Latitude distribution of vertically precipitating energetic neutral atoms observed at low altitudes

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[1] Earlier modeling work of the latitude distribution of earthward traveling energetic neutral atoms (ENA) originating in the ring current have suggested that an isotropic ring current with an empty loss cone will deposit most ENA away from the magnetic equator, while a ring current with an equatorial pitch angle distribution peaked at 90° will deposit most ENA at the magnetic equator. We present the first direct low altitude measurements of energetic particles at low and equatorial latitudes supporting this model. The evolution from an isotropic ring current to a more anisotropic one is manifested in the latitude distribution of the low altitude energetic particles during a geomagnetic storm. In the growth and main phase of the storm the latitude distribution of the energetic particles is wide and often show secondary peaks away from the equator, while in the recovery phase the latitude distribution narrows and peaks at the magnetic equator.
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1. Introduction

[2] The first low altitude observations of energetic charged particles at equatorial latitudes, were obtained by the German research satellite Azur in 1969 and 1970 [*Moritz*, 1972; *Hovestadt et al.*, 1972]. *Moritz* [1972] suggested that the source region of the low altitude protons detected by Azur was the ring current and that the charged particles were re-ionized ENA. This view was supported by *Mizera and Blake* [1973], who also reported the detection of energetic protons at low altitudes near the magnetic equator by the satellite OV 1–17. *Hovestadt and Scholer* [1976] also supported a ring current origin of the low altitude particles. The same view has later been confirmed by observations of ENA from outside the ring current. *Roelof et al.* [1985] reported direct measurements of ENA outside the radiation belts with instruments on board the IMP7/8 and ISEE 1 spacecraft, and they related the measurements to the activity in the ring current.

[3] Later Polar [*Henderson et al.*, 1997], Geotail [*Lui et al.*, 1996] and IMAGE [*C:son Brandt et al.*, 2002b, 2002a] have presented observations of ENA coming from the ring current. In particular IMAGE has presented impressive pictures of the ring current based on ENA.

[4] Most observations of energetic neutral particles at low altitudes are from higher latitudes. *Søraas and Aarsnes* [1996] detected ENA from a proton arc observed by the Poleward Leap rocket launched in 1983. The Swedish satellite Astrid carried the camera PIPPI (Prelude in Planetary Particle Imaging), designed to obtain ENA images. Most of the images from PIPPI are from high latitudes [*Barabash et al.*, 1997; *C:son Brandt et al.*, 1997, 2000].

[5] The detection of a Storm Time Equatorial Belt (STEB) of energetic particles observed by the low altitude polar orbiting NOAA satellites is reported by *Søraas et al.* [2003]. They found STEB to reveal the asymmetry of the growth and main phase ring current and its symmetry in the recovery phase. The drift of ring current ions from the night side toward the day side was also manifested in STEB. *Søraas et al.* [2003] established that STEB mimicked the MLT behavior of the ring current. In their study only particles measured in the magnetic equatorial plane were considered.

[6] The present work examines the STEB in more detail. The latitude distribution of the energetic particles precipitating radially toward the Earth measured by the NOAA satellites from the magnetic equatorial plane to ±40° magnetic latitude is studied and found to be strongly dependent on the storm phase. Measurements obtained during two different geomagnetic storms are considered.

2. Production and Precipitation of ENA

[7] ENA are produced in charge-exchange reactions between energetic ions in the ring current and cold neutral hydrogen atoms in the geocorona. In the reaction an electron is transferred from the neutral atom to the ion, producing an energetic neutral atom with almost the same energy as the original ring current ion. The new ENA travel unaffected by the magnetic field on straight line paths determined by the velocity and pitch angle of the ion before the collision. Most of the ENA will be lost in space, but a small fraction will move toward the Earth. At low altitudes where the geocorona is dense the ENA can be re-ionized through new charge-exchange reactions and get trapped in the geomagnetic field.

[8] In 1979 *Tinsley* [1979] calculated the latitude distribution of the earthward deposited ENA to be dependent on the pitch angle distribution of the ring current ions. He found that an isotropic ring current will deposit most of its earthward traveling ENA at low latitudes but away from the magnetic equator, while a ring current with an equatorial pitch angle distribution peaked at 90° will deposit

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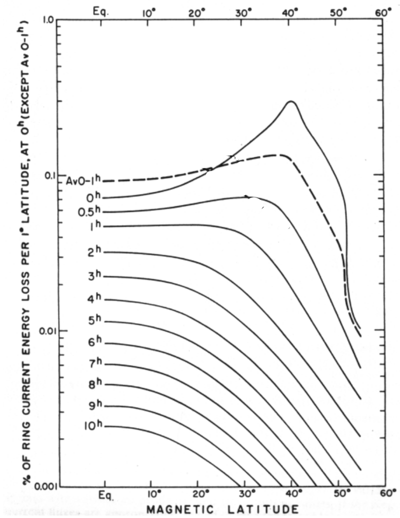

Figure 1. Ring current energy loss per 1° latitude from a ring current at L = 3 which is initially isotropic except from an empty loss cone and decays through charge exchange [from *Tinsley*, 1979].

most ENA at the magnetic equator. Figure 1 shows the percentage of ring current energy lost to the thermosphere through charge exchange per 1° latitude for a ring current located at L = 3. The line labeled 0h shows the latitude distribution of ENA coming from a ring current which is isotropic (except for an empty loss cone). The lines labeled 1h through 10h show the evolving latitude distribution of the precipitating ENA at one-hour intervals, assuming that the only loss process for ring current ions is through charge exchange. The latitude distribution peaks at the magnetic equator after a short time.

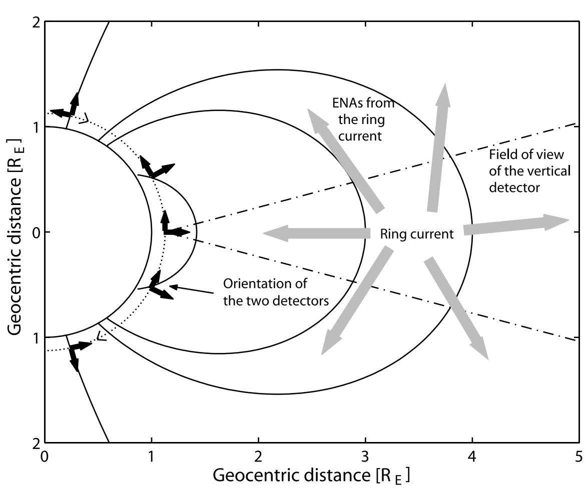

Figure 2. The configuration of the vertical and the horizontal detectors on the NOAA (15-16) satellites (perpendicular arrows) relative to the geomagnetic field during one southbound equator crossing. The dotted line shows the satellite orbit. The dashed-dotted lines drawn from equatorial latitudes and outward show the field of view of the vertical detector at the equator. The detector has a ±15° field of view. The grey arrows indicate that ENA are produced in the ring current and that they travel in all directions.

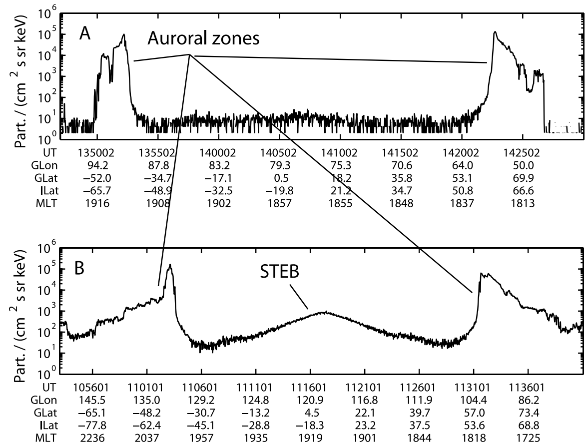

Figure 3. Measurements of 30–80 keV particles by the vertical detector on NOAA 15 during two equator crossings (a) on a quiet day, March 28, and (b) on a storm-day, March 31 in 2001. The Figures show the particle flux measured from the southern polar cap to the northern polar cap. The southern and northern auroral zones are seen with high fluxes of protons. Very low fluxes are seen between ±40° magnetic latitude on the quiet day (Figure 3a) but considerable fluxes of particles are seen on the storm-day (Figure 3b).

3. Instrumentation

[9] NOAA 15 and 16 are the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellites (POES) which are used in this study. The orbits of these satellites are polar and sun-synchronous at an altitude of about 850 km and with a period of ~100 minutes. The orbits of the two satellites cover different local times. NOAA 15 orbits the Earth in the morning-evening plane with a Local Time Ascending Node (LTAN) at approximately 1900. NOAA 16 have LTAN at approximately 1400.

[10] On board each satellite is the Medium Energy Proton and Electron Detector (MEPED) providing directional measurements of energetic particles [*Evans and Greer*, 2000]. The instrument hold two directional solid-state detectors. The two detectors measure 9° and 81° to the local vertical, they are referred to as the vertical and the horizontal detectors, respectively. In this study only the vertical detector is used. At high latitudes the vertical detector views nearly along the magnetic field lines while at equatorial latitudes the detector views perpendicular to the magnetic field. The detectors have a ±15° (total 30°) field of view. The particles are measured in six energy ranges: 30–80, 80–250, 250–800, 800–2500, 2500–6900 and >6900 keV. In this study only the 30–80 keV energy channel is used. The detectors are sensitive to both charged and neutral particles, but cannot distinguish between the two.

[11] Figure 2 illustrates the Earth with its dipole field. The dotted line shows the satellite orbit. The black arrows represent the orientation of the two perpendicular detectors during one southbound equator crossing for NOAA 15-16.

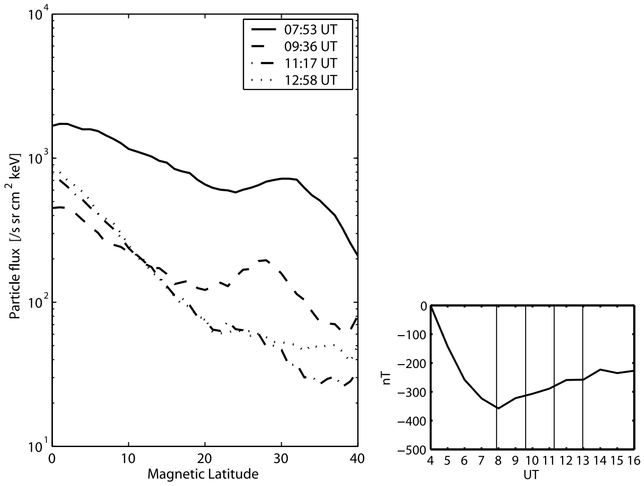

Figure 4. (left) The particle flux measured by the vertical detector on NOAA 15 on March 31, 2001, during four consecutive equatorial crossings around 2000 magnetic local time. (right) The Dst-index, and the vertical lines mark the times of the four equator crossings.

[12] Figure 3 shows how the observed flux of 30–80 keV particles measured by the vertical detector is typically distributed from pole to pole on a quiet day (Figure 3a) and on a day when there is a storm (Figure 3b). The southern and northern auroral zones are clearly seen to the left and right in each panel. The region between the two auroral zones shows a significantly higher flux level on the storm day than on the quiet day and this is STEB. This region of elevated fluxes will be studied in detail in the next section.

4. Observations

[13] The particle flux measured by the vertical viewing proton detector while transiting from 40° magnetic latitude in one hemisphere across the magnetic equator to 40° magnetic latitude in the other hemisphere are analyzed for two geomagnetic storms. The minimum in the Dst-index for the two storms were −358 nT and −373 nT, thus both storms were very strong storms.

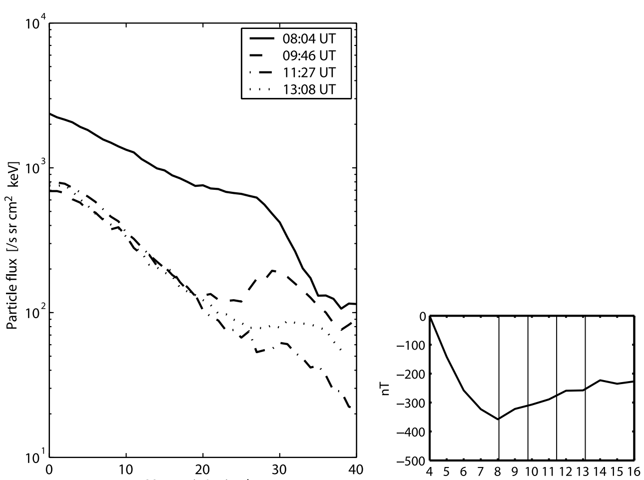

Figure 5. Similar to Figure 4, but the observations are from NOAA 16 on March 31, 2001, during four equatorial crossings around 0230 magnetic local time.

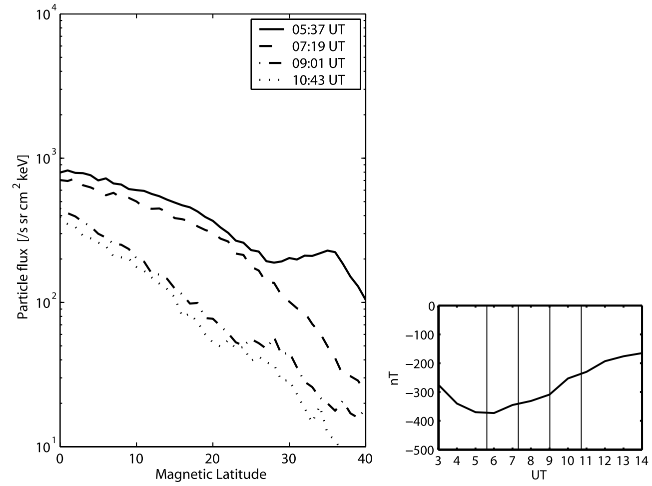

Figure 6. Similar to Figure 4 except that the observations are from NOAA 15 on November 8, 2004, during four equatorial crossings around 1900 magnetic local time.

[14] Figure 4 shows the particle flux as measured by the vertical detector on NOAA 15 on March 31, 2001. The fluxes are obtained during four consecutive northbound equatorial crossings on the evening side, approximately at a magnetic local time of 2000. The data is plotted in a flux vs magnetic latitude diagram. (Only data from 0° to 40° magnetic latitude at the northern hemisphere is shown in order to avoid effects of the South Atlantic Anomaly). The Dst-index for the time period of concern is shown in the rightmost diagram. The four vertical lines in the Dst-plot indicate the time of the four equatorial crossings. The first crossing occurs when the Dst-index is at its lowest. The three next crossings are in the recovery phase of the storm.

[15] The flux measured during the first crossing, shown as the solid line, has a peak flux at the magnetic equator. There is also a secondary peak approximately at 30° magnetic latitude. The observation is from the main phase of the storm, when it is reasonable to assume that the ring current has a pitch angle distribution close to isotropic. The secondary peak is believed to be the observation of the off-equatorial peak of precipitating ENA as modeled by *Tinsley* [1979] (the line marked 0h in Figure 1). The flux intensity in the next crossing at 0936 UT is lower, but the secondary peak is still present. In the two last crossings at 1117 UT and 1258 UT the flux above ~10° latitudes has decreased still more and the secondary peak at 30° magnetic latitude has almost disappeared.

[16] Figure 5 shows the particle flux measured by NOAA 16 in the same time period. The measurements are from the night side where NOAA 16 crosses the equator around magnetic local time 0230. The solid line shows the flux when the Dst was at its minimum, around 0800 UT. The flux is most intense at the magnetic equator, but there is an enhancement around 30° magnetic latitude. The dashed line shows the flux measured during the next equator crossing. The flux has decreased at all latitudes, but a secondary peak at 30° latitude has appeared. The two next crossings show very stable equatorial fluxes but fast decay at latitudes above 20° magnetic latitude.

[17] Figure 6 shows the particle flux obtained during four equatorial crossings on November 8, 2004. The crossings are from the evening side around 1900 magnetic local time. Only the first crossing at 0537 UT reveals a secondary low-latitude peak in the particle flux. The peak is located approximately at 35° magnetic latitude. The three next equator crossings, taking place in the recovery phase of the storm, show maximum particle flux only at the magnetic equator and no secondary peak. The two last crossings show very stable fluxes.

5. Discussion and Conclusion

[18] The presented observations show that the off-equatorial peak of precipitating ENA from an isotropic ring current as calculated by *Tinsley* [1979] are indeed observed. The peak is usually seen in the observations as a secondary peak away from the equator and not as a maximum for the whole distribution from the equator to ±40° magnetic latitude. During the storm recovery phase these peaks disappear as predicted by the calculations.

[19] Even if the MEPED detector cannot distinguish between charged and neutral particles we argue that most particles both in the secondary peak and in the peak at the magnetic equator are neutral particles and not re-ionized ENA trapped on low altitude magnetic field lines. This because an ENA beam coming from the ring current has experienced very little re-ionization at the altitude of the satellite (850 km). The main re-ionization of ENA happens between 200 and 400 km altitude [*Eather*, 1967; *Orsini et al.*, 1994].

[20] Then to the question of why the peak at the magnetic equator almost always is present also in the main phase of the storm and not only in the recovery phase as modeled by *Tinsley* [1979]. The modeled latitude distributions of precipitating ENA are calculated under the assumptions that the ring current is initially isotropic except from an empty loss cone and that the only loss process for the ring current ions is through charge exchange. But even when particles are injected with an isotropic pitch angle distribution on the night side the innermost region of the ring current will have maximum intensity at 90° equatorial pitch angle as inward drifting particles move closer to the equator [*Nakada et al.*, 1965]. The magnetic field lines also become less stretched and the protons are not undergoing chaotic scattering to maintain isotropy [*Sergeev et al.*, 1983]. The modeled distributions are calculated for a ring current located at a particular L-shell. In reality the ring current extends over several L-shells.

[21] It is also important to note that the modeled distribution shows the total influx from the upper hemisphere while the MEPED detector only measures the particles which precipitate within an angle of ±15° to the local vertical. The detector thus excludes ENA moving outside this cone.

[22] Work is in progress for modeling the latitude distribution of ENA from a spatial extended ring current in order to make a more realistic comparison with the observations done by the satellites. But regardless of later answers on these issues the origin of the low altitude energetic particles is the ring current and the latitude distribution of the low altitude particles during a storm reflects the ring current intensity and pitch angle distribution.

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