Filling the South Atlantic anomaly by energetic electrons during a great magnetic storm

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[1] We study energetic particles in the inner magnetosphere during the great storm of March 31, 2001, using low-altitude NOAA-15 and 16 satellites. The NOAA/SEM-2 instruments can monitor energetic particles above 30 keV from the equator to nearly polar latitudes. The South Atlantic anomaly (SAA) is seen by NOAA/SEM-2 as a region of an increased flux of precipitating energetic protons in a limited MLT sector at low latitudes. At 0945 UT the NOAA-16 satellite observed a strong increase of trapped 100–300 keV electrons at a very low invariant latitude of L = 1.14 in the 02 MLT sector, i.e., a few MLT hours behind SAA. The injected electrons drifted eastwards and joined SAA, as first observed by the NOAA-15 satellite at 1030 UT in the 07 MLT sector. Thereafter the electrons were permanently trapped within the SAA and drifted around the Earth together with SAA. The lower-energy (30–100 keV) part of the injected electrons was first detected by NOAA-16 at 1125 UT in the same MLT, and L region. These electrons drifted longer behind the SAA region at a drift speed which agrees well with the theoretical estimate. Later, they also joined SAA and were thereafter trapped in it. Inside the SAA region the electron fluxes decreased exponentially with an e-folding decay time of about 8.6 h. The results show that a great storm can effectively fill the SAA region by trapped energetic electrons. We present the observations and discuss the generation of energetic electrons at very low latitudes, as well as the mechanism of trapping them inside the SAA. **Citation:** Asikainen, T., and K. Mursula (2005), Filling the South Atlantic anomaly by energetic electrons during a great magnetic storm, *Geophys. Res. Lett.*, *32*, L16102, doi:10.1029/2005GL023634.

1. Introduction

[2] The South Atlantic anomaly is a region of weakened magnetic field at the coast of Brazil [*Pinto et al.*, 1992]. Because of weaker magnetic field the precipitation of energetic particles is stronger than elsewhere at the same geographic latitudes (see review by [*Pinto and Gonzalez*, 1989] and references therein). Numerous magnetospheric mechanisms, such as pitch-angle scattering [*Abel and Thorne*, 1999] and storm-time magnetic disturbances [*Abdu et al.*, 1981] can cause enhanced precipitation in SAA. Majority of past studies has concentrated on MeV range electron precipitation.

[3] In this paper we present observations of an intense keV range electron population that gets trapped in the SAA region and remains there, decaying exponentially with a lifetime of about 8 hours. Such a process is, to our knowledge, unique and has not been observed or documented earlier.

2. Instrumentation

[4] We use energetic particle data from the MEPED (Medium Energy Proton Electron Detector) instruments onboard polar orbiting NOAA-15 and NOAA-16 satellites. The altitude of the satellites is 850 km. The orbital planes of NOAA-15 and NOAA-16 are 7–19 MLT and 2–14 MLT. We will call the 02, 07, 14 and 19 MLT sectors as post-midnight, morning, afternoon and evening, respectively. Using the two NOAA satellites we can monitor energetic particle fluxes at four different MLT sectors at the time resolution of one orbit (about 1.5 h).

[5] MEPED includes two sensors that measure particle fluxes in two independent directions, one (so called 0° detector) roughly along the local vertical direction, the other (90° detector) perpendicular to it. At low (high) latitudes the 0° detector measures mainly trapped (field-aligned) particles and vice versa for the 90° detector. Electrons are measured at three energy channels (30–100, 100–300 and >300 keV) and protons at six energy channels (30–80, 80–240, 800–2500, 2500–6900 and >6900 keV).

3. Observations

3.1. Detection of SAA Region

[6] In order to study the particle fluxes in SAA the region itself must be identified in the data. Figures 1 and 2 display the data from NOAA-15 and 16 satellites during the great magnetic storm of March 31, 2001, which is discussed in more detail by [*Asikainen et al.*, 2005]. The plots from top to bottom show the geographic latitude and longitude, magnetic local time and proton (90°) and electron (0°) spectra first for NOAA-16 and then for NOAA-15. A notable feature in proton spectra are the two flux peaks around high latitude regions due to ring current crossings. (Note that as the storm main phase starts at about 04 UT these two peaks diverge as ring current moves to lower L-shells [*Asikainen et al.*, 2005]). In addition to the ring current peaks another proton population just below the geographic equator is first seen in NOAA-16 data at about 03 UT, 0425 UT and 0630 UT. This same proton signature is seen at 09 UT 1030 UT and 1210 UT in NOAA-15 and 12 hours after first observed again by both satellites. These protons are a signature of SAA and can be used to identify the region. (Also electron fluxes are enhanced in SAA). Note that the proton signature rotates with the Earth (thus opposite to proton

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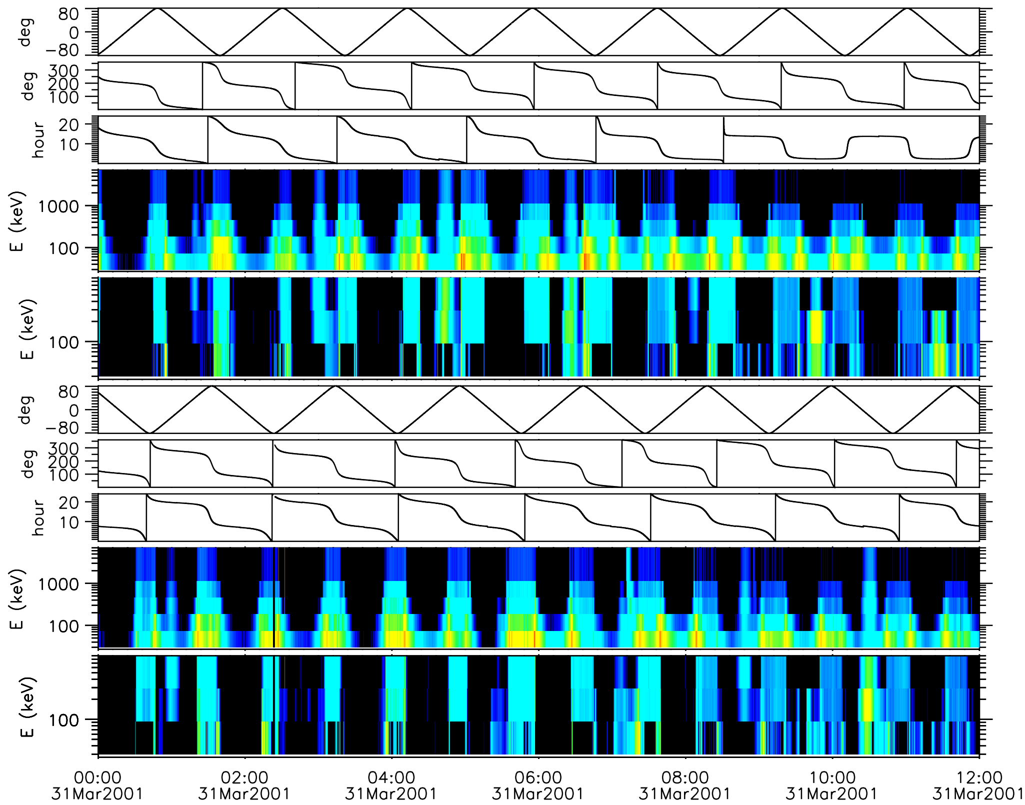

Figure 1. NOAA data 31 March 2001, 0000–1200 UT. From top to bottom: NOAA-16 Geographic latitude, longitude, Magnetic Local Time, 90° proton spectrum, 0° electron spectrum and corresponding data for NOAA-15 below.

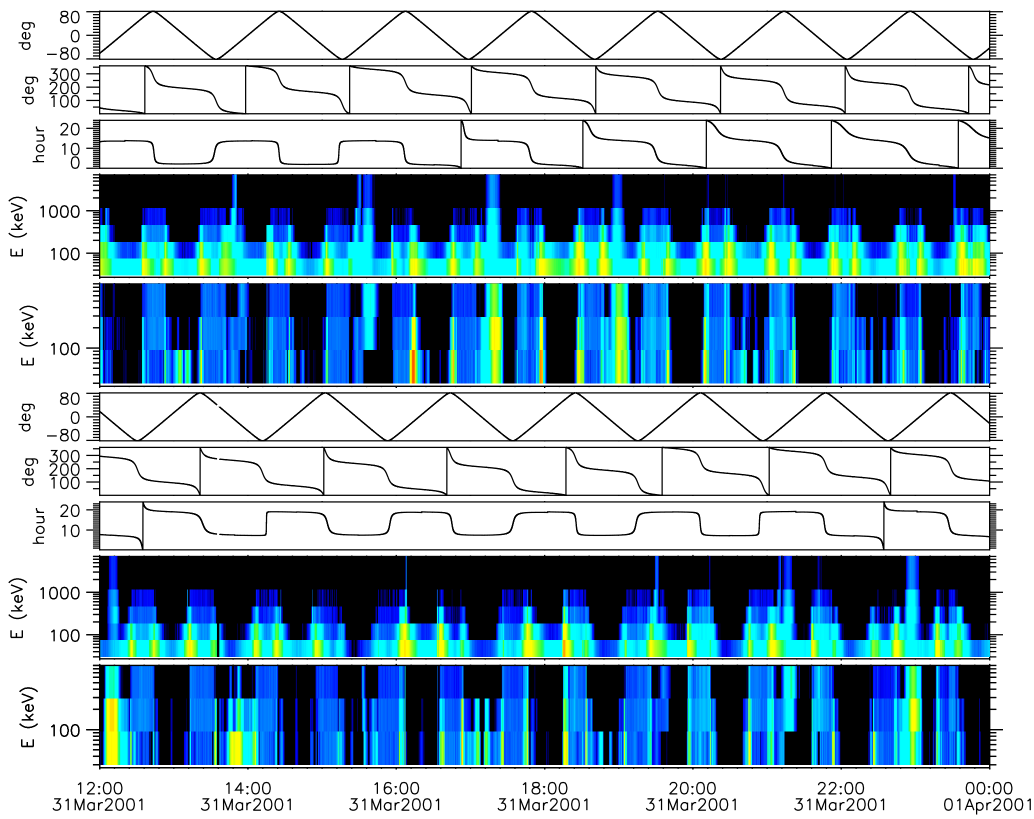

Figure 2. NOAA data 31 March 2001, 1200–2400 UT. Data content is the same as in Figure 1.

drift direction) and is centered around 3 MLT behind the respective UT time, such as SAA.

3.2. NOAA-16 in Post-Midnight Sector

[7] At 0945 UT and 1125 UT NOAA-16 detected two intensifications of transverse energetic electrons at a very low L value of about 1.14, the first centered in the 100–300 keV range (HE, high-energy electrons), the second at 30–100 keV (LE, low-energy electrons). These flux intensifications are not related to SAA which was located at about 8 MLT, i.e., several MLT hours away from NOAA-16. Note also that NOAA satellites do not detect any simultaneous increases in proton fluxes, i.e., the intensifications consist of electrons only.

3.3. NOAA-15 in Morning Sector

[8] At about 1030 UT, while inside SAA, NOAA-15 detected the HE electrons in the morning sector. Even a greater intensification of HE electrons was observed during the next orbit at 1210 UT also within SAA. The LE electrons are seen only at about 1350 UT, outside the SAA region.

3.4. NOAA-16 in Afternoon Sector

[9] NOAA-16 detected the HE electrons next time in the afternoon sector at 1720 UT while in the middle of SAA. A significant (respectively, weak) HE electron flux was also observed during the next (previous, resp.) orbit at about 1900 UT (1530 UT, resp.) when NOAA-16 was still inside (just entering, resp.) SAA, but not on any other orbits. Note that also the LE observations were limited to the two latter orbits. Accordingly, in the afternoon sector, the LE electrons were only seen inside SAA.

3.5. NOAA-15 in Evening Sector

[10] In the evening sector a strong (weak) intensification of HE electrons was observed by NOAA-15 at about 2300 UT (2115 UT) during the first two SAA orbits. As in NOAA-16, LE electrons were seen on the second SAA orbit at 2300 UT. Again, no HE or LE flux enhancements were observed before or after the SAA orbits.

4. Discussion

[11] NOAA-16 detected the HE electrons first at 0945 UT at L = 1.14 and some 1 h 40 min later the LE electrons in the same MLT and L-value region. This is a clear signature of energy dispersion due to the different drift speeds of particles of different energies. We used the gradient-curvature drift theory in a dipole field to estimate the drift speeds (in units of MLT hour/UT hour) of the two observed electron populations by the formula $v_d \approx 24LE/1047$, where E is the particle energy in keV. For the lower limit of the two energy channels (i.e., 30 keV and 100 keV) the drift speeds are 0.78 MLT-h/UT-h and 2.61 MLT-h/UT-h. Using these values and the NOAA-16 observation times we estimated that the common origin for the electrons is at 24 MLT at 0902 UT. On the other hand, using the upper limits of each energy channel (i.e., 100 keV and 300 keV) the drift speeds are 2.61 MLT-h/UT-h and 7.84 MLT-h/UT-h which put the common origin at 19.5 MLT at 0855 UT. Accordingly, the energetic electrons were injected in the pre-midnight sector 19.5–24 MLT range at about 0855–0902 UT.

[12] It is worthwhile to note that we also get an estimate for the drift speed of the LE electrons directly from observations. These electrons were observed by NOAA-16 in 02 MLT at about 1125 UT and by NOAA-15 in 07 MLT at 1350 UT. These values yield a drift speed of about 2 MLT-h/UT-h which fits well within the above theoretical limits. (Note that a similar estimate of drift speed cannot be obtained for HE electrons since they already have fallen in SAA before the second observation by NOAA-15 at 1030 UT).

[13] Since the theoretical drift speed of HE electrons and the observed drift speed of LE electrons are both higher than the rotation speed of Earth (1 MLT-h/UT-h) the eastward drifting electrons are bound to catch up with SAA at some point. According to observations the HE electrons reach SAA already in the morning sector, but the LE electrons reach SAA somewhere between 06 MLT and 14 MLT. Note that none of the two electron populations are able to drift past SAA. Moreover, they do not precipitate inside SAA instantly but rather get trapped in SAA for hours and rotate around the Earth with it. The flux levels of the electrons inside SAA were found to decrease approximately exponentially with an e-folding decay time of about 8.6 h.

[14] Traditionally it is thought that the effect of SAA is to enhance the precipitation (of those particles that are in the drift loss cone) for a short while when the particles are drifting past SAA. Based on this, one might argue that, because of the present, low time resolution of one orbital period, the satellites might miss the majority of particles drifting past the SAA. There are several arguments that exclude this possibility. First of all, the flux levels are quite similar at the first observation by NOAA-16 at 0945 UT outside SAA, and at the second observation by NOAA-15 at 1030 UT inside SAA. Second, the HE electrons drift at the theoretical speed roughly 2–7 MLT hours within the 45 min time difference, in agreement with the 5 hour MLT difference between the two satellites. If these electrons would, rather than stay within SAA, continue drifting at the same speed, they would have to be observed in the early afternoon UT time in the early afternoon MLT sector by NOAA-16, and slightly later in the evening sector by NOAA-15. Still, there is no sign of these electrons in either of the satellites until the time of SAA passage. Third, the flux level of the HE electrons seen by NOAA-15 at 1205 UT is the highest for this energy range. A part of the HE electrons did not yet reach SAA by the previous observation at 1030 UT. Also, there are HE electrons that have been trapped inside SAA before the 09 UT injection. These can be first seen by NOAA-15 in the evening at 01 UT, and by NOAA-16 during the three post-midnight SAA orbits between about 03 UT and 0630 UT. This gives further evidence that the electrons are not lost when they enter SAA but rather get trapped there for many hours.

[15] Obviously, the unique and exceptional nature of the present observations impose several questions. E.g., what is the mechanism that can inject the energetic electrons to so very low L-values? One possibility could be the charge exchange mechanism [*Lyons and Richmond*, 1978; *Søraas et al.*, 2003] in which the ring current ions first produce energetic neutral atoms (ENA) by charge exchange with

neutral hydrogens of the geocorona. ENAs then move freely to very low L-shells where they collide with ionospheric atoms producing energetic electrons that are discussed here. This mechanism is supported by the location (19–24 MLT) and timing (end of storm main phase; minimum Dst is at 08 UT) of the injection, and by the extreme intensity (Dst = −360 nT) of the storm.

[16] Another problem relates to the mechanism trapping the electrons inside SAA. It is possible that the magnetic field lines at low altitudes around the SAA region form a topology where the magnetic gradient has a component pointing away from the center of the region rather than only in the radial direction. Then, due to this gradient, the electrons would experience at either end of the short field line, a westward azimuthal drift component oppositely directed to the normal eastward drift. Thus, the total azimuthal drift speed could be strongly reduced from its dipolar value around SAA, leading to effective trapping. This mechanism reduces the drift speed of electrons of all energies by the same fraction. Naturally, the drift of protons is similarly reduced. However, even the reduced total drift speed of protons is westwards, i.e., opposite to the rotation direction of SAA (and electrons). Therefore, protons are not trapped. Another possible trapping mechanism is offered by strong electric fields that have recently been observed within SAA during magnetic storms, and have a large outward directed radial component [*Lin and Yeh*, 2005]. The observed radial electric fields are large enough to exceed the corotation field and to cause a strong westward directed drift speed around the SAA region.

5. Conclusions

[17] We have studied the drift of an intense electron population during a great magnetic storm. Energetic electrons were injected at pre-midnight sector to a very low L value of about 1.14 at the end of the storm's main phase. While drifting eastwards the more energetic (100–300 keV) electrons reached the SAA region in the morning sector soon after injection. The electrons did not drift past SAA but were trapped in it. The lower-energy (30–100 keV) electrons of the injected population drifted longer behind SAA at a drift speed which agrees well with the theoretical estimate. After reaching SAA they were also trapped there. Inside the SAA region the electron fluxes decreased exponentially with an e-folding decay time of about 8.6 h. Energetic neutral atoms produced by charge exchange of ring current ions with geocoronal hydrogen can reach very low latitudes and produce the observed population of energetic electrons. We have also discussed possible mechanisms of trapping the electrons (but not protons) inside the SAA region.

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