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Relativistic electron microbursts during the GEM storms

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Abstract. Observations of relativistic (>1 MeV) electron microbursts by the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellite are frequently associated with geomagnetic storms. We examine the characteristics of these microbursts during 1997 and 1998, paying particular attention to the three storms selected by the Geospace Environment Modeling (GEM) community for special study: May 15, 1997, September 25, 1998, and October 19, 1998. The relativistic electron microbursts strongly correlate with both the *Dst* and K_p indices and generally increase in intensity and move to lower L shells during the recovery phases of geomagnetic storms. During the recovery phases of the September and October 1998 storms, the numbers of >1 MeV electrons lost from the radiation belts to the microburst precipitation are estimated to be 2.5×10^{25} and 3.3×10^{24}, respectively. In both cases, the microburst loss is a significant fraction of the total radiation belt population.

Introduction

The relativistic electron population in the Earth's radiation belts has been the subject of much recent interest. Although it has long been known that the relativistic electron content increases with increasing solar wind speed [*Paulikas and Blake*, 1979], the exact mechanisms causing variations in the population of electrons >1 MeV are still not understood. These variations are also frequently associated with geomagnetic storms. The Geospace Environment Modeling (GEM) community has selected three geomagnetic storms for detailed analysis and comparison. These storms occurred on May 15, 1997 (day 135), September 25, 1998 (day 268), and October 19, 1998 (day 292). They produced different responses in the radiation belts, although all three resulted in increases in the relativistic electron population [*McAdams et al.*, 2001].

Observations of changes in relativistic electron populations for other storms have been described by *Baker et al.* [1998] and *Reeves* [1998]. Typically, the relativistic electron population will drop out during the main phase of a storm, and then recover on a time scale of ~1 day to a level that may or may not be greater than the prestorm level. The adiabatic "*Dst* effect" can account for part, but not all, of this dropout [*Li et al.*, 1997; *Kim and Chan*, 1997]. Some of the dropout may also be due to interactions with the magnetopause or loss to the atmosphere through precipitation.

One form of precipitation that has been associated with geomagnetic storms and may account from some of this dropout is relativistic electron microbursts [*Friedel et al.*, 2000; *Blake et al.*, 2001]. These >1 MeV microbursts last <1 s and are typically observed at the outer edge of the radiation belt. They have been observed at all local times, but occur predominantly in the morning sector, where they have been associated with VLF chorus waves [*Lorentzen et al.*, 2001]. The microbursts may be a signature of wave-particle interactions that also are important for acceleration of electrons. Acceleration by interaction with whistler mode waves has been suggested by *Summers et al.* [1998], *Roth et al.* [1999], and *Summers and Ma* [2000]. In this letter we examine observations of relativistic electron microbursts associated with the three GEM storms.

Instrumentation

The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellite was launched on July 3, 1992 into an orbit of 520 × 670 km altitude and 82° inclination [*Baker et al.*, 1993]. The orbit period is ~96 minutes. The Heavy Ion Large Telescope (HILT) is sensitive to electrons >1 MeV when passing through the radiation belts and has a geometric factor of 100 cm^2 sr and a view angle of 68° × 68° [*Klecker et al.*, 1993]. Data were sampled every 20 ms during 1997 and 1998. From May 8, 1996 until May 7, 1998 the satellite was spinning once per minute, giving coverage over a range of pitch angles. At other times, the satellite was pointed towards the zenith, approximately along the field lines at high latitudes.

Observations

Observations of relativistic electron microbursts from the SAMPEX satellite have been presented elsewhere [*Nakamura et al.*, 1995, 2000; *Blake et al.*, 1996; *Lorentzen et al.*, 2001], but here we focus on the three GEM storms and provide quantitative estimates of the precipitating flux in order to facilitate comparison with theory.

Figure 1 shows an example of a SAMPEX pass through the radiation belts on October 19, 1998 at 0940 magnetic local time (MLT). At this time, the spacecraft was in zenith-pointing mode. The solid red line shows the >1 MeV electron flux and the blue dotted line shows the spacecraft position in L shell. The microbursts were most prominent when SAMPEX was located between L = 4 and L = 6. Because of the large field of view of the instrument, it samples both trapped and precipitating particles at the same time. However, previous studies have shown that the microbursts are precipitating and frequently fill the loss cone [*Blake et al.*, 1996]. The black dashed line shows the envelope of the locally trapped portion of the flux, which will be discussed later.

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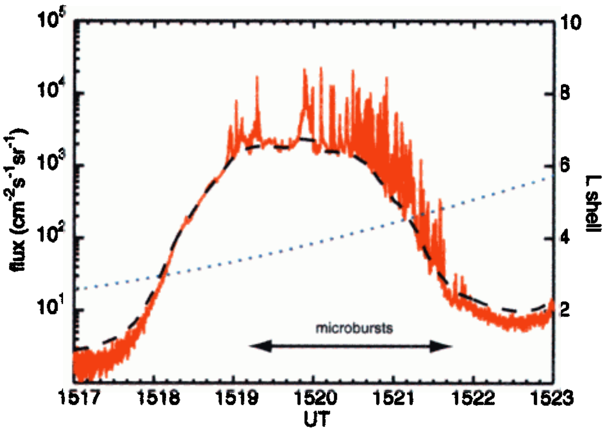

Figure 1. Electrons >1 MeV microbursts on October 19, 1998 (red). The satellite was in zenith-pointing mode at this time, so the instrument was looking approximately along the field lines at the microburst precipitation. The black dashed line shows our estimate of the locally trapped population and the blue dotted line shows the position in L shell.

Distribution of Microbursts

Figures 2c and 2f show histograms of the number of passes during which SAMPEX observed relativistic electron microbursts in the outer radiation belts each day in 1997 and 1998. The relativistic electron microburst events were selected automatically by comparing the average count rate in a 100-ms period with a 500-ms running average. Radiation belt passes for which the difference exceeded ten times the standard deviation were identified as containing microbursts. Since the satellite passes through the radiation belt four times on each 96-min orbit, the maximum number of microburst events is 60 per day. Figures 2a and 2d show K_p and Figures 2b and 2e show Dst for this period. There is a clear association between microburst events and the geomagnetic indices. When the number of microburst events are cross-correlated with daily averages of these indices, the correlation coefficients are found to be 0.75 for K_p and -0.72 for Dst in 1997. In 1998 the correlation coefficient for K_p is 0.80 and for Dst is -0.76. Both the number of microbursts and the indices show that 1998 was more active than 1997. Some care must be taken in comparing microburst occurrence between periods when the satellite was in spin mode and zenith-pointing mode, however. In spin mode the satellite spends less time sampling precipitating particles.

Figure 3 shows K_p and Dst for each of the three GEM storms, along with the position in L where the bursts were observed. The bursts tended to start during the main phase of the storm and continue into the recovery phase. The bursts also moved to lower L shell during the storm. The location of the inner plasmapause boundary was also calculated from the formula $L_{\mathrm{ppi}} = 5.6 - 0.46K_{p\mathrm{max}}$, where $K_{p\mathrm{max}}$ is the maximum K_p value in the preceding 24 hours [*Carpenter and Anderson*, 1992]. The inner edge of the bursts generally followed the plasmapause location. In both the May 1997 and October 1998 storms, the largest microburst events began during the storm recovery phase, although some smaller events were seen during the storm main phase. This pattern is similar to the 1993 storms examined by *Nakamura* [2000]. However, the September 1998 storm looked different because the microbursts started well before the storm main phase, in association with an enhanced K_p.

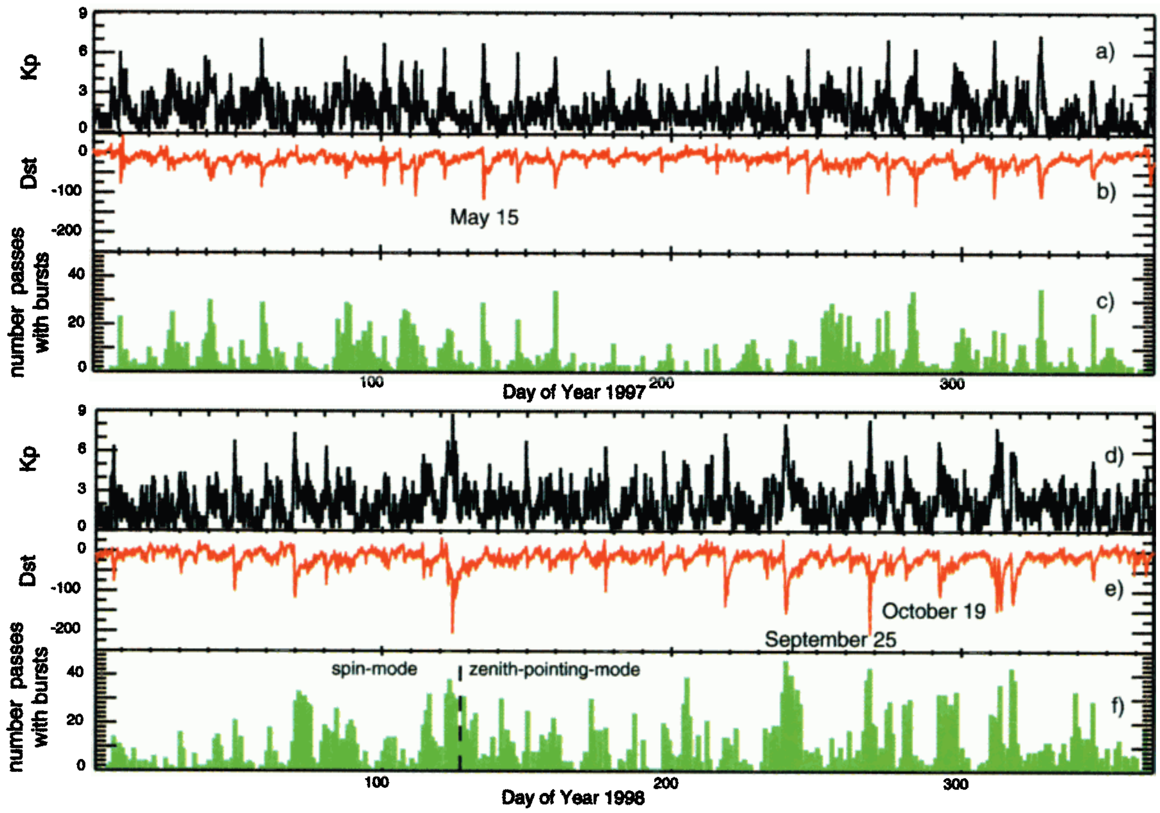

Figure 2. Correlation of microburst events with Dst and K_p for 1997 and 1998.

Estimate of Microburst Precipitation Loss

Because the microbursts look different depending on where SAMPEX is located in local time and with respect to the South Atlantic magnetic anomaly, it is difficult to quantify the electrons lost over multi-day intervals. However, by examining individual passes, it is possible to estimate the flux lost during a short period. As an example, we return to Figure 1. An examination of every pass during the October 1998 storm shows that the morningside microbursts continued at this intensity for ~6 h. At other times, the microbursts were over an order of magnitude less intense.

In order to quantify the number of electrons lost to microburst precipitation, we need to separate the non-microburst locally trapped background. To estimate this background, we traced the lower envelope of the timeseries, and added a multiple of the Poisson error. This procedure created a profile that sits above the statistical variations in the trapped background and below the microbursts, as shown by the dashed black line in Figure 1. Averaging the flux above this profile, we obtain 275 cm^{-2} s^{-1} sr^{-1}.

To obtain a global estimate of the microburst precipitation, we assume downward isotropy. Previous observations have shown that microburst precipitation peaks between L shells of 4 and 6 and in the morning sector between MLT 0300 and 0900 [*Nakamura et al.*, 2000; *Lorentzen et al.*, 2001]. The area of that portion of a sphere at 600 km altitude extending over 6 hours MLT from $L = 4$ to $L = 6$ is 8.5×10^{16} cm^2. Multiplying the average flux by this area and by 2π sr and by 6 h gives the total number of electrons. Using this technique, we estimate that 3.3×10^{24} relativistic electrons were lost to microburst precipitation during the October 1998 storm.

The September 1998 storm had even more intense microbursts, and we estimate that 2.5×10^{25} relativistic electrons were lost during the ~6 hours of intense microburst precipitation observed. The preceding global estimates depend on the assumption that the microburst flux is isotropic and constant over the L and MLT ranges specified. Each value in the calculation may vary by a factor of 2-3, possibly introducing a total variation of up to an order of magnitude. Because the spacecraft was spinning in May 1997, it is not possible to estimate the number of electrons lost during that storm.

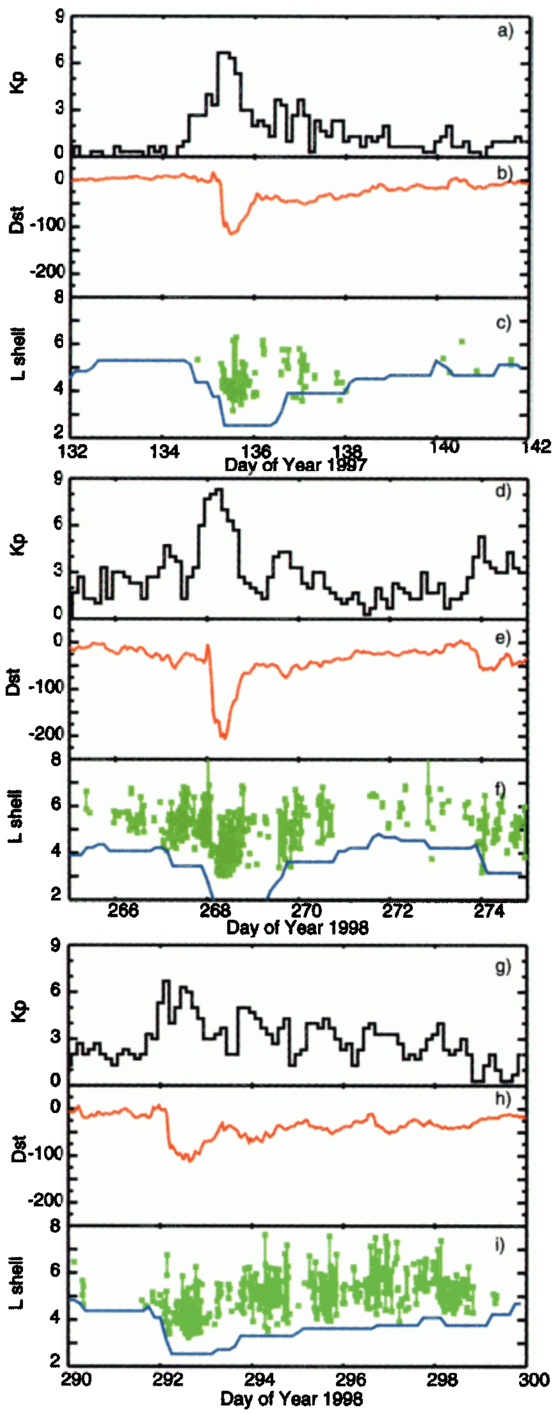

Figure 3. Microburst occurrence and geomagnetic activity for all three storms. The lower panels show the location and extent in L shell of the microburst events (green) along with the calculated plasmapause location (blue).

Discussion

Baker et al. [1998] estimated the average 2-6 MeV electron content in the radiation belts from $L = 2.5$ to $L = 6.5$ before and after the January 10, 1997 storm. Although no total electron content values have been published for the GEM storms, *McAdams et al.* [2001] have shown that the poststorm flux in all 3 GEM storms was within an order of magnitude of that for the January 1997 storm. *Baker et al.* [1998] found that the radiation belts contained 8.6×10^{22} electrons on January 9 and 1.0×10^{26} electrons on January 11. The prestorm electron content is smaller than our estimates for >1 MeV microburst precipitation losses, implying that microburst precipitation losses can be very significant in the radiation belts. A single storm could essentially flush out the entire relativistic electron population. Thus, models for electron acceleration need to account for an increase in particles above and beyond a simple difference between pre- and post-storm fluxes. The microbursts may also be involved in both acceleration and loss processes at the same time.

These data have important implications for theoretical models of the behavior of relativistic electrons in the radiation belts. The model of *Bourdarie et al.* [1997] invokes losses due to wave particle interactions with VLF hiss inside the plasmasphere while the model of *Summers et al.* [1998] uses losses on the duskside due to wave particle interactions with ion cyclotron mode waves. These types of wave particle interactions are not consistent with SAMPEX observations of relativistic electron microburst precipitation because they occur at different L shells and local times. In a more recent model, *Summers and Ma* [2000] include morningside losses through an escape term, although the relative contributions from whistler and ion cyclotron waves are not specified.

Inward radial diffusion is believed to be one source of relativistic electrons [*Schulz and Lanzerotti*, 1974; *Li et al.*, 2001]. However, other acceleration mechanisms may also be important. *Summers and Ma* [2000] suggest that the source of the relativistic electrons is morningside wave particle interactions with whistler-mode chorus. The relativistic electron microbursts may be the signature of such an interaction with chorus [*Lorentzen et al.*, 2001]. Wave particle interactions in the inner magnetosphere are consistent with peaks in phase space density observed by *Selesnick and Blake* [2000]. The variations in relativistic electron content may actually result from a combination of multiple source and loss mechanisms.

The number and magnitude of the relativistic electron microburst events indicate the importance of this phenomenon to radiation belt dynamics. Future models of radiation belt source and loss processes need to consider microburst effects in order to understand fully the processes causing changes in relativistic electrons during geomagnetic storms.

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References

Baker, D. N., G. M. Mason, O. Figueroa, G. Colon, J. G. Watzin, and R. M. Aleman, An overview of the solar, anomalous and magnetospheric particle explorer (SAMPEX) mission, *IEEE Trans. Geosci. and Remote Sens.*, *31*, 531, 1993.

Baker, D. N., et al., Coronal mass ejections, magnetic clouds, and relativistic magnetospheric electron events: ISTP, *J. Geophys. Res.*, *103*, 17,279, 1998.

Blake, J. B., M. D. Looper, D. N. Baker, R. Nakamura, B. Klecker, and D. Hovestadt, New high temporal and spatial resolution measurements by SAMPEX of the precipitation of relativistic electrons, *Adv. Space Res.*, *18 (8)*, 171, 1996.

Blake, J. B., R. S. Selesnick, D. N. Baker, and S. G. Kanekal, Studies of relativistic electron injection events in 1997 and 1998, *J. Geophys. Res.*, *in press*, 2001.

Bourdarie, S., D. Boscher, T. Beutier, J.-A. Sauvaud, and M. Blanc, Electron and proton radiation belt dynamic simulations during storm periods: A new assymmetric convection-diffusion model, *J. Geophys. Res.*, *102*, 17,541, 1997.

Carpenter, D. L., and R. R. Anderson, An ISEE/whistler model of equatorial electron density, *J. Geophys. Res.*, *97*, 1097, 1992.

Friedel, R. H., T. E. Cayton, S. G. Kanekal, D. M. Baker, S. Bourdarie, and J. B. Blake, Relativistic electron losses in the inner magnetosphere, *Eos Trans. AGU*, *81 (48)*, F1047, 2000.

Kim, H. J., and A. A. Chan, Fully adiabatic changes in storm time relativistic electron fluxes, *J. Geophys. Res.*, *102*, 22,107, 1997.

Klecker, B., et al., HILT: A heavy ion large area proportional counter telescope for solar and anomalous cosmic rays, *IEEE Trans. Geosc. and Remote Sens.*, *31*, 542, 1993.

Li, X., D. N. Baker, M. Temerin, D. N. Baker, G. D. Reeves, and D. Larson, Quantitative prediction of radiation belt electrons at geostationary orbit on the basis of solar wind measurements, *Geophys. Res. Lett.*, *in press*, 2001.

Li, X., et al., Multisatellite observations of the outer zone electron variation during the November 3-4, 1993, magnetic storm, *J. Geophys. Res.*, *102*, 14,123, 1997.

Lorentzen, K. R., J. B. Blake, U. S. Inan, and J. Bortnik, Observations of relativistic electron microbursts in association with VLF chorus, *J. Geophys. Res.*, *106*, 6017, 2001.

McAdams, K. L., G. D. Reeves, and R. Friedel, Multisatellite comparisons of the radiation belt response to the GEM magnetic storms, *J. Geophys. Res.*, *in press*, 2001.

Nakamura, R., D. N. Baker, J. B. Blake, S. Kanekal, B. Klecker, and D. Hovestadt, Relativistic electron precipitation enhancements near the outer edge of the radiation belt, *Geophys. Res. Lett.*, *22*, 1129, 1995.

Nakamura, R., M. Isowa, Y. Kamide, D. N. Baker, J. B. Blake, and M. Looper, SAMPEX observations of precipitation bursts in the outer radiation belt, *J. Geophys. Res.*, *105*, 15,875, 2000.

Paulikas, G. A., and J. B. Blake, Effects of the solar wind on magnetospheric dynamics: energetic electrons at the synchronous orbit, in *Quantitative Modeling of Magnetospheric Processes*, edited by W. P. Olson, p. 180, AGU, Washington, D. C., 1979.

Reeves, G. D., Relativistic electrons and magnetic storms: 1992-1995, *Geophys. Res. Lett.*, *25*, 1817, 1998.

Roth, I., M. Temerin, and M. K. Hudson, Resonant enhancement of relativistic electron fluxes during geomagnetically active periods, *Ann. Geophys.*, *17*, 631, 1999.

Schulz, M., and L. J. Lanzerotti, *Particle Diffusion in the Radiation Belts*, Springer-Verlag, New York, 1974.

Selesnick, R. S., and J. B. Blake, On the source location of radiation belt relativistic electrons, *J. Geophys. Res.*, *105*, 2607, 2000.

Summers, D., and C. Ma, A model for generating relativistic electron in the Earth's inner magnetosphere based on gyroresonant wave- particle interactions, *J. Geophys. Res.*, *105*, 2625, 2000.

Summers, D., R. M. Thorne, and F. Xiao, Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the magnetosphere, *J. Geophys. Res.*, *103*, 20,487, 1998.

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