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The importance of atmospheric precipitation in storm-time relativistic electron flux drop outs

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[1] During the sudden decrease of geosynchronous electron flux (>2 MeV) of 17:10–17:20 UT, January 21, 2005 large-scale precipitation into the atmosphere was observed. Estimates from ground-based radio propagation experiments at $L{\sim}5$ in the Northern and Southern hemispheres suggest that the atmospheric precipitation was less than 1/10 of the flux apparently lost during this 10 minute period. However, continuing precipitation losses from $4 < L < 6$, observed for the next 2.7 hours, provides about 1/2 of the total relativistic electron content lost.

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1. Introduction

[2] At geostationary orbit radiation belt relativistic flux variations are the result of complex interplay between competing acceleration and loss mechanisms. *Reeves* [1998] found that geomagnetic storms produce all possible responses in the outer belt flux levels, i.e., flux increases (53%), flux decreases (19%), and no change (28%). Understanding these flux changes is important in developing theoretical models of the radiation belts. Large flux decrease events were first studied by *Onsager et al.* [2002], while an extended dataset was investigated by *Green et al.* [2004]. Flux decrease events usually begin in the pre-midnight sector (1500–2400 MLT), and typically show decreases of around 3 three orders of magnitude in >2 MeV electron flux within a few hours of onset, followed by an extended period of low flux suggesting permanent electron loss.

[3] *Green et al.* [2004] investigated three possible mechanisms for the apparent loss of electrons during the flux decrease events: (1) adiabatic motion; (2) magnetopause encounters; and (3) precipitation into the atmosphere. Adiabatic motion caused by the stretching of magnetospheric field lines during a magnetic storm was suggested as the cause of the flux decreases, but not the permanent loss of electrons. Magnetopause encounters were discounted as a mechanism for electron loss as the magnetopause did not overlap with the loss regions, and the associated loss of protons expected through this mechanism was not detected either. Precipitation into the atmosphere of electrons driven into the bounce loss cone was suggested as the primary loss mechanism, through interaction with electron cyclotron harmonic waves [*Horne and Thorne*, 2000], electromagnetic ion cyclotron waves [*Summers and Thorne*, 2003], whistler waves [*Horne and Thorne*, 2003], separately or in combination.

[4] Relativistic Electron Precipitation (REP) into the atmosphere has been observed to take several forms. Relativistic microbursts observed from the SAMPEX satellite last less than one second, occur at about L = 4–6, are observed predominantly in the morning sector, and are associated with VLF chorus waves [*Nakamura et al.*, 2000; *Lorentzen et al.*, 2001]. The flux losses from microbursts appear to be able to empty the radiation belt in about a day [*O'Brien et al.*, 2004]. Precipitation events lasting minutes to hours have been observed from the MAXIS balloon. They occur at about L = 4–7, are observed in the late afternoon/dusk sector, and may be produced by EMIC waves [*Millan et al.*, 2002]. Loss rates suggest that these minute-hour events are the primary loss mechanism for outer zone relativistic electrons.

[5] In this study we analyze ground-based ionospheric data during the sudden electron flux decrease of 17 UT January 21, 2005. The event shows similar local time dependence and flux level changes as those reported by *Onsager et al.* [2002] and *Green et al.* [2004]. We use subionospheric VLF signals to determine the regional effect of the flux decrease event on the Southern and Northern hemispheres high latitude ionospheres in terms of enhanced energetic particle precipitation. VLF radio wave propagation is sensitive to relativistic electron precipitation events during geomagnetic disturbances [*Thorne and Larsen*, 1976]. The effect on the signals can be either an increase or decrease in signal amplitude, depending on the modal mixture of each signal observed. We contrast the timing and location of precipitation events with preliminary observations of X-ray bursts from the same event made during the January 2005 "MINIS" balloon campaign.

2. Experimental Setup

[6] Here we use narrow band subionospheric VLF/LF data spanning 20–40 kHz received at three sites: Sodankylä, Finland (67°N, 23°E, L = 5.2); Ny Ålesund, Svalbard (79°N, 11°E, L = 18.3); and Halley, Antarctica (76°S, 26°W, L = 4.7). These sites are part of the Antarctic-Arctic Radiation-belt Dynamic Deposition VLF Atmospheric Research Konsortia (AARDDVARK). Figure 1 shows the location of the receiver sites (diamonds), and the transmitter-receiver paths that were under study during the event period (transmitter locations are given by the circles). The majority of the paths studied here are in the same longitude sector as the GEOS-12 satellite. The solid squares show the location where the MINIS balloons were operating and hollow

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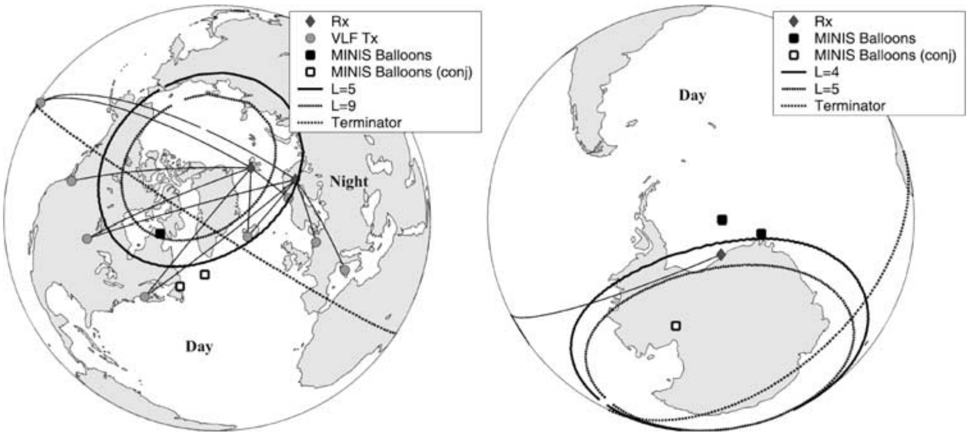

Figure 1. The location of subionospheric propagation paths to AARDDVARK receiver sites. (left) The Northern Hemisphere paths to Sodankylä, Finland, and Ny Ålesund, Svalbard. (right) The Southern Hemisphere path from Hawaii (NPM) to Halley, Antarctica.

squares their equivalent conjugate (E. Bering, personal communication). The location of the terminator is also shown (dotted line), America and Antarctica are daylit during the events.

3. Event Conditions on January 21, 2005

[7] An X7 solar flare at 07 UT on January 20, 2005 was followed by an unusually hard solar proton event within an hour. Recovery of the ionosphere to the declining levels of proton flux was well underway late in January 21 when an associated coronal mass ejection triggered a $K_p = 8$ geomagnetic storm, leading to the relativistic electron drop-out at geosynchronous orbit starting at ~17:10 UT. GOES-10 and GOES-12 >2 MeV electron fluxes had decreased by three orders of magnitude by 18 UT. GOES-12 saw the fastest change i.e., two orders of magnitude decrease in 10 minutes.

[8] The MINIS balloon experiment has reported X-ray bursts produced by REP into the atmosphere above the balloons during this event. The balloons observed significant X-ray counts from 17:10–17:40 UT, and 18:30–19:50 UT. Most of the bursts were observed from $L = 3.5$ and $L = 4.1$ in the Southern Hemisphere, although the first burst at 17:12 was also seen at $L = 10$ in the Northern Hemisphere [*Bering and the MINIS Team*, 2005]. Here we consider the coincidence in the subionospheric radio propagation data of 2 specific times of X-ray count peaks seen by MINIS i.e., 17:12, and 17:20 UT.

4. Ionospheric Data: Northern Hemisphere

[9] In Figure 2 we show the amplitude of the N. Dakota transmitter (NDK, 25.2 kHz) received at Sodankylä during the flux decrease event. The propagation path is primarily high latitude, starting at about $L = 3.5$, peaking at $L > 10$, and received at $L = 5.0$ in Finland. The first half of this 6,500 km path lies close to the longitudes where the MINIS balloons were observing, either in the north, or in the Southern Hemisphere. The times of significant X-ray count levels observed by the MINIS balloons from 17–20 UT are indicated in Figure 2 by thick horizontal bars. During these periods the amplitude of the transmitter signal shows decreases of 1–2 dB lasting 5–10 minutes, and also large short-lived spike events of 2–5 dB, both increases and decreases. Here we describe these features as SLOW and FAST events. Also plotted is the >2 MeV electron flux from GOES-12 (dotted line), a sharp decrease in flux can be observed at 17:10–17:20 UT. These observations indicate that the N. Dakota propagation path is seeing similar event timing to the MINIS balloons, and that the onset of the geosynchronous >2 MeV electron flux decrease is associated with precipitation into the atmosphere. Several other paths also showed absorption of several dB continuing over this 3-hour period.

[10] Figures 3 and 4 show the period 17–18 UT in detail. Figure 3 plots transmitter signals received at Sodankylä. The amplitudes are offset, with the most westerly transmitter given the highest amplitude (N. Dakota, NDK) and the most easterly given the lowest (Germany, DHO). The times of two

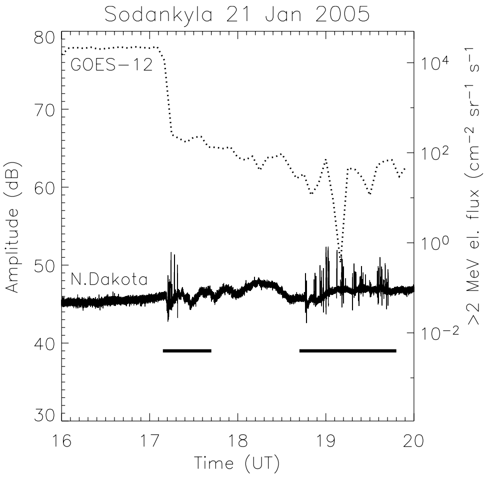

Figure 2. The amplitude of the N. Dakota (NDK) transmitter received at Sodankylä, Finland, and the GOES-12 >2MeV electron flux during 16–20 UT. The horizontal bars represent the approximate times during which the MINIS balloons observed X-ray burst activity.

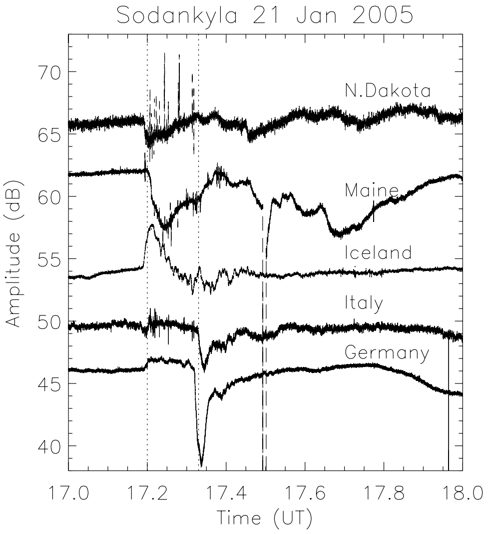

Figure 3. The amplitude of transmitters received at Sodankylä, Finland, during 17–18 UT. The vertical dashed lines indicate times of X-ray bursts observed on the MINIS balloons.

periods of high X-ray counts observed by the MINIS balloons are approximately indicated by vertically dotted lines. The first SLOW event occurs at about 17:12 UT and produces a response in all paths, in some cases this is seen as an increase in amplitude, but in others it is a decrease. In most cases the precipitation driving the amplitude changes appears to last for at least 5 minutes. The second SLOW event occurred at about 17:20 UT and produced clear signatures on only two transmitters i.e., Italy (ICV) and Germany (DHO), both lasting ~5 minutes.

[11] In three of the transmitter signals (N. Dakota, Maine, and Italy) there are a series of FAST short-lived spike events of a few dB, starting during the first SLOW event and recurring over ~10 minutes. These were noted in Figure 2 previously. The FAST events are not co-incident on the three propagation paths. Typically the signal changes last 1–3 s, consistent with ionization produced by the precipitation of high energy electrons (>1 MeV) deep into the fast-recombination region of the atmosphere (40–60 km). The short rise and recovery times suggest that these events maybe associated with microbursts - their lack of co-incidence from one path to another in this study suggests a spatial size <2,000 km and a narrow *L*-shell range equatorwards of $L = 5$.

[12] Figure 4 shows transmitter signals received at the high latitude receiver in Ny Ålesund. The amplitudes are offset as in Figure 3. The times of high X-ray counts observed by the MINIS balloons are again indicated by vertically dotted lines. The first event is seen on three of the propagation paths as sudden changes in amplitude of a few dB, lasting at least 5 minutes. The second event is not detected. No FAST events are observed from Ny Ålesund.

[13] The results from Figures 3 and 4 suggest that the first SLOW event is spatially large, influencing a wide range of latitudes and longitudes, probably $L > 2$ to $L < 18$, and ~9 hours in LT. The observation of the second SLOW event (at 17:20 UT) is restricted to low-latitude European propagation paths, as well as the $L = 3.5$ and $L = 4.1$ MINIS balloons near Halley. None of the high latitude, high *L*-shell propagation paths responded to the precipitation event. This suggests a precipitation zone that is confined in *L*-shell to $L < 5.0$, but still extended in longitude, as the two regions are separated by ~90°. This suggests that the area of precipitation reduces in *L*-shell as the magnetosphere contracts after the onset of the CME.

5. Ionospheric Data: Southern Hemisphere

[14] In the Southern Hemisphere the data for this period comes from a receiver at Halley logging transmissions from Hawaii (NPM, 21.4 kHz). Figure 1 (right) shows that the propagation path is almost directly west of Halley and limited to the $L = 4–5$ band around the region of the Antarctic Peninsula. Figure 5 is the same format as Figures 3 and 4. As in the Northern Hemisphere there is a clear 1–2 dB SLOW absorption effect caused by precipitation lasting ~5 minutes during the first event, but the second event produces no clear signature. However, the signature of SLOW precipitation is observed at 17:22 UT, possibly at 17:33 UT, and again at 17:51 UT. Because the NPM propagation path in the region of the Antarctic Peninsula is about 1 *L*-shell poleward of the MINIS balloon locations it is probable that the second precipitation event is strongly confined in L-shell i.e., $L < 5$. Signal to noise quality at this time is not good enough to provide detection of any FAST events that might be occurring.

6. Discussion

[15] At the onset of the geosynchronous electron flux decrease nearly all subionospheric propagation paths show that large-scale precipitation into the atmosphere occurred. This allows us to make some estimate of the flux deposited, and the overall significance.

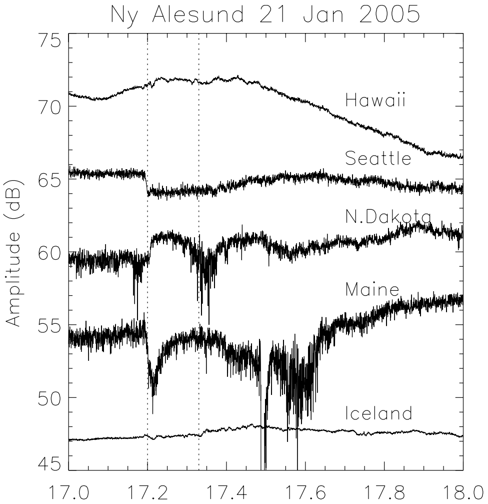

Figure 4. The amplitude of transmitters received at Ny Ålesund, Svalbard, during 17–18 UT.

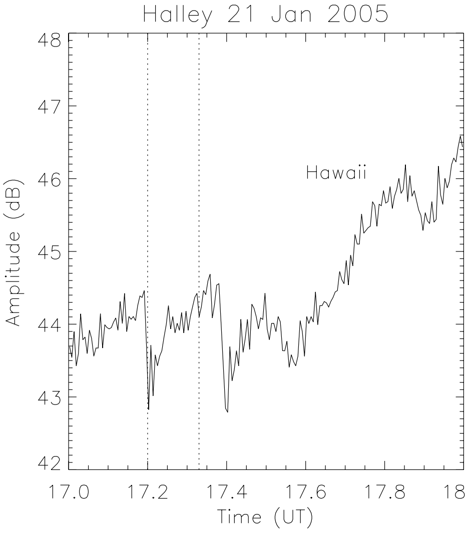

Figure 5. The amplitude of the Hawaii transmitter (NPM) received at Halley, Antarctica, during 17–18 UT.

[16] Previously *Clilverd et al.* [2005] estimated the change in the amplitude of the Hawaii (NPM) transmitter received at Halley as a function of >50 MeV proton fluxes, particularly for large-scale polar region events occurring within a few months of the December solstice. We can check that this applies here. At the start and the end of January 21 the NPM amplitude is 9 dB and 4 dB lower than the quiet day curve respectively. The integral fluxes from GOES-11 were about 40 and 2 protons $cm^{-2}sr^{-1}s^{-1}$ at the start and the end of the day. The formulation from *Clilverd et al.* [2005] predicts the proton-induced amplitude absorption to be 8.3 dB and 4.4 dB. This close agreement suggests good understanding of the effect of the continuing proton event.

[17] Because the radio propagation technique is sensitive to the lower boundary of the ionization, only energetic protons or relativistic electrons would cause additional absorption during the proton event. The REP at 17:12 UT increases the absorption of NPM by 1.5 dB in addition to the proton absorption. This is equivalent to doubling the precipitating proton flux at the time by adding ~7 protons $cm^{-2}sr^{-1}s^{-1}$. Protons of 50 MeV penetrate into the atmosphere to about 50 km altitude, the same altitude as 2 MeV electrons. However, it takes about 100 times the number of electrons to produce the same ionization rates as a proton at the same altitude [*Banks and Kockarts*, 1973]. Thus, we estimate that about 700 electrons $cm^{-2}sr^{-1}s^{-1}$ >2 Mev are being deposited into the atmosphere as a REP event at the onset of the electron flux decrease event. This flux is relatively small in comparison with the 26,000 electrons $cm^{-2}sr^{-1}s^{-1}$ apparently lost from geosynchronous orbit at this time based on GOES-12 data.

[18] If the total population of 10^{25} 2–6 MeV electrons in the outer radiation belt [*O'Brien et al.*, 2004] were depleted in 10 minutes it would require a loss rate of 1.7×10^{22} s^{-1}. If this loss occurred over an area of $L = 4–6$ and across 9 hours of MLT, i.e. an area of $1.5 \times 8.5 \times 10^{16}$ cm^2 [*Lorentzen et al.*, 2001], this would suggest $\sim 1.3 \times 10^5$ $cm^{-2}s^{-1}$, and assuming downward isotropy, a loss rate of 2×10^4 electrons $cm^{-2}sr^{-1}s^{-1}$. If however, we more conservatively used $L = 3–10$ to describe the precipitation region we would reduce the loss rate by a factor of 3. Our estimate of 700 electrons $cm^{-2}s^{-1}sr^{-1}$ would therefore deplete only ~1/10 to 1/30 of the total content. However, our ground-based observations suggest that precipitation continued for 2.7 hours between $L = 4$ and 6, producing about 2 dB of NPM absorption at Halley. Similar results were observed in the Northern Hemisphere. Over this length of time a loss rate of 700 electrons $cm^{-2}s^{-1}sr^{-1}$ over $4 < L < 6$ would deplete $\sim 6 \times 10^{24}$ electrons or ~1/2 of the total content.

7. Summary

[19] During the sudden decrease of geosynchronous >2 MeV electron flux of 17:10–17:20 UT, January 21, 2005 large-scale precipitation into the atmosphere was observed. Three radio propagation experiments, 2 in the Northern Hemisphere, and 1 in the south, were monitoring the same longitude sector as GOES-12. The precipitation began at the same time as the geosynchronous flux decrease. Estimates suggest that the atmospheric precipitation was only a small fraction of the flux apparently lost (~1/10 to 1/30) over this 10 minute period. However, continuing precipitation from $4 < L < 6$ which lasts for 2.7 hours would account for about 1/2 of the total relativistic electron content lost.

[20] Very short-lived spike events were also observed during the flux decrease event. These are consistent with the expected impact of microbursts of relativistic electrons on the atmosphere. The short-lived events were concurrent with the longer-lasting burst events.

[21] **Acknowledgment.** We gratefully acknowledge E. Bering and the MINIS balloon team for the X-ray event timing information.

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