X-ray observations of MeV electron precipitation with a balloon-borne germanium spectrometer

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Received 19 July 2002; revised 27 September 2002; accepted 27 September 2002; published 26 December 2002.

[1] The high-resolution germanium detector aboard the MAXIS (MeV Auroral X-ray Imaging and Spectroscopy) balloon payload detected nine X-ray bursts with significant flux extending above 0.5 MeV during an 18 day flight over Antarctica. These minutes-to-hours-long events are characterized by an extremely flat spectrum ($\sim E^{-2}$) similar to the first MeV event discovered in 1996, indicating that the bulk of parent precipitating electrons is at relativistic energies. The MeV bursts were detected between magnetic latitudes 58°–68° (L-values of 3.8–6.7) but only in the late afternoon/dusk sectors (14:30–00:00 MLT), suggesting scattering by EMIC (electromagnetic ion cyclotron) waves as a precipitation mechanism. We estimate the average flux of precipitating $E \geq 0.5$ MeV electrons to be ~ 360 cm^{-2}s^{-1}, corresponding to about 5×10^{25} such electrons precipitated during the eight days at L = 3.8–6.7, compared to $\sim 2 \times 10^{25}$ trapped 0.5–3.6 MeV electrons estimated from dosimeter measurements on a GPS spacecraft. These observations show that MeV electron precipitation events are a primary loss mechanism for outer zone relativistic electrons. *INDEX TERMS:* 2716 Magnetospheric Physics: Energetic particles, precipitating; 2730 Magnetospheric Physics: Magnetosphere—inner; 2720 Magnetospheric Physics: Energetic particles, trapped. **Citation:** Millan, R. M., R. P. Lin, D. M. Smith, K. R. Lorentzen, and M. P. McCarthy, X-ray observations of MeV electron precipitation with a balloon-borne germanium spectrometer, *Geophys. Res. Lett.*, *29*(24), 2194, doi:10.1029/2002GL015922, 2002.

1. Introduction

[2] The first detection of a terrestrial X-ray burst extending up to MeV energies was made in 1996 by a balloon-borne germanium spectrometer near Kiruna, Sweden (L = 5.7), at a time of low geomagnetic activity ($K_p \sim 2$) [*Foat et al.*, 1998]. The observed X-ray spectrum was extremely flat ($E^{-1.6}$, from 100 to 250 keV), consistent with a model of bremsstrahlung emission by $\sim$1.7 MeV electrons incident at the top of the atmosphere. If these electrons are precipitated from a trapped population with falling energy spectrum, the mechanism must be more efficient for high energy electrons.

[3] So-called "Relativistic Electron Precipitation" (REP), first inferred from daytime decreases of forward scatter radio signals [*Bailey*, 1968] due to enhanced ionization at unusually low altitudes ($\leq$75 km), appears to involve $\sim$0.1–1 MeV electrons. Most balloon-borne X-ray measurements of REP have been limited to energies below $\sim$200 keV [*Rosenberg et al.*, 1972; *Parks et al*, 1979]. The first high spectral resolution measurements made by a balloon-borne germanium spectrometer detected several events up to $\sim$300 keV [*Smith et al.*, 1995]. X rays up to $\sim$600 keV were observed by polar orbiting spacecraft, near midnight at magnetic storm onset [*Imhof et al.*, 1990].

[4] Direct spacecraft particle measurements also show that most REP events are dominated by electrons with energies well below 1 MeV [*Thorne and Andreoli*, 1980; *Imhof et al.*, 1991]; only four out of 313 events observed with the S3-3 satellite showed precipitation exclusively at high energies, starting at 160 keV and reaching the level of strong diffusion at 850 keV. These events occurred in the dusk sector. The S81-1 and P78-1 spacecraft detected narrow electron spikes near the plasmapause in the evening sector, with precipitation stronger above 300 keV than below [*Imhof et al.*, 1986]. More recent high time resolution measurements from SAMPEX show two classes of energetic (>1 MeV) electron precipitation [*Blake et al.*, 1996; *Nakamura et al.*, 1995]: bands that occur near the high latitude trapping boundary (similar to the electron spikes reported by *Brown and Stone* [1972]), and relativistic electron microbursts with <1 s temporal structure, that occur both near the trapping boundary and at lower latitudes.

[5] The MAXIS payload, with the germanium detector (GeD) flown previously in Antarctica and Sweden, plus a bismuth germanate (BGO) scintillator for measurements up to $\sim$10 MeV and two X-ray (20–200 keV) imagers (XRI), was flown on an 18-day long duration balloon flight in Antarctica to search for Kiruna-like MeV events. Here we present the first results from the GeD, which detected nine MeV X-ray events with a time-averaged precipitating rela-

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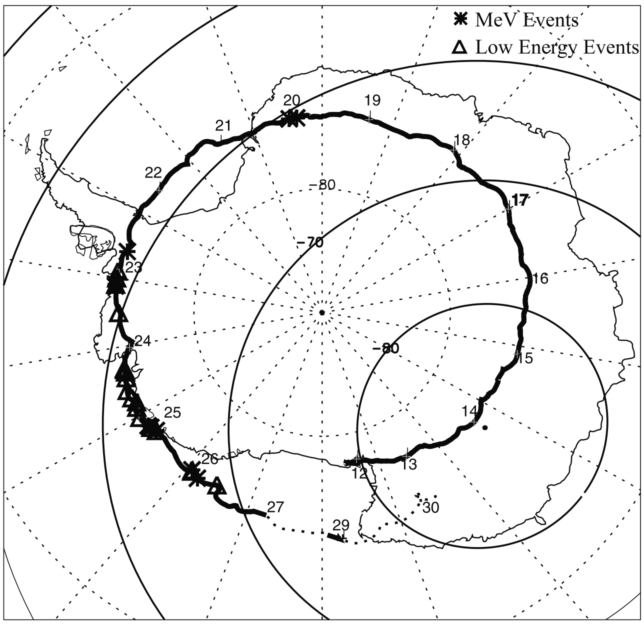

Figure 1. Trajectory of the MAXIS balloon over Antarctica (numbers indicate day in January) with the location of MeV and low energy bursts (asterisks/triangles). The solid curves are lines of constant magnetic latitude.

tivistic electron flux that would deplete the trapped relativistic outer zone population in a few days.

2. Observations

[6] The liquid nitrogen-cooled GeD (5.5 cm × 5.5 cm coaxial) measures 20 keV–10 MeV X-rays with high energy resolution (2.7 keV FWHM at 835 keV). A 0.54 cm thick lead collimator defines a 45° half-angle vertical cone field of view. At count rates below 400 c/s, every energy deposition is measured with 12 bit precision (0.34 keV/channel from 20 keV to 1.3 MeV, and 2.5 keV/channel from 1.3 to 10 MeV) and stored in a 8.4 Gbyte hard disk. Above 400 c/s, 96 channel energy spectra covering 20 keV–1.3 MeV were recorded every 1/4 second, with count rates and instrument live time recorded every 10 ms.

[7] MAXIS was launched from McMurdo, Antarctica, on January 12, 2000, on a 29 million cubic foot helium-filled balloon. The trajectory covered magnetic latitudes 58°–90°S in 18 days (Figure 1). The hard disk recorded almost 15 days of data from each of the four instruments; X-ray count rates for the last three days were transmitted through the TDRSS satellites. After flight termination, the hard disk was recovered.

[8] The five minute average GeD count rate (Figure 2a and 2b) shows no X-ray activity from Jan 12 to 16, when the balloon was at high (>71°) magnetic latitude (Figure 2c). Sporadic X-ray activity, including the most intense burst, was detected from Jan 17 to 22, during low geomagnetic activity ($K_p \sim 0$–3), followed by continual X-ray bursting during a moderate geomagnetic storm (D_{st} reached −91 nT, Figure 2d).

[9] Event intervals were defined by a rise from, and return to, background or near-background levels (~180 c/s) and only events with peak 20–1300 keV count rate above 500 c/s were chosen for analysis since weaker events had poor statistics. This resulted in a total of 25 events. The closest pre-event or post-event ~1 hour interval was used to create a background spectrum. Both the background and event interval spectra were gain calibrated and dead time corrected, and the background was subtracted to obtain the event count spectrum uncorrected for atmospheric attenuation (Figure 3a).

[10] A power law, $dJ/dE \sim E^{-\alpha}$, was fit to each spectrum between 100–180 keV. The power law index, α, shows a bimodal distribution (Figure 4) indicating two distinct classes of precipitation: "soft" events ($3.3 < \alpha < 6$) with steeply falling spectra (Figure 3a, solid diamonds) typical of most previous balloon measurements [e.g. *Smith et al.*, 1995], and "hard" events ($1.7 < \alpha < 2.8$) with flatter spectra similar to the Kiruna event (Figure 3a, open diamonds). Occasionally, an MeV burst occurred during a soft event (Figure 3b) resulting in a spectrum (Figure 3a, crosses) with both hard Kiruna-like and soft components, indicating that two different processes were precipitating electrons simultaneously.

[11] The extremely flat spectra of the MeV events imply that the bulk of the precipitation is at relativistic energies. To characterize the parent electron energy and flux, a simple model of monoenergetic electrons incident at the top of the atmosphere was assumed, and the electron propagation in the atmosphere was modeled, including energy losses and bremsstrahlung production. The bremsstrahlung photons are propagated through the atmosphere and instrument, taking into account scattering and absorption, and the resulting model count spectrum is compared to the observations [*Foat et al.*, 1998]. The best fit electron energies for MeV events ranged from 0.5 to 2.5 MeV with fluxes ranging from 10^{16} to 5×10^{17} electrons/s. Most of the events had durations of tens of minutes, similar to the Kiruna event. The Jan. 19 event ($L = 4.7$, $K_p = 3$), was a notable exception, lasting for over 2 hours (Figure 3c), with a flux of 4×10^{17}

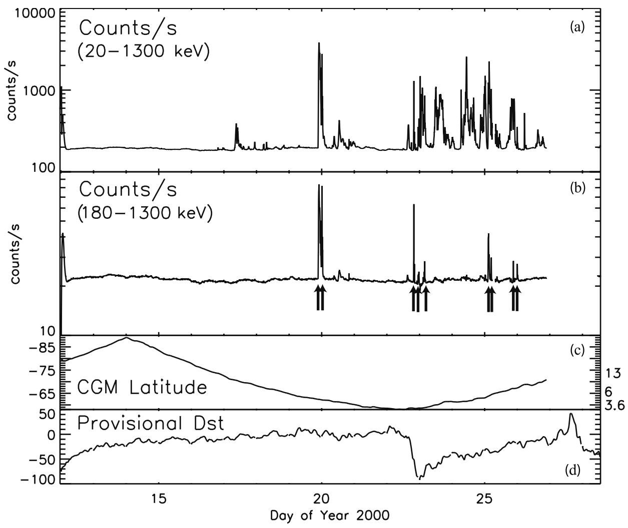

Figure 2. Five minute average count rate from the GeD from Jan. 12–27, 2000 for (a) 20–1300 keV and (b) 180–1300 keV X-rays, with MeV events indicated by arrows. (c) Corrected geomagnetic latitude and approximate L-shell of the balloon. (d) Dst during the flight.

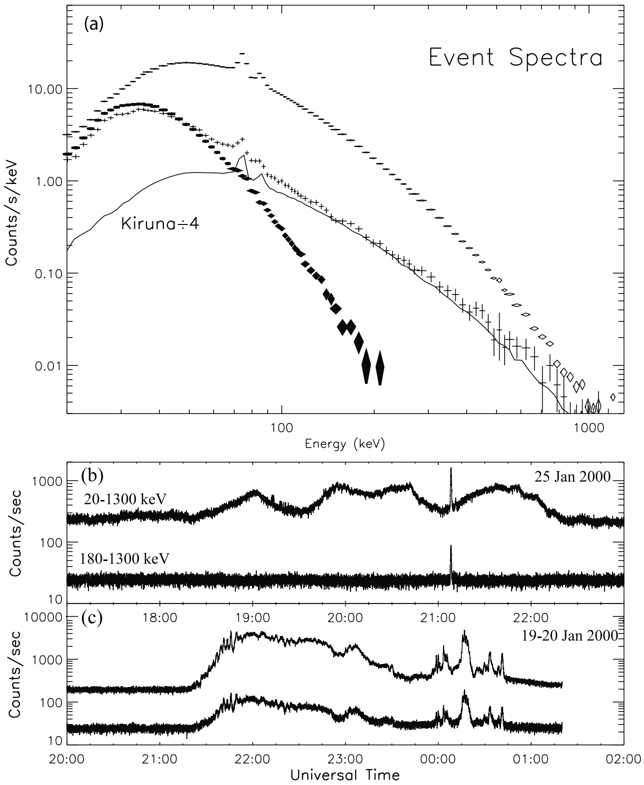

Figure 3. (a) Count spectra for two MeV X-ray events and a soft event together with the Kiruna event spectrum (solid line). The GeD count rates for (b) the short MeV event on Jan. 25 (crosses in a) that occurred during an interval of slowly varying low energy precipitation (solid diamonds), and (c) the longest and brightest MeV event observed (Jan. 19, open diamonds in a).

e^-/s at 0.9 MeV. (Kiruna was 2×10^{17} e^-/s at 1.7 MeV). The January 19 event contributed four times as many precipitated electrons as all the other MeV events combined.

[12] Figure 5 shows the spatial distributions of soft (triangles) and hard MeV (asterisks) events in MLT and magnetic latitude; MeV events were only detected in the afternoon or evening, while soft events were seen at all local times, again demonstrating that the MeV events are distinct from the softer precipitation.

3. Discussion

[13] Considerable attention has been recently focussed on relativistic electrons in the radiation belts and on acceleration processes in particular [*Fujimoto and Nishida*, 1990; *Summers et al.*, 1998; *Hudson et al.*, 1999; *Friedel et al,*, 2002]. However, understanding and quantifying the losses is equally important; the required source strength depends on both the trapped flux and loss rate.

[14] The MAXIS GeD detected nine Kiruna-like MeV precipitation events, with ~40 minute average duration, during the eight days it spent between 58°–68° magnetic latitude (L = 3.8–6.7). From the X-ray fluxes, we infer the total number of ≥0.5 MeV precipitating electrons to be ~9 $\times$ 10^{21}. Dividing by the instrument field of view and the observing time of 8 days, we find an average precipitating electron flux of ~360 $cm^{-2}s^{-1}$. Assuming that the GeD

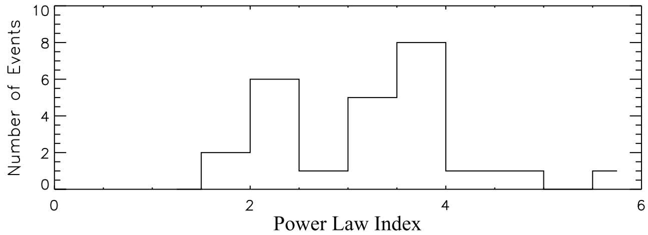

Figure 4. Histogram of spectral power law index between 100–180 keV for the 25 MAXIS events.

observed a representative sample of the precipitation, we multiply this average flux by the total area between 58° and 68° magnetic latitude ($2 \times 10^{17} cm^2$), and the observing time to obtain a total of $\sim 5 \times 10^{25} \geq 0.5$ MeV electrons lost during the eight day interval.

[15] To estimate the total number of trapped electrons, dosimeter measurements on one of the GPS satellites in a 20,200 km altitude, 55° inclination circular orbit were used. The outer radiation belt was assumed to be a torus extending from L = 2 to L = 7 [*Baker et al.*, 1998] giving a total volume between L = 4 and L = 7 (where measurements were available) of 1.1×10^{29} cm^3. Assuming an isotropic pitch angle distribution, the median flux of 0.5–3.6 MeV electrons measured between L = 4 and L = 7 by GPS on January 19 between 2:30–6:10 UT, prior to any observed MeV events, was 4.4×10^6 $cm^{-2}s^{-1}$. The total number of trapped 0.5–3.6 MeV electrons is then estimated to be $\sim 2 \times 10^{25}$, so on average, the MeV precipitation events would empty the outer radiation belts of relativistic electrons in ~3 days. Previous in-situ >450 keV electron measurements found an e-folding decay time of ~6 days after a storm-related enhancement [*Schulz and Lanzerotti*, 1974]. Thus, these MeV precipitation events are likely to

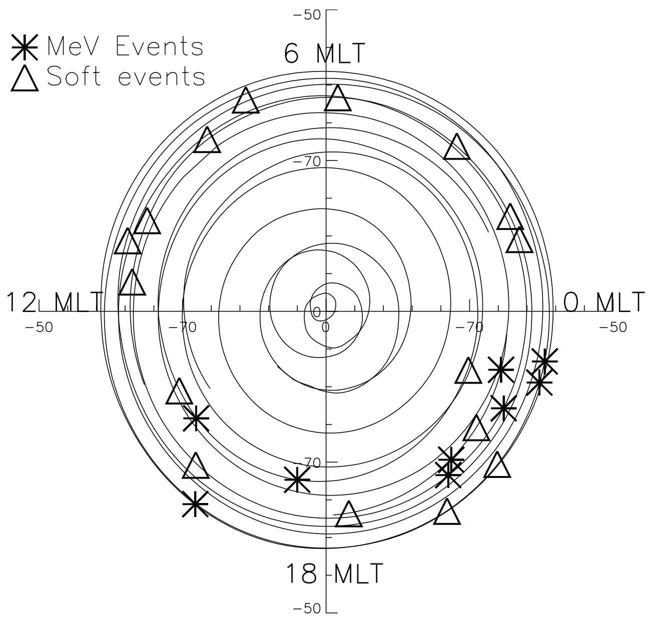

Figure 5. The distribution in magnetic latitude and magnetic local time of MeV events (asterisks) and soft precipitation (triangles). The solid line shows the balloon trajectory.

be a major contributor for the loss of relativistic electrons from the outer radiation belts.

[16] During geomagnetic storms, SAMPEX observations indicate that relativistic electron microbursts are a major loss mechanism [*Lorentzen et al.*, 2001]. However, during this flight, both MAXIS and SAMPEX detected very few relativistic electron microbursts, indicating that the minutes-to-hours MeV precipitation events dominated.

[17] Near the trapping boundary, where the magnetic field becomes distorted enough so the gyroradius becomes comparable to the radius of curvature of the field, a relativistic electron may lose its adiabaticity and be precipitated [*Sergeev and Tsyganenko*, 1982]. This mechanism, called the Sergeev mechanism, may play a role in some of the MeV events, but is unlikely to explain the events at low L values. Scattering of relativistic electrons by electromagnetic ion cyclotron (EMIC) waves is a good candidate for the precipitation mechanism in these MeV events [*Thorne and Andreoli*, 1980]. These waves are observed along the plasmapause boundary in the dusk sector where the plasmapause bulges outward [*Erlandson and Ukhorskiy*, 2001], and where all the MeV events occurred. Relativistic electrons above a cut-off energy will be resonant with EMIC inside the dense plasmasphere [*Thorne and Kennel*, 1971; *Summers et al.*, 1998], consistent with the flat X-ray spectrum of the MeV events. For the Kiruna event, *Foat et al.* [1998] found that if the frequency ($\sim$0.05–0.1 Hz) of quasi-periodic modulations observed in the X-ray flux was assumed to be the EMIC frequency, the implied plasmaspheric densities are unusually high. However, although ULF modulations (mHz) were observed in the MAXIS MeV events (see Figure 3c), no similar high frequency modulations were detected.

[18] *Lorentzen et al.* [2000] suggested EMIC waves were excited by substorm-injected 60 keV protons in the Kiruna event. The January 19/20 events occurred during times of low geomagnetic activity ($K_p \sim 2-3$) but substorm activity was also detected near the time of each of these events as well as during the moderate geomagnetic storm when the other MAXIS MeV events occurred. The relation to substorms, if confirmed, may provide further evidence that scattering by EMIC waves is the precipitation mechanism.

[19] **Acknowledgments.** This research was supported in part by NASA grants NGT5-30110, FDNAG5-6870-1/99, and NAG5-10428-02/02 at U. C. Berkeley, and by the National Science Foundation grants ATM-9806400 and ATM-9975475 at the University of Washington. GPS data were supplied by Reiner Friedel and Tom Cayton. Contract Z667103 between the University of Maryland and the Aerospace Corporation supported part of this work. We thank Richard Sterling, John Chin, Marsha Colby and the National Scientific Balloon Facility for their contributions.

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