Quantification of relativistic electron microburst losses during the GEM storms

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Received 12 September 2003; revised 29 December 2003; accepted 21 January 2004; published 19 February 2004.

[1] Bursty precipitation of relativistic electrons has been implicated as a major loss process during magnetic storms. One type of precipitation, microbursts, appears to contain enough electrons to empty the prestorm outer radiation belt in approximately a day. During storms that result in high fluxes of trapped relativistic electrons, microbursts continue for several days into the recovery phase, when trapped fluxes are dramatically increasing. The present study shows that this apparent inconsistency is resolved by observations that the number of electrons lost through microbursts is 10–100 times larger during the main phase than during the recovery phase of several magnetic storms chosen by the Geospace Environment Modeling (GEM) program. *INDEX TERMS:* 2716 Magnetospheric Physics: Energetic particles, precipitating; 2720 Magnetospheric Physics: Energetic particles, trapped; 2730 Magnetospheric Physics: Magnetosphere—inner; 2772 Magnetospheric Physics: Plasma waves and instabilities. **Citation:** O'Brien, T. P., M. D. Looper, and J. B. Blake (2004), Quantification of relativistic electron microburst losses during the GEM storms, *Geophys. Res. Lett.*, *31*, L04802, doi:10.1029/2003GL018621.

1. Purpose

[2] Essentially all magnetic storms substantially alter the electron radiation belts, and losses play a major role in that alteration [*Reeves et al.*, 2003]. Extensive research has focused on the storm-time acceleration processes [for reviews, see *Friedel et al.*, 2002; *O'Brien et al.*, 2003], but recently interest in loss processes has increased since it has been shown that adiabatic ("*Dst*") effects cannot account for all of the apparent electron losses [*Kim and Chan*, 1997; *Li et al.*, 1997; *McAdams and Reeves*, 2001]. Specifically, *Reeves et al.* argued that the net outer radiation belt response to a magnetic storm was a "delicate and complicated balance between the effects of particle acceleration and loss."

[3] The two most promising acceleration processes are enhanced radial diffusion caused by drift resonance with ULF waves [*Elkington et al.*, 2003, and references therein], and pitch-angle and energy diffusion caused by cyclotron resonance with VLF chorus waves [*Meredith et al.*, 2002, and references therein]. Of these, the latter has been closely identified with a particular variety of bursty ~1 MeV precipitation observed at low altitude typically on the dawn side beyond the plasmasphere [*O'Brien et al.*, 2003; *Horne and Thorne*, 2003]. The cyclotron resonance between chorus and ~1 MeV electrons near the magnetic equator is thought to result in net diffusion toward 90 degrees pitch-angle and higher energies, whereas beyond ~15 degrees off the equator the resonant interaction is thought to result in particles being scattered into the loss cone, forming <1 second bursts of precipitation known as microbursts [*Lorentzen et al.*, 2001a; *Horne and Thorne*, 2003]. Thus, relativistic microbursts serve both as a direct measure of loss and as a proxy for an acceleration process. Quantitative estimates by *Lorentzen et al.* [2001b] have shown that microbursts may be capable of emptying the outer radiation belt of ~1 MeV electrons in about 1 day. Yet *O'Brien et al.* [2003] found that microbursts were more common throughout the recovery phase of magnetic storms that resulted in high ~2 MeV electron fluxes than in storms resulting in low fluxes.

[4] In the present study, we build on the earlier work of *Lorentzen et al.* [2001b] to determine whether microbursts in the recovery phase somehow result in less electron loss than microbursts in the main phase. We note that the microbursts under consideration are much shorter than the longer (minutes to hours) precipitation phenomena that have been tentatively associated with electromagnetic ion-cyclotron (EMIC) waves [*Lorentzen et al.*, 2000; *Millan et al.*, 2002], but which may also play a substantial role in electron losses.

[5] The seven magnetic storms listed in Table 1 have been selected by the Geospace Environment Modeling (GEM) community for focused study. Of these storms, October 1998, October 2000, and March 2001 will be the focus of our study because the only vehicle capable of measuring MeV microbursts, the Solar Anomalous and Magnetospheric Particles EXplorer (SAMPEX), was not spinning and was in a roughly dawn-dusk polar orbit ideal for observing microbursts on the dawn side. SAMPEX was spinning during the May 1997 event, so that event is not included, as the spin affects the quantification of microbursts. The September 1998 storm had some contamination from a Solar particle event, and so it will only be included in some qualitative comparisons. We provide only qualitative results for the October 2001 and April 2002 events because SAMPEX was in a roughly noon-midnight orbit, causing it to miss much of the presumed microburst activity on the dawn side.

[6] We will describe our method for quantifying microburst losses observed by SAMPEX, compare the pass-by-pass, daily, and cumulative losses to the total trapped ~1 MeV electron content derived from Polar observations, and finally demonstrate that losses through microbursts are greatest during the main phase and the first few hours of the recovery phase, with weaker, though frequent, microbursts during the rest of the recovery phase.

2. Procedure

[7] SAMPEX executes a low-altitude polar orbit about every 90 minutes, making 4 passes through the radiation

0094-8276/04/2003GL018621$05.00

Table 1. GEM Storms

Time of Min *Dst*	Event Start	Event End	Notes
15 May 1997 UT 12	14 May	22 May	Spinning
25 Sep 1998 UT 09	24 Sep	30 Sep	Contaminated
19 Oct 1998 UT 15	18 Oct	27 Oct	Dawn-Dusk
05 Oct 2000 UT 13	01 Oct	09 Oct	Dawn-Dusk
31 Mar 2001 UT 08	30 Mar	04 Apr	Dawn-Dusk
21 Oct 2001 UT 22	20 Oct	25 Oct	Noon-Midnight
20 Apr 2002 UT 07	17 Apr	24 Apr	Noon-Midnight

belts every orbit. A typical magnetic storm will span hundreds of passes. In order to quantify electron losses through microbursts, we must automate the identification of microbursts and the calculation of losses. Figure 1 shows an example SAMPEX pass through the outer radiation belt. The black trace is J the 20 msec flux of >1 MeV electrons measured by the Solid State Detector (SSD) on the Heavy Ion Large Telescope (HILT) [for instrument description, see *Klecker et al.*, 1993]. To calculate the flux in a microburst, we must subtract the baseline flux of electrons temporarily trapped in the drift loss cone (J_{DLC}). The flux time series is broken into $1/16 - L$ bins. The 10th percentile is calculated as the baseline for each bin, and then that baseline is interpolated onto the L values of the high-time-resolution fluxes using a spline fit. A floor of 10 (cm^2 s sr)$^{-1}$ is imposed on the baseline flux, since very low fluxes often artificially look bursty due to statistical variations in the underlying low count rates. Microbursts are identified by $J > \sqrt{10}J_{DLC}$. It should be noted that, when not in the South Atlantic Anomaly (SAA) or conjugate to it, SAMPEX observes fluxes in both the bounce and drift loss cones (i.e., particles that may be lost before completing a bounce or drift orbit). We assume that the microbursts are incoherent in space and time, so that within a few bounce periods, much of the microburst flux is lost to the atmosphere, and the remainder adds slightly to flux in the drift loss cone.

[8] To compute N_{pass}, the total number of electrons lost through microbursts during a pass, we must assume that microbursts observed during a single pass are representative of microburst activity nearby in longitude and time. We performed the following summation:

$$N_{pass} = T \sum_{J > \sqrt{10}J_{DLC}}^{(pass)} 2(J - J_{DLC})\Delta(\sin\lambda)\Delta\phi(2\pi \mathrm{sr}), \qquad (1)$$

where T is the assumed duration of the microburst activity (not the duration of individual microbursts), the factor of 2 results from assuming conjugate precipitation into both hemispheres, λ and ϕ are magnetic latitude and longitude, and the sum is taken over every point in the high resolution time series for a given pass. We assume the precipitation is isotropic over the down-going hemisphere (2π sr). As we are attempting to represent the microburst precipitation over the entire globe, we adhere to the following constraint

$$T \sum_{orbit} \Delta\phi = (90\,\mathrm{minutes}) \times (360\,\mathrm{degrees}), \qquad (2)$$

$$T\Delta\phi = \frac{(90\,\mathrm{minutes}) \times (360\,\mathrm{degrees})}{4}, \qquad (3)$$

where the latter expression utilizes the fact that SAMPEX makes 4 passes through the radiation belts per orbit. For a polar orbiting spacecraft, we can satisfy the constraint by treating each pass as representing 45 minutes and 180 degrees of longitude (12 hours of magnetic local time, MLT). Since the assumptions built into the loss calculation are largely geometric and do not depend strongly on magnetic topology, a single method can be used for all phases of a magnetic storm, with the largest uncertainty arising from the limited longitude/MLT sampling.

[9] The loss calculated for the pass in Figure 1 is 8.3×10^{23} electrons over an area of 9.1×10^{15} cm^2. Using a less sophisticated algorithm, *Lorentzen et al.* [2001b] calculated a loss of 3.3×10^{24} electrons lost over 8.5×10^{16} cm^2 for this same SAMPEX pass. The two calculations differ primarily in that the new algorithm accounts for the spatial structure of the microbursts, whereas *Lorentzen et al.* applied the time-averaged microburst flux over the entire precipitation area from L = 4–6. The new algorithm is somewhat more precise because it accounts for the fact that the microburst flux varies substantially with L. We have applied our automated algorithm to all SAMPEX passes for all of the GEM storms, with the exception of May 1997, which is excluded because SAMPEX was spinning. The three storms selected for detailed focus included some 1600 passes, of which about one third were excluded because they were in the SAA or conjugate to it. Of the remaining passes, about two thirds (641) exhibited microbursts.

[10] For comparison with the microburst losses, we calculated the total content of trapped >1 MeV electrons in the outer radiation belt using data from the Polar spacecraft's HIgh Sensitivity Telescope (HIST) instrument [for description, see *Blake et al.*, 1995]. To do this, we assumed a $\sin^n$ pitch-angle distribution, with n given at each L shell by *Vampola* [1996] (this approximation gave more stable results pass-by-pass than using the locally measured pitch-angle distribution, R. Selesnick, private communication). We then integrated over the pitch-angle distribution, dipole L shell volume, and energy to obtain the total number of electrons trapped between $L = 2 - 9$. Only for the September and October 1998 storms was Polar in a favorable orbit for this calculation. For the September 1998 storm, the prestorm content was 1.3×10^{24} electrons, and

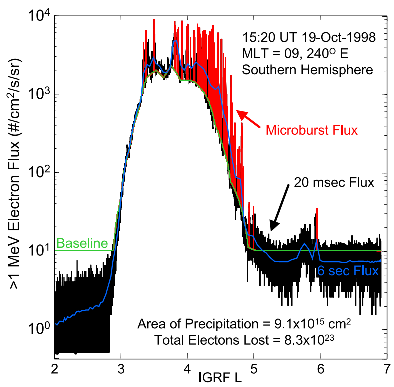

Figure 1. A single SAMPEX pass through the outer radiation belt on October 19, 1998. High resolution >1 MeV fluxes reveal microburst structures. An automated algorithm identifies and measures the electron content of the microbursts.

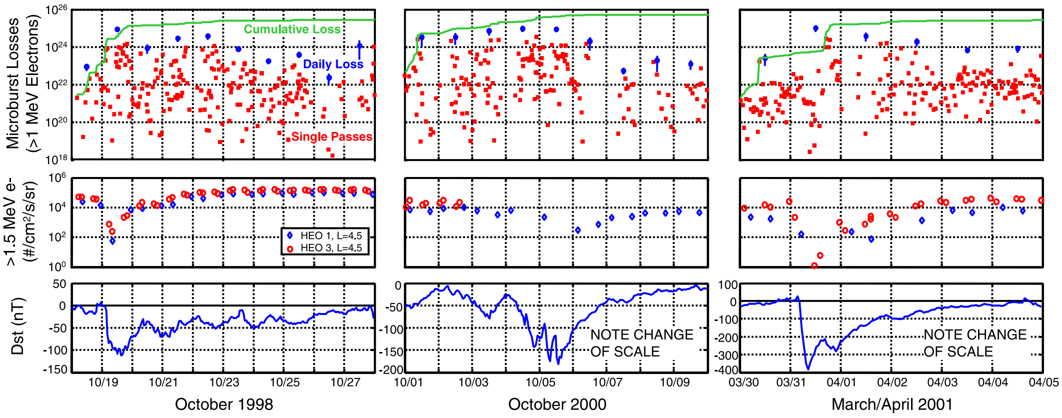

Figure 2. Microburst losses, HEO fluxes at L = 4.5, and *Dst* for three GEM storms. SAMPEX is in a roughly dawn-dusk orientation, favorable for microburst observations. Note: Cumulative loss has been adjusted by 1.5 to account for passes in the SAA and conjugate.

after the storm the content was 4.5×10^{25}. For the October 1998 storm, the content grew slightly from 1.1×10^{25} prestorm to a final value of 2.6×10^{25}. Similar calculations by *Baker et al.* [1998] for 2–6 MeV electrons gave prestorm and poststorm content of 10^{23} and 10^{26} for the January 1997 storm. Thus, a reasonable upper limit for typical prestorm fluxes would be about 10^{25} ~1 MeV electrons.

3. Results

[11] From our database of pass-by-pass microburst losses for six of the GEM storms, we compute daily total electron losses and cumulative electron losses during the storms. Figure 2 shows the time evolution of the three GEM storms for which SAMPEX was in a dawn-dusk orbit. Pass by pass, the electron loss varies by orders of magnitude. This variation is much larger than the calculated statistical variation indicated by the small vertical 95% confidence bars on the daily totals. This variation results from both the local-time variation of microbursts and the episodic nature of substorm injections, which generate chorus. The daily totals combine roughly 60 orbits, and thus are likely to accommodate much of the episodic behavior.

[12] In each storm, the greatest single-day loss was on the same day as minimum *Dst*, with losses typically reaching 10^{25} electrons on the day of the main phase. Thus, it is quite possible that microbursts could empty the prestorm outer radiation belt in a single day.

[13] Along with the microburst analysis, we have included >1.5 MeV electron fluxes observed at $L = 4.5$ by two HEO spacecraft (HEO 1 1994-026, and HEO 3 1997-068) in highly inclined orbits [see *Blake et al.*, 1997]. The HEO fluxes show the combined influences on the electrons of adiabatic ("*Dst*") effects associated with the magnetic field of the ring current, real losses, and acceleration, but they are nonetheless useful for showing the storm-time dynamics of the trapped ~1 MeV electrons. Geosynchronous ~2 MeV electron fluxes (not shown) show the same qualitative changes during each storm as those seen by the HEO vehicles.

[14] In the October 1998 storm, strong losses were observed for the entire interval during which *Dst* was near its minimum of −100 nT. In fact, the pass given as an example in Figure 1 occurred right at minimum *Dst*. Once *Dst* started making a substantial recovery, microburst losses dropped dramatically. Subsequent ring current injections during the recovery phase showed secondary, lesser intervals of loss. Microbursts continued throughout the recovery phase, but loss dropped substantially. The HEO fluxes dropped quickly with *Dst* but began to recovery equally quickly immediately after minimum *Dst*, and before the losses actually diminished substantially or *Dst* had recovered very much; thus, it appears in this storm that an acceleration process was very active either during or shortly after the descent of *Dst* to minimum.

[15] In the October 2000 storm, the main phase was prolonged over several days of strong ring current driving. Each interval of driving was accompanied by large numbers of electrons being lost through microbursts. The recovery phase was marked by few microbursts. HEO fluxes, which are about an order of magnitude below those of the October 1998 storm, returned roughly to their prestorm levels. There was probably substantial acceleration and loss, possibly removing and replacing the entire trapped population.

[16] In the March 2001 superstorm, the main phase was marked by large decreases in HEO fluxes. However, microburst losses did not really get going until the second injection late on 31 March. From 1 April onward, microburst losses dropped off rapidly. The HEO fluxes followed *Dst* rather closely, with a slight increase over prestorm fluxes indicating some net acceleration. Again, in spite of enormous losses through microbursts, the ~1 MeV electron population was not wiped out by the storm, indicating strong replacement of lost electrons by acceleration.

[17] The September 1998, October 2001, and April 2002 storms qualitatively show similar effects to the three storms shown in Figure 2. Microburst losses are very strong on the day of the main phase and during individual ring current intensifications. During the recovery phase, microbursts may be common in some storms, but tend not to result in strong losses unless accompanied by renewed magnetic activity.

4. Conclusion

[18] It appears quite clear from our results that ~1 MeV microbursts are a substantial loss process during the main phase, but considerably weaker in content during the recovery phase. This justifies their interpretation as both a loss process and a proxy for chorus-related acceleration near the magnetic equator. The microbursts also suggest that

much of the storm-time changes in observed electron fluxes reflect genuine acceleration and loss processes during the main phase and early recovery phase rather than reversible adiabatic effects. Additionally, comparable or greater electron loss by EMIC waves is possible and would further suggest that the main phase is a time of substantial electron loss and acceleration.

[19] There are several possible explanations for the dependence of microburst losses on storm phase. Some of the dependence likely results from the penetration of microbursts to $L \sim 4$, where fluxes are highest, during the main phase, as shown in the superposed epoch analysis by *O'Brien et al.* [2003]. Also, chorus waves may differ substantially in strength, latitude, propagation, or occurrence frequency during the main phase relative to the recovery phase. Further, plasma density structure along field lines, which determines the resonance conditions for microbursts, may differ with storm phase, especially during plasmasphere refilling in the recovery phase. Finally, electron energy and pitch-angle distributions may be systematically distorted by the adiabatic effects of growing or decaying ring current. These distortions may result in phase-space density gradients more or less favorable for loss or acceleration.

[20] Large uncertainties still remain in the MLT scales and time duration of microbursts extrapolated from measurements by a single spacecraft. These uncertainties can easily be as large as a factor of 2, but are unlikely to be larger than a factor of 10. Such uncertainties cannot be resolved easily without multipoint or nearly stationary measurements of precipitation at high time resolution ($\sim$100 msec). Such measurements might be possible with high-altitude balloons or rockets launched into magnetic storms. A still more robust and long-term measurement could be made by two or more SAMPEX-like missions on orbit simultaneously.

[21] **Acknowledgments.** This research project was supported by NSF grant ATM 0202107 and NASA grant NAG5-10972. The authors thank the Kyoto World Data Center (WDC C-2) for geomagnetism and the observatories that produce *Dst*. The authors also thank R. Thorne, N. Meredith, and our many colleagues at The Aerospace Corporation for valuable input to this project. We acknowledge R. Selesnick, who provided data and assistance for the electron content calculation from Polar. The authors would also like to make a special acknowledgment of K. Lorentzen who initiated and inspired the work that is continued herein.

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