Results from the SEEP active space plasma experiment: Effects on the ionosphere

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An active satellite-ground coordinated space plasma experiment was conducted from May to December, 1982, to which electrons were precipitated from the radiation belts into the ionosphere by the controlled injection of VLF signals from ground-based transmitters. The results confirm the hypothesis that electrons can be precipitated from the radiation belts by ground-based VLF transmitters, and they provide information relating to the effects of such precipitation on the ionosphere. The ionization produced in the atmosphere of the northern latitudes at \( L = 2.3 \) by the modulated signals from ground-based VLF transmitters was shown to be great as one cm sec\(^{-1}\) cm\(^{-2}\) at 80 km altitude. The ionization at comparable positions produced by naturally occurring electron precipitation was greater, and can be as large as 0.1 cm sec\(^{-1}\) cm\(^{-2}\), but is also sometimes larger than 100 cm sec\(^{-1}\) cm\(^{-2}\) at times of lightning flashes.

INTRODUCTION

An active experiment, stimulated emission of energetic particles (SEEP), was conducted during May-December 1982. In this experiment the U.S. Navy operational VLF transmitters at Cutler, Maine (NAA); Annapolis, Maryland (NSS); and Jim Creek, Washington (NLK) and the Stanford University research VLF transmitter at Siple Station, Antarctica, were operated in special controlled formats at times of overpasses of the low-altitude polar-orbiting satellite S81-1. The spacecraft payload measured both direct electron precipitation \( > 2 \) keV and bremsstrahlung X rays \( > 4 \) keV from the atmosphere. The experiment concept is illustrated schematically in Figure 1. The locations of the VLF transmitters are indicated along with a representation of the satellite paths during three successive passes. In addition, the modulated VLF waves and their regions of interaction with the trapped electrons are also shown.

The SEEP experiment payload on the three-axis stabilized polar-orbiting S81-1 spacecraft contained an array of cooled silicon solid state detectors to measure electrons and ions directly with high sensitivity and fine energy resolution [Voss et al., 1982]. The data presented here were taken with electron spectrometers mounted at 90° zenith angle and at 90° to the orbit plane (TE detector), at 0° zenith angle (MEI) and at 10° zenith angle (ME2). The TE spectrometer had an electron threshold energy of 5 keV, an acceptance angle of \( \pm 20° \) and a geometric factor of 0.17 cm\(^{-2}\) sc at 0.17. It is sensitive to both electrons and ions, but on the basis of the responses of other detectors in the payload, all of the precipitation events presented here are taken to be associated with electrons. Each of the MEI and ME2 spectrometers had an electron threshold energy of 45 keV, an acceptance angle of \( \pm 30° \) and a geometric factor of 2.47 cm\(^{-2}\) sc. A thick window on MEI and ME2 prevented ions with energies below 0.5 MeV from impinging on the silicon detector, and therefore in all of the data shown the counts were predominately due to electrons. The measurements were performed at satellite altitudes of \( \sim 220 \) km.
With this payload the first observations were made of direct bounce loss cone precipitation of radiation belt electrons by the controlled injection of VLF signals from a ground based transmitter [Imhof et al., 1983c]. Although past observations had shown that electrons can be precipitated from the radiation belts by ground-based VLF transmitters, the evidence was based predominantly on observations of electrons in the drift loss cone. Narrow resonant peaks in the energy spectra [Imhof et al., 1974, 1981; Vampola and Kuck, 1978; Koons et al., 1981] and coordinated wave-particle observations [Imhof et al., 1981] had provided evidence for the effects of transmitters. In spite of the SEEP findings, relatively little is known about the importance of transmitters in relation to other loss processes for radiation belt particles. It is realized, however, that electrons are regularly precipitated from the radiation belts and that these electrons can cause measurable ionization at midlatitudes.

The purpose of this paper is to assess the effects on the ionosphere of electrons precipitated by the transmitters NAA and NSS during the observed SEEP events and to compare these with the effects of electron precipitation induced by natural causes.

**OBSERVATIONS OF ELECTRONS PRECIPITATED BY VLF TRANSMITTERS**

A good example of electron flux modulations in correlation with the transmitter on-off signals occurred on August 17, 1982 at 8680-8740 seconds UT when the SEEP payload was passing near the NAA transmitter as it was being modulated with a 3-s on and 2-s off pattern. In Figure 2 the electron fluxes measured at various zenith angles are plotted as a function of time. A modulation period of 5 ± 0.1 s is clearly seen for 12 consecutive cycles. For reference, the measured on times of the transmitter at NAA are indicated. The risetime of the electron flux and the observed delay in decay time of ~1.5 s are now understood [Imhof et al., 1985] in terms of the pitch angle dependence of the particle distribution near the edge of the loss cone and by the multiple interaction of the particles with the waves due to significant atmospheric backscatter.

Differential energy spectra of the precipitating electrons taken during the times of enhanced electron precipitation showed prominent peaks but there was little evidence of their presence during times of minimum intensity. It was shown that the measured peak energies and their variations with L are consistent...
with those expected for cyclotron resonance with waves of the transmitter frequency travelling parallel to the earth's magnetic field lines [Jinbof et al., 1983a].

From surveys of the SEEP data five electron modulation events were found from the 65 passes of the satellite when one of the transmitters was being modulated in a special 3-s on and 2-s off format. No such events were found in the 175 passes when neither the NAA nor NSS transmitter was being modulated in one of the special SEEP formats. All of the time profiles for the events displayed a similar pattern in which the fluxes increased rather slowly after start of the on period and reached a maximum about 2 s later. The temporal profile and the absolute counts rates of the observed fluxes were found to be in good agreement with the predictions of an extended test particle model of the wave-particle interaction in the magnetosphere [Jinbof et al., 1985].

Although modulated electron precipitation events associated with the controlled injection of VLF signals from a ground-based transmitter were not observed frequently, transmitters may still play a strong role in the precipitation of electrons from the radiation belts. Narrow peaks in the energy spectra of electrons precipitating from the inner radiation belt in the drift loss cone have been shown to result from cyclotron resonance interactions with waves from ground-based transmitters [Jinbof et al., 1981].

In the bounce loss cone the transmitters might have contributed significantly to the observed fluxes in the absence of a detectable modulation. To assess the role of transmitters it is important, therefore, to compare the absolute fluxes of electrons measured during normal operations with those observed when the transmitters were either off or operated in a special manner such as in the SEEP 3-s on and 2-s off format. Unfortunately, no significant amount of data were not acquired with both the NAA and NSS transmitters off. Normal operation consisted of a constant amplitude signal with the frequency shifted as often as once every 25 ms. In the SEEP format the frequency was fixed during the on time of 3 s. The wider bandwidth signal during normal operations may possibly have inhibited temporal growth of the waves, as found in earlier Stile experiments [Rupham et al., 1977].

The possible effects of transmitter operation on the fluxes of precipitating electrons are illustrated in Figure 3 where the median electron fluxes > 5 keV observed during a 5.6-s period centered at L = 3.3 are plotted as a function of longitude. Separate symbols are used for the normal operation of both transmitters and for the special modulation of either transmitter in the 3-s on and 2-s off format. During the normal mode pass on August 11, 1982, a narrow spike of precipitating electrons with the clear characteristic of those induced by lightning [Plote et al.,
1984] was observed at an L value close to 2.3 and that event is treated later in this paper with a shorter summation time interval. To minimize the flux variations associated with magnetic activity the time period July 7–21, 1982, has been excluded from the plot. At the times covered in the figure the electron flux in this longitude interval increased by as much as an order of magnitude subsequent to the magnetic storms with a peaking at a time delay of about 4 days [Voy et al., 1984a]. The pronounced transmitter modulation event on August 17, 1982, occurred during one of these enhanced electron periods. The median flux levels shown for 10° longitude bins do not seem to indicate a significant change in the average precipitation rate when the transmitters were operated at fixed frequency with a 60% duty cycle as compared to the normal broader frequency operation at 100% duty cycle. Although evidence for a strong effect of the transmitters was not found by this technique (see also Imhof et al. [1983]), it should be emphasized that the ideal experiment was not conducted in which one could compare the fluxes of precipitating electrons observed when both NAA and NSS transmitters were off and when both were on.

EFFECTS OF PRECIPITATED ELECTRONS ON THE IONOSPHERE

We now consider the ionization in the atmosphere that would be associated with the pronounced transmitter modulation events of August 17 and August 25, 1982, and compare the ionization profiles with other representative cases of electron precipitation.
Based on both the energy spectrum and the pitch angle distribution of the precipitating electrons, the ionization profile can be calculated by using the AURORA computer program [Waite et al., 1968]. Energy spectra of the electrons in the northern hemisphere were measured with fine energy resolution, and the spectra at $L = 2.3$ and longitudes of 280°E to 290°E during these transmitter modulation events and at other selected times are shown in Figure 4. The applicable time interval is 8.19 s except for the lightning associated spectrum on August 11, 1982, for which the summation time is 0.70 s. These spectra represent electrons observed with the detector at a central pitch angle of 90°–96°. All of the observed electrons have mirror points below sea level in the southern hemisphere; i.e., the electrons were all precipitating within one bounce, except for backscattering. Only those with pitch angles less than ~78° precipitated in the northern hemisphere, but for purposes of calculating energy deposition profiles we shall assume the spectra of electrons precipitating in the north are the same as shown in Figure 4.

The pitch angle distributions were measured directly at positions above the atmosphere with the array of collimated electron spectrometers in the SEEP payload. However, measurements were made at only a few pitch angles with relatively broad angular resolution. A histogram representation of the fluxes observed in those detectors during the August 17, 1982, measurement is shown in Figure 5. A Gaussian fit (B) to the northern hemisphere measurements is also shown in the figure, normalized to unity at 90°. In addition, a narrower Gaussian pitch angle distribution (C) is plotted based on the measurements in the northern hemisphere for some of the other events. It should be realized that both the absolute fluxes and the shapes of the pitch angle distributions can vary considerably from one satellite pass to another. Although the transmitters were routinely operated at the same power level, the intensities of the waves after passage through the ionosphere are known to vary considerably due to changes in ionospheric conditions [Heyborne, 1966].

We have calculated energy deposition profiles at
Fig. 5. Pitch angle distributions at $L = 2.3$ in the northern hemisphere for electrons $> 45$ keV. Curves A and B are histogram and Gaussian representations, respectively, of the distribution measured during the maximum modulation event on August 17, 1982. Curve C is a narrower Gaussian distribution based on the TE measurements at a variety of longitudes. The pitch angle distributions are normalized to 1.0 at 90$^\circ$.

$L = 2.3$ using the AURORA program for the pitch angle distributions shown in Figure 5 each normalized to the same flux at 90$^\circ$ pitch angle and for the observed spectral shape. The results are shown in Figure 6. As one can see, the differences between the histogram (A) and the corresponding Gaussian pitch angle distribution (B) for the August 17, 1982, event are only of the order of 25% and therefore the details of the pitch angle distribution measured during this event are not critical in regard to the calculated energy deposition profiles. The deposition profile for the August 17, 1982, event was also calculated assuming the narrower pitch angle distribution (C) shown in Figure 5. For this narrower distribution, not actually measured during the event, the energy deposition profile would be reduced by a factor of 2-3. The energy deposition profiles A and B in Figure 6 are equivalent to an energy input of $\sim 10^{-3}$ erg/cm$^2$ s and a corresponding riometer absorption of $\sim 0.004$ dB at 30 MHz [Rogers et al., 1983].

Energy deposition profiles corresponding to the various energy spectra in Figure 4 and for the appropriate histogram pitch angle distributions are presented in Figure 7. The applicable histogram pitch angle distribution is based on the observed responses in detector TB and ME1 during the satellite pass of interest, and the ratios of these responses are provided in Table 1. In all of these cases the counting rate in detector ME2 were much lower than in ME1. The modulated signals from the NAA transmitter during the August 17, 1982, event produced an ionization rate of $\sim 1$ ion pair/cm$^2$ s at 80 km altitude. Both the shapes and the absolute intensities of the ionization
profiles at \( L = 2.3 \) vary over a wide dynamic range, but may be as low as 0.1 ions/cm\(^2\) s at (260°–310°) E in the northern hemisphere. Some of the precipitation events were fairly steady as observed from the satellite over broad time and latitude intervals. At other times, such as during the modulated transmitter events or lightning associated precipitation, significant variations were observed on a short time scale. These fluctuations can be particularly large for the precipitation produced by lightning. The latter type event on August 11, 1982 was studied over the peak burst period of 0.70 s, but all of the other profiles were averaged over 8.19 s. For this and other lightning flashes the ionization rates at ~80 km altitudes can be of the order of 100 ions/cm\(^2\) s or greater. Since the average electron precipitation is comparable to that observed during the August 17 event, it is not known at present how much of the ionization normally occurring in the northern hemisphere at \( L = 2.3 \) in this longitude region is associated with transmitters and how much results from other processes.

Analysis of the data acquired on many satellite passes through the regions of space considered here shows that a measurable ionization from precipitating electrons is generally produced at altitudes of 70-120 km. Some portion of this ionization in the northern hemisphere is generally present as a result of backscatter in the southern hemisphere of electrons in the drift loss cone. One of the two transmitters NAA and NSS was usually operating and so it has not been possible in this experiment to establish conclusively what the contribution of these transmitters is to the electrons precipitation normally occurring. These ambiguities could be resolved with use of a much more powerful transmitter operating at a lower frequency, on a different \( L \) shell and/or one placed above the ionosphere on a satellite such that the waves from the transmitter are much stronger in the near equatorial regions and the associated ionization effects considerably greater. It may then be possible to affect the ionosphere significantly through the controlled precipitation of electrons from the radiation belts.

**Table 1. MEIKTE Flux Ratios**

<table>
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<tr>
<th>Date</th>
<th>UT</th>
<th>Ratio</th>
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</thead>
<tbody>
<tr>
<td>Aug. 8, 1982</td>
<td>0228</td>
<td>0.241</td>
</tr>
<tr>
<td>Aug. 11, 1982</td>
<td>0256</td>
<td>0.808</td>
</tr>
<tr>
<td>Aug. 17, 1982</td>
<td>0225</td>
<td>0.155</td>
</tr>
<tr>
<td>Aug. 25, 1982</td>
<td>0241</td>
<td>0.149</td>
</tr>
<tr>
<td>Sept. 1, 1982</td>
<td>0224</td>
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SUMMARY

The modulated signals from a ground-based VLF transmitter have been shown to produce ionization rates at altitudes of ~80 km in the midlatitude (L = 2-3) northern hemisphere as high as 1 ion pair/cm² s. The naturally occurring ionization rates in this latitude region show large variations, are longitude dependent, and at (260°-310°)E in the northern hemisphere may be as low as 0.1 ion pair/cm² s. At these same locations the ionization at ~80 km associated with lightning flashes is sometimes in excess of 100 ion pairs/cm² s, but for each flash the time duration of the intense precipitation is of the order of only 1 s.

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