



Enhanced Pitch Angle Scattering of Protons at Mid-Latitudes During Geomagnetic Storms

F. Søråas¹, K. Aarsnes¹, J. Å. Lundblad² and D. S. Evans³

¹Department of Physics, University of Bergen, Norway

²Statoil, Bergen, Norway

³NOAA Space Environment Center, Boulder, Colorado, U.S.A.

Received 17 September 1997; accepted 24 March 1998

Abstract. During geomagnetic storms highly localized regions of enhanced proton (ion) precipitation in the tens to several hundred keV energy range can appear at mid-latitudes. The particle pitch angle distribution in these enhanced regions is anisotropic with maximum intensity perpendicular to the magnetic field. In a few cases, however, the distribution can approach isotropy. These regions typically have widths of a few degrees invariant latitude, but can be as narrow as 0.25° . The intensity peak is most often concentrated in a specific particle energy range, although in many cases the intensity peak at a given location is distributed over a broader energy range. During the main phase of the storms the ion enhancement is mostly observed in the highest energy protons and only in the midnight/evening MLT sector. Coincident with the ion enhancement there was often an enhancement in electrons with energies > 300 keV. In the recovery phase of the storms the ion enhancement can be observed at all local times covered by our observations and there was not any coincident enhancement in the high energy electrons. Overall the observations seem to support a picture where scattering of protons into the loss cone by cyclotron resonant wave-particle interaction occurs, while high energy electrons are parasitically scattered into the loss cone by the same ion cyclotron waves. Throughout the storm the L-dependence of the enhancements in proton fluxes is similar to the K_p dependence of the location of the plasmopause. Whenever a direct comparison could be made, the SAR arc and the ion enhancement overlap. Thus the ion enhancement and SAR arc are associated, but not necessarily on a cause-effect basis. © 1998 Elsevier Science Ltd. All rights reserved.

istic region of anisotropic proton precipitation on field lines that thread the outer plasmasphere (Hauge and Søråas, 1975; Søråas et al., 1977). Imhof et al. (1986) reported on energetic ion precipitation spikes near the plasmopause in association with relativistic electron precipitation. In particular Lundblad and Søråas (1978) showed the existence of very localized regions of proton precipitation at mid-latitudes during the recovery phase of large storms. A close connection was established between these localized peaks in ion intensities above 100 keV and stable auroral red (SAR) arc. They interpreted this correlation between enhanced proton pitch angle scattering and SAR arc emissions as support for the ion cyclotron wave damping theory of SAR arc formation (Cornwall et al., 1971).

A number of investigators have shown that the energy transferred to the plasmaspheric electron population through Coulomb collisions with the ring current ions is responsible for enhanced plasmaspheric electron temperatures resulting in ionospheric electron temperature peaks and associated SAR arc emissions (Cole, 1965; Kozyra et al., 1987; Chandler et al., 1988). Kozyra et al. (1987) calculated that sufficient energy is transferred to the electron gas at high altitudes by Coulomb collisions between the observed ring current ions and thermal electrons to support the SAR arc. In all cases examined by Kozyra et al., ring current O^+ was the major source of energy for heating the thermal electrons. There remained, however, the question of how this energy is transported to the ionosphere to produce the SAR arc. Thorne and Horne (1992) in addressing this issue demonstrated that ion cyclotron waves can play an important role in both the energy transfer from energetic ions to plasmaspheric electrons and the subsequent downward heat conduction to SAR altitudes.

The enhancement in ion intensities, both inside and outside the loss cone, that is observed in the same region as the SAR arc implies that the process that causes in-

1. Introduction

Mid-altitude satellite observations of locally mirroring and precipitating ions have documented a character-

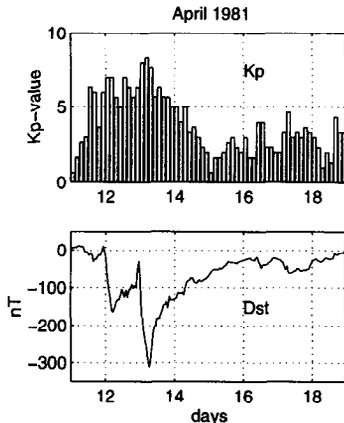


Fig. 1. The geomagnetic conditions prevailing during the April 1981 storm as given by K_p and D_{st} .

creased pitch angle scattering of ions also takes place on these field lines. It is important to be able to determine the processes which scatter the ions into the loss cone at mid-latitudes during disturbed geomagnetic conditions as those processes may also help govern associated phenomena such as the elevated electron temperatures and SAR arc formation. The ion enhancement at mid latitudes could also be important as a loss process for the ring current ions.

With this in mind, the paper presents additional observational data on localized, mid-latitude enhancements in ion intensities.

2. Instrumentation

Lundblad and Søråas (1978) reported observations of enhanced 100–200 keV ion precipitation at mid-latitudes. The data used in that study were primarily from the ESRO I instrument (Søråas *et al.*, 1970) which had a low energy cutoff that precluded the study of ions below 100 keV energy.

The present study uses observations from the MEPED and TED instruments on board the NOAA-6 satellite. These detectors provide observations of both ions to a lower energy and high energy electrons. Extending the observations to lower ion energies reveals more cases making it possible to study how the enhanced precipitation depends on local time, the phase of the geomagnetic storm, and ion energy. The NOAA particle data are, in one case, supplemented by measurements from the DE-2 satellite and ground-based observations of SAR arcs.

The local time orbit of the spacecraft was dawn-dusk. The spacecraft orbit was circular at an altitude of about 850 km. A more fully description of the satellite and the instrumentation is given by Hill *et al.* (1995).

3. Observations

Observations during a number of geomagnetic storms have been examined and in all cases the mid-latitude ion precipitation displayed the same characteristics. To illustrate these characteristics, we present mostly observations made during the April 1981 storm.

3.1. The April 1981 storm

Figure 1 displays the geomagnetic conditions prevailing during the April storm. It is a large storm with a double main phase. The storm started on April 12 and during the first main phase of the storm on April 12, D_{st} reached a minimum of -163 nT at 06 UT. In the second main phase of the storm a large intensification took place and D_{st} fell to -310 nT at 07 UT on April 13. The recovery of the storm continued for many days.

3.1.1. Late recovery phase

Figure 2a presents particle data for the time interval 12:06 to 12:29 UT on April 17. These data are taken well into the recovery phase of the storm and are displayed vs. invariant latitude (ILAT), geographic latitude (GLAT) and longitude (GLON), magnetic local time (MLT) and universal time (UT). Observations from three of the proton differential energy channels available from the NOAA-6 MEPED instrument are plotted: 30 to 80 keV, 80 to 250 keV, and 250 to 800 keV. The measurements were made both nearly parallel (solid) and nearly normal (dotted) to the magnetic field.

The latitude distribution of the protons observed during this period generally agrees with the three zone structure described by Hauge and Søråas (1975) and Søråas *et al.* (1977). 1. For invariant latitudes greater than about 65° the proton precipitation is observed to be isotropic. 2. Immediately to the equator-ward side of the isotropic zone, the flux parallel to the magnetic field decreases to very low values within a latitude width of a few degrees. The intensities of locally mirroring protons are also reduced within this region. 3. Further equatorward, proton fluxes within the loss-cone exhibit a slight increase in intensity. The intensity of locally mirroring protons exhibit a smooth increase reaching a maximum around 55° ILAT.

The data presented in Figure 2a have, however, a distinct departure from the general description. A sharply defined peak in the fluxes of locally mirroring protons at all energies is clearly seen at about 1207 UT when the satellite was in the morning sector (0700 MLT) at about 54° ILAT. A similar, sharply defined, intensity peak can also be seen in the evening sector at the same ILAT, although now confined to protons above 250 keV. There were no corresponding increases in the fluxes of protons within the loss-cone in either case. It thus appears that the pitch angle distributions within these intensity enhancements are highly anisotropic with maximum intensities at large pitch angles. In the morning sector the

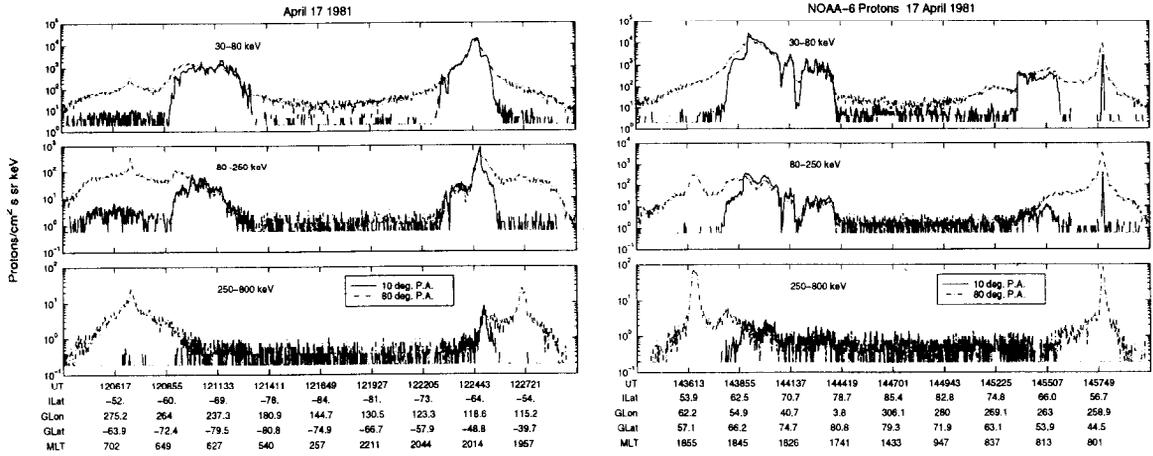


Fig. 2a-b. The three panels give the flux of protons in the energy channels (30 to 80 keV), (80 to 240 keV) and (240 to 800 keV) vs. UT. The data referring to the locally mirroring particles are given by dots and the precipitating ones are given by a solid line. Along the abscissa values of geographic longitude (GLON) and latitude (GLAT), magnetic local time (MLT) and invariant latitude (ILAT) are also given.

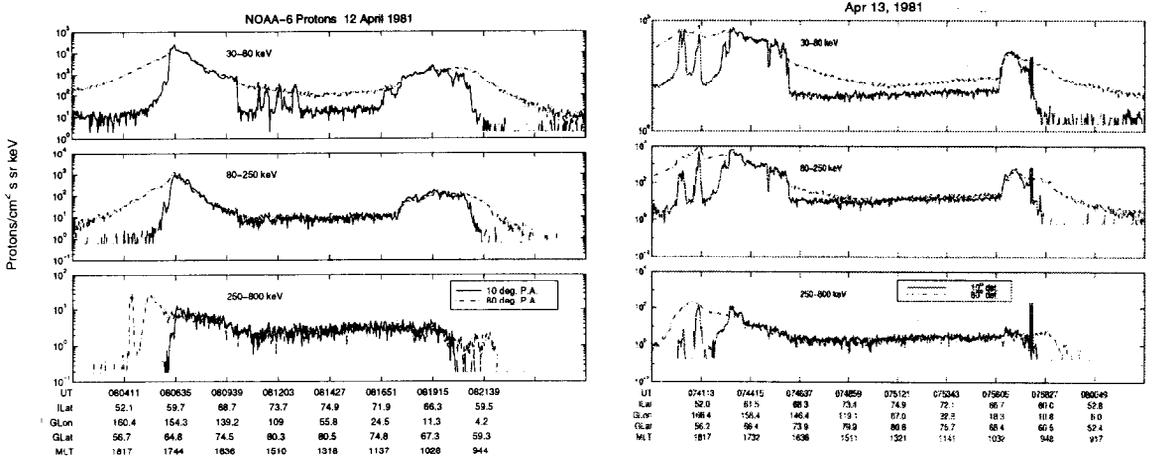


Fig. 3a-b. Text see figure 2.

local enhancement occurred over the full energy range observed, while in the evening sector the enhancement was confined to energies above 250 keV. No significant enhancement in proton fluxes at energies below 20 keV was detected by the NOAA-6 TED instrument.

A detailed investigation of all NOAA-6 passes throughout the storm reveals the ion enhancement dur-

ing most, but not on every pass. However, beginning at 1114 UT, and continuing for the remainder of April 17, clear mid-latitude ion flux enhancements were observed during every pass. Figure 2b is an example of observations during this lengthy period. On the morning-side around 0800 MLT a very pronounced enhancement in ion fluxes is observed at 55.8° ILAT. The enhancement

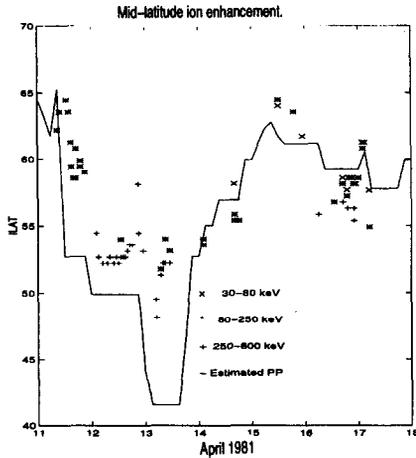


Fig. 4. The positions of the observed ion enhancement and the calculated K_p -position of the plasmapause are shown throughout the storm. The ion enhancement referring to different ion energies are indicated with specific symbols.

in locally mirroring protons is evident in all three energy channels. It also appears in the nearly parallel ions, but now in the two lowest energy channels only. These intensity increases are large, the intensities of locally mirroring protons increase by around 2 orders of magnitude and protons in the loss-cone by almost by 3 orders of magnitude. The intensities observed at these mid-latitudes are comparable with those observed in the auroral zone during active times. It should be also noted that the pitch angle distribution at lower energies approaches isotropy. During this pass an enhancement is also observed on the evening-side at 1855 MLT. Here, as on the morning-side, the intensity peak is located at 55° ILAT, but unlike the morning-side, it is evident only in the locally mirroring protons of energies above 80 keV and most pronounced in the energies above 250 keV.

The observations during the immediately previous, southern hemisphere pass, are almost an exact image of the pass shown. Both passes exhibit very localized ion enhancements and pitch angle distributions that tend towards isotropy in the two lowest energy channels.

The width (FWHM) of the morning side enhancement, shown in Figure 2b, is about 80 km in the perpendicular - and 25 km in the field-aligned component, both referenced to ionospheric altitudes. The observations demonstrate that the ion precipitation continued to be intense for more than an hour. It should, however, be noted that such precipitation events with near isotropic precipitation are rare. Most often the ion enhancement has an anisotropic pitch angle distribution with maximum towards 90° pitch angles as shown in Figure 2a.

During the storm recovery phase the NOAA-6 observations of electrons from 30 to > 300 keV have been examined, but no increase in the electrons were found coincident with the ion enhancements.

3.1.2. Main phase

Figure 3a presents NOAA-6 observations from the time interval between 0804 and 0824 UT on April 12 during the first main phase of the storm. A very localized peak in the intensity of locally mirroring, greater than 250 keV protons was observed near 0804 UT at 53° ILAT. There was no coincident enhancement in the fluxes of protons below 250 keV. An examination of the ion observations throughout the main phase of the storm showed that there was a localized, mid-latitude enhancement in ion fluxes on virtually every pass. The intensity enhancements were most prominent in the fluxes of near locally mirroring, > 250 keV ions. Coincident enhancements in the fluxes of < 250 keV ions were much smaller in amplitude or, most often, absent.

Close to storm main phase, however, on the 13 of April two precipitation peaks appear in the evening sector around ILAT 52°. As seen in Figure 3b the increase is evident in all three energy channels, indicating heavy precipitation losses from the ring current.

During the storm main phase the ion mid-latitude enhancement was only observed in the evening/midnight sector. This is in contrast to the recovery phase where the ion enhancement could be observed both in the evening/midnight and the noon/morning local time sectors. In the storm main phase the poleward isotropic zone almost bordered the mid-latitude enhancement.

During the main phase of the storm a clear enhancement is also evident in the electrons > 300 keV (not shown) and in fact most of the observations examined in the initial/main phase of the storm show that high energy electrons were scattered into the loss cone coincident with the enhanced ion scattering.

3.1.3. The location of the ion enhancement throughout the storm

Figure 4 shows the ILAT locations of observed ion flux enhancements throughout the storm. Also shown are the positions of the plasmapause as estimated from the empirical relationship $L_{pp} = 5.7 - 0.47K_p$, where the value of K_p is the largest observed in the preceding 12 hours. In general, the empirical location of the plasmapause and the observed location of the ion intensity peak track one another rather well. Both locations move to lower latitudes as K_p increases. In the main phase of the storm, however, the calculated plasmapause position was found at a lower ILAT than the ion enhancement.

Using only the statistical plasmapause position it cannot be determined definitively if the observed locations of the proton intensity peaks are coincident with the plasmapause or are located just within or just outside the plasmasphere. What is clear, however, is that the locations of the intensity peak follow the plasmapause movements throughout the storm. Lundblad and Søråas (1978) presented case studies indicating that the ion enhancement was located inside the plasmapause. It can also be seen from Figure 4 that the location of the

ion enhancement tends to be observed at lowest ILAT for the highest energy.

3.2. NOAA-6, DE-2 and SAR arc observations

Slater *et al.* (1987) have presented results of coincident measurements by ground-based photometers and plasma-instruments on board the DE-2 satellite that demonstrated the association between low-energy electron (5 to 20 eV) precipitation and SAR arcs.

Figure 5 shows a comparison between eV energy electron and SAR arc observations on October 23, 1981 reported by Slater *et al.* (1987) and corresponding NOAA-6 measurements of protons. The third panel from the top displays, on a relative scale, 6.7 eV electron intensities measured by the DE-2 satellite. The fourth panel from the top shows the intensity of the SAR arc as a function of ILAT. Both the DE-2 and the ground SAR arc measurements were made at 0210 UT in the Northern hemisphere. The values in Figure 5 have been scaled from the Slater *et al.* (1987) paper. The two top and the two bottom panels display the count rate from the NOAA-6 of locally mirroring protons in the energy range 250 - 800 keV as a function of ILAT. No enhancements could be observed in the protons with energies below 250 keV. The universal times of the NOAA-6 observations bracket the DE-2 and SAR arc observations.

Note that: (1) the 0210 and 0240 UT NOAA-6 observations, second and fifth panel, were made at nearly the same UT and MLT as the Slater *et al.* (1987) 0229 UT observations and (2) the 0149 and 0330 UT NOAA-6 observations, top and bottom panel, were made at the same ILAT and near the same UT but well removed in MLT from the DE-2 and SAR arc observations.

This means that (a) the energetic proton enhancements are well associated in time and location with the SAR arc and (b) this association is likely to extend over many hours in MLT. Slater *et al.* observed the SAR arc for many hours during that night - the arc extended over a broad longitude range, and NOAA-6 observed ion intensity peaks over a broad MLT range. Therefore the ion intensity peaks and the SAR arc association is likely to also be true over a large MLT/longitude range.

The comparison between ground based and satellite observations indicate that the processes which scatter the energetic protons into the loss cone, give rise to the SAR arcs and produce the hot thermal electron population are all located along the same magnetic flux tube.

4. Discussion

Cornwall *et al.* (1970) suggested that pitch-angle diffusion of ions driven by resonant interactions with ion cyclotron waves generated within the plasmopause should be an important loss process for the ring current ions.

The losses were predicted to occur first at the lower L-values within the location of the compressed, storm-time plasmopause. The ion losses should then extend

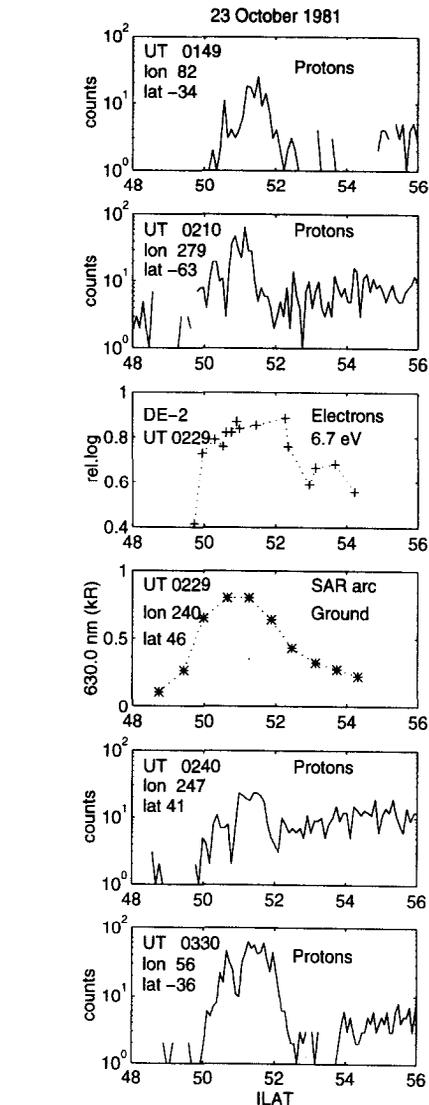


Fig. 5. Observations of SAR arcs (ground), eV electrons (DE-2) and high energy (250 - 800 keV) protons (NOAA-6) all plotted vs. ILAT.

outwards to higher L-values as the plasmasphere refills during the recovery phase of the storm.

Both these predictions are born out by the observations presented in this study (see Figure 4) as the ion intensity enhancements are first located at small L-values during the main phase of the storm and then move to higher L-values, closely tracking the estimated

position of the plasmopause as the plasmasphere refills during the storm recovery phase.

Kozyra *et al.* (1994) challenged this explanation on the grounds that satellites traversing the outer plasmasphere have been unable to detect the electromagnetic ion cyclotron waves with sufficient regularity. They, therefore, suggested that the ring current ions are pitch angle scattered through interaction with ducted plasmaspheric hiss in the outer plasmasphere by means of an anomalous Doppler-shifted cyclotron resonance. This mechanism predicts that ions with ring current energies will scatter into the loss cone on SAR arc field lines. The ion precipitation will thus follow the movement of the SAR arc and thus be in accordance with the observed behavior of the mid-latitude ion enhancement. The calculated diffusion timescales are estimated to be in the order of tens of days, which are definitely too slow to explain the sometime near isotropic ion precipitation observed at mid-latitudes.

The observations show that the enhancement most often occurs in a specific energy range. In many cases though the enhancement can be observed at the same location over an extended energy range.

That the ion scattering mostly appears at energies above 250 keV in the main phase of the storm, when the plasmopause is depressed, is consistent with an increase in the resonance energy at low ILAT.

The observed ion enhancements do demonstrate or suggest that ion cyclotron waves are present under conditions that produce SAR arcs. The ion enhancements are associated with SAR arcs but not necessarily on a cause-effect basis.

The energy- and L-dependence of the ion enhancement and its occasional association with precipitation of high energy electrons suggests that the proton distribution is unstable and produce ion cyclotron waves.

According to Thorne and Kennel (1971) one should expect high energy electrons around 1 MeV to be parasitically scattered into the loss cone by ion cyclotron waves generated by the unstable proton population. They explained the loss of 1.6 MeV electrons from the radiation belts in the main phase of a storm due to this effect.

Imhof *et al.* (1986) examined a large number of satellite passes occurring under different geophysical conditions for relativistic electron precipitation spikes near the plasmopause. They found that in 1 % of the crossings relativistic electron precipitation were observed and about one fourth of these cases were also associated with ion precipitation.

Our investigation shows that this loss of electrons above 300 keV is associated with the ion enhancement in the main phase of the storm and in the evening MLT sector. Only in this phase of the storm are the ion and electron spikes at the same location.

Any mid-latitude ion enhancement depends both on the plasma density and the ring current distribution function. The ring current and the plasmasphere must to some extent overlap and the protons must be unstable for wave growth. This is not always the case, as the ion enhancement is not observed at every pass during the storm.

In order to resolve the many questions raised in connection with enhanced ion precipitation at mid-latitudes a full set of relevant ground-based- and satellite observations must be studied. These studies must be backed up with theoretical work on energy transfer between hot and cold plasma and wave/particle interaction.

Acknowledgement. Thanks to Norsk forskningsråd for providing financial support for the project.

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