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Review Article

Global Pattern of Auroral Ion Precipitation: A Review of the Results from the AUREOLE-1 and AUREOLE-2 Satellites

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Abstract. The ion measurements (0.2–30 keV) made onboard the AUREOLE-1 and 2 polar orbiting satellites are reviewed in order to construct a synthetic global pattern of the auroral ion precipitation. The more prominent features of the picture obtained can be summarized as follow: (1) A narrowly localized zone of the near-noon direct penetration of magnetosheath protons in the dayside cusp, located *inside* the dayside auroral oval. (2) A low energy ion precipitation ($E<3$ keV) at the polar border of the nightside auroral oval occurring during periods of very quiet magnetic conditions and after storm recovery. (3) A continuous and homogeneous band of proton aurora all along the auroral oval due to adiabatic drift of plasmasheet protons ($E>1$–3 keV) in the magnetosphere, accompanied by their pitch angle scattering above the diffuse auroral zone. (4) The presence in diffuse aurora of a less regular but denser soft ion component ($E<1$–3 keV) in the precipitation spectra. (5) A morning sector, substorm-related, low energy proton (ion) precipitation dispersive structure at auroral and sub-auroral latitudes due to the differential eastward drift of particles after substorm injection (with the lowest energy part presumably of ionospheric origin).

This global pattern is discussed in the context of the distribution of the various plasma domains in the outer magnetosphere.

Key words: Auroral ion precipitation – Polar cusp – Acceleration – Convection

Introduction

Studies of the so-called "proton aurora" have constituted a typical aim of auroral investigations over the last few decades (Chamberlain, 1961; Eather, 1967; Vallance Jones, 1974). Although there are far fewer experimental results on the ion than on the electron component of auroral precipitation, direct measurements of the precipitating energetic protons responsible for the proton aurora were made before the ARCAD project from several near-earth polar satellites: ESRO-1 (Hultqvist, 1973; 1979), INJUN-5 (Frank and Ackerson, 1971; Frank, 1975), ISIS (Heikkila, 1972), COSMOS-261 and COSMOS-348 (Kovrazhkin, 1976).

It became clear from these results that the flux of precipitating auroral protons rarely exceeds 10^7 particles $(\mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{keV})^{-1}$ and that their average energy is of the order of 10–30 keV in the evening sector of the proton auroral band during substorms. During magnetically quiet periods the sensitivity and spectral range of the spectrometers used on these satellites were not adequate to study much less intense proton precipitation.

The French-Soviet ARCAD experiments, launched aboard the polar satellites AUREOLE-1 and 2, were designed to allow the study of these quiet-time low ion fluxes. Nevertheless, they revealed (and for the first time analysed in detail) the prominent features of the auroral ion precipitation:

- A narrowly localized zone for the near-noon direct penetration of magnetosheath protons in the dayside cusp.
- A continuous and homogeneous band of proton aurora all along the auroral oval ($E>1$–3 keV) due to adiabatic drift of plasmasheet protons in the magnetosphere. Also, for the diffuse aurora, an additional soft ion component <1 keV in the precipitation spectra observed at all local times,
- A low-energy ion precipitation ($E<3$ keV) at the polar border of the nightside auroral oval.
- A morning sector low-energy ion precipitation at auroral and sub-auroral latitudes due to the differential eastward drift of particles after a substorm injection.

In this paper the essential characteristics of these regions will be reviewed in the context of the distribution of the various hot plasma domains in the outer magnetosphere.

Dayside Polar Cusp

The shape of the region at the ionospheric projection of the magnetosheath plasma penetration into the magneto-

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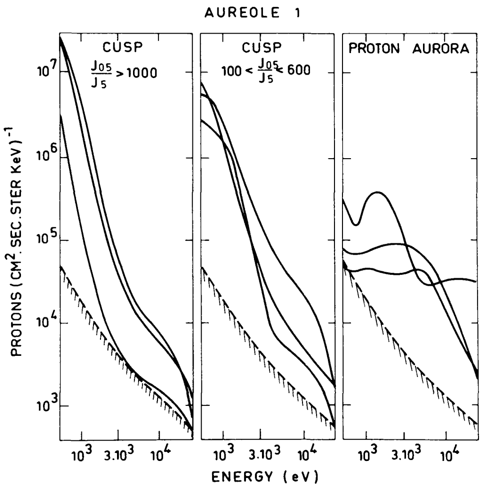

Fig. 1. Typical proton energy spectra at the dayside cusp and at the dayside auroral oval near magnetic noon

sphere was first considered as a more or less homogeneous band along the dayside auroral oval 08 h$\lesssim$MLT$\gtrsim$16 h with a latitudinal width of several degrees (Winningham, 1970; Heikkila et al., 1972; Vasyliunas, 1974). This has led to the widely adopted concept of a free penetration of magnetosheath plasma through an ever present cleft-like magnetic field branching structure extending from the dawn side to the dusk side, through noon. An initial analysis of the ARCAD results appeared to contradict this proposed pattern (Gladyshev et al., 1974). The shape of the polar cusp has been studied extensively from the ARCAD experiment by using nearly simultaneous, sequential oblique crossings on the same polar pass. The proton precipitations were categorized by their spectra. The magnetosheath-like spectra were defined according to the following criteria: the ratio α of the differential flux at 0.5 keV to that at 5 keV is greater than 100; the hot proton density N_p is higher than 1–3 cm^{-3}. It was assumed that such high densities of energetic particles at the dayside can be reached only in the magnetic flux tubes that are (or recently were) directly connected to the magnetosheath and filled with solar wind plasma. Spectra with lower values of α and N_p were considered as plasmasheet-like (Fig. 1) and were actually observed in all local time sectors along the auroral oval.

These soft protons with the magnetosheath-like spectra were found only near the magnetic noon meridian in a narrowly localized zone lying at auroral latitudes (Figs. 2 and 3) poleward of the so-called "sharp trapping boundary" (Cambou and Galperin, 1974a, b, 1982; Gladyshev et al., 1974; Sauvaud et al., 1980; Muliarchik et al., 1982). It turned out that this region can be non stationary (intermittent), and that this localisation indicates a funnel pattern of the cusp region at the magnetopause in contradiction to the longitudinally extended cleft inferred by other experimenters (Sauvaud et al., 1980).

Furthermore, it was recently shown (Muliarchik et al., 1982) by the analysis of simultaneous measurements of protons and electrons from the ARCAD experiment that the above mentioned near-noon area of soft protons with temperatures and fluxes similar to those in the magnetosheath

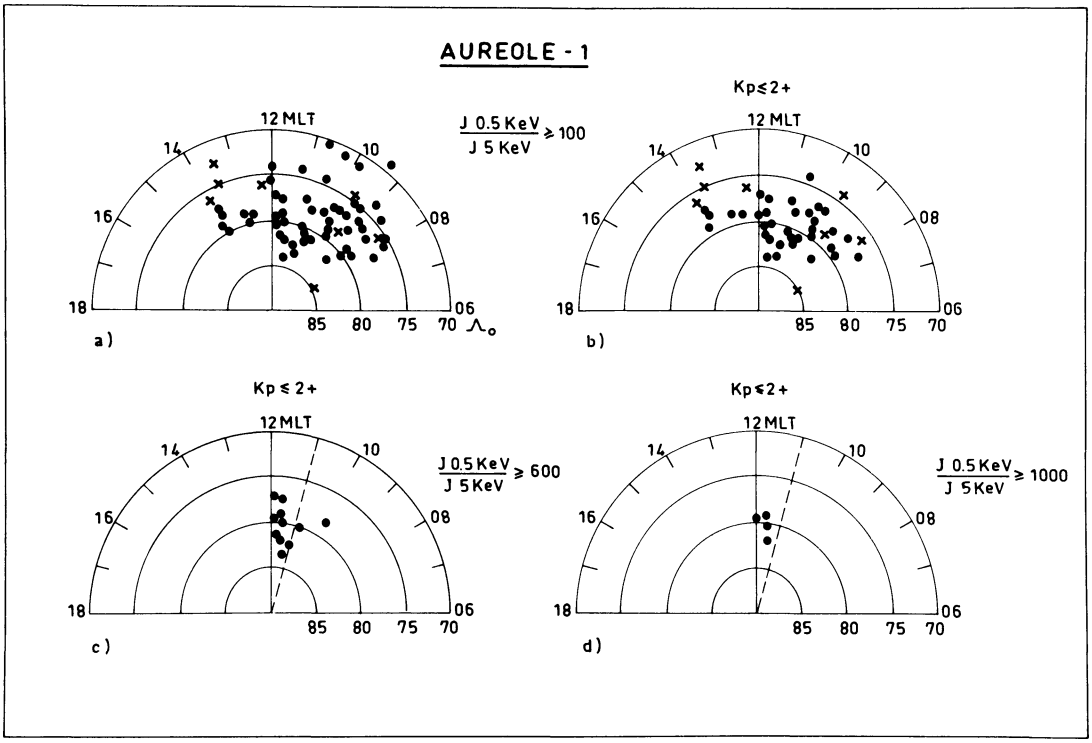

Fig. 2a–d. Polar Λ_0 – MLT plots of the positions of the maximum 0.5 keV proton fluxes in the polar cusp with a spectral ratio α equal to or higher than 100 ($\alpha = (dJ/dE)$ 0.5 keV$/(dJ/dE)$ 5.0 keV) for **a** all passes and **b** quiet period passes $Kp \lesssim 2_+$, for **c** quiet period passes with a spectral ratio $\alpha > 600$, and for **d** quiet period passes with a spectral ratio $\alpha > 1000$. Secondary maxima are shown by crosses if their intensity is not less than a half of the principal maximum of the pass and if they are not adjacent to the principal maximum (from Sauvaud et al. 1980)

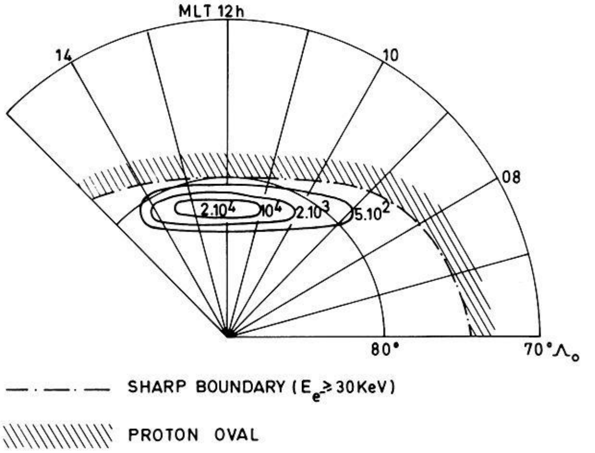

Fig. 3. Isocontours of the 0.5 keV proton fluxes at the dayside cusp in the summer hemisphere. The position of the sharp boundary (Λ_s) defined as a sharp drop in the flux of the energetic electrons ($E \gtrsim 30$ keV), is indicated by a dot-dashed line. The hatched region corresponds to the band of the higher energy protons drifting inside the trapping zone (from Muliarchik et al., 1982)

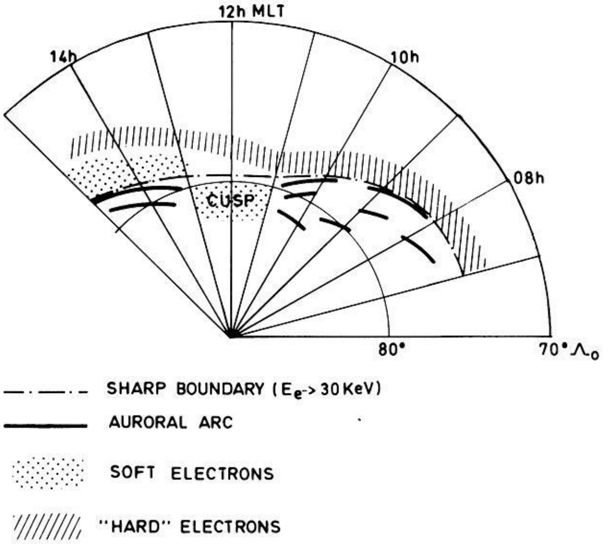

Fig. 4. View of electron precipitation at the dayside auroral oval. (from Muliarchik et al. 1982)

is situated just inside the dayside part of the discrete auroral oval (Fig. 4) and just coincides in position with the analogous zone of soft electrons recently found by Meng (1981). It also coincides with the so-called "gap" in the discrete auroral arcs found in this same noon region (Ismail et al., 1977; Dandekar and Pike, 1978; Reiff et al., 1978; Meng, 1981).

In contrast to these "cusp protons", significantly harder "plasma-sheet-like" proton spectra (usually with an additional maximum at keV energies) were invariably observed on every oval crossing equatorward of the trapping boundary.

Quiet Auroral Precipitation

During quiet times the proton auroral band must be regarded as practically continuous in local time (Crasnier et al., 1974). The energy spectra of precipitating protons in sequential local time sectors change gradually in shape (Galperin et al., 1976a), and the spectral forms have been found to be rather similar to those observed in the same local time sectors from ATS-5 at geostationary orbit (De Forest and McIlwain, 1971).

The "plamsasheet-like" spectra, usually with additional maxima at several keV for particles precipitating in the noon and postnoon sectors, were observed in the region of the diffuse electron aurora, that is, equatorward of the trapping boundary on the dayside, at the *L*-shells of stable trapping. it was concluded (Galperin et al., 1976a), that the origin of these harder protons is the adiabatic particle drift around the earth. Their drift paths can be traced from a "source" region situated, according to the E3–M2 model, in the nightside plasmasheet up to the region of pitch-angle scattering and precipitation at the dayside. The strong reduction of proton fluxes for energies higher than 15–20 keV, observed in the late morning sector, can be explained as due to the loss at the magnetopause of such protons drifting from the nightside towards the dayside along the E3–M2 drift paths.

The scattering processes were not identified, but some inferences on their characteristics and localisation have been made. First of all, the similarity between the high energy part ($E \gtrsim 1$–3 keV) of the precipitating and equatorial (Maxwellian-like) proton (ion) energy spectra along the proton auroral band suggests that there is no very significant energy diffusion inherent in this spectral component in the scattering process and also that there is no significant field-aligned electric potential drop in this region (Galperin et al., 1976a). (For the lower energy part of the energy spectrum the situation is much more complex). Secondly, the scattering takes place in dayside *L*-shells where stable trapping of hard electrons and protons is maintained. According to the recent data taken close to the magnetopause (Williams et al., 1979; Williams, 1980), this region can be identified with the Low Latitude Boundary Layer (LLBL), or even with the region earthward from it on the dayside. The conventional auroral oval on the dayside, as well as on the nightside, is defined by discrete auroral arcs and lies along and poleward of the "sharp trapping boundary", Λ_c (McDiarmid and Burrows, 1968). It lies at least partly, however, on the closed magnetic field lines. Hence the proton auroral band, both on the nightside and on the dayside, lies on closed, adiabatically drifting, field tubes (within the so-called diffuse auroral zone) bordering, on the equatorial side, the conventional auroral oval and discrete arcs (Feldstein and Starkov, 1967). Thirdly, the shape of the porton (ion) precipitation spectrum in the proton auroral band normally consists of two distinct populations. The higher energy population, which mainly carries the energy flux, varies in a systematic manner along the proton auroral band. The lower energy part of the spectrum ($E \lesssim 1$–3 keV) is less regular but usually carries the main density of hot ions in magnetospheric field tubes above the proton auroral band, that is in the same range of latitudes as the diffuse auroral zone.

The latitudinal variation of the precipitating proton spectra across the nightside proton auroral band reflects variations of the proton characteristics in the magnetospheric equatorial region. By field line tracing of the position of the AUREOLE satellite to the equatorial plane with the magnetospheric models of Mead-Fairfield MF-73 Q

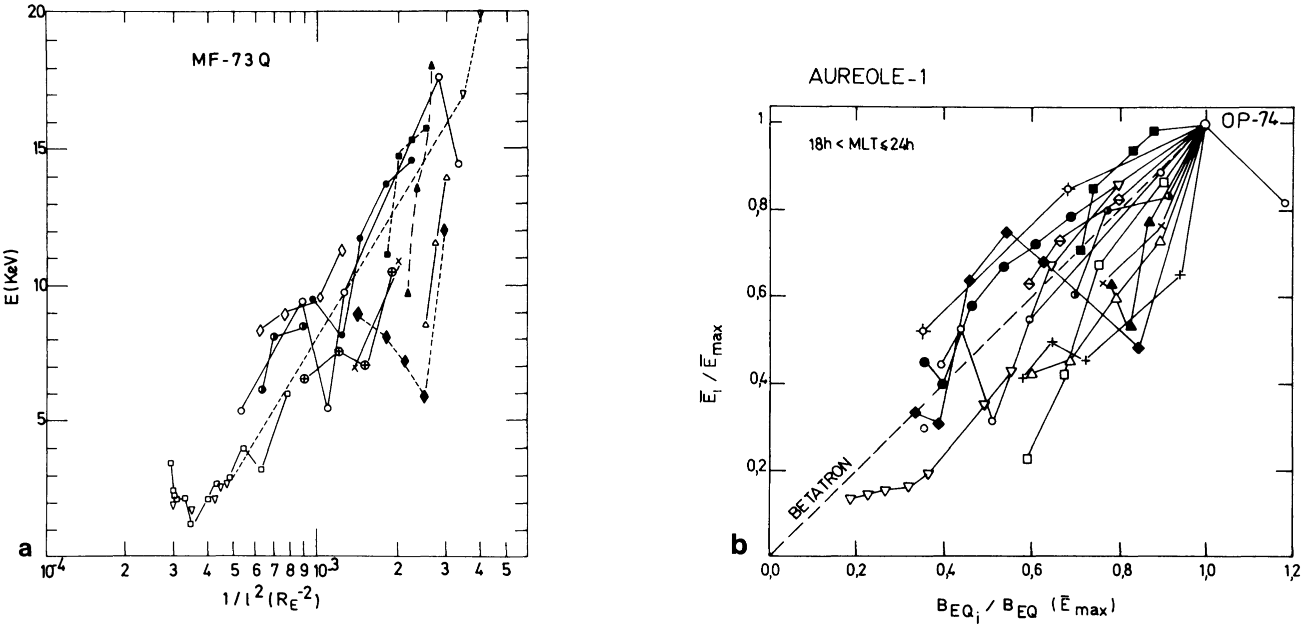

Fig. 5a, b. Correlation of the auroral proton (0.4–30 keV) average energy $\bar{E}$, with the magnetospheric field tube characteristics of the models OP-74 and MF-73 Q for the evening and midnight sectors. **a** Correlation with l^{-2} (l equals field tube length in earth radii R_E). **b** Correlation with B_{eq} (equatorial magnetic field); for each pass the average energy $\bar{E}$ has been normalized to its maximum value $\bar{E}_{max}$ and B_{eq} has been normalized to the respective value B_{eq} ($\bar{E}_{max}$). (from Galperin et al., 1978)

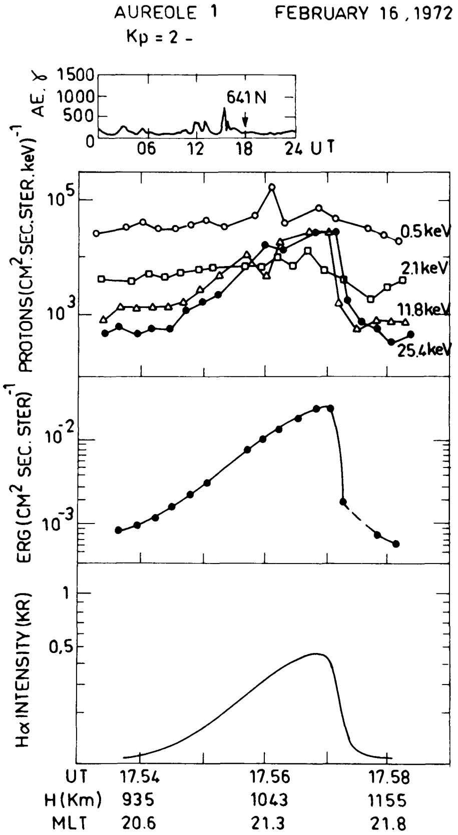

Fig. 6. Example of a coordinated observation between low-energy ions (0.5–25 keV) measured on board AUREOLE-2 and H_α intensity measured from the Loparskaya station. The AE index variation, the ion differential flux, the ion integral energy flux and the H_α intensity for the pass 641 N on 16 February 1972 are illustrated

(Mead and Fairfield, 1975) and of Olson and Pfitzer OF-74 (Olson and Pfitzer, 1974), it was possible to compare the average ion energy $\bar{E}$ (or Maxwellian temperature) variation across the band with the variation of the equatorial magnetic field B_{eq}, and with the variation of the length of the satellite field line l. During the particle's earthward drift inside the plasmasheet a proportionality is expected between the perpendicular particle energy component $E_\perp$, and B_{eq} (betatron and acceleration) and a similar relation is expected between the particle's parallel energy $E_\|$ and l^{-2} (Fermi acceleration).

The comparisons made using the ARCAD observational data (Galperin et al., 1978) have shown that both such proportionalities are equally consistent (within experimental scatter) with the observed variations of the proton energy spectra across the nightside part of the proton auroral band (Fig. 5a, b). It was concluded that during quiet times the observed particle drift in the plasmasheet is indeed adiabatic, but it is still impossible to discriminate between betatron (near equatorial drift until the moment of precipitation) and Fermi acceleration (gradual lowering of mirror points for particles with low equatorial pitch angles) or a combination of the two, as the dominant process.

It must be stressed that the ARCAD spectrometers did not make a mass selection. Therefore, it is not possible to decide directly if the analyzed particles are protons or other ions. For this reason simultaneous coordinated observations of the Balmer auroral emissions from the Loparskaya station near Murmansk were correlated with ion differential flux and integral energy flux measurements from AUREOLE-1 passes above this region (Bolunova et al., 1982). From photometric ground-based observations the extent of the H_α intensity along the magnetic meridian was measured. For the case illustrated by Fig. 6 the low-latitdue border of the proton auroral band was seen from the Lo-

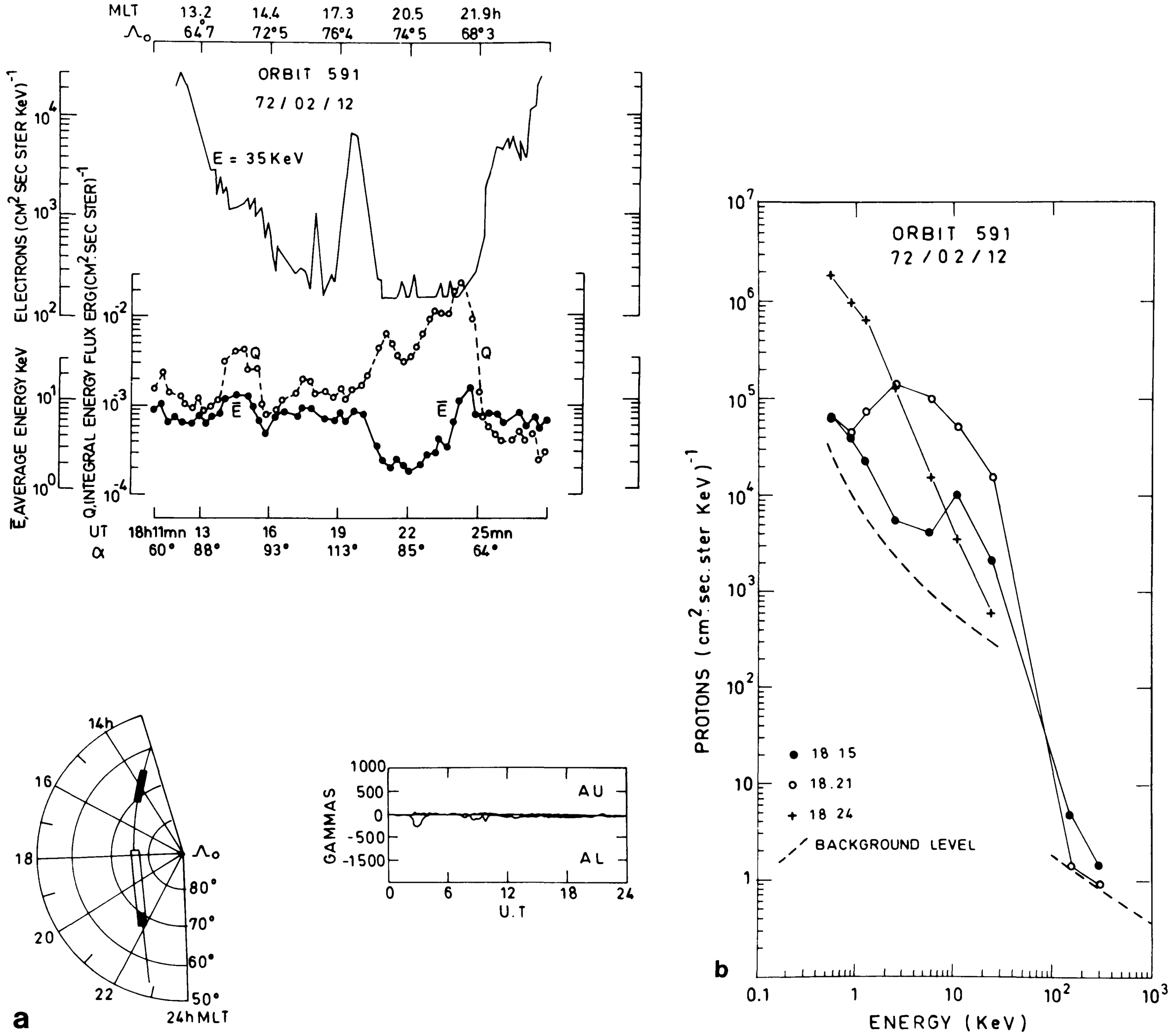

Fig. 7a and b. Example of soft ion precipitation on the polar side ($\Lambda_0 \simeq 75°$) of the auroral oval during very quiet magnetic conditions. **a** In the upper part of the figure the flux of high energy electrons ($E = 35$ keV), the auroral proton (0.4–30 keV) average energy $\bar{E}$, and their integral energy flux Q, are plotted as a function of universal time. The pitch angle α of the detected particles, the magnetic local time MLT and the invariant latitude Λ_0 of the satellite are also indicated. The low energy ion precipitation is detected between approximately 18:20 and 18:23 UT In the lower part of the figure the AU and AL indices and the satellite trajectory in a Λ_0 – MLT polar plot are illustrated. **b** Three typical energy spectra. The points and circles indicate auroral proton energy spectra while the crosses are for a typical spectra of soft ion precipitation

parskaya station and its position coincided very well with the equatorial boundary of the ion precipitation measured simultaneously from AUREOLE-1. In other cases during more disturbed conditions the proton auroral band filled the sky from the horizon at Loparskaya, and the satellite data also show an extended proton auroral band above this region with its low latitude border at lower subauroral latitudes. The intensities of Balmer emissions and of particles assumed to be protons were in reasonable agreement in both of these cases showing that protons constitute more than 50% of the precipitating ions (Ponomarev, 1976).

Polar Low-Energy Precipitation

Sometimes during periods of very low global magnetic activity, i.e. low convection electric field, very soft proton (ion) precipitation extended more poleward than the normal proton auroral band through the auroral oval and even further poleward into the polar cap (Cambou et al., 1975; Galperin et al., 1978). An example of this type of precipitation is shown in Fig. 7a. Between 18:20 and 18:23 UT ($70° \lesssim \Lambda_0 \lesssim 75°$, $18{:}00 \lesssim \mathrm{MLT} \lesssim 21{:}00$), AUREOLE-1 detected a low energy ($\bar{E} \simeq 3$ keV) precipitation beyond the trapping boundary for 35 keV electrons, while an auroral precipitation ($E > 10$ keV) was observed inside this boundary. The typical energy spectrum of this precipitation is compared to two spectra characteristic of auroral-type ion precipitation in Fig. 7b. It has already been noted that a closed field-line region during such quiet periods, usually characterized by strong positive B_z (IMF), can extend far into the polar cap (McDiarmid et al., 1980) while the average characteristics of plasmasheet particles are similar to those of magnetosheath particles (Akasofu, 1977); these reconfigurations of the magnetospheric tail during such specific conditions with $B_z > 0$ must therefore be reflected somehow in the precipitating particle spectra and location. More sensitive ion detectors are needed in future experiments for detailed investigations of these interesting phenomena during intervals of $B_z > 0$.

Substorm-Related Flux Variations

One of the significant new findings from the AUREOLE-1 data base was that in the post-midnight and early morning sectors a peculiar structure with energy separation in the latitudinal profile of ions was found at the equatorial edge of the proton precipitation band from one to several hours after a subtorm. Fig. 8 shows a measurement taken near 24:00 MLT, for which a precipitation zone at subauroral latitudes appears, and for which 24.4 keV ion fluxes are absent. In general, the average energy of precipitated particles decreases later in the morning sector. This dispersive pattern was observed on several occasions at low energies, making it possible to establish typical characteristics of this morning-side substorm injection phenomena (Sauvaud et al., 1981). This appears to be somewhat related to the previously discovered (Smith and Hoffman, 1974) evening energetic proton "nose" events resulting from substorm ion energisation/injection near midnight followed by westward gradient and curvature drift.

Here, for low energy ions in the morning subauroral sector, the eastward E_{cor} x B drift dominated in accordance with the E3–M2 electric field model (Fig. 9). Trajectory tracing calculations have confirmed that the substorm timings, according to ground-based data, were consistent with the positions of the observed eastward-drifting dispersive structure of low-energy ions injected at midnight during a substorm (presumed, without definite proof, to be protons, as they were measured by an electrostatic analyser which selects particles only according to their E/Q ratio.

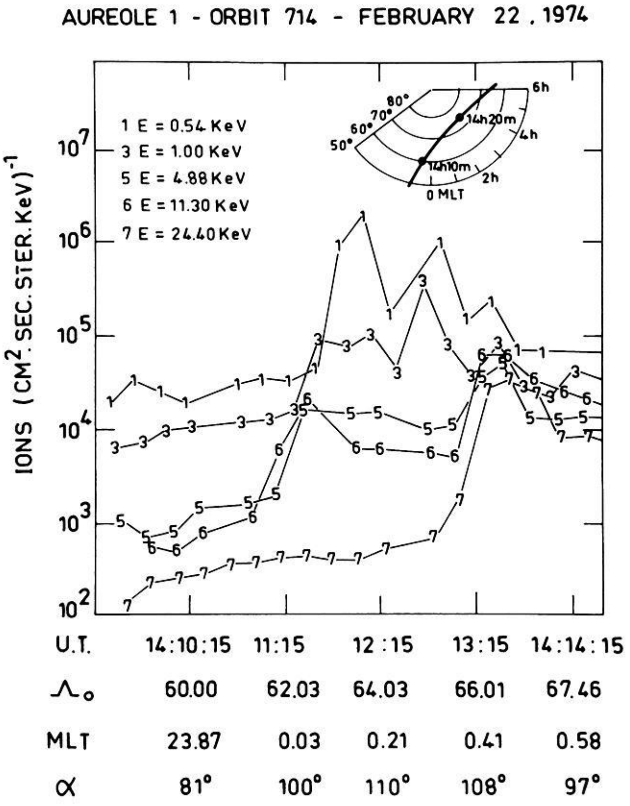

Fig. 8. Ion differential energy flux for 5 energy levels. The AUREOLE-1 satellite orbit is illustrated in the upper part of the figure on a Λ_0 – MLT polar plot. The invariant latitude (Λ_0), the magnetic local time (MLT) of the satellite, and the pitch-angle α of the detected ions are also indicated. The morning subauroral precipitation of low energy ions is recognizable between approximately 14:11:15 and 14:12:45 UT. (From Sauvaud et al., 1981)

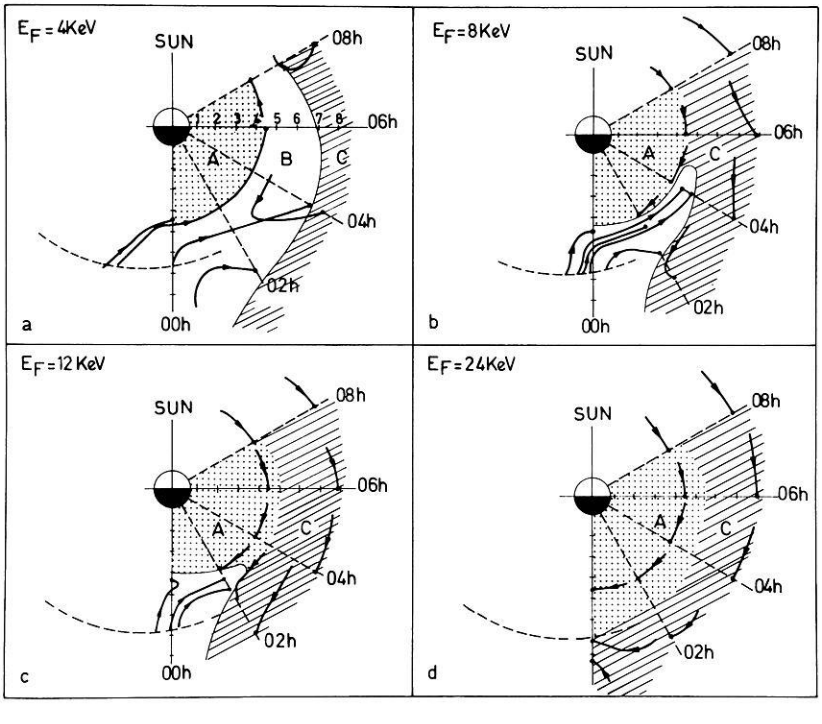

Fig. 9. Results of the calculations of ion trajectories (E3–M2 model) in the equatorial plane of the magnetosphere for 4 final eneries (4, 8, 12, and 24 keV) assuming a pitch-angle of 90°. The dashed line indicates the "injection boundary" position ($Kp = 1$). Zone A is the trapping region, zone B is accessible to particles drifting eastward from the injection boundary. Zone C is accessible to particles drifting westward, from the injection boundary, around the Earth. (From Sauvaud et al., 1981)

Discussion

The global pattern of ion precipitation presented in this paper leads to a tentative classification as a function of its origin and of the physical mechanisms responsible for its main characteristics. The picture constructed can be used as a reference for future observations related to ion precipitation and acceleration. However, it has strong limitations, especially due to the instrument performance which does not allow a mass analysis. Furthermore, it is evident that a detailed analysis of the precipitating regions would require simultaneous plasma, energetic particle, wave, magnetic and electric field measurements. These will be the main goals for more advanced future experiments in order to find an unifying pattern for the hot particle structure, field-aligned currents and convection in these complex and important regions of the near-Earth magnetosphere.

On the other hand, it must be stressed that one of the most important results deduced from AUREOLE-1 is that the ion energy spectra of precipitation in the diffuse aurora, which extend several degrees equatorward of the classical auroral oval defined from observations of auroral arcs, show two components. A suprathermal component from several 10's of eV to 3 keV and a more energetic component ($E \gtrsim 3$ keV), which had been proven to be of magnetospheric origin and adiabatically accelerated during the ions' drift toward the earth. The origin of the suprathermal component ($E \lesssim 1$–3 keV) which is also detected in the equatorial plane (Balsiger et al., 1980) remains unclear. It seems however reasonable to propose that a direct connection exists between this suprathermal ion population and the dense secondary electron produced by the plasmasheet electron precipitation in the diffuse auroral zone (Evans and Moore, 1979). Indeed, this high number densities (>1–3 cm^{-3}) found for this secondary electron population of ionospheric origin well above the night-side diffuse auroral zone evidently implies equal ion densities. Such high ion densities can be supplied by the ionosphere in the "source cone" and released into the magnetospheric field tube together with secondary electrons (Cambou and Galperin, 1982). It is possible to suggest that thermal protons from the upper ionosphere probably constitute the main part of this outward flowing ion population, but other ionospheric constituents, presumably He$^+$ and O$^+$, may participate in this additional ionosperic source above the diffuse auroral zone. This hypothesis must be directly verified by simultaneous measurements of the velocity distribution functions of the electrons and of the main ionospheric ions in a wide energy range in order to taken into account the "background" ionospheric plasma as well as the accelerated particles. This kind of study is one of the main goals of the new ARCAD-3 experiment.

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