found also on the nightside. This is illustrated by Fig. 4, for the dawn and early morning; by Fig. 5 for late afternoon and dusk; and by Fig. 6 for the nightside.

The examples shown in Figs. 5 and 6 are contrary to the frequently cited result of optical observations of electron- and proton-produced aurora that the proton precipitation normally is equatorward of the electron precipitation in the evening and poleward of it in the morning (see, e.g., Derblom, 1968; Wiens, 1968; Wiens and Vallance Jones, 1969, and the reviews by Eather, 1967; Eather and Carovillano, 1971; and Om-

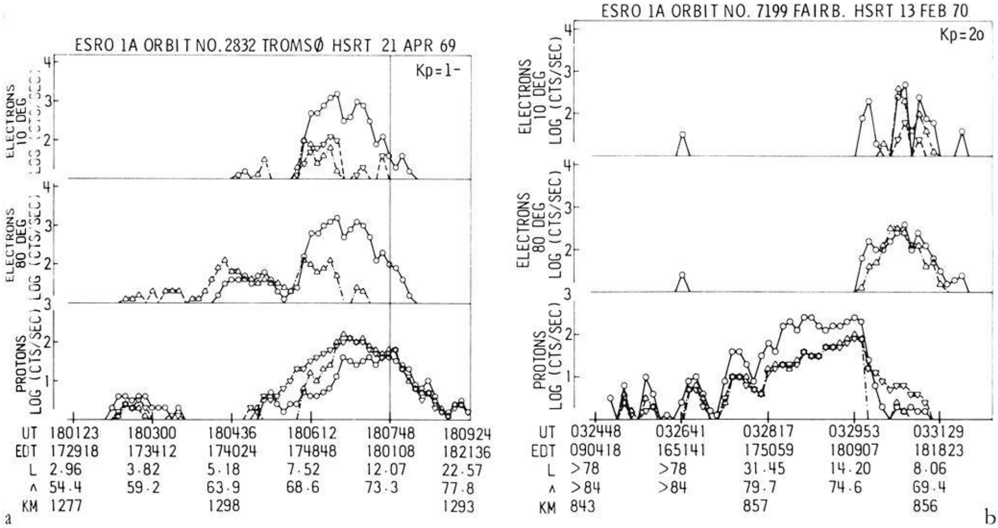


Fig. 5a and b. KeV electron and proton data from ESRO I A passes through the dusk sector. For the meaning of the symbols see figs. 3 or 4, and concerning the straight vertical line in (a) see caption of fig. 3

holt, 1971). This disagreement is, however, most likely not a real one. The hydrogen aurora in the evening is to a large extent produced by protons of energies above those measured by the auroral particle experiment on ESRO I. These protons drift into the evening sector from local night at latitudes which on the average are lower than those where the keV protons are precipitated with highest intensity. There are also in the keV proton latitude profiles some differences between evening and morning sectors.

The poleward displacement of the keV proton profile relative to the distributions of the $\gtrsim 3$ keV electrons occurs more frequently on the morning side than in the evening and the difference in occurrence frequency is so large that it is clearly seen in statistical averages, as shown by Riedler (1972).

Whereas in the morning a relative north–south displacement of the keV proton and electron profiles is the dominating situation, in the evening a quite different relation between electrons and protons is seen about as frequently as the one described above. This other relation is one with the keV electron and proton precipitation zones having closely coinciding boundaries. An example is shown in Fig. 7. These closely coinciding keV electron and proton latitudinal distributions are characteristic for the dusk to midnight sector. They contain frequently inverted V regions as well as field-aligned proton pitch-angle distributions (Hultqvist *et al.*, 1974).

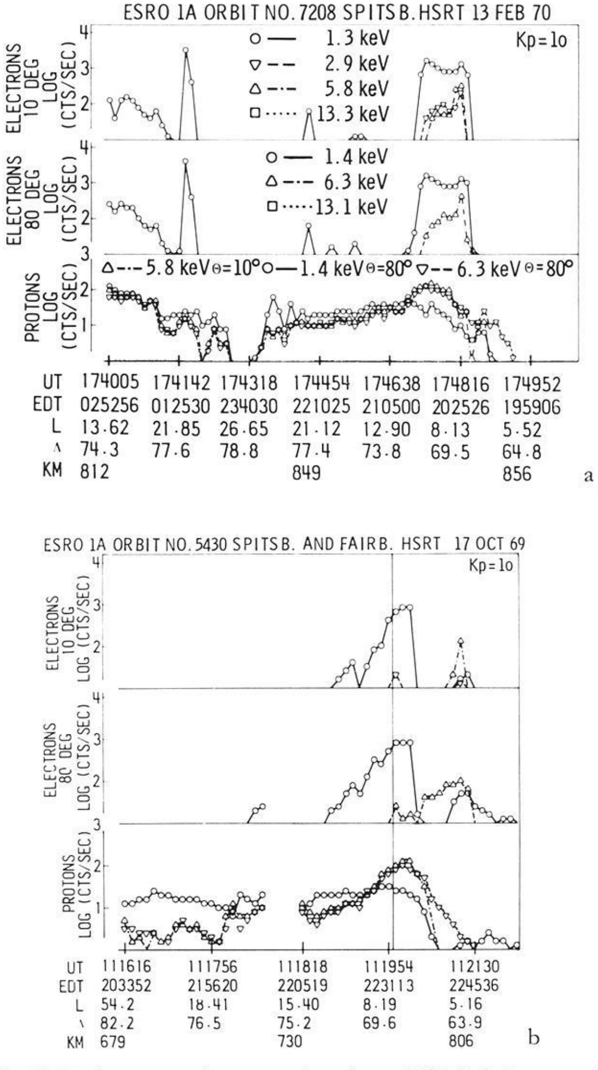


Fig. 6a and b. KeV electron and proton data from ESRO I A passes in the late evening with >2 keV electrons only reaching to about the latitude of the proton peak flux. Concerning the straight vertical line in (b) see caption of Fig. 3

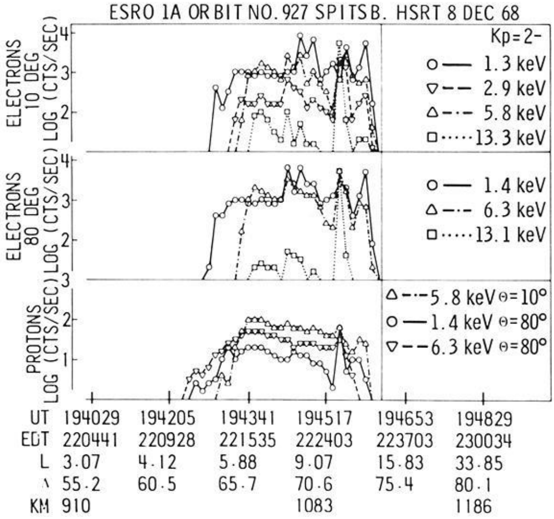


Fig. 7. A fairly typical example of a kind of latitudinal distributions of keV electrons and protons which is found almost only between dusk and midnight and which is characterized by relatively much structure and by closely coinciding boundaries for keV electron and proton precipitation

There seems to be two competing processes present in the evening. One appears to be connected with the injection of magnetosheath plasma through the polar cusps with subsequent convection along the flanks into the tail of the magnetosphere. The other shows no traces of this polar cusp injection in the latitude profiles, but contains a lot more of spatial/temporal structure (associated with discrete auroral forms) with keV electrons and protons being precipitated together in a sharply bounded zone with strong gradients at the edges. Which of the two kinds of profiles that dominates depends on magnetic local time: the later the hour the more dominant the sharply defined precipitation zone, common for keV electrons and protons, appears to be.

We will not discuss further here the special phenomena in the evening wich give rise to the structure in many parameters characteristic for this sector, but we will instead emphasize the observations of displaced keV proton and electron profiles, of which Fig. 5b is a most extreme case. It seems natural to associate this kind of distribution set with the noon sector profiles where the polar cusp influence generally dominates, in particular as the occurrence of such sets of latitude profiles can be seen all the way from noon to the nightside along both the morning and evening sides of the earth, with diminishing occurrence frequency as the distance from noon grows.

The relative latitudinal displacement of the keV proton and electron profiles tends to decrease with increasing distance from the noon meridian. Already in the forenoon and afternoon sectors the latitudinal distributions overlap somewhat more than around midday and at dawn and dusk the overlap is mostly quite large, as Figs. 4—6 show. It therefore appears that the two particle populations originating in the polar cusp and in the plasma sheet, respectively, in general mix more and more the farther away they are from noon and midnight.

It is evident also that the fluxes of 1 keV electrons in the region of maximum keV proton fluxes in general is higher at dawn and dusk than in the polar cusps near noon, although the 1 keV flux in the polar cusp is sometimes much higher than in the examples shown in Fig. 3 (see Hultqvist *et al.*, 1974).

On the basis of the observational evidence presented above we conclude that the auroral particle data obtained in the upper ionosphere support the existence of injection of magnetosheath plasma through the polar cusps into the nightside magnetosphere as proposed by Frank (1971 a,b). But the data also show that this injection, involving convection from day to night is limited to the most poleward part of the precipitation zone. Equatorward of this region the hot plasma is convected from night to day. This is obviously in agreement with the observations of sharp reversals of the dawn–dusk component of the magnetospheric electric field reported by Frank and Gurnett (1971).

Which convection pattern transports more particles and energy is difficult to give a good estimate of on the basis of the ESRO I data because of their limitations with regard to the width of the energy ranges measured and the pour energy spectrum information contained in them. A subjective impression is, however, after having studied many hundred passes, that there is more particles and energy transported from the night to the dayside of the earth than in the opposite direction.

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