Auroral secondary ions in the inner magnetosphere

G. Sofko, M. Watanabe, R. Schwab, and C. Huang

Abstract: Radar measurements of the global convection pattern and satellite observations of nightside low-energy ion populations are presented for magnetically disturbed conditions. The results form a consistent picture, namely that the ions are secondary ions (mostly O^+) produced in the auroral zone ionospheric F-region during bombardment by primary auroral electrons, and that these ions subsequently undergo TAI (transverse acceleration of ions) which raises their energy from the ionospheric value of about 0.1 eV to suprathermal and sub-auroral energies from a few tens of eV to a few hundred eV. The ions subsequently undergo a combination of bounce motion and ExB drift along the streamlines of the convection pattern, which has recently been shown to include some new features. We can classify three populations of these low-energy ions, namely DAPS (Dusk Auroral Positive Stream) ions, SAPS (Sub-Auroral Polarization (or Positive) Stream) ions and MAPS (Morning Auroral Positive Stream) ions. When conditions are not too disturbed, these ions show some characteristic features such as energy bands with integer energy ratios and a dispersive signature (decreasing energy with decreasing latitude). It is proposed that these low-energy ions, particularly the MAPS ions on the dawnside, may alter the shielding conditions in the inner magnetosphere.

Key words: Auroral secondary ions, Radar convection, Shielding, Satellite particle observations.

1. Introduction

As the dayside ionosphere rotates around to the nightside, the photoionization in the E-region disappears and the F-region survives only because the loss rate is low. During magnetically disturbed conditions when the electric field increases, the loss rates increase and the photoionization can decrease to very low levels, or even disappear. However, during disturbed conditions, a strong new source of ionization appears, namely bombardment of the ionosphere by auroral primary particles, mainly precipitating electrons in the 1–10 keV range which flow from the central plasma sheet to the ionosphere and are associated with upward field-aligned currents (FACs). These FACs carry substantial energy, as evidenced by the optical aurora they produce. Every kiloRayleigh (kR) of optical emission requires a primary energy flux of about 1 erg cm^{-2} s^{-1}. Typically, optical auroras are at least about 10 kR during moderately disturbed conditions, but they can attain intensities of more than 100 kR during intense events. Thus, substantial energy fluxes from 10–100 ergs cm^{-2} s^{-1} are carried by the primary electrons, resulting in a large production of secondary ion-electron pairs.

In a sense, the ionosphere acts as a "particle amplifier" since an average energy of only about 35 eV from a primary precipitating particle is required to produce a secondary ion-electron pair. Thus, a 1 keV auroral primary electron can produce about 30 low-energy secondary ions and electrons. Furthermore, the number of secondary pairs produced is large, since an energy flux of 1 erg cm^{-2} s^{-1} produces 1.79×10^{10} secondary pairs cm^{-2} s^{-1}. The observed auroral optical intensities of 10–100 kR require that the actual secondary production rate would be 10–100 times the above figure. As shown in Figs. 3.3.4. of [17], the secondary electrons will have energies up to a few tens of eV (some of them will have enough energy to produce another secondary pair) but the secondary ions will remain near their ionospheric energy (~ 0.1 eV). In the present paper, we focus on the ion production in the F-region, particularly above about 160 km where the loss rates are low and the lifetimes are long. Figure 3.3.3 of [17] shows that, particularly for the primary electrons in the 1–5 keV range, a non-negligible fraction of the secondary ions would be produced above 160 km, these being predominantly O^+ ions. The contribution of ionospheric O^+ to the magnetosphere has been noted in many satellite papers (e.g., [1, 3, 8, 11, 22]). As a result, there will be a reasonable supply of low-energy secondary O^+ ions from the upper E-region and lower F-region, even if only a percent or two of the original primary bombardment energy goes into secondary production above 160 km.

It is well known that magnetic storms and substorms are accompanied by turbulence that is both electrostatic and electromagnetic. One example of the electromagnetic turbulence is the presence of ion cyclotron waves, whose effects have been invoked (e.g., [4, 15]) to explain the transverse acceleration of ions (TAI) (see the extensive list of references in [16] and the review by [2]) that leads to the many observations of ion conics. Such transverse energization of the secondary ions above 160 km leads to a strengthening of their magnetic moment, and hence of the mirror force $\vec{F} = -\mu \nabla B$. As a result, F-region secondary ions above 160 km that undergo TAI will travel up the magnetic field lines, executing bounce motion. (There also is ample evidence of parallel acceleration above auroras, presumably due to the upward polarization field caused when the secondary electrons move up the field line away from the secondary ions.)

Satellite observations of TAI and ion conics show that most of these secondary ions, even after some TAI and parallel acceleration, remain at energies below 1 keV, most being in the range from a few tens to a few hundreds of eV. Because of their low energies, they participate only in ExB drift, not curvature-gradient drift. These bouncing and drifting low-energy sec-

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G. Sofko, M. Watanabe, and R. Schwab. Institute of Space and Atmospheric Studies, University of Saskatchewan, 116 Science Place, Saskatoon, Saskatchewan, Canada
C. Huang. Atmospheric Sciences Group, Haystack Observatory, Massachusetts Institute of Technology, Westford, Massachusetts, USA

ondary ions thus will act as tracers of the streamlines (equipotentials) of the convective flow patterns in the ionosphere and magnetosphere. New pictures of the convection streamlines have been obtained using recent Millstone Hill and Wallops Island SuperDARN results. A cartoon summarizing the convection pattern results is presented in the next Section.

We shall present satellite evidence showing that there are three distinct populations of the low-energy secondary ions that have bounced and drifted away from their production sites in the auroral zone. Indeed, many satellites have shown the presence of these ions, such as DE1 and 2 [21], AKEBONO (EXOS-D) [9, 10], DMSP and CRRES. A recent statistical study of DMSP and CRRES data [14] has revealed the frequent presence of these low-energy ions on the morning side. We will show only a small sample of the extensive satellite results.

Because the ions are positive particles that flow along the equipotential streamlines, we will refer to them as "Auroral Positive Stream (APS)" ions. Two of the three ion populations will remain at auroral latitudes on auroral streamlines, namely the population that drifts to the west in the afternoon convection cell (the **D**usk **A**uroral **P**ositive **S**tream, or **DAPS**, ions) and the one that drifts to the east in the morning convection cell (the **M**orning **A**uroral **P**ositive **S**tream, or **MAPS**, ions). The third stream flows westward in the SAPS (**S**ub-**A**uroral **P**olarization **S**tream) region defined by [5]. These westward-drifting ions in the plasmatrough region will be referred to as **SAPS** (**S**ub-**A**uroral **P**ositive **S**tream) ions. Their ExB motion is an ideal tracer of the equipotentials in the Sub-Auroral Polarization Stream.

2. The Ionospheric Convection Pattern

Figure 1 shows a pictorial representation of the convection pattern during disturbed conditions with a By+ IMF. This is basically the two-cell convection pattern, but with the recent radar observations relevant to the SAPS region. The SAPS flows result from an arm of the afternoon cell that protrudes into the morning sector at low latitudes. There is a convection reversal associated with this arm, and the heavy dashed line in the figure divides the eastward flows in the auroral zone portion of the arm from the westward streaming flows in the equatorward SAPS region of the arm.

SAPS has been defined [5] as a relatively broad ($\sim 5^\circ$ latitude) region of poleward (ionosphere) or radially outward (magnetosphere) electric field in the region equatorward of the inner auroral-energy electron boundary of the plasma sheet. At ionospheric heights, the SAPS region is one of low density and conductivity, particularly during disturbed periods when the electric field and the resulting ion convective speed are higher so that the cross-section for recombination of ionospheric ions and electrons is elevated, with the result that the electron density in the plasmatrough is further decreased [18, 20]. As a result, the electric field must strengthen in order to increase the Pedersen closure currents to the level required for Region 2 current closure in this subauroral region. The resulting strong convective flows, first seen as latitudinally confined (about 1°) regions, were referred to as Polarization Jets (PJ) [7] and SAIDs (Sub-Auroral Ion Drifts) [19]. It was observed that the flows could be broader, spanning about 5° [23]. The acronym SAPS

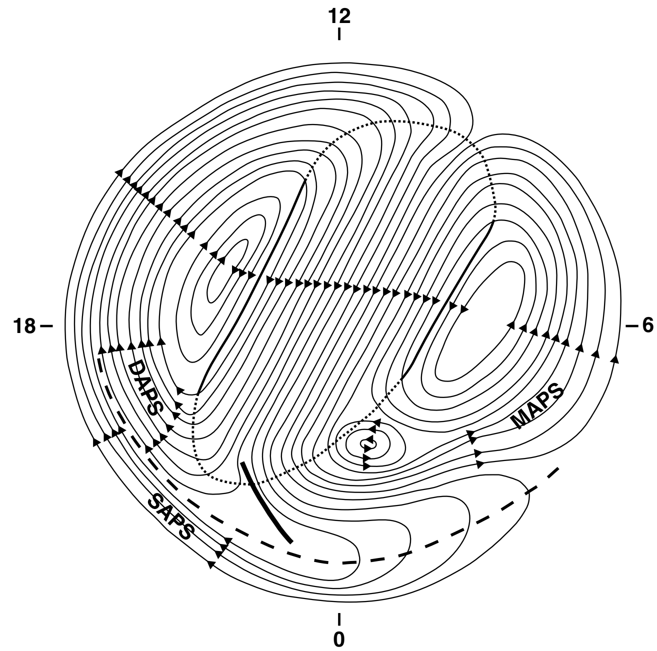

Fig. 1. Pictorial representation of convection including trends indicated by recent SuperDARN and Millstone Hill convection results. The pattern indicates the locations of the DAPS, MAPS and SAPS populations. The heavy line near midnight marks a very rough approximation to the location of the Harang discontinuity. The dotted lines are the mappings of the dayside and nightside reconnection lines to the ionosphere and the solid lines that join the dotted lines represent the OCFLB (open-closed field line boundary). The heavy dashed line spanning the midnight sector represents the convection reversal boundary which separates the SAPS region from the auroral zone. The small counterclockwise cell is not discussed here.

was defined in part to describe the broadened electric field region associated with the latter broader flows [23], which presumably incorporate the narrower PJ and SAID flows seen earlier. Millstone radar results [12] showed that the westward flows of the Polarization Jet (they used this term because the definition of SAPS occurred a year later) could be seen well into the postmidnight sector, as late as 04 or 05 LT. Although not specifically stated in the original SAPS definition by Foster and Burke [2002], the region of the SAPS poleward electric field is within the nightside low-latitude portion of the afternoon convection cell, which develops the arm shown in Fig. 1 that can extend well into the post-midnight sector during disturbed conditions. In addition to the [12] study, the postmidnight SAPS occurrence was revealed in a statistical study by [6] who, for the relatively large KP value of 6^-, showed that the penetration of SAPS into low latitudes in the postmidnight sector could extend almost as far eastward as dawn.

In Figure 1, the auroral zone includes the streamlines that, starting from the dayside, cross the polar cap and then flow through the "merging line" (dashed) on the nightside. Many streamlines then turn westward into the afternoon cell. Since these streamlines turn clockwise, the flow is characterized by downward vorticity, which is associated with upward FACs, particularly near the late evening convection reversal region.

It is there that the auroral secondaries will be produced, after which they flow westward on auroral zone streamlines, leading to the observations of DAPS ions in the post-evening sector.

However, some of the afternoon (PM) cell streamlines emerging from the polar cap first turn eastward on the poleward portion of a morning-side low latitude "extension arm" of the PM cell, and then they undergo a convection reversal so that the flow on the equatorward side of the reversal is westward in the poleward electric field of the SAPS region, where the SAPS ions are found. It should be noted that the downward flow vorticity across that convection reversal is again consistent with the presence of upward field-aligned currents; the SAPS ions are the secondary ions that result from the primary electron bombardment associated with those upward FACs. Consistent with this scenario are observations of strong optical aurora in the vicinity of that low-latitude early morning convection reversal, and even onsets of substorm expansive phases in that region.

Finally, the origin of the MAPS particles should be addressed. At first sight, it would seem that the morning auroral streamlines emerging from the polar cap undergo a counterclockwise rotation, which implies downward, rather than upward, FAC. However, if the streamlines in Fig. 1 are examined just equatorward of the small counterclockwise cell, it will be noticed that their separation increases in the equatorward direction. This shows that there is a shear which is characterized by downward vorticity. Further along these streamlines, there is more downward vorticity as the streamlines curve clockwise to lower latitudes around the eastward end of the PM cell "extension arm" where the SAPS ions are produced. Overall, then, there are indeed several regions of downward vorticity (upward FACs) in the morningside auroral zone too, and these regions are where the MAPS ions will be produced. After production, they simply undergo drift eastward toward dawn, where we will show in the following section some AKEBONO measurements [9, 10] and discuss the DMSP statistical study by [14] which shows that dawnside low-energy ions are a persistent feature during disturbed conditions.

3. Satellite Observations Of Low-Energy Ions

Some of the earliest low-energy SAPS ion observations were made by the Dynamics Explorer satellites DE-1 (∼10,000 km latitude) and DE-2 (∼925 km). Two fine examples of pitch angle observations near 0° in the evening sector on October 22, 1981, are shown by [21], in their Plate 1 which shows LAPI (Low Altitude Particle Instrument) data.

Figure 2 shows DMSP evening sector results at about 20 MLT from both the SSJ/4 and ion drift meter instruments. The figure clearly reveals two of the three low-energy ion populations, namely the SAPS ions, found equatorward of the auroral particles, and the DAPS ions, seen within the auroral zone in the latitude range from about -53.7° to -56.5° MLAT. Of course, the DAPS ions are coincident with the more energetic (∼1 keV) auroral ions and electrons. The electron and ion spectra in the top panels of Fig. 2 show that the inner edge of both the electron and ion auroral energy precipitation on this very disturbed day is located at about -53.6° in the southern hemisphere. The SAPS ions (∼1 keV) extend into the plasmatrough region well equatorward of the auroral electron boundary, which would be conjugate to the inner edge of the electron plasma sheet. The low-energy SAPS ions have the following features: (a) they are bursty in space and time; (b) their energies range from the detector low-limit energy (30 eV) up to ∼1 keV; (c) they have a banded structure in energy, with several bands of energy occurring at any given latitude; (d) they show a signature of dispersion, namely a slope that reflects a decrease in energy with decreasing latitude; (e) the lowest energy band ($<$ 100 eV) is usually the strongest in flux, as seen clearly in Fig. 2 at the lower latitude end (-50° to -52°).

The DAPS ions have similar features except that the dispersion slope (property d) is smaller than that of the SAPS ions. The ion drift meter convective motion results seen in the bottom panel show that both the auroral zone DAPS ions and the plasmatrough SAPS ions are drifting westward, although there is a latitudinal region (from about -53° to -52°) of weaker drift separating these two low-energy populations. Most of the SAPS secondary ions produced in the zone of primary electron precipitation initially move eastward just poleward of the convection reversal before turning equatorward and then traveling westward in the plasmatrough, as shown in Figure 1. The DAPS secondary ions are produced at slightly higher latitudes nearer to dusk and subsequently drift directly westward toward dusk on evening cell streamlines. It should be noted that the DAPS ions all travel directly along streamlines from the auroral production region toward dusk, and these paths do not differ much in length. On the other hand, the SAPS ions travel on longer routes because they may first travel eastward at auroral latitudes before crossing the convection reversal to travel westward in the plasmatrough. As a result, there can be a considerable difference in length between adjacent paths of the SAPS ions. This accounts for the different slopes in the dispersion signatures of the DAPS and SAPS ions.

Because of their shorter paths, DAPS ions are not subject to as much loss as the SAPS ions, and would be expected to show higher energy fluxes. This is revealed rather clearly in the middle panel of Figure 2, where the DAPS population has fluxes well in excess of 10^7 eV cm^{-2} s^{-1} sr^{-1} eV^{-1} whereas the SAPS population values are close to 10^7. In Figure 2, the important boundary between the DAPS and SAPS ion populations is the equatorward auroral boundary at -53.7°, which is roughly the low-latitude boundary for both auroral energy ions and electrons. (Although ring current ions are normally too high in energy to be seen by the SSJ/4 detector, Fig. 2 shows a ring current ion population - the whitish-pink high flux region - seen both in the auroral zone in the plasmatrough from $\sim-53.7^\circ$ to $\sim-52.1^\circ$ at the highest SSJ/4 energies ($>$ 10 keV)).

The SAPS and DAPS energy bands, which are shown even more clearly in upcoming Figure 3, have been explained in detail by [9, 10]. They result from differences in lengths of the streamline paths between the secondary production region and the satellite. When DMSP is traveling poleward through the plasmatrough, as in Fig. 2, the streamline path lengths are shorter at the higher latitudes, longer at the lower latitudes. If we assume for simplicity that the electric field is roughly constant in the plasmatrough, the ExB drift time will be directly proportional to the path length. For the longer path lengths, the time must be longer. That time must be equal to the time for the half-bounce along the field line from the northern hemi-

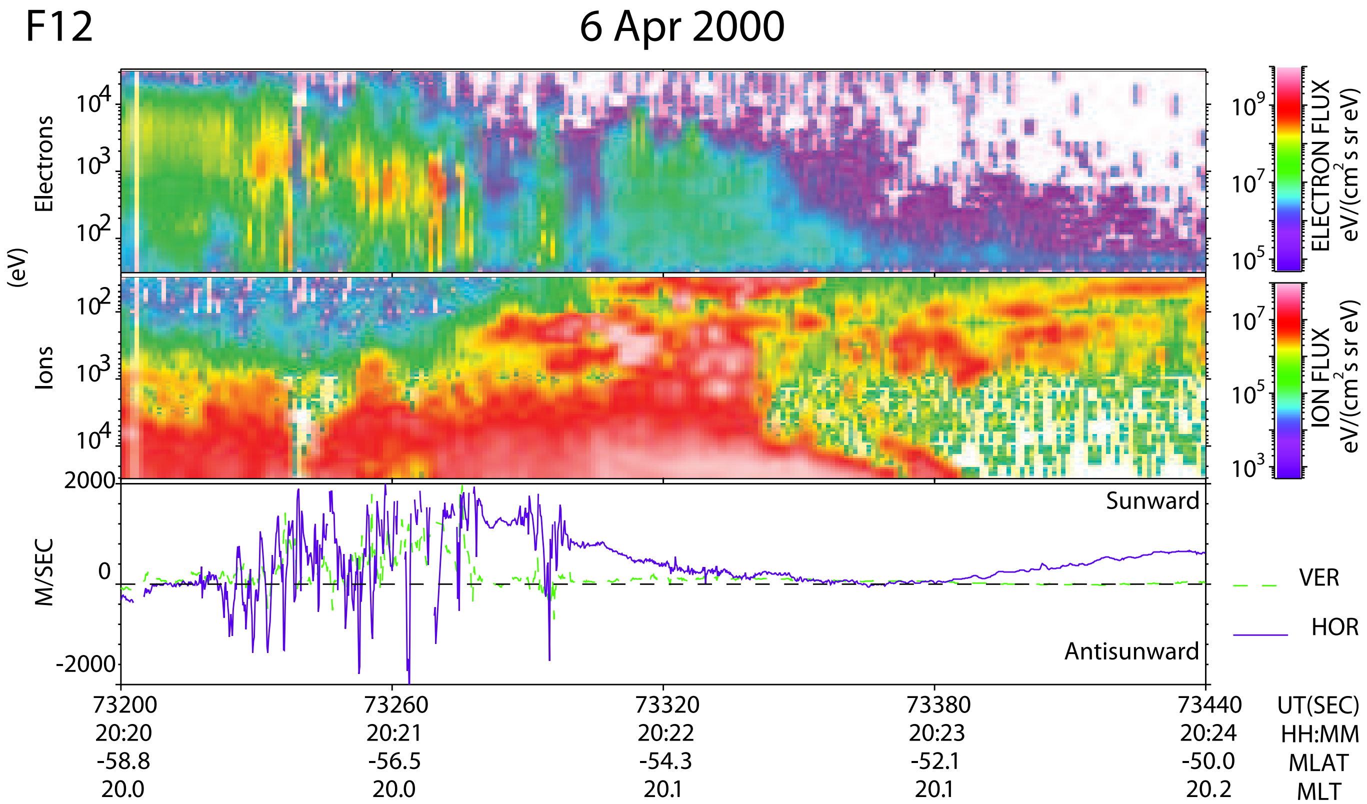

Fig. 2. DMSP evening sector SSJ/4 particle spectra (electrons in the top panel, ions in the middle panel) and ion drifts (bottom panel), in the evening sector. Low-energy ions in the SAPS region are clearly seen in the low latitude portion of the ion spectrum.

sphere production site to the southern hemisphere observation site. Therefore, the lower-latitude bouncing particles must have lower energy so that their half-bounce time matches the long drift time. On the other hand, the shorter drift times on the shorter paths at higher latitudes require that the half-bounce be made in a shorter time, which can only be done if the energy of the bouncing particles is higher. Thus, higher energies are seen at higher latitudes.

Actually, in travelling from the initial northern hemisphere production site to the southern hemisphere satellite, the ions can make either one half-bounce, three-half-bounces, five half-bounces, etc. This is the reason for the observed energy-banding. Since the field-aligned bounce path lengths have ratios of 1:3:5:7, the parallel speed ratios must be 1:3:5:7 and therefore the energy ratios must be 1:9:25:49. Our analysis of the bands in Figure 2 showed that the ratios are close to the values 1:9:25:49, so we assume the ionization source for the southern hemisphere observations of Figure 2 was indeed in the northern hemisphere. If the particles had originated in the same (southern) hemisphere that they were observed, then they would have had to make one, two, three, etc. complete bounces between production and observation, in which case their velocities would have been in the ratios 1:2:3:4. . ., and their energies in the ratios 1:4:9:16.

We now turn our attention to the third low-energy population, namely the MAPS ions near dawn. Figure 3 shows EXOS/D (AKEBONO) ion spectra in the dawn sector at about 4.5 MLT (taken from Plate 3 of [9]). This time, however, the ions were detected in four sets of pitch angles in 20° intervals, starting with the $0-20^\circ$ range of nearly field-aligned ions. In the upper panel, we see characteristics similar to those of the premidnight DAPS and SAPS ions observations by DMSP in Figure 2, namely the bursty nature, several energy bands, the dispersion signature of decreasing energy with decreasing latitude, and the prominence of the lowest-energy band of particles. The AKEBONO mass spectrometers (IMS, SMS) showed that this band is composed primarily of O+ ions. The drift meter showed that these particles convect eastward, as expected for ions on streamlines in the morning convection cell. The banded energy structure is much clearer at the higher pitch angles, such as $40-60^\circ$, where the bands are characterized by energy ratios of 1:9:25:49, or 1^2:3^2:5^2:7^2. As mentioned above, this is a direct result of the fact that these particles were produced in the opposite hemisphere to that of the AKEBONO observations.

4. Discussion

The satellite results shown in Figures 2 and 3 reveal three classes of low-energy ions, namely SAPS, DAPS and MAPS ions, all with similar characteristics - multiple energy bands, bursty appearance in space and time (particularly those in the loss cone), and often an energy dispersion signature. We note that the latter is not always seen, particularly during fairly disturbed conditions when the secondary source region is extended and the energy banding is "smeared out" as a consequence.

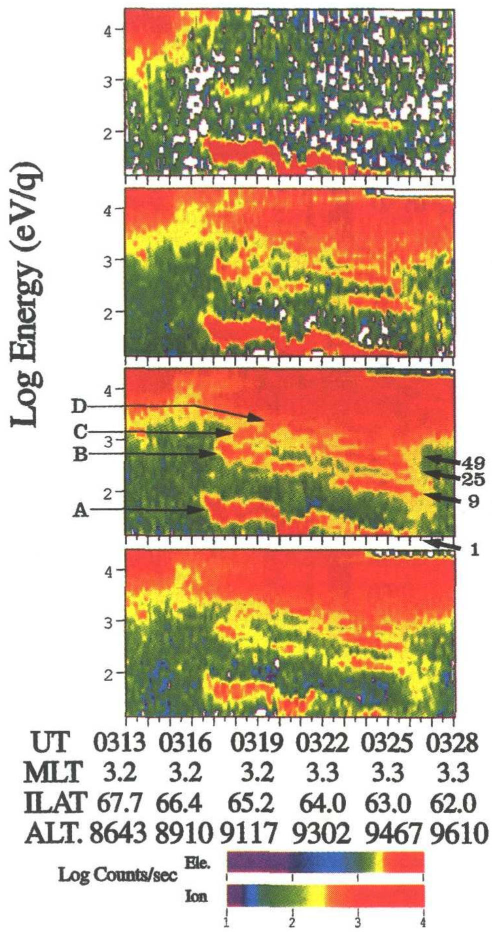

Fig. 3. AKEBONO Ion spectra in four pitch-angle ranges (permission granted by Dr. Hirahara) in the postmidnight sector. Note the banding of the low-energy ions, best seen in the $40^\circ - 60^\circ$ pitch angle panel, and the presence of the auroral ions which show a flat top at an energy of just under 10 keV. These measurements were made in the auroral zone, which is seen to extend at these times to latitudes lower than 63.8° ILAT.

During any major storm, the primary auroral bombardment would result in a large production of the secondary ions (principally O^+) because O^+ ions dominate in the upper E- and lower F-regions of the auroral ionosphere, where the SAPS, DAPS and MAPS ions are produced.

The MAPS secondary ions could play an important role in reducing the shielding in the morning sector. Normally, that shielding would be attributed to the effect of the curvature-gradient (CG) drift of the high-energy particles, leading to a separation between the high-energy ions and electrons, with the electrons drifting toward dawn while the ions drift toward the evening sector. The eastward CG drift of the high-energy electrons to the dawnside leads to a negative charge layer which shields the morning plasmasphere from the dawn-dusk field. Sometimes this is stated in a different manner, because the dawnside at low latitudes outside the plasmasphere is also where the Region 2 upward FACs occur, and the precipitation of dawnside high-energy electrons in the associated upward FACs is said to cause the shielding. Here, we prefer the Gauss' law approach in which electric fields start and stop on charge distributions. It is not difficult to show from a kinetic approach that the higher energy particles produce a total drift (the sum of three drifts, namely the gradient, curvature and magnetization drifts) given by

$$\vec{v_D} = \frac{\vec{B} \times \nabla p_\perp}{qnB^2} + \frac{p_\parallel - p_\perp}{qnB^2} \cdot \frac{\vec{B}}{B^2} \times [(\vec{B} \cdot \nabla)\vec{B}]. \quad (1)$$

This shows that, when the pressure is isotropic, the drift arises from the first term on the right, namely the pressure gradient drift, to which the shielding has sometimes been attributed. By undergoing eastward ExB drift along the streamlines that pass through the auroral zone, the low-energy MAPS ions can arrive at the same position as the high energy electrons. The overall net effect would be the cancelation of the shielding negative charge of the high-energy electrons by the positive charge of the low-energy ions. This might explain the loss of shielding discussed by [13].

Confirmation of the low-energy ions in the morning sector is well-documented by [14], who undertook a statistical study of DMSP results and also looked at CRRES data. They modeled the particle trajectories using a Volland-Stern model, making allowances for time-varying electric fields and azimuthal magnetic field gradients. Another possible explanation for their observations is that adopted here, namely that these ions were originally secondaries from the auroral zone F-region.

5. Conclusions

(a) Satellite observations in the evening sector (DMSP results in Fig. 2), and the morning sector (such as the AKEBONO results in Fig. 3 and an extensive DMSP study by [14], reveal the presence of three low-energy ion populations during disturbed conditions. We propose that these ions (mainly O^+) are the secondary ions that result from primary auroral electron bombardment of the auroral zone ionosphere.

(b) The secondary ions populations undergo ExB drift along the streamlines of the global convection pattern, sketched in Figure 1. Two of these populations flow on afternoon convection cell streamlines, namely the westward-flowing SAPS (SubAuroral Plasma Stream) ions in the plasmatrough (which can flow westward from postmidnight locations), and the DAPS (Dusk Auroral Positive Stream) ions which are produced mainly in the evening sector at auroral latitudes and which subsequently flow almost directly westward on auroral streamlines that are poleward of those on which the SAPS ions are seen. There is evidence in Figure 2 of a small observable latitudinal gap between these two ion populations in the evening sector. The third population consists of ions which have flowed eastward from the auroral zone on morning-cell streamlines. They are MAPS (Morning Auroral Positive Stream) ions seen clearly in the dawn sector.

(c) The observations of bright visual aurora in the auroral zone reveal that primary particle energy fluxes of tens of ergs $cm^{-2}\ s^{-1}$ are common during disturbed periods. Making conservative estimates of the resulting secondary particle production, it is not unreasonable to expect that the low-energy ion populations, particularly the MAPS ions, could be strong enough to add enough positive charge in the region of the negative shielding charge provided by high-energy electrons on the dawnside to reduce the shielding effect of the electrons.

(d) The low-energy secondary ions clearly undergo some initial acceleration that raises their energies to the range 0.1 eV to energies from a few tens to a few hundred eV. There has been ample evidence of TAI (transverse acceleration of ions) leading to ion conics, and of parallel acceleration, causing beams. As a result of such energization, the DAPS, SAPS and MAPS populations consist of suprathermal to sub-auroral energy ions that undergo bounce and convective drift motions in traveling along the streamlines (equipotential contours) from the source region in the auroral ionosphere to the observation regions in the evening or morning sectors. The combination of these motions leads to the energy banding and dispersive signature of decreasing energy with decreasing latitude. The observed satellite locations of these ions are in good agreement with the predictions of the convection patterns.

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