GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 23, PAGES 3557-3560, DECEMBER 1, 1999

Ionospheric Effects of Relativistic Electron Enhancement Events

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Abstract. The relativistic electron population as measured both at geosynchronous orbit and at low altitudes at subauroral latitudes exhibits pronounced fluctuations in association with magnetospheric substorm and solar activity. A ground-satellite correlative study based on amplitude and phase measurements of VLF signals propagating in the earth-ionosphere waveguide indicates that the relativistic electron enhancements are accompanied by similar enhancements in nighttime ionospheric conductivity produced by associated enhanced precipitation. VLF signal amplitudes are found to exhibit >10 dB changes, showing the same 27 day cycle and 2-3 day rise and fall time pattern as relativistic electron enhancement events recorded by GOES 7 and SAMPEX, and indicating that the nighttime lower ionospheric electron density at subauroral latitudes is detectably affected by 27-day periodicity in solar rotation.

1. Introduction

The Earth's outer magnetosphere is often populated to a surprising degree by relativistic electrons [*Paulikas and Blake*, 1979]. Enhancements in the relativistic electron fluxes may be an important source of energy input to the atmosphere. Those precipitating electrons with energies >1 MeV can penetrate to altitudes as low as 50 km, affecting the atmospheric chemistry throughout the mesosphere [*Gaines et al.*, 1995]. Relativistic electron precipitation events are also believed to be a significant source of odd nitrogen in the middle atmosphere, possibly affecting ozone concentrations in some regions of the atmosphere [*Callis et al.*, 1991]. Relativistic electron precipitation events are associated with magnetospheric activity and may appear more frequently near a solar minimum than solar maximum [*Baker et al.*, 1986]. These events are strongest at subauroral (4.5 < L < 7) latitudes. The enhancements of energetic particle fluxes within and near the local loss cone are documented in data from low altitude satellites such as SAMPEX [*Baker et al.*, 1993] and UARS [*Gaines et al.*, 1995], while the relativistic electron population at geosynchronous orbit is measured on GOES-7 and GOES-8. The particle flux as measured on these satellites exhibits the well known relatively regular 27-day periodicity with typical rises on a 2- to 3-day time scale and decays on a 3- to 4-day scale [*Baker et al.*, 1986].

Very Low Frequency (VLF) sounding of the lower ionosphere (i.e., the measurement of the amplitude and phase of subionospherically propagating VLF signals) is a sensitive tool for the detection of ionospheric conductivity changes due to changes in electron density and/or temperature, especially at altitudes below 90 km [*Sechrist*, 1974]. Some of the early work on relativistic electron precipitation events has indeed relied on subionospheric VLF measurements [*Thorne and Larsen*, 1976].

In this paper we use the VLF method to quantitatively assess the degree to which relativistic electron enhancements observed at satellite altitudes are accompanied by enhanced precipitation into the ionosphere. We search for the ionospheric signatures of relativistic electron precipitation by interpreting the observed VLF amplitude variations in the light of theoretical models of VLF subionospheric wave propagation [*Poulsen et al.*, 1993]. Our results indicate that the nighttime D-region is indeed strongly affected by this precipitation, with the electron density at 40-70 km altitudes clearly exhibiting the 27-day cycle associated with solar rotation. The VLF response is likely to be largely due to the lower energy 100-300 keV electrons which accompany the 2-5 Mev electrons that signify relativistic electron enhancement events, because these are the particles which produce most of the ionization enhancement in the D-region where the VLF waves reflect. Even though 2–5 MeV electrons may penetrate down to the <65 km altitudes and may create significant secondary ionization, the enhanced electron densities will have a smaller effect on the conductivity and hence on the VLF signal because of the much higher collision frequency at the lower altitudes.

2. Description of data

For this study, we focus our attention on the two month period of October and November 1992 (for which VLF data from Fort Yukon is continuously available) and utilize three different data sets, namely (i)VLF data, (ii) SAMPEX data, and (iii) GOES 7 data. Each of these data sets is briefly described below.

Paper number 1999GL010686.
0094-8276/99/1999GL010686$05.00

2.1. Ground based VLF data

The VLF data consists of the recorded amplitude and phase of the subionospheric signal from the NLK transmitter (24.8 kHz) in Jim Creek, Washington (121.91° W, 48.20° N) as received at Fort Yukon (FY), Alaska (145.218° W, 66.56° N) during the period Oct-Nov 1992. Figure 1 shows the NLK-FY great circle propagation path as well as lines of constant geomagnetic latitude. Since the fluxes of relativistic electrons exhibit fluctuations primarily at subauroral latitudes ($4.5 < L < 7$), the NLK-FY path is well situated for monitoring the ionospheric effects of these relativistic electron enhancements.

Subionospheric VLF signals are known to be very sensitive to D region ionospheric parameters [*Galejs*, 1972]. Increases in the D region electron density caused by the high-energy particle precipitation increases the local electrical conductivity and perturbs the VLF signal propagating under the disturbed ionosphere. Figure 2 shows a schematic description of this process.

The VLF data at FY during the Oct-Nov 1992 period was typically recorded during the period 0000 to 1200 UT. The signal amplitude in a 300 Hz band centered at the transmitter frequency (24.8 kHz) is regularly sampled and digitally recorded at a resolution of 100 Hz (i.e., samples taken at 10 ms intervals). Since the VLF signal amplitude can exhibit significant variation over short time scales, for example in response to burst precipitation effects [*Cotton and Smith,* 1991] or auroral electrojet enhancements [*Cummer et al.*, 1996], studies of long term behavior are facilitated through the use of data averaged over a number of hours on each day. For this purpose we have chosen to average the VLF data over the time interval 0600 to 0900 UT each day, during which the entire NLK-FY path was under darkness throughout the study period. For each day, this simple 3 hour average of the signal amplitude is designated as the 'average' signal amplitude.

2.2. SAMPEX and GOES data

The details of the energetic particle instruments with which SAMPEX and GOES satellite data were acquired are described elsewhere. We provide a brief summary below.

The Proton/Electron Telescope (PET) [*Cook et al.*, 1993] on SAMPEX is composed of an array of silicon solid state detectors that identify and measure the kinetic energy of electrons from 1 to 30 MeV and of H and He isotopes from 20 to 80 MeV/nuc. The SAMPEX data used in this paper are integral fluxes of > 4MeV electrons measured in specific passes nearby the subionospheric paths.

The GOES-7 Energetic Particle Sensor (EPS) measures electrons from 0.6 to greater than 4.0 MeV, protons from .8 to 500 MeV, and alpha-particles from 4 to 500 MeV [*Goes Operations Handbook,* 1994]. The electron measurements are made via solid state surface barrier detectors within a dome subassembly. The data used in this paper are 5-minute averages of the integral fluxes of > 2 MeV electrons.

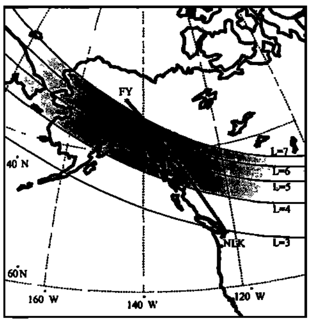

Figure 1. A geographic view of the VLF propagation path from NLK to Fort Yukon, Alaska. The NLK-FY path is situated such that the relativistic precipitation region (shown shaded) covers a significant portion of the great circle propagation path.

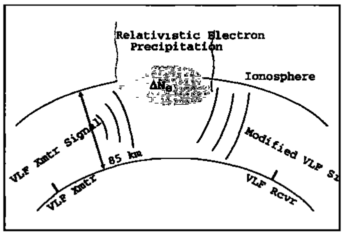

Figure 2. The mechanism of the particle precipitation-VLF interaction is schematically shown above. A ground VLF transmitter (T) launches a signal into the Earth-Ionosphere waveguide. In the region of relativistic particle precipitation the local electron density is increased by ΔNe and the local collision frequency is increased by $\Delta\nu$. The changes cause the local electrical conductivity to change. The waveguide signal propagating under the region of relativistic electron precipitation is modified in response to the conductivity changes, allowing the observation of this conductivity change as phase and amplitude variations in the VLF signal.

3. Ground and Satellite Data Comparisons

The 'averaged' VLF amplitude for the October and November 1992 period is compared in Figure 3 with the corresponding satellite particle data measured by GOES-7. The GOES-7 electron flux maxima are clearly associated with the amplitude minima in the VLF data. A 27-day cycle is clearly apparent in the VLF data, similar to that observed in GOES data for the relativistic electron enhancement events, with the same 3-4 days of rise and fall times. In association with the two large electron flux enhancements which peak on days 276 and 305, the VLF signal amplitude exhibits changes > 9 dB with rise and fall times of a few days. The VLF amplitude minima are delayed by about two days with respect to the peaks in GOES data; possible reasons for this delay are discussed later. The two smaller peaks in the GOES data, which are an order of magnitude below the two main peaks, are not associated with strong VLF amplitude minima.

To our knowledge this is the first observation of a subionospheric VLF amplitude variation exhibiting the same 27-day cycle as the relativistic electron enhancements events, thus indicating that the nighttime lower ionospheric electron density is detectably affected by the solar rotation. We note that since we use 3 hr averages of the VLF data, any measurement noise in the 300 Hz VLF channel is completely removed, and the daily variations shown in Figure 3-a are true indications of day to day changes in the lower ionosphere, principally due to auroral effects and long term precipitation associated with the auroral electrojet [*Cummer et al.*, 1996]. The 27 day variation is clearly the dominant effect, imposed on top of these other variations. At the same time the variability of the nighttime ionosphere due to the other auroral effects probably accounts for the lack of a VLF amplitude minima associated with the smaller peak in the GOES data near day 292 (Figure 3). Using the three-hour-averaged amplitude, it appears that only relativistic electron enhanced flux levels above $\sim 3\times10^3$ el/cm^2-sr-s produce ionospheric effects that stand out in the presence of other ionospheric variations.

4. Model Calculations

The coincident occurrence of subionospheric VLF signal changes and relativistic electron enhancement peaks suggest that significant enhanced precipitation accompanies the enhancement events. In order to determine whether the observed VLF amplitude signatures are consistent with the ionospheric changes expected to be produced by such relativistic electron precipitation, we theoretically model the propagation of the VLF signal in the earth-ionosphere waveguide along the great circle path from NLK to FY. For this purpose, we use the Long Wave Propagation Capability (LWPC) code [*Ferguson and Snyder*, 1987]. The disturbance along the NLK-FY propagation path is modeled as a segment of the Earth-Ionosphere waveguide with a perturbed electron density profile caused by relativistic electron precipitation. Figure 4-a and 4-b show perturbed electron density profiles associated with different flux levels as determined by the method of *Gaines* et al. [1995]. Energetic electron data from SAMPEX, specifically the integral flux of > 4MeV electrons, which was recorded during passes when the satellite was closest (in longitude) to the propagation path, is used in order to have the best estimate of electron flux levels in the ionospheric region which lies above the VLF path. A time period in the vicinity of the peak in relativistic flux on day 305 was chosen for this purpose. There are two notable characteristic of the flux enhancements shown in Figure 4-a. First, we note that the largest flux level changes

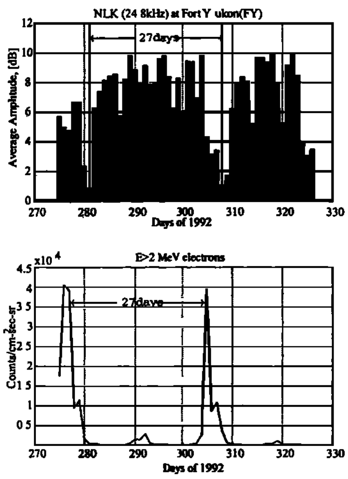

Figure 3. (a) The three-hour-averaged amplitude of the NLK signal (24.8 kHz) at Fort Yukon (FY) on each day. (b) Electron precipitation flux as measured on GOES 7. A 27 day variation is apparent in each data set.

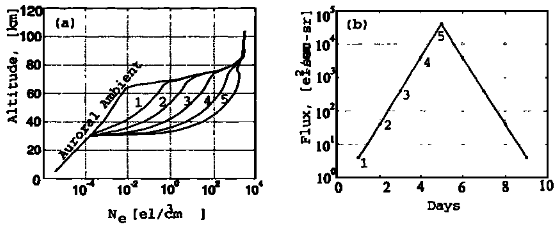

Figure 4. (a) Ionization profiles corresponding to the different levels (1, 2, 3, 4, 5) of relativistic electron precipitation fluxes as shown in (b) A typical relativistic electron precipitation enhancement, shown here rising and falling in 9 days. In most cases event durations are as much as 10-15 days. The flux levels and energy spectra of the precipitation was taken to be as given by Gaines et al. [1995], based on measurements on the UARS satellite.

occur between 5<L<7. Second, we note a significant spatial expansion of the disturbed region following day 304 which covers an increasingly larger segment of the NLK-FY path. This spatial expansion is the likely reason for the ~2 day delay of the VLF amplitude minima with respect to the relativistic enhancement peak which was noted earlier in connection with Figure 3. Note that the VLF amplitude change is proportional to the electron enhancement as well as the path segment affected [*Inan and Carpenter* 1987].

For the VLF propagation model calculations, the propagation path NLK-FY was segmented using electron density profiles associated with the actual flux levels shown in Figure 5-a. Figure 5-b shows flux levels used in our model as derived from SAMPEX data for $L \simeq 6$. LWPC code calculations were carried out using these models of the ionospheric disturbance. The results shown in Figure 6 predict ~7 dB maximum amplitude decrease, which compares generally well with the observed 9 dB signal amplitude decrease. The somewhat lower calculated amplitude change may be due to the fact that the >4 MeV electron flux used to determine the associated electron density profiles, underestimated the relativistic electron enhancements which generally involve electrons with energies >0.5 MeV. The higher predicted amplitude value in day 305 is mainly due to multi-mode effects. When the ionospheric disturbance is very large, the secondary waveguide modes increase in amplitude and begin to interfere with the dominant mode. There is constructive interference on day 305.

5. Conclusions

Comparison of VLF amplitude data with GOES-7 and SAMPEX data on relativistic electron flux levels show a clear association between the two data sets in the

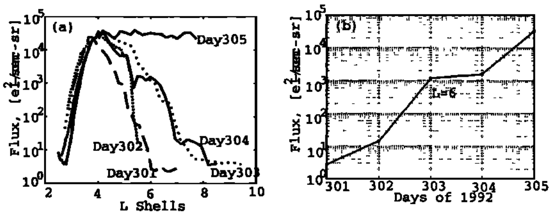

Figure 5. (a) Integral flux of >4 MeV electrons measured as each day by SAMPEX during passes nearest (in longitude) to the NLK-FY path. The largest flux variation occurs near L≈ 6. (b) Flux level at L=6 as a function of day.

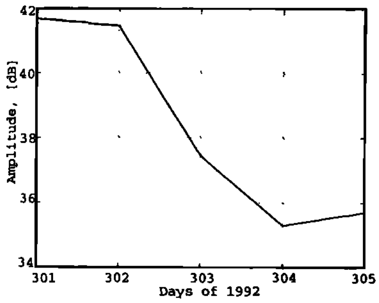

Figure 6. The predicted NLK signal amplitude variation as observed at Fort Yukon.

case of two successive relativistic electron enhancement episodes for which VLF data is available. The VLF amplitude and particle flux levels measured on GOES-7 show the same 27 day cycle and 2-3 days of rise and fall times for a characteristic relativistic precipitation enhancement event. VLF signal amplitudes exhibited >9 dB decreases associated with the electron flux level enhancements indicating that the nighttime electron density at 40-70 km altitudes is strongly influenced by the solar rotation, via the relativistic electron enhancement events driven by the solar wind. The ionospheric effect of the relativistic electron enhancements was observed only when the flux was above 3×10^3el/cm^2-sr-s , apparently because of the fact that the VLF signature of the enhancement for lower fluxes is suppressed by other ionospheric variations.

Comparison of our VLF observations with theoretical predictions of amplitude decreases of >7 dB obtained using propagation model calculations provides satisfactory agreement. Calculations also show that the amplitude change associated with the lower peaks of the relativistic electron enhancement are less than 1 dB, not observable in the presence of larger ionospheric variations associated with auroral effects.

We conclude on the basis of both observation and the theoretical analysis presented here that the conductivity of the nighttime lower ionosphere at subauroral latitudes is strongly modulated by the relativistic electron precipitation which accompanies relativistic electron enhancements. High-energy precipitation causes electron density enhancements in the D region of the ionosphere, which in turn affect VLF waves propagating in the perturbed Earth-Ionosphere waveguide. This realization also provides the first evidence of a detectable influence on the nighttime lower ionosphere of solar rotation, imposing a 27-day cycle on top of other variations of this region of our atmosphere.

Our results further indicate that VLF remote sensing can be a powerful tool for investigation of relativistic electron flux enhancements and their ionospheric and mesospheric effects. A system with multiple receiving stations observing VLF signals that cross the affected regions (see Figure 2) could be used to assess the spatial distribution of precipitation as well as the precipitation flux levels.

Acknowledgments. This work was supported by the Air Force Research Laboratory under contract F1962B-96-C-0149 and by NASA under NAg5-8040 at Stanford University. We thank S. Reising for his installation of the VLF system at Fort Yukon, and Dr. J. Olson of University of Alaska for hosting and operating our equipment. We thank G. Olgun for his initial analysis of the VLF data and S. Cummer and S. Lev-tov for their help with the use of the LWPC code.

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(Received August 20, 1998; revised August 20, 1998; accepted August 20, 1998.)