Observation of relativistic electron precipitation during a rapid decrease of trapped relativistic electron flux

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[1] We present the first quantitative comparison of precipitating and geomagnetically trapped electron flux during a relativistic electron depletion event. Intense bremsstrahlung X-ray emission from relativistic electron precipitation was observed on January 19–20, 2000 (21:20–00:45 UT) by the germanium spectrometer on the MAXIS balloon payload (−7.2 to −9.3 E, 74 S corresponding to IGRF L = 4.7, 1920–2240 MLT). A rapid decrease in the geosynchronous >2 MeV electron flux was simultaneously observed at GOES-8 and GOES-10, and between 0.34–3.6 MeV by GPS ns33 at L = 4.7. The observations show that electrons were lost to the atmosphere early in the flux depletion event, during a period of magnetic field stretching in the tail. The observed X-ray spectrum is well modeled by an exponential distribution of precipitating electrons with an e-folding energy of 290 keV and a lower-energy cut-off of 400 keV. The duration of the event implies precipitation extended over at least 3 hours of MLT, assuming a source fixed in local time. Comparison of the precipitation rate with the flux decrease measured at GPS implies that the loss cone flux was only ~1% of the equatorial flux. However, precipitation is sufficient to account for the rate of flux decrease if it extended over 2–3 hours of local time.
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1. Introduction

[2] The important role played by losses in controlling relativistic electron variability in the radiation belts has become increasingly clear over the last few years. Recent work has focused on studying acceleration in order to explain the large increases in the trapped flux often observed during the recovery phase of geomagnetic storms [*Elkington et al.*, 2003; *O'Brien et al.*, 2003] (see also *Friedel et al.* [2002] for a review of acceleration mechanisms). However, a study of 276 storms by *Reeves et al.* [2003] found only 53% of the storms showed an overall increase in the trapped flux over pre-storm levels, while 19% showed a decrease, indicating a competition between acceleration and loss. There is strong evidence that losses are strong enough to empty the radiation belts in a few days or less in some cases [*Lorentzen et al.*, 2001; *Millan et al.*, 2002; *O'Brien et al.*, 2004a; *Thorne et al.*, 2005]. *Selesnick* [2006] quantified the relative strength of the source versus losses for two geomagnetic storms and showed significant losses deplete the radiation belts of relativistic electrons in about 1 hour during the storm main phase. However, the mechanisms leading to such strong losses are still not fully understood.

[3] Rapid (~hours) decreases by 1–2 orders of magnitude in the >2 MeV electron flux at geosynchronous orbit were reported by *Onsager et al.* [2002] using GOES, and a superposed-epoch analysis of 52 similar events showed they are likely due to precipitation into the atmosphere [*Green et al.*, 2004]. The decrease is first observed in the dusk sector, concurrent with the formation of a partial ring current causing the stretching of the magnetic field into a more tail-like configuration. Adiabatic motions could satisfactorily explain the local time dependence of the flux depletions, but could not account for the entire decrease since the phase space density remained low even after the magnetic field returned to its initial dipolar configuration. Since adiabatic effects associated with the magnetic field stretching may contribute to the initial flux decrease, in situ observations cannot easily determine when and how rapidly the particles are actually lost [*Onsager et al.*, 2002].

[4] *Green et al.* [2004] also found an increase in the >400 keV bounce loss cone flux near the time of the dropout events using data from the PET instrument on SAMPEX. However, since SAMPEX spends only a small fraction of its time measuring the bounce loss cone flux, only fluxes averaged over 0.5 days were available, and the precipitation onset time and the local time of pitch angle scattering could not be determined. Such information is important for identifying where and when the scattering mechanism acts, and could help identify the mechanism responsible for these catastrophic depletions of relativistic electrons. Additionally, a quantitative comparison of precipitation rates with the trapped flux decrease has not been carried out before this work, thus the fraction of electrons lost due to precipitation is currently unknown. The typical relative onset times and relative contributions of precipitation, magnetopause losses, and adiabatic effects need to be determined.

[5] We present observations of duskside relativistic electron precipitation (DREP) during a rapid flux decrease event observed at GOES-8 and GOES-10 and at L = 4.7 by GPS on January 19–20, 2000. The observations were made with the MAXIS balloon payload which measures the brems-

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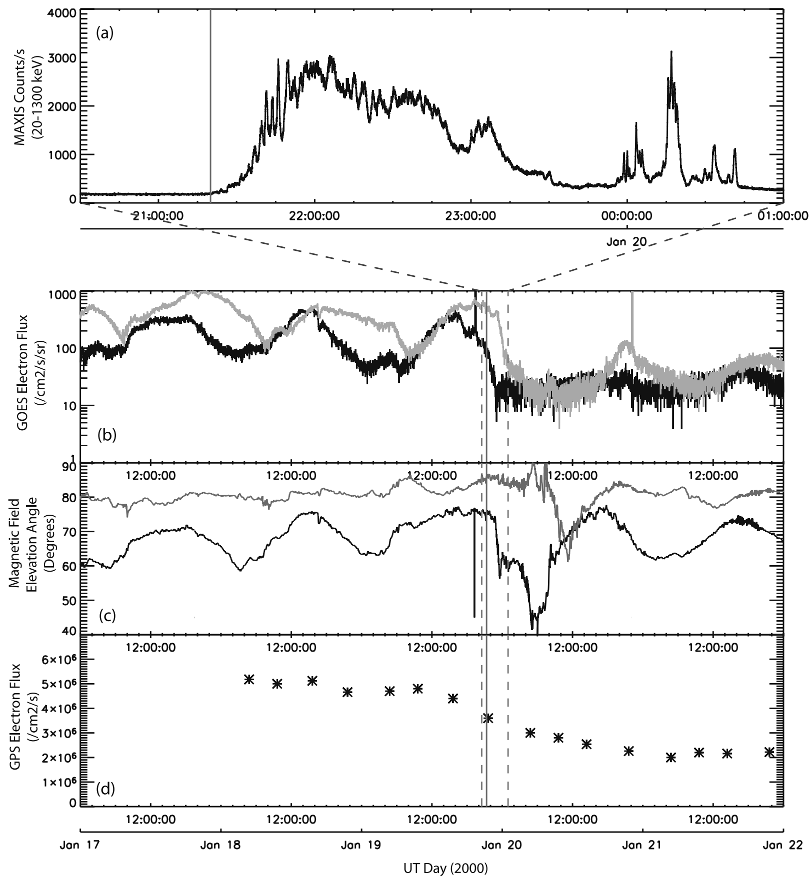

Figure 1. (a) MAXIS X-ray count rate from Jan. 19 (1920 UT) – Jan. 20 (0100 UT). (b) GOES-8 (black) and GOES-10 (grey) electron flux from January 17–22. (c) GOES-8 (black) and GOES-10 (grey) magnetic field elevation angle in degrees. (d) GPS > 500 keV electron flux at L = 4.7 from January 18–22. Vertical dashed lines in Figures 1b–1d indicate time interval shown in Figure 1a. Solid line in all plots indicates onset time of precipitation.

strahlung X-rays produced when precipitating electrons collide with neutrals in the atmosphere. During its January 2000 flight, MAXIS detected a total of nine duskside REP events [*Millan et al.*, 2002] of the type first reported by *Foat et al.* [1998].

2. Observations and Analysis

2.1. Spacecraft and Balloon Observations

[6] On January 19–20, 2000 a series of energetic X-ray bursts (Figure 1a) was detected between 20–1300 keV by the MAXIS 5.5 cm × 5.5 cm coaxial germanium detector. The balloon was located between −7 and −9 E longitude, and 74 S latitude (GEO) corresponding to $L = 4.7$, and MLT = 1920 (IGRF). A description of the MAXIS balloon flight and instrumentation is given by *Millan et al.* [2002]. The event occurred in two main bursts separated by a short interval where the X-ray count rate was near background levels. The first main burst, beginning at 2120 UT, lasted over 2 hours and was about four times stronger than the Kiruna precipitation event reported by *Foat et al.* [1998]; the secondary burst occurred at 2345 UT. Both bursts show temporal modulation on ULF-timescales (∼80–140 s) similar to the Kiruna event. Geomagnetic activity was mostly quiet ($D_{st} \sim -1$), but there was a small isolated substorm ($K_p \sim 3$) during this interval.

[7] Figure 1b shows the >2 MeV electron flux measured by the Space Environment Monitor (SEM) instruments on GOES-8 and GOES-10 between January 17–22, 2000. A sharp drop in the flux is evident on January 19 beginning near 2200–2400 UT, and low fluxes persist for several days after the initial decrease. Since the MAXIS balloon was located near L = 4.7, we also examined data from a Global Positioning Satellite (GPS) to determine whether the flux dropout extended to the location of the balloon and the observed precipitation. Figure 1d shows the GPS >500 keV electron flux, obtained by summing over four energy channels and averaged over L = 4.6–4.8, as a function of time. The flux measured during the precipitation event (vertical line) is lower than during the previous GPS pass, and continues to decrease into January 20. The decrease extended down to L = 4.2 (where GPS cross the equator), indicating a depletion of the trapped electron population across the entire outer zone, including the balloon location.

[8] Similar to the events described by *Green et al.* [2004], the flux dropout coincides with a decrease in magnetic field elevation angle (Figure 1c), indicating a stretching of the magnetic field to a more tail-like configuration. The flux did not return to pre-dropout flux levels even after the magnetic field had returned to a more dipolar configuration, indicating that real losses of electrons occurred.

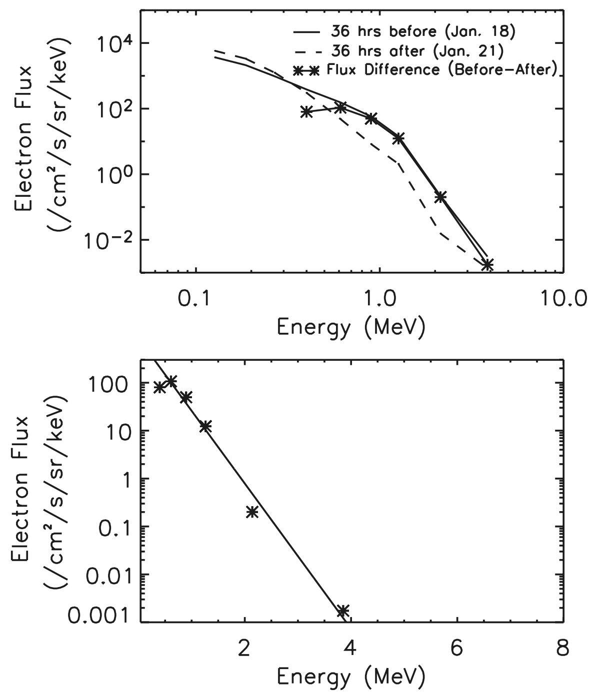

Figure 2. (top) Electron flux measured by LANL 1994-084 36 hours before (solid) and 36 hours after (dashed) flux depletion event. Asterisks show the flux difference. (bottom) Change in electron flux measured by LANL from 36 hours before the event to 36 hours after with superposed best fit exponential.

[9] Both the electron flux decrease and magnetic field stretching are first seen at GOES-8 at 22.8 UT (~17.5 MLT), and then at GOES-10 which was located further west, consistent with observations by both *Onsager et al.* [2002] and *Green et al.* [2004]. The field line stretching was first observed by the duskward spacecraft (GOES-8) as it moved into the 1800 MLT range, about 1.5 hours after the onset of the precipitation event. At the onset of precipitation, GOES-8 was located at ~16.5 MLT, possibly too far west to observe the change in magnetic elevation angle. Because of the spacecraft locations, we cannot determine whether precipitation started simultaneously with the onset of magnetic field stretching. However, electrons were being precipitated during the interval that the magnetic field was being stretched, indicating that the flux decrease during this early time is at least partly due to real losses and not just an adiabatic effect associated with the changing magnetic field. This is in contrast to previous results which suggested the initial decrease is purely adiabatic [*Onsager et al.*, 2002].

2.2. Precipitating Electron Spectrum

[10] Following an analysis similar to *O'Brien et al.* [2004b], we examined the change in the trapped electron spectrum for the flux depletion event on January 19–20 using LANL 1994-084 geosynchronous data. Figure 2 (top) shows the electron energy spectrum 36 hours before the flux dropout (solid), 36 hours following the event (dashed), and the difference (asterisks). A decrease in trapped electron flux is observed for all energies above the 315–500 keV channel (mean energy 400 keV), while the flux *increases* at lower energies. Electrons below ~400 keV were either replenished more quickly than they were being lost, or were not lost at all. Figure 2 (bottom) shows the difference between the flux 36 hours after the dropout and the flux 36 hours before the dropout on a log-linear plot. The resulting difference spectrum is well fit from 0.61–3.8 MeV by an exponential with e-folding energy 290 ± 20 keV (solid line). The decrease in trapped flux is weaker in the 315–500 keV energy channel, and there is no decrease at lower energies.

[11] We next examine the MAXIS X-ray observations which can be used to constrain the precipitating electron energy spectrum, and infer the precipitating electron flux. Figure 3 shows the average background-subtracted X-ray photon spectrum from 2120–2345 UT on January 19 (crosses). A model X-ray spectrum, assuming the source fills the instrument field of view [*Smith et al.*, 1995] (Figure 3, dashed line) based on the exponential fit (Figure 2, bottom) of the LANL data (electron e-folding energy of 290 keV and low-energy cutoff of 610 keV) is not consistent with the observed spectrum. A low-energy cutoff of 610 keV produces a harder (flatter) spectrum than observed. A cutoff of 400 keV(solid line) is consistent with the observed spectrum and provides a better fit than no cut-off (dot-dashed line).

[12] The X-ray observations show that significantly more electrons between 400 and 600 keV were precipitated during this event than is inferred from the change in trapped flux measured by LANL; the trapped energy spectrum was influenced by injection or acceleration of lower energy electrons in addition to the effects of losses. More significantly, the precipitation mechanism must be able to account

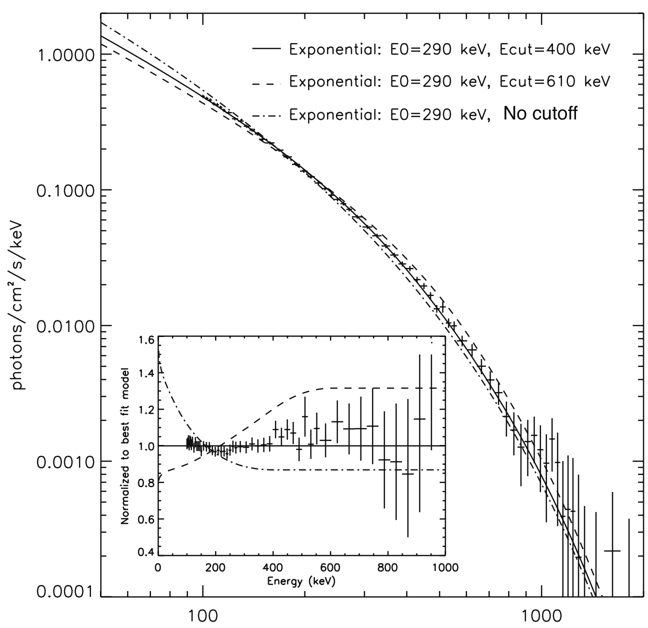

Figure 3. MAXIS X-ray photon spectrum on January 19, 2000 from 2120–2345 UT with superposed model spectra assuming an exponential precipitating electron energy distribution with lower energy cut-off at 400 keV (solid), 610 keV (dashed) and no cut-off (dot-dashed). The inset shows the model spectra and data divided by the best fit model.

for precipitation of electrons with energies at least as low as 400 keV and an exponential energy distribution.

[13] To determine the precipitating electron flux, the model spectra were normalized to the observed spectrum above 100 keV and integrated above 500 keV. The average >500 keV electron loss rate in the MAXIS field of view was $1.0-1.3 \times 10^{18}$ e-/s for the different model spectra shown in Figure 3. The best fit model (solid line) gives 1.2×10^{18} e-/s.

3. Discussion

[14] We have directly observed DREP near the start of a rapid decrease in trapped relativistic electron flux, during a period of magnetic field stretching in the tail. The precipitation was observed in the afternoon/dusk sector and shows similar characteristics to a distinct class of precipitation observed near dusk [*Foat et al.*, 1998; *Millan et al.*, 2002] and attributed to strong scattering of relativistic electrons by electromagnetic ion cyclotron waves [*Lorentzen et al.*, 2000]. Resonance between electrons and EMIC waves can only occur above a minimum energy that depends on the cold plasma density, the wave frequency and the magnetic field strength [*Thorne and Andreoli*, 1980]. In general, this minimum energy is below 2 MeV only near the duskside plasmapause, and only 4 of 416 EMIC events observed by CRRES had minimum resonance energies below 700 keV while none were observed below 500 keV [*Meredith et al.*, 2003]. Lowering the minimum resonant energy to $\sim$400 keV requires large ω_{pe}/Ω_e, implying high cold plasma density and low magnetic field strength, and $\omega/\Omega_i > 0.7$ [*Albert*, 2003].

[15] The flux dropout extended to the balloon location (L = 4.7) where precipitation was observed, indicating that some fraction of the trapped electrons lost were precipitated into the atmosphere, causing the observed X-ray bursts. Assuming the precipitating electron flux is proportional to the trapped flux measured at the equator, J_e, and assuming a fraction, ϵ, of the loss cone is filled, the number of electrons lost per second in one hemisphere from a given L-shell of thickness ΔL over a local time extent η (in hours), is given by

$$f_e = \epsilon \Delta\Omega J_e \frac{\eta}{24} L \Delta L R_E^2 \quad (1)$$

where $\Delta\Omega$ is the size of the loss cone in steradians and is equal to 0.015 sr at L = 4.7 assuming all particles are lost below 100 km altitude, and R_E is Earth's radius. The >500 keV omnidirectional electron flux measured by GPS 36 hours prior to the dropout event was $J_e = 5 \times 10^6$/cm^2/s. The MAXIS balloon field of view of 70 km corresponds to ΔL = 0.2, and a local time extent of η = 0.09 hours, assuming a dipolar magnetic field. Using a loss rate of 1.2×10^{18} e-/s (Section 2.2), we find a loss cone filling factor of $\epsilon \sim 0.01$; to produce the observed precipitation, only about one percent of the loss cone was filled on average. Note that the peak precipitating fluxes observed were up to five times higher, but still well below a mostly-filled loss cone. These observations are consistent with typical bounce loss cone fluxes observed by SAMPEX [*Selesnick et al.*, 2003], but are to our knowledge the first measurement of the bounce loss cone filling factor during a rapid flux depletion event.

[16] With a loss rate proportional to J_e, the number of trapped electrons decreases exponentially with e-folding time N/f_e where N is the total number of trapped electrons within the drift shell (L = 4.6–4.8). N was obtained using GPS observations and assuming a dipole magnetic field to calculate the volume [*Baker et al.*, 1998], and was about 1.5×10^{24} electrons 36 hours before the dropout. An isotropic pitch angle distribution was assumed here, but N would increase by only $\sim$5% for a $\sin^2\alpha$ distribution. With f_e from (1) above, the e-folding loss time is

$$\tau \approx \frac{1200s}{\eta\epsilon} \approx \frac{0.33hrs}{\eta\epsilon} \quad (2)$$

The total loss rate of electrons from this drift shell depends on the longitudinal extent of the precipitation, η, which can be constrained by but not determined from the single balloon observations. The balloon moved about 150 km during the 3.5 hour interval that precipitation was observed and the balloon field of view is 70 km. If the precipitation source was fixed geographically (co-rotating with Earth at fixed longitude), the minimum size of the precipitation region was thus 220 km, corresponding to 0.3 hours of local time. With ϵ = 0.01, this corresponds to the maximum loss timescale of about 5 days. If instead, the precipitation source was fixed with respect to the magnetosphere (at a fixed local time), the balloon moved through the source region, as the Earth rotated, from 1920–2240 MLT. In this case, the precipitation region extended over at least 3.3 hours of MLT, corresponding to an electron loss time of $\sim$10 hours. The GPS flux was observed to decrease from 5×10^6 cm^{-2} s^{-1} to 3×10^6 cm^{-2} s^{-1} in 7.5 hours giving an e-folding time of about 15 hours. Thus, precipitation occurring at the rate observed by MAXIS is sufficient to account for the flux decrease assuming precipitation occurred over a fixed MLT range.

[17] The above analysis does not include precipitation that could be occurring at other local times (outside the balloon field of view) or the effect of a relativistic electron source. However, because this event occurred during relatively quiet conditions, the source is expected to be weak. The choice of magnetic field model (IGRF) may also introduce inaccuracies, therefore, the analysis was also carried out using the T89 L-value for the balloon (L = 5.3). The resulting loss cone filling factor is 4% smaller and the decay time is increased from 10 to 12 hours.

[18] In conclusion, precipitation observed in association with a rapid decrease in trapped radiation belt electron flux indicates that electrons were lost to the atmosphere even early in the decrease, during a period of magnetic field stretching in the tail. The decrease during this early time has previously been attributed to purely adiabatic effects, but our observations show that real losses were occurring at this time. Electrons with energy at least as low as 400 keV were precipitated and about one percent of the loss cone was filled on average. Future work will investigate whether this is consistent with the strong scattering expected from EMIC waves [*Thorne and Andreoli*, 1980] over a limited part of an electron drift orbit. Our results also show that precipitation alone could account for the flux decrease if it extended over 2–3 hours of local time. During the recent MINIS balloon campaign of January 2005, relativistic precipitation was simultaneously observed by two balloons separated by about one hour of local time, indicating that duskside precipitation

does occur over spatial scales of this magnitude (J. Sample et al., MINIS observations of duskside relativistic electron precipitation during the January 21, 2005 storm, manuscript in preparation, 2007). With the limited MAXIS field of view, we are unable to determine if precipitation continued at some location for long enough to account for the entire flux decrease. Future work will include more multi-point measurements like MINIS, and exploration of ground-based techniques (e.g., riometers) to quantify the spatial scale of precipitation in order to better compare the precipitation rate with in situ measurements, and provide precipitation monitoring over a much larger area.

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