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INTERBALL-Auroral observations of 0.1-12 keV ion gaps in the diffuse auroral zone

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Abstract. We examine ion flux dropouts detected by INTERBALL-Auroral upon traversal of the auroral zone at altitudes of ~13 000 up to 20 000 km. These dropouts which we refer to as "gaps", are frequently observed irrespectively of longitudinal sector and appear characteristic of INTERBALL-Auroral ion spectrograms. Whereas some of these gaps display a nearly monoenergetic character (~12 keV), others occur at energies of a few hundreds of eV up to several keV. INTERBALL-Auroral data exhibit the former monoenergetic gap variety essentially in the evening sector. As examined in previous studies, these gaps appear related to transition from particle orbits that are connected with the magnetotail plasma source to closed orbits encircling the Earth. The latter gap variety, which spreads over several hundreds of eV to a few keV is often observed in the dayside magnetosphere. It is argued that such gaps are due to magnetospheric residence times well above the ion lifetime. This interpretation is supported by numerical orbit calculations which reveal extremely large (up to several tens of hours) times of flight in a limited energy range as a result of conflicting $\mathbf{E} \times \mathbf{B}$ and gradient-curvature drifts. The characteristic energies obtained numerically depend upon both longitude and latitude and are quite consistent with those measured in-situ.

Key words. Magnetospheric physics (auroral phenomena; plasma convection).

1 Introduction

In the inner magnetosphere, nearly equatorial high-altitude orbiting spacecraft often reveal a decrease or even an absence (i.e., below the detection threshold of the instrument) of ion fluxes at energies ranging from ~1 up to several tens of keV. At geosynchronous altitude, McIlwain (1972) reported a flux minimum with an energy decreasing from 10 keV to ~1 keV as the spacecraft travels from midnight to dawn and noon sectors. This flux minimum was interpreted as the result of very large proton residence times (from 12 to 120 hours) as compared to characteristic loss times. Near the equatorial plane, such flux variations were also observed by the AMPTE spacecraft at radial distances of ~3 R_E to ~7 R_E (e.g., Kistler *et al.*, 1989). These features were successfully reproduced by numerical modeling taking into account charge exchange losses and wave-particle interactions in a dipolar geomagnetic field (Fok *et al.*, 1995; Jordanova *et al.*, 1996, 1997).

Early studies of auroral satellite data (Jorjio and Kovrazhkin, 1976; Galperin *et al.*, 1976) similarly reported sharp flux dropouts in the ~10–30 keV range in the pre-noon sector. These dropouts were interpreted in terms of magnetopause shadowing for ions drifting from the nightside sector. Recently, Shirai *et al.* (1997) examined monoenergetic (~12 keV) dropouts recorded by the AKEBONO auroral spacecraft at altitudes of 5000 to 10 000 km near the equatorward edge of the discrete auroral zone. The study of Shirai *et al.* (1997) suggests that these structures are direct consequences of the open/closed character of the ion drift paths in the inner magnetosphere. In this work, we report on (H^+) gaps observed by the ION experiment onboard INTERBALL-Auroral (Sauvaud *et al.*, 1998) We show that these gaps which are quite frequently observed by INTERBALL-Auroral at altitudes of 13 000 to 20 000 km (~2 to 3 R_E) in the diffuse auroral zone, call for different interpretations depending upon magnetic local time. In particular, in line with previous studies (McIlwain, 1972; Fok *et al.*, 1995; Jordanova *et al.*, 1996, 1997), we demonstrate that, in the morning and afternoon sectors, these gaps are most probably due to magnetospheric residence times greatly exceeding the ion lifetime.

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2 Observations

INTERBALL-Auroral was launched on August 29, 1996 into an orbit with 62.8° inclination, 20 000 km apogee and 750 km perigee. The other satellite of the mission, INTERBALL-Tail, was launched one year before. Both satellites have a sub-satellite. The data presented in this work are from the ION experiment onboard the INTERBALL-Auroral spacecraft. The ION experiment consists of four detectors, i.e., two mass spectrometers which use Wien filters to measure ion fluxes in the 30–14 000 eV energy range and two cylindrical spectrometers which measure electrons in the 10–22 000 eV energy range (Sauvaud *et al.*, 1998). Figure 1a presents an example of INTERBALL-Auroral/ION observations achieved in the morning sector on November 10, 1996. During this pass which corresponds to moderate magnetic activity ($Kp = 2$), the spacecraft was traveling from high to low invariant latitudes (ILAT), the magnetic local time (MLT) varying from 4.4 to 6.5 h and the altitude from 19 000 to 14 700 km (i.e., ~3 to ~2.3 R_E). The top and bottom panels in Fig. 1a present energy-time spectrograms for electrons and ions, respectively. Note that, throughout the study energy-time spectrograms are shown in units of flux, $(cm^2.sec.ster.keV)^{-1}$.

In the bottom panel of Fig. 1a, plasma sheet ions are noticeable between ~1215 and ~1235 UT with energies from <100 eV to >10 keV characteristic of the proton aurora. The repeated vertical streaks with low count levels here coincide with pitch angles approaching 180°. These streaks accordingly reveal negligible ion flux in the nearly anti-parallel direction. However, note the substantial flux of outgoing ions at low energies (in the hundreds of eV range) near 1227 UT, indicative of significant outflow from the ionosphere. Subsequently, upon transport into the magnetosphere, such ionospheric ions will contribute to populating the plasma sheet (e.g., Sauvaud *et al.*, 1985; Delcourt *et al.*, 1989) and may be the origin of the low-energy component detected at low latitudes (typically, after 1245 UT in Fig. 1a). After ~1235 UT, a clear gap is noticeable in the ion spectrogram. As the spacecraft travels from high to low latitudes, this gap first extends from ~3 to ~6 keV and is gradually shifted toward larger energies. It reaches the ~5–10 keV range near 1310 UT and subsequently disappears as INTERBALL-Auroral enters the outer radiation belts (~63.8° ILAT) where a nearly uniform background is measured. In conjunction with the ion gap, at high energies significant flux can be seen in the hundreds of eV range, as expected from the dawnward transport of low-energy ion component of the plasma sheet (e.g., Sauvaud *et al.*, 1981). Inside the ion gap itself note the appearance of vertical streaks coinciding with pitch angle approaching both 0° and 180°; i.e., for particles having a low altitude mirror point. At high latitudes, before 1215 UT the satellite encounters intense fluxes of low energy electrons from the dawn boundary layer. These are associated with ion injections.

The pitch angle distribution within the ion gap can be better appreciated in Fig. 1b which shows an enlargement of the energy-time spectrogram during two spin periods (from 1250 UT to 1254 UT). This figure clearly puts forward a prominent dependence of the gap boundaries upon energy and pitch angle. Indeed, on the high-energy side of the gap, it can be seen that the ion flux exhibits a V-like shape with significant flux only near 90° at the edge (i.e., at ~7 keV) and over a wider angular range at larger energies. In other words, since ~7 keV ions are close to their mirror point, they do not have access to lower altitudes and, at these altitudes, one may expect a shift of the V-like flux pattern toward higher energies. Conversely, at higher altitudes, the gap energy range may significantly shrink due to inclusion of particles mirroring below the spacecraft. Inspection of energy-time spectrograms reveals that such a V-like pattern is fairly systematically obtained on the high-energy side of the gap. As for its low-energy side, Fig. 1b displays a pattern more square and also noticeable low energy flux ($E < 600$ eV) in the anti-parallel (outgoing) direction. Note also the absence of downflowing ions. This latter pattern was also found to be quite typical of the gap lower energy boundary. As we will examine in the Discussion section, particles with energies below and above the central energy of the gap drift in "opposite" directions from the nightside plasma sheet, their different history leading to different pitch angle distributions. INTERBALL-Auroral Ion measurements frequently exhibit such gap features which clearly contrast with those reported by Shirai *et al.* (1997) in the morning sector, namely, the gap portrayed in Fig. 1a is not monoenergetic and the "nose" structure of Shirai *et al.* (1997) is not observed here.

On the other hand, throughout the time interval considered, the top panel of Fig. 1a displays significant electron flux with energies ranging from ~1 keV at high latitudes (~1217 UT) up to 8 keV and above at low latitudes (~1250 UT). These variations are consistent with adiabatic Fermi-type energization of the electron population during convection into the inner magnetosphere (e.g., Galperin *et al.*, 1978, Sauvaud *et al.*, 1981). A similar trend, although less clear, is noticeable for the H^+ average energy in the bottom panel of Fig. 1a. Such an evolution of the particle fluxes makes clear that the ion gap occurs within the diffuse auroral zone, at the outer edge of the radiation belts. As mentioned already, note again the flux depletion in directions nearly parallel and anti-parallel to the magnetic field, yielding repeated vertical streaks in the bottom panel of Fig. 1a.

Figure 2 presents another example of ion gaps observed by INTERBALL-Auroral. The top panel shows the ion energy-time spectrogram obtained while the spacecraft was traversing the dayside magnetosphere from ~14.20 MLT to ~18.70 MLT on February 5, 1997. The bottom panel shows the ion spectrogram recorded subsequently in the evening sector, from ~18.7 MLT to ~21.7 MLT ($Kp = 0$). The spectrograms shown in Fig. 2 are quite typical of INTERBALL-Auroral dayside-to-nightside traversals. They exhibit three well-developed ion gaps, labeled *a, b,* and *c,* respectively. If we first consider gap *a* (from ~0835 UT to ~0857 UT in Fig. 2b), it is apparent that this structure occurs at nearly constant energy (of the order of 12 keV) in the

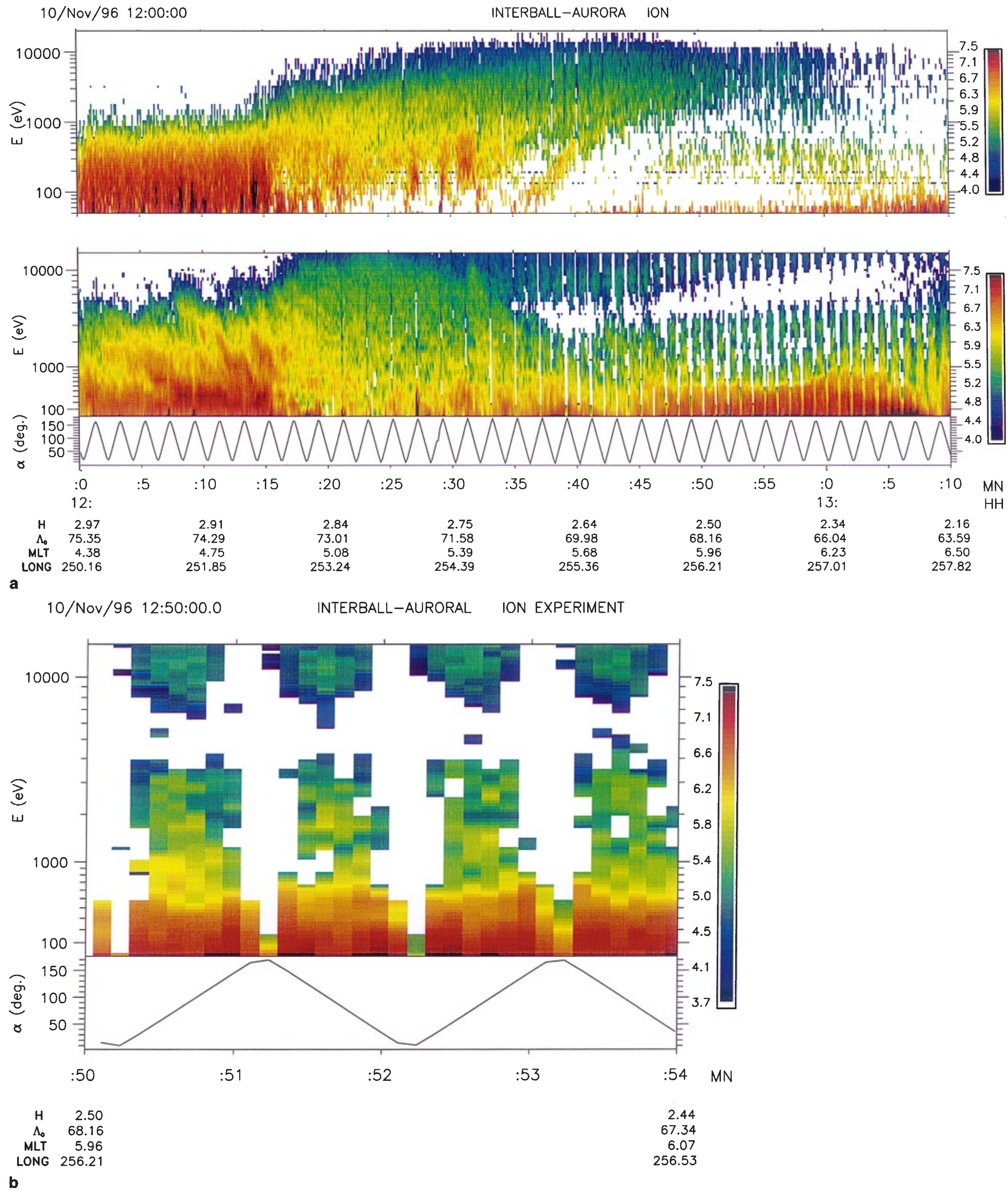

Fig. 1. **a** (*Top*) electron and (*bottom*) ion energy-time spectrograms recorded by INTERBALL-Auroral on November 10, 1996 from 1200 to 1310 UT. Fluxes in $(cm^2.sec.ster.keV)^{-1}$. Pitch angle versus time is given for the ions. **b** Ion energy time spectrogram during a two spin period (from 1250 UT to 1254 UT) for the November 10, 1996 pass (see ***a***)

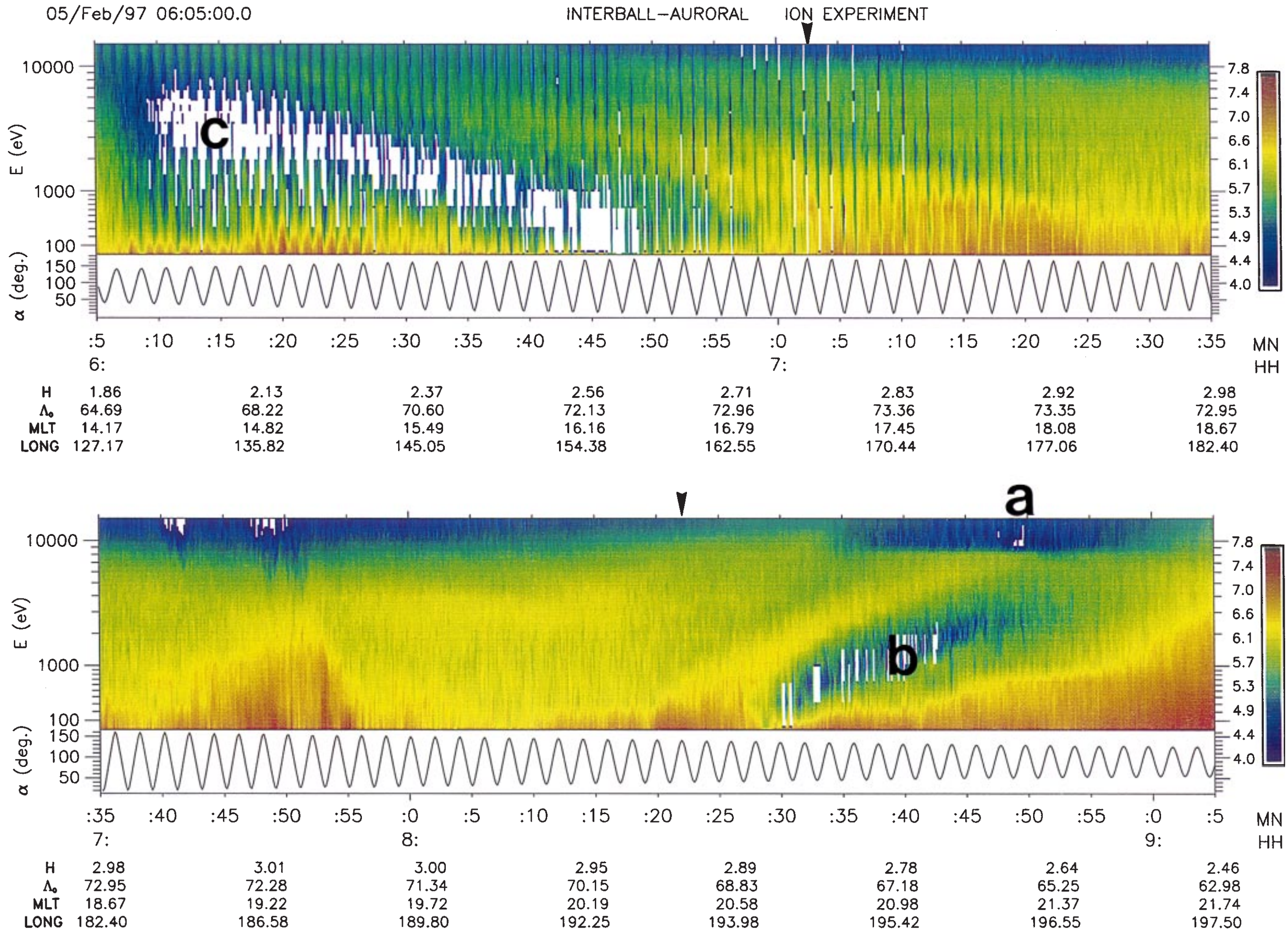

Fig. 2a, b. Ion energy-time spectrograms recorded by INTERBALL-Auroral on February 5, 1997: **a** in the afternoon sector (from 0605 UT until 0735 UT), **b** in the evening sector (from 0735 UT until 0900 UT). *Arrows* at the *top* of each *panel* indicate the diffuse auroral zone boundaries for electrons. Ion gaps in the evening and afternoon sectors are labeled *a*, *b* and *c*

pre-midnight sector while the spacecraft is traveling toward low latitudes. This structure is interrupted by S/C entry into the outer radiation belts. As for gap *b*, it is observed nearly simultaneously, from ~0827 UT to ~0855 UT. However, in contrast to gap *a*, this latter structure exhibits a prominent energy variation, from several hundreds of eV at high latitudes (~0830 UT) up to several keV at low latitudes (~0850 UT). Combination of gaps *a* and *b* in Fig. 2b yields the formation of a "nose" made of enhanced ion flux.

In Fig. 2a, gap *c* extends from ~0607 UT (which coincides with S/C exit from the radiation belts) until ~0650 UT. The energy range of this gap similarly exhibits a prominent latitudinal dependence, from ~3–6 keV at ~66.2° ILAT down to ~0.1–1 keV at ~72.7° ILAT. Repeated streaks due to negligible field-aligned ion flux are again noticeable and a detailed analysis of the upper and lower edges of the gap reveals a structure quite similar to that in Fig. 1b. Note moreover that gaps *a*, *b*, and *c* occur within the diffuse auroral zone as can be seen from the arrows at top of Fig. 2a,b which indicate the boundary of the electron diffuse auroral region.

To provide a more global view of INTERBALL-Auroral gap observations, Fig. 3 presents the statistical distribution obtained from 168 passes over the auroral zone. In Fig. 3, the color-coded average energy of H^+ gaps is shown as a function of both magnetic local time and invariant latitude. Monoenergetic gaps such as type *a* in Fig. 2 were not considered in these statistics. In Fig. 3, it can be seen that ion gaps extend over a wide interval of MLT at low latitudes (typically, over more than 18 h at 64° ILAT). This extension drastically decreases as latitude increases, reaching ~10 h at 70° ILAT. Also, it is apparent that, at a given latitude, the average gap energy decreases when MLT increases. For example, at 65° ILAT, one has energies of ~6 and ~1 keV at 02 and 20 MLT, respectively, whereas at 70° ILAT, one has ~3 and ~1 keV at 05 and 18 MLT, respectively.

Finally, in order to obtain a first estimation of the stability of the gaps, we computed their occurrence normalized to the number of INTERBALL-Auroral passes in elementary MLT-ILAT bins of 0.25 H × 0.5°. The result is presented in Fig. 4. Gaps are more frequent

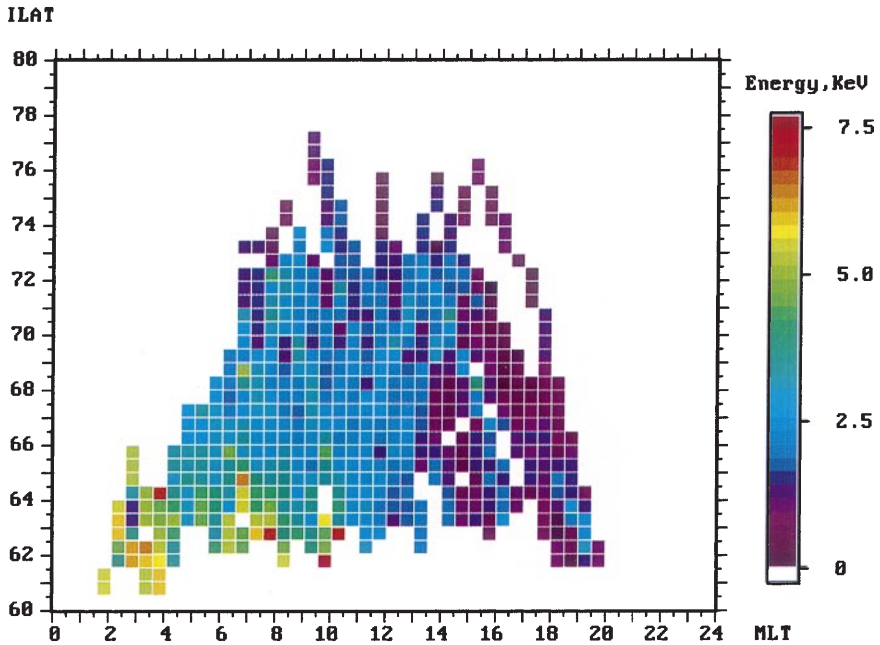

Fig. 3. Statistical distribution of the average H^+ energy (coded according to the *color scale at right*) within gaps as a function of MLT and ILAT. This statistics is based upon 168 passes of INTERBALL-Auroral over the auroral zone, from October 1, 1996 to June 27, 1997 and regardless of magnetic activity

at latitudes lower than about 70° for local times between 06 and 14 H MLT, i.e., in the inner dayside magnetosphere.

3 Discussion

It was mentioned already that the ion gaps displayed in Figs. 1 and 2 are quite frequently observed by INTERBALL-Auroral near the outer edge of the radiation belts. In the evening sector, early in-situ measurements (e.g., Smith and Hoffman, 1974) already put forward the existence of nose structures similar to that in Fig. 2b, with clear nearly monoenergetic cutoffs at high energy. In a recent study of AKEBONO data, Shirai *et al.* (1997) reported similar cutoffs (referred to as ion drop-off bands) in the morning sector. Though at much higher latitudes, Shirai *et al.* (1997) pointed out that these features can be viewed as the same phenomenon as that investigated by Smith and Hoffman (1974) in the equatorial region. These features were interpreted as the result of open/closed particle orbits, that is, particles having drift paths connected or not to the magnetotail plasma source. Even though INTERBALL-Auroral

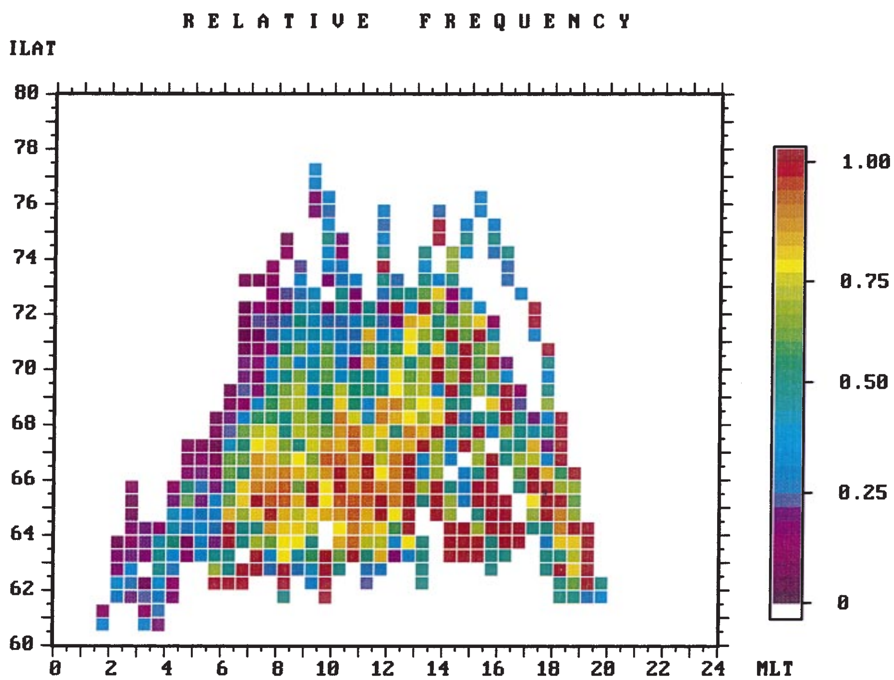

Fig. 4. Distribution of the gap crossings as a function of magnetic local time (MLT) and invariant latitude (ILAT). Data have been normalized taking into account the number of satellite passes in each bin. The total number of passes is 168 (see Fig. 3)

measurements do not exhibit such sharp monoenergetic cutoffs in the morning sector, it is clear that gap *a* in Fig. 2b is in agreement with these observations. As for gap *b* (i.e., the low-energy edge of the nose), it is due to dawnward (corotation and convection) transport of the relatively low-energy ions, which makes the evening sector inaccessible to this population. On the other hand, if one considers gap *c* in Fig. 2a, this structure is observed over a fairly large range of energies in the afternoon sector, in which case an interpretation based upon open/closed orbits or preferential dawnward/duskward transport becomes questionable. As initially proposed by McIlwain (1972), this leads us to consider a different cause for this ion gap, namely, the magnetospheric residence time of the particles.

To investigate this effect, we performed single-particle trajectory calculations within the Tsyganeko (1989) model, considering an average magnetospheric configuration ($Kp = 2^{-}, 2, 2^{+}$) (see Delcourt *et al.* 1989 for details on the trajectory code). These calculations were carried out adopting a Volland (1978) potential distribution in the ionosphere, with an average cross-polar cap potential drop of 60 kV. Test protons were launched from a given position with parameters consistent with INTERBALL-Auroral observations. They were traced backward in time using the guiding center approximation which is appropriate here since we focus on the inner magnetosphere. The tracing was interrupted when the particle drifted back to its initial position (i.e., it evolves onto a closed orbit) or when it reached a nonadiabatic regime in the mid-tail (as identified by $\kappa < 3$, κ being the square root of the minimum curvature radius to maximum Larmor radius ratio). Figure 5 presents the results of these calculations for two distinct longitudinal locations of INTERBALL-Auroral (0600 and 1300 MLT in the top and bottom panels, respectively). In this figure, test protons were initialized at 67° ILAT with distinct energies (from 1 to 20 keV by steps of 1 keV) and 90° pitch angle at INTERBALL-Auroral altitude ($\sim$2.5 R_E).

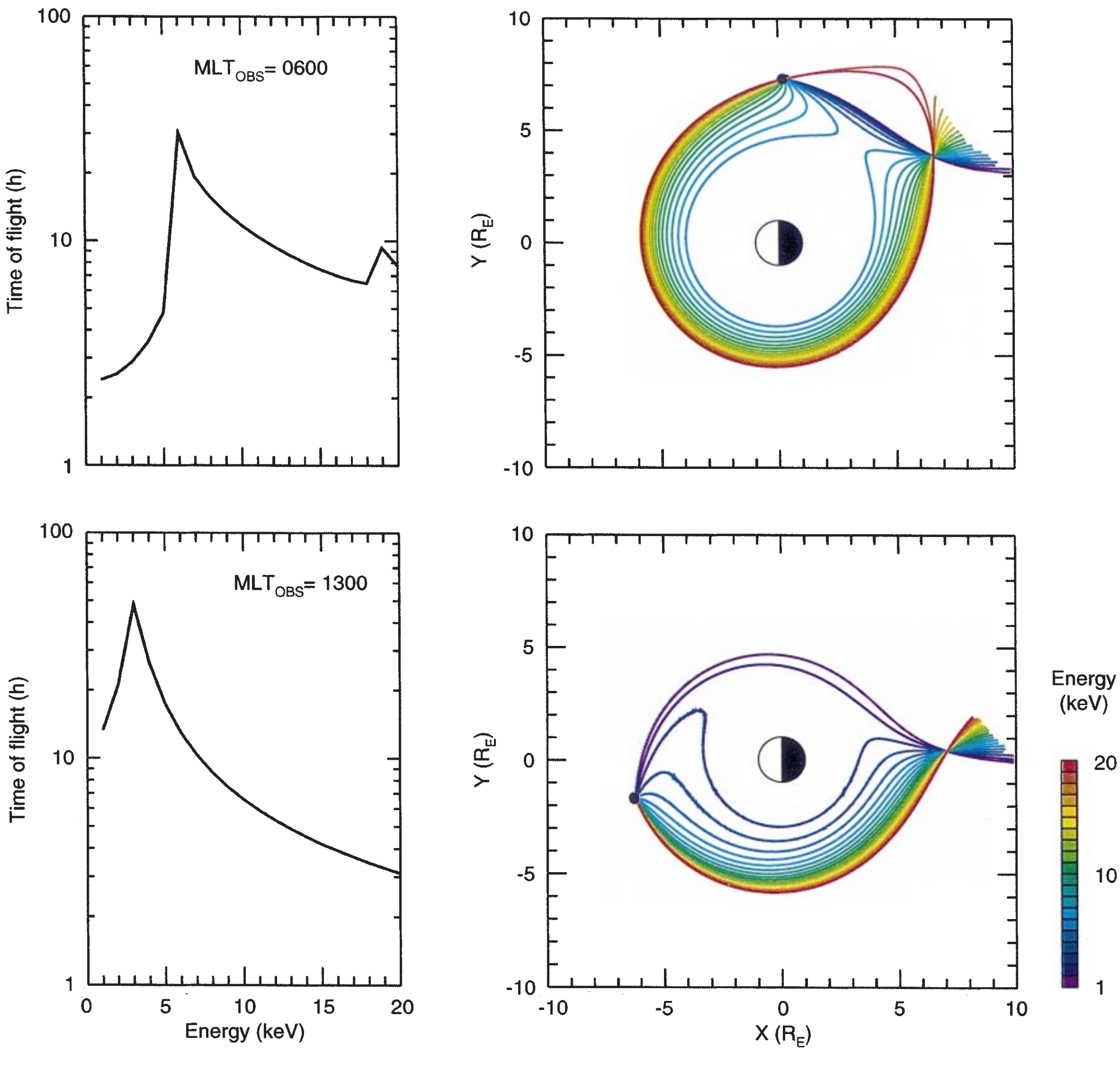

Fig. 5. Model H^+ trajectories in the *Tsyganenko* (1998) model: (*right*) equatorial crossing points, (*left*) time of flight versus initial energy. The test protons are traced backward in time from an observation point placed at (*top*) 0600 MLT and (*bottom*) 1300 MLT. In the *right panels,* the distinct energies at the observation point (*closed circle*) are coded according to the *color scale* at *right*

The right panels of Fig. 5 show the equatorial crossing points of the H^+ orbits, the energy at the observation point being coded according to the color scale at right. Not surprisingly, it is apparent from these panels that the low-energy (viz., up to 4 keV and 2 keV in the top and bottom panels, respectively) protons reaching INTERBALL-Auroral (closed circles) travel eastward under the predominant effect of the $\mathbf{E} \times \mathbf{B}$ drift. In contrast, high-energy H^+ are transported westward under the predominant effect of gradient curvature drifts. However, an interesting feature in Fig. 5 is that ions with intermediate energies and for which the eastward $\mathbf{E} \times \mathbf{B}$ drift temporarily balances the westward gradient drift exhibit extremely long residence times. This is clearly noticeable in the left panels of Fig. 5, which present the H^+ time of flight as a function of initial energy. For an observation point placed at 0600 MLT (top panel), it can be seen that, whereas low-energy H^+ are convected from the mid-tail to INTERBALL-Auroral in a few hours, an abrupt increase in residence time (up to ~30 hours) is obtained for ~5-keV H^+. At higher energies (up to ~18 keV), this residence time gradually decreases due to more effective gradient drift. Finally, at energies above ~18 keV, a slight increase in residence time is also noticeable due to closing of the particle orbits around the Earth (red lines in the top right panel). The bottom panels of Fig. 5 display a somewhat similar behavior if the observation point is placed at 1300 MLT. In this case, eastward drifting low-energy H^+ reach INTERBALL-Auroral in 10–20 h and a maximum in residence time (up to ~50 h) is again obtained at intermediate energies (~3 keV) due to conflicting $\mathbf{E} \times \mathbf{B}$ and gradient-curvature drifts.

Another intriguing feature in Fig. 5 is that the H^+ drift paths exhibit a focal point in the post-midnight sector. Such a focal point is due to the fact that, via gradient-curvature drift, particles gain and lose energy in the nightside and dayside sectors, respectively. That is, for any given point in the dayside magnetosphere, there exists an "image" position in the nightside region where the particle has identical energy and is accordingly located on the same electric field equipotential. This effect combined with the fact that particles have the same pitch angle at INTERBALL-Auroral (or, equivalently, same mirror point magnetic field, B_M) and travel adiabatically (i.e., with constant magnetic moment $E_\perp/B$ and parallel invariant or, equivalently, particles conserve the geometrical integral $I = \int(1-B/B_M)^{1/2}ds$) is responsible for the focal points in Fig. 5. In a simple dipole field (where the intersection of iso-I contours with the equator are circles) with dawn-to-dusk convection (where the electric field equipotentials lie in the Earth-tail direction), we expect observation point and focal point to be symmetrical about the terminator. This not the case in the present calculations because of the magnetic field model considered (Tsyganenko, 1989, featuring no azimuthal symmetry) as well as the tilted electric potential distribution adopted in the ionosphere. In fact, focal points in Fig. 4 do not exhibit any straightforward symmetry axis.

The numerical results displayed in Fig. 5 suggest that extremely large times of flight may be at the root of specific ion gaps observed by INTERBALL-Auroral. That is, particles with intermediate energies which exhibit enhanced residence times in the magnetosphere are unlikely to reach the spacecraft without being subjected to charge exchange and/or wave-particle interactions. In other words, as put forward in previous studies focusing on equatorial particles (McIlwain, 1972; Fok *et al.*, 1995; Jordanova *et al.*, 1996, 1997), the ion gaps observed here at auroral latitudes are due to residence times largely exceeding the life time of the particles. In this regard, it should be noted that, at 0600 MLT (top panels of Fig. 5), enhanced times of flight are obtained for 5–6 keV H^+ which nearly corresponds with the gap energy range observed by INTERBALL-Auroral in this azimuthal sector (Fig. 1a). Also, it should be emphasized that enhanced time of flight affects particles originating from the tail and by no means coincides with transition from open to closed orbits which occurs at significantly higher energies (top panels of Fig. 5). The interpretation framework we consider here thus clearly differs from that of Smith and Hoffman (1974) or Shirai *et al.* (1997). Whereas interpretation in these latter studies is relevant to high energies exclusively (see, e.g., gap *a* in Fig. 2b), arguments based upon time-of-flight apply to a wider or narrower range of energies depending upon MLT.

To investigate this dependence upon MLT, we performed systematic trajectory calculations similar to those in Fig. 5, considering two distinct initial ILATs (65° and 70°) and various initial MLTs. The results of these calculations are presented in Fig. 6 which shows the H^+ residence time (coded according to the gray scale at right) as a function of both MLT and energy (left and right panels corresponding 65° and 70° ILAT, respectively). Figure 6 puts forward two notable features, namely: (1) at given ILAT, enhanced residence times (above 20 h) occur at lower energies as MLT varies from ~0600 to ~1800, consistently with the longer eastward transport of low-energy particles. (2) At given MLT, comparison of the left and right panels in Fig. 5 indicates that enhanced residence times are obtained at higher energies as ILAT decreases, due to comparatively larger eastward oriented $\mathbf{E} \times \mathbf{B}$ drift. Regardless of ILAT, note also the short residence times in the pre- and post-midnight sectors, as expected from the proximity of the magnetotail plasma source.

On the whole, Fig. 6 clearly suggests that residence time is a critical aspect of plasma transport throughout the inner dayside magnetosphere and is at the root of the ion gaps observed by INTERBALL-Auroral in this region of space. In particular, the pattern achieved in Fig. 5 with extremely long residence times over an energy range of a few keV bears a close resemblance to Figs. 1 and 2a. For instance, Fig. 2a which relates to the afternoon sector, exhibits an ion gap extending over a few keV and occurring at lower energies as ILAT increases. In addition, comparison of Figs. 3 and 6

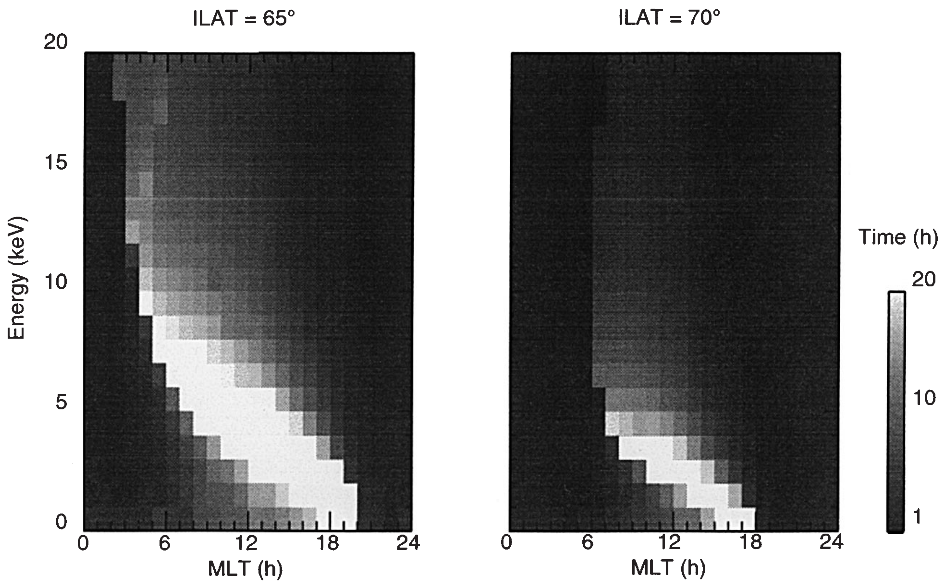

Fig. 6. Proton residence time (coded according to the color scale at *right*) as a function of MLT and energy at the observation point. These calculations are shown for two distinct initial ILATs: (*left*) 65° and (*right*) 70°

reveals that, at given ILAT, maximum H^+ residence times (Fig. 6) closely coincide with the gap distribution observed by INTERBALL-Auroral (Fig. 3). Note also that the transition between short and long times of flights occurs simultaneously for a large range of energies. For example, at ILAT = 70° and near MLT = 6 H, the computations indicate the appearance of ions which are much older (Fig. 6). This coincides nicely with empty loss cone in Fig. 1a after 12:35 UT and in event *c* (Fig. 2). Altogether, these results clearly support our residence time versus life-time interpretation framework.

4 Conclusion

In the diffuse auroral zone, INTERBALL-Auroral measurements often reveal prominent dropouts (generally below the detection threshold of the instrument) of the ion flux. These ion gaps which form a characteristic feature of INTERBALL-Auroral observations at low altitudes (below ~3 R_E), are detected in various MLT sectors and occur either at nearly constant energy or over a wide range of energies (from a few hundreds of eV up to several keV). Distinct processes must be invoked to explain these features. Transition from open orbits connected with the magnetotail plasma source to closed orbits encircling the Earth appears responsible for the nearly monoenergetic (of the order of 12 keV) ion gaps. Such ion gaps are frequently observed in the evening sector by INTERBALL-Auroral, together with dropouts at lower energies due to eastward transport of the low-energy plasma sheet population. The combination of these features results into a "nose" structure in energy-time spectrograms. On the other hand, gaps observed in the dayside magnetosphere call for a different interpretation based upon time of flight. Numerical orbit calculations demonstrate that ions originating from the magnetotail possibly exhibit extremely large (several tens of hours) residence times in a limited energy range, due to the conflicting effects of $\mathbf{E} \times \mathbf{B}$ and gradient drifts. Gaps in the dayside sector follow from these residence times largely exceeding the life time of the particles with respect to the charge exchange process. The computed energy range of these gaps exhibits a prominent MLT-ILAT dependence, which is in good general agreement with the observations.

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