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Storm time equatorial belt – an "image" of RC behavior

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[1] During geomagnetic storms a well defined belt of trapped protons and ENAs (energetic neutral atoms) is observed around geomagnetic equator at low L-values. Their source is RC (ring current) protons existing at larger L-values. Through charge exchange with the geocorona RC protons become ENAs and if subjected to a new charge exchange become trapped protons. From low latitude particle observations at four different local times we follow; the RC injection region, the drift of RC-particles through the evening/afternoon into the morning sector, the RC-asymmetry and convection loss to the dayside during the storm initial and main phase, and its development into a symmetric RC in the recovery phase of the storm. *INDEX TERMS:* 2778 Magnetospheric Physics: Ring current; 2720 Magnetospheric Physics: Energetic particles, trapped; 2730 Magnetospheric Physics: Magnetosphere—inner; 2788 Magnetospheric Physics: Storms and substorms. **Citation:** Søraas, F., K. Oksavik, K. Aarsnes, D. S. Evans, and M. S. Greer, Storm time equatorial belt – an ''image'' of RC behavior, *Geophys. Res. Lett.*, *30*(2), 1052, doi:10.1029/2002GL015636, 2003.

1. Introduction

[2] Production of ENAs (energetic neutral atoms) by charge exchange of RC (ring current) ions with neutral hydrogen in the geocorona was predicted by *Dessler et al.* [1961] and is an important loss process for the RC. The range 20–200 keV includes the carriers of the major part of the RC energy. The first observational data on ENA precipitation giving rise to low latitude protons was obtained in 1969 and 1970 from the satellite AZUR [*Moritz*, 1972; *Hovstadt et al.*, 1972]. The energy of the ions was in the range 0.25–1.05 MeV, if protons, or greater, if they were heavier ions. *Moritz* [1972] suggests that these ions at low L-values near the equatorial plane come from ENAs born in charge exchange of RC ions. ENAs originating from higher L-values may reach low altitudes where they are re-ionized by charge exchange and become energetic ions trapped by the magnetic field. *Mizera and Blake* [1973] extended these observations to lower energies. Those early studies were limited to single cases and the observations were not directly related to the trapped radiation existing at larger L-values. The one exception, however, was the report by *Moritz* [1972] where measurements of an intensity increase in the low latitude belt occur simultaneously with an increase at L = 3 indicating a close connection between the two particle populations. In more recent years *Gusev et al.* [1996] considered low altitude >640 keV protons during a 3-year period starting in 1984, and *Greenspan et al.* [1999] studied low altitude >300 keV ions using 6 years of SAMPEX data. As the energies of the observed low altitude particles are well above the bulk RC ion populations, no detailed information about the RC could be obtained. *Tinsley* [1981] has given a comprehensive review of these equatorial ions and some of their consequences for the equatorial atmosphere.

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2. Instrumentation

[3] The present study examines observations of protons from the MEPED (Medium Energy Proton and Electron Detector) on board the NOAA 15 and NOAA 16 satellites. The MEPED instrument measures protons and electrons at angles of 10° and 90° with the local vertical. MEPED is sensitive to all energetic ions. The most abundant ions in the RC are hydrogen and oxygen. The relation between these ions varies throughout the storm as discussed by *Daglis et al.* [1996]. As MEPED can not distinguish between different ion species we will use the term protons throughout this paper. The instrument will also respond to ENAs (Energetic Neutral Atoms). For a discussion of the instrument response to heavier ions see *Søraas et al.* [2002]. A full description of the NOAA spacecraft and the MEPED instrument is given by *Evans and Greer* [2000]. At low latitudes around the geomagnetic equator the 10° detector will measure trapped particles and downward moving ENAs. The NOAA 15 and 16 orbits are sun-synchronous circular at an altitude of about 850 km.

3. Observations

[4] In the auroral zone and at mid geomagnetic latitudes the behavior of energetic trapped and precipitating protons in the range from keV to several hundred keV have been extensively studied, mostly from low altitude polar orbiting satellites. Energetic particles at low L-values close to the equator have, however, only been systematically studied at energies above several hundred keV [*Gusev et al.*, 1996; *Greenspan et al.*, 1999].

[5] The present study report new findings on energetic protons (ions)/ENAs observed at low L-values in the range 30 to 250 keV during two geomagnetic storms (March and November 2001). Our objective is to study the time behavior of protons and ENAs in this region of near Earth space at several local times in order to determine those processes that govern the STEB (storm time equatorial belt) and to establish how this belt relates to the higher L-value RC.

3.1. The November 2001 Storm

[6] The vertical looking 10° MEPED detector on the NOAA 15 spacecraft showed a well defined belt of enhanced proton intensity at low L-values during the November storm. An example of this belt, as observed on November 7, is

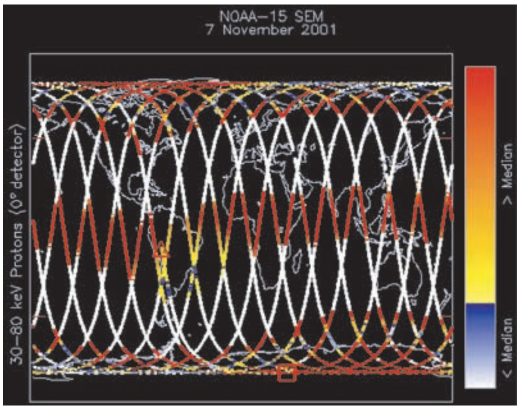

Figure 1. STEB as observed on 7 November 2001 in the early recovery phase of a geomagnetic storm.

shown in Figure 1. The intensity of protons in the energy range (30–80) keV is well above the median value in an approximately ±30° latitude belt bracketing the geomagnetic equator. The median sensor response was determined using the previous year's observations at each location visited by the satellite. This belt is absent during quiet times.

[7] Figure 2 shows a single dayside satellite pass of NOAA 15 on November 6 well into the recovery phase of a storm. The three top panels give intensities of protons/ENA in energy channels (30–80), (80–250), and (250–800) keV for the vertical 10° detector. The fourth panel gives the ratio between the fluxes in energy channels 1 and 2. The bottom panel exhibits the ILAT (invariant latitude). All parameters are plotted vs. UT (universal time). The pass starts at high latitudes in the northern auroral zone, crosses STEB around 0° ILAT, and then reaches the southern auroral zone. The particle intensities in the two lowest energy channels exhibit a maximum at the geomagnetic equator and fall off towards increasing latitudes. From panel four it is seen that the particle energy spectrum is much softer in STEB than in the auroral zone. If STEB particles are due to charge exchange of RC particles, it is expected that the ratio between the flux in channels 1 and 2 would be softer in STEB than in the RC by a factor $\sigma_{10}(30keV)/\sigma_{10}(80keV)$ where σ_{10} is the charge exchange cross section for proton neutral charge transfer. This factor is roughly 5, a value not in conflict with what is shown in the fourth panel of Figure 2 comparing the ratio in the auroral zone with the one in STEB. *Søraas et al.* [2002] have shown that precipitating auroral protons are a good measure of RC proton injection. No STEB increase is seen in the 250–800 keV channel, not unlikely as $\sigma_{10}(250keV)$ is down a factor of 100 compared with the cross section at 30 keV.

[8] Figure 3 exhibits particle observations at the magnetic equator performed by the NOAA 15 and 16 satellites at low L-values through the period 5 to 8 November 2001. The top four panels display observations of trapped protons and downward moving ENAs ordered versus LT, the top panels 1 and 3 refer to NOAA 16 (at LT 2 and 14), panels 2 and 4 refer to NOAA 15 (at LT 19 and 7). The fifth panel gives the D_{st}, and the bottom one gives the ratio between the evening (LT 19) and the morning (LT 07) STEB intensities. As seen from the D_{st} the storm has a well defined main phase with a quick and then a slower recovery. The main STEB injection appeared first at 19 LT, and then after a short delay at 2 LT. At both 14 LT and 7 LT the intensities are lower, rise times are longer, and the start of the intensity increases are delayed compared with the evening/midnight sector. In the recovery phase of the storm STEB is almost independent of LT and decay in a similar fashion as D_{st} recovers.

3.2. The 31 March 2001 Storm

[9] Figure 4 displays the observations of the particles measured at the dip equator during a major geomagnetic storm ($D_{st} = -358nT$) arranged in the same way as in Figure 3. In the storm main phase the low L-value particles exhibit a clear LT asymmetry. The intensity in the midnight/evening sector is markedly higher than in the postnoon/morning sector. A delay in the appearance of the particles vs. LT can also be noticed. The 30–80 keV particles appear simultaneously at LT 02 and 19. There is, however, a delay before they appear in the morning sector (LT 14 and 07). As seen from the D_{st}-index the March storm exhibits the double main phase depression typical of large storms. This double structure is also clearly seen in the intensity of low latitude particles. It appears that the RC injection region is more widespread in LT in the first RC-injection than in the second one. The intensity in the first injection is almost equal at LT 02 and 19, but the second injection is more concentrated

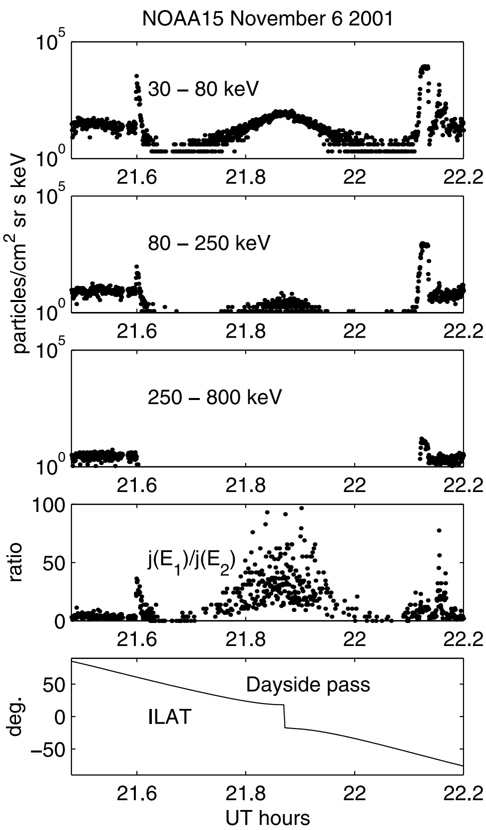

Figure 2. The three top panels give intensities of protons/ENA in energy channels (30–80), (80–250), and (250–800) keV for the 10° detector. The fourth panel gives the ratio between the fluxes of the two first energy channels (1 and 2). The bottom panel exhibits the ILAT (invariant latitude) vs. universal time.

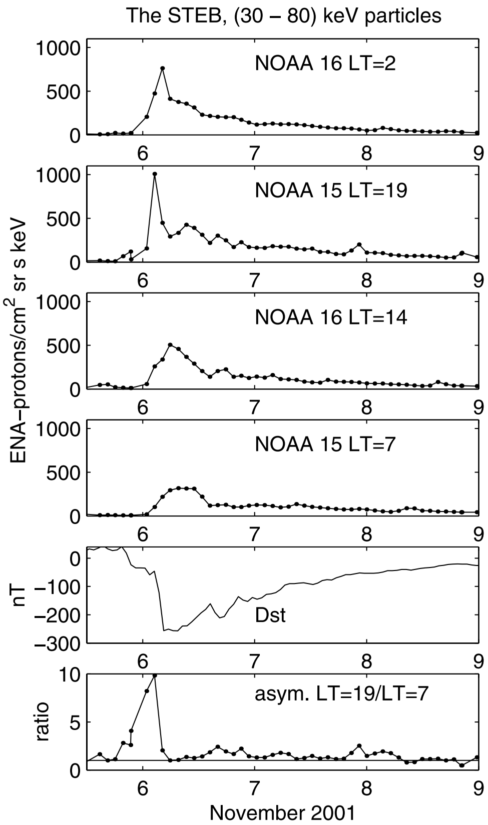

Figure 3. The four top panels display the time variation in the intensity of 30–80 keV trapped protons observed at low L-values during the November 2001 storm. Each panel refers to a different local time, and data from both NOAA 15 and 16 is shown. The D_{st}-index for the storm is shown in the fifth panel. The bottom panel gives the ratio of the intensities measured at LT 19 and 07.

around LT 19. In the storm recovery phase the intensities at all local times decay in a similar fashion with almost equal intensities, even though the evening intensity is slightly above the morning intensity.

3.3. Drift and Charge Exchange Times

[10] The time resolution in the data is 100 minutes, the orbit period of the satellites. In Figure 4 it is seen that the onset delay between LT 19 and 07 is around 1 to 2 sample periods, i.e. 100 to 200 minutes. The delay between the first maxima at LT 19 and the first at LT 7 is around 200 minutes. Similar delays can be seen in Figure 3 for the November storm. The equatorward edge of the isotropic proton precipitation as observed by NOAA 15 in these two storms corresponds roughly to L = 3. It is reasonable to expect that most ENAs are produced near the equatorward edge, where the density of the geocorona is highest. 50 keV is a representative energy for the energy band 30–80 keV, and using the formula $\tau = \frac{44}{EL}$ a time of ~150 minutes for drifting 12 hours in LT is found. This shows that the observed delay in the STEB response vs. LT is not inconsistent with protons drifting from the evening side. The drift time for a singly charged oxygen ion is equal to the proton drift time.

[11] If STEB shall "image" the LT distribution of the RC, then STEB ions must charge exchange rapidly before they have time to drift far. The drift time for singly charged ions at L = 1.1 (STEB region) would be approximately 3 times longer than at L = 3, thus a 50 keV particle will drift 12 hours in local time in 450 minutes. As the geocorona is more than a factor 100 denser at L = 1.1 compared with the density at L = 3 the charge exchange time drops from around 10 hours to 5 minutes. STEB particles will thus only be able to drift around 0.25 hours in LT during their charge exchange lifetime. In this sense STEB is an "image" of the RC. The build up of STEB is directly related to the product of the RC intensity and the geocorona. As the charge exchange lifetime of STEB is much shorter than the lifetime of the RC there will hardly be any build up of STEB, it will faithfully track the production of ENAs in the RC.

3.4. The Asymmetric RC and Convection Loss

[12] The observations show that the low latitude particle belt is highly asymmetric. As STEB is due to a proton loss from the higher L-value RC through charge exchange, these observations demonstrate that the RC is highly asymmetric in LT during the storm initial and main phases. The bottom panels in Figures 3 and 4 illustrate this behavior, where the ratio between the intensities at LT 19 and 07 are given. It is seen that STEB is highly asymmetric in the main phases of the storm. The evening/morning ratio reaches a value of 10 and in the recovery phase changes to a value near 1, indicating a symmetric RC.

[13] As seen from Figures 3 and 4 the maximum intensity in the morning sector (LT = 7) is roughly 30% of the main phase intensity in the injection region (LT = 19). If RC particles were subjected only to charge

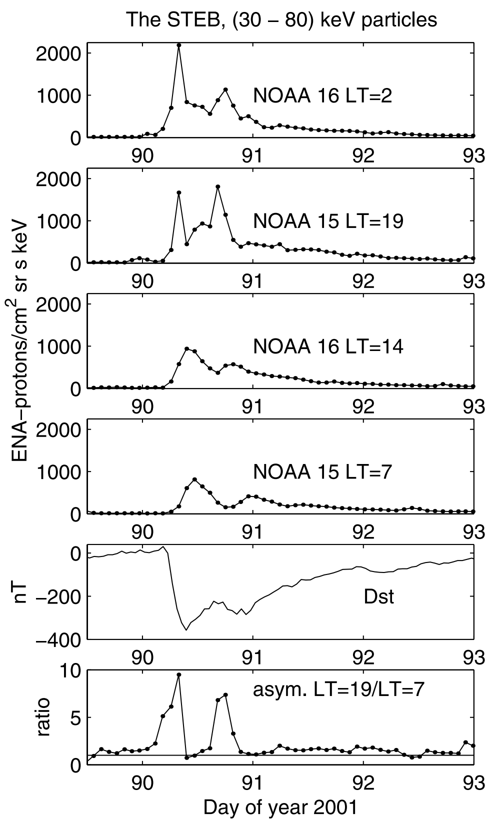

Figure 4. The 31 March 2001 storm. Caption see Figure 3.

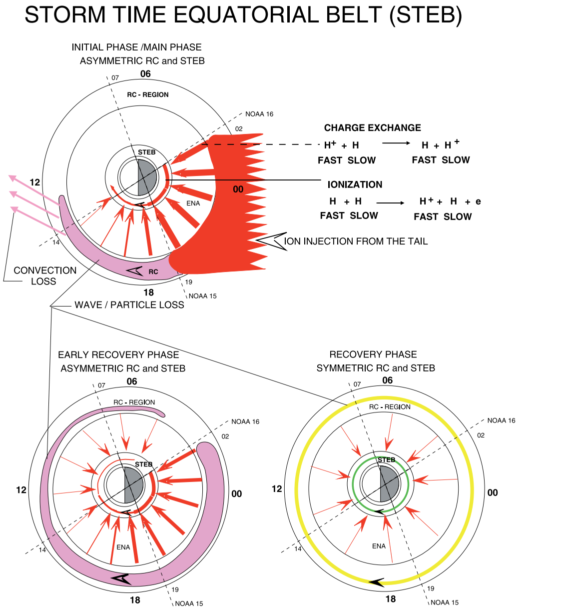

Figure 5. The RC behavior during the different phases of a geomagnetic storm as revealed by STEB. The LTs for the NOAA 15 and 16 orbits are shown.

exchange losses their intensity in the morning sector would be larger as the decay time for charge exchange is long compared to their drift time. This indicates that the RC particles could be subjected to large convection losses through the dayside magnetosphere in the main phase of the storm in agreement with model calculations performed by *Liemohn et al.* [2001]. *Liemohn et al.* [1999] have further shown that the convection loss can be a factor of 10 higher than the charge exchange loss during the asymmetric phase of the storm.

4. Summary and Conclusion

[14] Our findings are in accordance with the model proposed by *Moritz* [1972] that was outlined in the introduction and can be summarized as follows:

1. The energy spectrum of STEB particles is softer than their parent RC particles, thus supporting the idea that STEB is created by the RC ions through charge exchange.
2. In the initial and main phase of the storm the intensity of STEB exhibits a strong LT asymmetry with the intensity in the evening/midnight sector being a factor of 5 to 10 larger than in the morning sector.
3. In the recovery phase of the storm the intensity of STEB becomes almost symmetric in LT as would be expected from a symmetric RC. The asymmetry ratio appear, however, to be slightly above 1 also in the recovery phase.
4. In the storm initial phase the delay of the appearance of particles from evening/midnight (the injection region) is consistent with the drift of RC particles.
5. In the storm main phase RC particles are subjected to convection losses on their drift towards the morning sector.

[15] In Figure 5 different aspects of our observations have been illustrated. This figure shows how particles in the storm main phase are injected from the tail, and gradient/curvature drift through the midnight/evening region giving the asymmetric part of the RC. While they drift and charge exchange, some ENAs are streaming towards the equatorial region of the Earth. Here some ENAs are ionized producing STEB in combination with downward moving ENAs. During this phase of the storm the RC is subjected to heavy convection loss. 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.

[16] Protons at low L-values will experience a rapid decay due to charge exchange processes in the dense geocorona. Due to this fast decay and their slow azimuthal drift the STEB intensity is determined by their source, the charge exchange of RC protons. The LT extension and intensity of the low latitude belt is thus an ''image'' of the RC. There are many factors, however, that prevent STEB from being a faithful image of the high altitude parent ring current. We are, however, of the opinion that STEB gives a picture of the RC, although rather blurred.

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References

Daglis, I. A., W. I. Axford, S. Livi, B. Wilken, M. Grande, and F. Søraas, Auroral ionospheric ion feeding of the inner plasma sheet during substorms, *J. Geomag. Geoelectr.*, *48*, 729, 1996.
Dessler, A. J., W. B. Hanson, and E. N. Parker, Formation of the geomagnetic storm main-phase ring current, *J. Geophys. Res.*, *66*, 3631, 1961.
Evans, D. S., and M. S. Greer, Polar orbiting environmental satellite space environment monitor - 2: Instrument descriptions and archive data documentation, *NOAA Technical Memorandum OAR SEC-93*, Boulder, Colorado, 2000.
Greenspan, M. E., G. M. Mason, and J. E. Mazur, Low-altitude equatorial ions: A new look with SAMPLEX, *J. Geophys. Res.*, *104*, 19,911, 1999.
Gusev, A. A., T. Kohno, W. N. Spjeldvik, I. M. Martin, and G. L. Pugacheva, Dynamics of low-altitude energetic proton fluxes beneath the main terrestrial radiation belts, *J. Geophys. Res.*, *101*, 19,659, 1996.
Hovstadt, D., B. Hausler, and M. Scholer, Observation of energetic particles at very low altitudes near the geomagnetic equator, *Phys. Rev. Lett.*, *28*, 1340, 1972.
Liemohn, M. W., J. U. Kozyra, C. R. Clauer, and A. J. Ridley, Computational analysis of near-Earth magnetispheric current system during two-phase decay storms, *J. Geophys. Res.*, *106*, 29,531, 2001.
Liemohn, M. W., J. U. Kozyra, V. K. Jordanova, G. V. Khazanov, M. F. Thomson, and T. E. Cayton, Analysis of early phase ring current revovery machanisms during geomagnetic storms, *Geophys. Res. Lett.*, *26*, 2845, 1999.
Mizera, P. F., and J. B. Blake, Observation of ring current protons at low altitudes, *J. Geophys. Res.*, *78*, 1058, 1973.
Moritz, J., Energetic protons at low equatorial altitudes: A newly discovered radiation belt phenomenon and its explanation, *Z. Geophys.*, *38*, 701, 1972.
Søraas, F., K. Aarsnes, K. Oksavik, and D. S. Evans, Ring current intensity estimated from low altitude proton observations, *J. Geophys. Res.*, *107*, 1149, 10.1029/2001JA000123, 2002.
Tinsley, B. A., Neutral atom precipitation - a review, *J. Atmos. Terr. Phys.*, *43*, 617, 1981.

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