Low altitude observations of ENA from the ring current and from the proton oval

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A B S T R A C T
Observations of Energetic Neutral Atoms (ENAs) emitted from the proton aurora and from the equatorial ring current at tens to a few hundred of keV during the Halloween 2003 storm are presented. From the proton oval a large number of ENAs are spread over the polar cap making a contribution to the ion outflow. From the Ring Current (RC) ENAs are spread in all directions. The Storm Time Equatorial Belt (STEB) consists of ENAs observed around the geomagnetic equator at low L-values. Their source is RC protons existing at larger L-values. The number of observed ENAs is directly dependent on the amount of ions (protons) present in the RC along the line of sight. Thus the time variations of the STEB enable us to monitor the behavior of the RC. Based on observations of the STEB at six different local times we discuss the RC injection region, the drift of RC-particles through the evening/afternoon sector into the morning sector and the RC decay time during the storm recovery phase. The MLT variation of the STEB gives information about the symmetry and asymmetry of the RC with no interference from other current systems. The revealed RC-symmetry and asymmetry complement magnetic ground observations.

1. Introduction

The RC ions charge exchange with the Earth's geocorona at all altitudes and create ENA. The number of ENA created is proportional to the ion flux, the density of the geocorona, and the charge exchange cross sections. The ENA emission is thus markedly brightest at the lowest altitudes, because the density of the ambient neutrals strongly increases with decreasing height. The proton aurora is therefore an intense source of ENA. The ENAs are spread in all directions and also over the polar cap.

In the auroral zone rocket observations of energetic proton fluxes with asymmetric gyro-phase distributions are indicative of a non-local source and have been interpreted as ENAs produced by the interaction of precipitating auroral/ring-current ions with the upper atmosphere (e.g., Søraas and Aarsnes, 1996).

Low altitude ENA emissions were first imaged by the Swedish ASTRID satellite (Brandt et al., 1997) and were extensively imaged by the Medium Energy Neutral Atom (MENA) and High Energy Neutral Atom (HENA) instruments on the IMAGE spacecraft during its 5.75-year mission (Pollock et al., 2000; Mitchell et al., 2000). Pollock et al. (2009) have reported global-scale observations of intense low altitude ENA emissions at high latitudes by comparing IMAGE observations of ENA and proton observations from NOAA satellites in the few keV range during the Halloween storm in 2003. ENA observations are currently an important method for magnetospheric studies. The most recent observations of ENA in the Earth’s magnetosphere are made by the TWIN satellites comparing the observed signatures from ENA images with simulated development of July 22, 2009 storm (Fok et al., 2010).

ENA with RC energies are also observed at low altitudes in the equatorial region during geomagnetic storms. These particles are a manifestation of one of the dominant loss processes, charge exchange, in the storm-time RC. Other loss processes are wave/particle interaction and losses through the day side magnetopause. These ENAs are observed in a belt around the Earth and has been given many names over the years: the secondary proton belt, the low altitude proton belt, and the Storm Time Equatorial Belt (STEB). In this study we will use the name STEB introduced by Søraas et al. (2003) when they reported the first observation of these particles measured by Polar Orbiting Environmental Satellites (POES). They showed how the particles circumvented the Earth and how the belt developed during magnetic storms. Søraas et al. (2002, 2006) inferred RC behavior from the STEB and compared them with ground magnetic observations and found a general good agreement. Sarøe et al. (2006) have reported on the latitude distribution of vertically precipitating ENAs. During proton injection into the RC maximum ENA precipitation...
was located 35° off equator in accordance with calculations performed by Tinsley (1979) assuming that the pitch angle distribution of the injected protons was isotropic at L = 3. Sørbo et al. (2009) also discussed the STEB during corotating interaction region (CIR) and high speed stream (HSS) events. They found that the intensification of the RC during CIR/HSS events is enough to produce a STEB, but the most intense STEB are seen in CME storms.

The ENA emission from the auroral protons is much brighter than from the STEB. The altitude of ENA production exhibits a broad maximum around 350 km. Lower altitudes it has a sharp cut off at 200 km and calculations by Roelof (1997) for a 40 keV proton show that the production at 1000 km is reduced by a factor of around 1000 compared with maximum production.

The STEB ENA is created in the equatorial region by the RC protons at an altitude of 2.5–4 Earth radii, depending on the penetration of the RC towards the Earth. Even if the energetic proton intensity is the same, the density and the composition of the exosphere are vastly different at the two locations. At high altitudes the density is low and dominated by hydrogen, while at low altitudes the density is high and its main constituent is atomic oxygen. Thus different cross sections for charge exchange apply. The objective of this paper is to discuss the energetic particles (protons and particularly the ENAs) that are originating from the proton aurora and from the equatorial RC during the Halloween storm.

2. Data and instrumentation

Data from the National Oceanic and Atmospheric Administration (NOAA) POES is used to study properties of precipitating protons and the ENA particle population at low altitudes. The POES are in sun-synchronous circular orbits that orbit the Earth 14–15 times each day at an altitude of around 800 km, which gives 28–30 equator crossings roughly 12 MLT hours apart. With several satellites in orbit at different local times the temporal and spatial dynamics of the particle flux at low altitudes, from equator to the PC can be monitored.

The MEPED (Medium Energy Proton and Electron Detector) instrument measures protons and electrons at angles of 10° and 90° with the local vertical and is sensitive to all energetic ions. The MEPED instrument gives no information on composition and cannot distinguish between charged and neutral atoms. The term protons or ENAs will be used in this paper. At low latitudes when the satellite is below the radiation belt, in a region normally void of energetic charged particles, the instrument can detect ENAs from the RC. If Solar Energetic Protons (SEP) are not present the instrument can detect ENAs coming from the proton aurora. Roelof et al. (1985) were the first to use an instrument with solid state detectors, intended to detect charged particles, to provide an ENA image showing a strong day–night asymmetry of the storm time RC.

In Fig. 1 the look directions of the horizontal and vertical detectors on the NOAA/POES satellites at high and low latitudes are shown. The horizontal detector looks in the anti-velocity direction and can detect ENAs which are coming from behind the satellite. In the equatorial regions the vertical detector will measure ENAs that are coming directly from the RC above. The opening angle of the detectors is 30° FWHM. The geometric factor of the instrument is 0.01 cm² sr.

The most abundant energetic ions in the RC are hydrogen and oxygen, but with a dominance of hydrogen. The relation between these ions varies throughout the storm as discussed by Daglis and Axford (1996). For a discussion of the instrument response to heavier ions see Søraas et al. (2002). A full description of the instrument response to proton shows that the production at 1000 km is reduced by a factor of around 1000 compared with maximum production.

Fig. 1. Illustrating the field of view and look directions of the two detectors on the satellites. In the polar cap the horizontal detector observes ENAs from the auroral oval, while at equatorial latitudes the vertical detector observes ENAs from the RC. If charged particles are present in these regions they will also be observed.

NOAA-POES spacecraft and the MEPED instrument is given by Evans and Greer (2000).

3. High latitude observations

3.1. ENAs over the PC

Precipitation of protons into the Earth’s upper atmosphere creates the strongest emissions of ENA in the magnetosphere-ionosphere system. The rapidly increasing density of atomic oxygen provides an effective charge exchange target that results in a significant ENA yield. The POES are frequently crossing the auroral zone and are thus in an excellent position to view the oval auroras and the spreading and escaping ENAs.

The observations shown in Fig. 2 are performed by the POES 15 satellite on October 29, 2003 when the satellite passed from dusk to dawn over the northern polar cap. The top three panels show proton fluxes in the energy range 30–80, 80–250, and 250–800 keV. The vertical detector is looking towards zenith and the data are plotted with a solid line. Data from the horizontal detector, looking in an anti-parallel direction of the satellite velocity, are plotted with a dotted line. The bottom panel shows the Dst index for the days 302–305. The time of the POES observations is indicated by two vertical lines in the Dst plot. The Dst was around −200 nT and in the storm main phase. The Dst gradient is large, indicating intense injection of particles into the RC.

The satellite encounters the night side auroral proton region at 18 MLT around 17:15 UT (302.72 DOY). The intensities in all three energy channels for both detectors increase and exhibit an isotropic pitch angle distribution (same intensity in the vertical and the horizontal detectors). When the satellite leaves the proton aurora and enters into the polar cap, there is a sharp intensity drop to a constant polar cap background level in the precipitating protons shown by the solid line. Particles within the loss cone will move along the magnetic field line and experience very little spatial spreading.

The particle intensities measured by the horizontal detector, however, behave differently. These fluxes are seen in the dotted line. The detector has an opening angle of 30° and covers 15° in the downward and upward directions. The detector is thus able to monitor the region from 550 km altitude and upwards to a few thousand km. The satellite is at an altitude of 807 km. This is a
fairly wide altitude region where ENAs are created. When the satellite leaves the isotropic zone, there is a slight drop in the 30–80 keV and the 80–250 keV channel intensities. Over the polar cap the particle intensity decays exponentially with the distance from the arc. Both channels reach background levels before the day side. When the proton aurora has been discussed among others by Hauge and Søraas (1975) and Lundblad et al. (1979) based on data from the low altitude polar orbiting ESRO I satellite.

4. STEB, low altitude observations of ENAs in the equatorial region

In order to get a view of the particle precipitation during the October storm the intensity of the precipitating protons (30–80 keV) at all latitudes measured by POES 15 is shown in Fig. 3. For references the Dst index is plotted in the bottom panels. High particle fluxes are seen in the northern and southern auroral zones. This precipitation of tens of keV protons contributing to the proton aurora has been discussed among others by Hauge and Søraas (1975) and Lundblad et al. (1979) based on data from the low altitude polar orbiting ESRO I satellite.

In Fig. 3 it is clearly seen how the two auroral zones expand, contract and vary in intensity throughout the storm. When the main phase of the storm starts on day 302 at 08 UT the intensity of the protons increases and the precipitation reaches towards lower latitudes. The width and the intensities of the zones represent an injection of protons into the RC and are reflected in the Dst values. The intensity enhancements are very sudden and extended in latitude in particular on the evening side. These enhancements are coincident with maximum change in Dst. The proton precipitation is more intense on the evening side than on the day side.

In addition to the auroral precipitation, a belt of elevated particle flux intensity, the STEB, is seen around the magnetic equator. The STEB is centered around the geomagnetic equator and is in rough agreement with the ratio of the charge exchange cross sections for protons in an oxygen rich atmosphere given by Hamre et al. (1999) which is 3.2.

The ENA produced in the auroral arc is spread by charge exchange in all directions and some of the ENAs move away from the Earth and represent a loss of energetic particles from the magnetosphere.

3.2. ENA production

The ENAs observed poleward of the proton precipitation region are created by charge exchange of locally mirroring protons in the proton aura. It is, however, not straight forward to relate the ENAs observed in the PC to their mother protons in the oval, but as a first approximation one can assume that the production of ENA at the two energies \( E_1 = 30 \text{ keV} \) and \( E_2 = 80 \text{ keV} \) is given by

\[
\frac{j_{\text{ENA}}(E_1)}{j_{\text{ENA}}(E_2)} = \frac{\sigma_{10}(E_1)j_p(E_1)}{\sigma_{10}(E_2)j_p(E_2)}
\]

where \( \sigma_{10} \) is the cross section for charge exchange for protons to ENAs in an oxygen rich geocorona. \( j_p \) and \( j_{\text{ENA}} \) are the proton and ENA flux, respectively.

\[
\frac{j_{\text{ENA}}(E_1)}{j_{\text{ENA}}(E_2)} = \frac{\sigma_{10}(E_1)j_p(E_1)}{\sigma_{10}(E_2)j_p(E_2)}
\]

The ratio \( j_p(E_1)/j_p(E_2) \) within the arc is observed to be around 20, but over poleward of the arc the ratio is around 60 indicating a softer spectrum for the ENAs. Within the arc the horizontal detector is measuring protons, but over the PC it measures ENAs coming from the arc and a low background of protons. The ratio between the first and second energy channel is thus three times higher for the ENA spectrum than for the proton spectrum. This is in rough agreement with the ratio of the charge exchange cross sections for protons in an oxygen rich atmosphere given by Hamre et al. (1999) which is 3.2.

The ENA produced in the auroral arc is spread by charge exchange in all directions and some of the ENAs move away from the Earth and represent a loss of energetic particles from the magnetosphere.
flux intensity is seen around the magnetic equator. The Dst index is plotted in the bottom panels. 

Halloween storm. The panels span all magnetic latitudes and high particle fluxes are seen in the northern and southern auroral zones. In addition a belt of elevated particle flux intensity is seen around the magnetic equator. The Dst index is plotted in the bottom panels.

4.1. STEB observations at different MLTs

The extensions are short lived as their parent RC protons mirror close to the Earth where the neutral density is high. The regular one day intensity enhancements seen 12 h out of phase at dawn and dusk are due to the weak magnetic field in the South Atlantic Anomaly causing the radiation belt particles to come closer to the Earth in their drift motion.

In order to see how the different particle energies behave throughout the storm, Fig. 4 exhibits STEB particle observations at the magnetic equator by POES 15 through the period October 28– November 6, 2003. The top two panels display observations of ENAs at 18 and 06 MLT in the three energy bands. The bottom panel exhibits the Dst. From the particle intensities for the three energies the ENA energy spectrum throughout the storm can be determined.

4.2. RC symmetry and asymmetry

In order to look more in details at the RC symmetry/asymmetry, the MLT behavior deduced from the STEB and from ground magnetometers is shown in Fig. 6. In the top panel the absolute value of the difference between the STEB intensity at the two equatorial MLT values crossed by each satellite is shown. This difference is zero if the RC is symmetric. It is clearly seen that there are three periods with a highly asymmetric RC. In between these periods the RC approaches symmetry. In the bottom panel the Asym index is shown, both with a 1 min and 60 min resolution. The STEB at MLT 18 compared with the STEB at 18 MLT. The STEB at MLT 18 exhibits three large latitudinal extensions and intensification all coincident with the three main phases of the storm. At dawn this latitudinal extension and intensification is only seen at the main phase in the evening of day 302. These latitudinal extensions of the STEB are due to an isotropic injection of protons into the RC (Tinsley, 1979).

The observations are marked with symbols and are not equally spaced as the contaminating observations in the inner edge of the RC is representative distance for where most of the ENAs are created because of the high geocorona density.

ENAs are observed at MLTs 22:00, 18:40 and at 06:40, but no increases are observed at MLTs 14:20 and 10:20. Even with the low time resolution one can state that there is most likely no increase in ENA at 10:20 MLT and 14:20 MLT at that time.

The first injection into the RC, marked by A, is around magnetic midnight and then after about 5.5 h it has reached to dusk (line B). This increase in STEB around magnetic midnight is not manifested in the Dst index, because it is very localized and do not contribute to the symmetric RC.

The lines at C and D mark peak intensities in the STEB, and within the time resolution of the measurements they appear to be simultaneously at MLTs reaching from midnight (MLT 01:50) to MLT 14:20 at line C. The peak intensity exhibits a delayed appearance at MLTs 10:20 and 06:40 at both C and D. At D the protons are seen simultaneously from 01:50 MLT 18:40 MLT and they exhibit a delayed appearance at 06:40 MLT by 5 h. This is consistent with a westward drift of a 30 keV particle at \( L = 2 \) which is 6 h. As seen from Fig. 3 the proton precipitation reached to \( L = 2 \) and this is taken as a proxy for the inner edge of the RC (although it could have reached to a somewhat smaller L). The inner edge of the RC is representative distance for where most of the ENAs are created because of the high geocorona density.

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RC that is unbiased by other current systems because it depends only on the number of protons along the line of sight.

4.3. Ring current decay times

The top panel in Fig. 7 shows observations of ENA flux at the equator at 18 MLT during the days 304–307. This is in the recovery phase of the storm when the injection of particles into the RC is small. As the ENA flux is proportional to the proton flux along the line of sight one should be able to determine the loss rate of the RC. The panel shows the ENA flux in the three energy channels (30 to 80), (80 to 250), and (250 to 800) keV.

Assuming that the flux in the recovery phase can be fitted by:

\[ j = j_0 \times \exp \left( \frac{-t}{\tau} \right) \]
and taking the logarithm
\[
\ln j = \ln j_0 - \tau(a_0 + a_1 t + a_2 t^2) = \ln j_0 - (a_0 t + a_1 t^2 + a_2 t^3)
\]
where \(\tau\) is given by \(\tau = 1/(q_0 + q_1 t + q_2 t^2)\).

The log-flux of the two lowest energies are fitted with a third degree polynomial, while the highest energy is fitted with a second degree one.

The bottom panel shows the decay times for the different energies. The decay times increase during the storm recovery phase. At the start of the recovery phase the inner edge of the RC is close to the Earth \(L = 2.3\) where the geocorona density is high, giving a fast decay, as the inner edge moves to higher altitudes the decay times increase. A proxy for the inner edge of the RC is the low latitude boundary for the proton precipitation shown in Fig. 3. This boundary makes a gradual movement to higher \(L_s\) during the storm recovery phase. The decay time for 30–80 keV varies from 9 to 18 and for the 80–250 keV from 11 to 21 from the beginning to late in the recovery phase. The decay rates are in accordance with what is expected from the charge exchange cross sections in hydrogen given by Liemohn (1961). In the bottom panel the decay time for the Dst is given. It has the same trend as calculated from the ENA observations. The decay time for the Dst increases during the storm recovery time, possibly due to the movement of the RC to larger distance from the Earth where the charge exchange losses are less.

5. Summary, discussion, and conclusion

From low altitude observations of ENA the following picture emerges. During the storm main phase protons are injected from the tail, and gradient/curvature drift through the midnight/evening region giving the asymmetric part of the RC. In large storms the injection can cover the region from dusk to dawn, that is, the whole night side of the magnetosphere. While injected into the RC the protons are chaotically scattered in the stretched tail field and precipitate into the atmosphere giving rise to the proton aurora an intense source of ENA. This precipitation of protons into the atmosphere occurs simultaneous with a fill up of the RC. Thus the intense proton aurora is not a loss of particles from the RC, but a result of filling it up Søraas et al. (2002). This support the splash-catcher model advocated by O’Brien (1964).

The width and the longitudinal extent of the proton precipitation vary greatly throughout the storm with the most intense precipitation taking place in the night/evening sectors.

The proton aurora is an intense source of ENAs, and ENAs moving over the polar cap in an upward direction contribute to the Earth’s ion outflow.

The energy spectrum of the ENA coming from the proton oval is softer than their proton mother spectrum, this is as expected from the charge exchange cross sections.

ENAs are observed in the two energy channels 30–80 keV and 80–250 keV, but not in the 250–800 keV channel over the polar cap. The reason for this is most likely that these protons penetrate deep into the atmosphere. A 250 keV proton can reach to below 100 km altitude and it starts to charge exchange in a fairly small region before it stops. At this altitude the neutral density so high that the probability for charge exchange gets large even if the cross section for charge exchange is small. This is, however, deep in the atmosphere where the mean free path is very short, and the stripping cross section is much higher than the pick-up cross section, so ENAs immediately convert back to ions, and cannot get away from that region.

While the RC protons drift and charge exchange, ENAs are streaming towards the low altitude equatorial region of the Earth. During this phase of the storm the RC is subjected to heavy convection losses. As time passes by, the convection field disappears, and the RC develops into a symmetric belt, which decays through charge exchange and wave/particle interaction.

In the beginning of the recovery phase the RC decay is fast as it reach to lower altitudes where the inner edge suffers heavy losses. The decay of the STEB has a similar decay as the Dst. The magnetic effects of the RC are dominated by the current closest to the Earth. The ENA flux thus gives a direct measure of the protons along the line of sight. The LT extension and intensity of the STEB are thus an image of the RC and can reveal much of its behavior.

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