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PHOTOMETRIC EVIDENCE OF ELECTRON PRECIPITATION INDUCED BY FIRST HOP WHISTLERS

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Abstract. Electron precipitation events induced by discrete VLF whistler mode waves have previously been detected by photometers at Siple Station, Antarctica. This paper presents the first observations of ionospheric optical emissions correlated with VLF waves at the conjugate location, near Roberval, Quebec. Since most whistlers recorded at Siple or Roberval originate in the north, Roberval affords a clear perspective on the direct precipitation induced during the first pass of the wave as it propagates southward. For such a wave the direct precipitation and that induced in the "mirrored mode" by the returning two-hop wave should differ in arrival time by roughly twice the wave propagation time between hemispheres, while at Siple the effects of the direct and mirrored modes may overlap in time. A well defined series of observations of structured λ4278 optical emissions was observed on August 30, 1979 in the aftermath of an intense magnetic storm. The optical emissions were found to lead the arrival time of the two-hop waves by about 0.7 s instead of lagging the local waves by about 1-2 s as had been previously observed for whistler driven events at Siple. The observed arrival time relationships are consistent with the predictions of a cyclotron resonance interaction model, and thus support previous observations of x-rays at Roberval. The importance of the first pass of the wave is further emphasized by an approximate proportionality between the amplitude of the VLF waves recorded at Siple and the intensity of the optical emission bursts at Roberval. Although structured optical emissions correlated with wave bursts can clearly be detected at Roberval, relatively large magnetospheric particle fluxes may be required to produce such events.

Introduction

Middle latitude observations have shown that isolated bursts of precipitating electrons can often be found in association with whistlers and very low frequency (VLF) triggered emissions. The first reported correlations between discrete VLF waves and effects of electron precipitation were observed by measuring bremsstralung x-ray bursts using a balloon-borne detector launched from Siple Station, Antarctica (L ≈ 4.2) in 1971 [Rosenberg et al., 1971]. Similar x-ray observations were made at the conjugate station Roberval, Quebec in 1975 [Rosenberg et al., 1978; Rosenberg et al., 1981]. Perturbations in the received amplitude of subionospherically propagating VLF signals were observed in association with whistlers as early as 1963, and are attributed to D region ionization enhancements resulting from wave induced precipitation [Helliwell et al., 1973]. Correlations have also been observed at Siple Station between whistler events and bursts of ionospheric optical emissions [Helliwell et al., 1980]. This paper describes similar correlations between whistlers and optical emissions obtained for the first time at Roberval.

The mechanism for precipitation which has been used to interpret the observations is based upon cyclotron resonance between a whistler mode wave propagating in a magnetospheric duct and counter streaming energetic electrons. The interaction results in pitch angle scattering of electrons into the loss cone, and because of wave echoing, may occur on successive passes of the wave back and forth along the path. Modeling of the arrival time relationships of the wave and particles at the observation site has been done in several cases [e.g. Helliwell et al., 1980; Rosenberg et al., 1981]. For interactions occurring in a distributed region about the magnetic equator, precipitating electrons and correlated waves are found to arrive at the ionosphere in time relationships that generally agree with the observations.

Two alternative interaction modes have been proposed; in one mode, the interacting electrons initially travel toward the observation site, are then scattered into the loss cone by a VLF wave and precipitate directly to the ionosphere. In the alternate mode, the interacting electrons initially travel away from the site, are scattered into the loss cone and then are mirrored or backscattered in the conjugate hemisphere before precipitating. The mirrored mode requires that a significant portion of the loss cone particle flux be returned from the conjugate mirror point. Atmospheric backscatter can account for about 10 percent of the incident flux being returned [Davidson and Walt, 1977]. At the longitude of Siple Station, an asymmetry in conjugate mirror heights [Barish and Wiley, 1970] can result in a return of as much as 75 percent of the incident flux [Chang and Inan, 1983].

The direct and mirrored modes of precipitation are shown schematically in Figure 1 for both ends of the field line. Consider t_w and t_e to be the one-hop travel times for the wave and the electron, respectively. For electrons satisfying the resonance condition near the equator on middle latitude field lines, t_w and t_e are about the same when the resonant frequency is in the range of 2-4 kHz. At the end labeled "wave injection site," an electron scattered at the equator in the direct mode (Figure 1a) will arrive before the (two-hop) wave by an amount equal to $1.5t_w$ -

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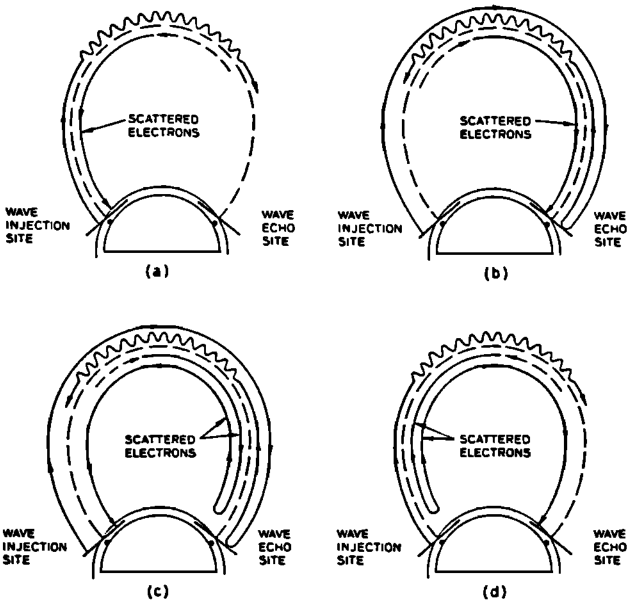

Figure 1. Schematic diagram of precipitation by the direct mode to (a) the wave injection site and (b) the wave echo site, and by the mirrored mode to (c) the wave injection site and (d) the wave echo site.

$0.5t_e$. In contrast, for the mirrored mode (Figure 1c), the electron is expected to arrive after the two-hop signal by an amount $1.5t_e - 0.5t_w$. At the conjugate or wave echo site, the separate effects of the direct and mirrored modes of precipitation are more difficult to distinguish. For the direct mode (Figure 1b), the electron arrives $0.5t_w + 0.5t_e$ after the wave, while in the mirrored mode it also arrives after the wave, by an amount $1.5t_e - 0.5t_w$. Thus the arrival times with respect to the waves for the two modes differ by roughly $2t_w$ for the wave injection site, but do not differ appreciably at the echo site. This suggests a need for measurements at both conjugate points; each tends to have an advantage for investigating particular aspects of the burst scattering process.

The present report is concerned with several questions that can be posed on the basis of previous experimental work. First, can wave-associated bursts of optical emissions be detected by an observing program at Roberval, given the fact that the equatorial loss cone for Roberval is ≈0.4 degrees smaller than that for Siple?

Second, will the arrival time relations of waves and optical bursts at Roberval differ significantly from those reported at Siple? Differences are to be expected in the case of whistler driven bursts. Most whistlers observed at Siple and Roberval originate in the north, causing Roberval to be the wave injection site and Siple to be the wave echo site (Figure 1).

Third, will the observed time relations be consistent with a cyclotron resonance interaction process? Rosenberg et al. [1981] correlated x-ray observations at Roberval with structured VLF chorus emissions at Siple, and found the time relationships to be in good agreement with a cyclotron resonance model. However there was a lack of the additional information available when whistlers are involved, such as known time of wave injection and comparison for timing purposes with locally received, two-hop waves.

In order to investigate these and related questions, a photometer was operated at Roberval beginning in 1978. The instrument monitored λ4278 ionospheric optical emissions of N_2^+ using an interference filter with a 30 angstrom bandwidth. It had a 10 degree field of view centered on the zenith. VLF audio recordings were made during synoptic intervals of one minute in every fifteen, both at Roberval and at Siple Station.

Observations

One-to-one correlations between λ4278 optical emissions and whistler triggered noise events were recorded at Roberval between 0735 and 0851 UT on August 30, 1979. These are the only such correlated events observed to date at Roberval. Figure 2 shows the chart record of the photometer and the integrated 2-3 kHz VLF amplitudes obtained from audio recordings made at Siple Station and Roberval during the 0750 UT synoptic interval. Conjugate VLF spectrograms for the interval appear in Figure 3 where the events are labeled to indicate the lightning source (e.g., H_0), the one-hop whistler (H_1), and the two-hop whistler (H_2).

The sequence of a typical event (e.g., H_0)

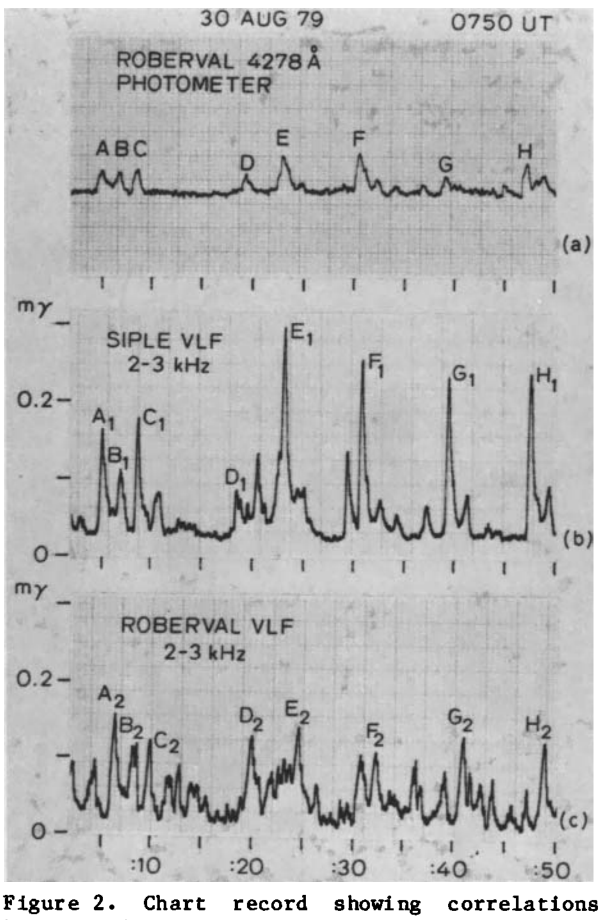

Figure 2. Chart record showing correlations between (a) the Roberval photometer and VLF events seen at (b) Siple Station and (c) Roberval.

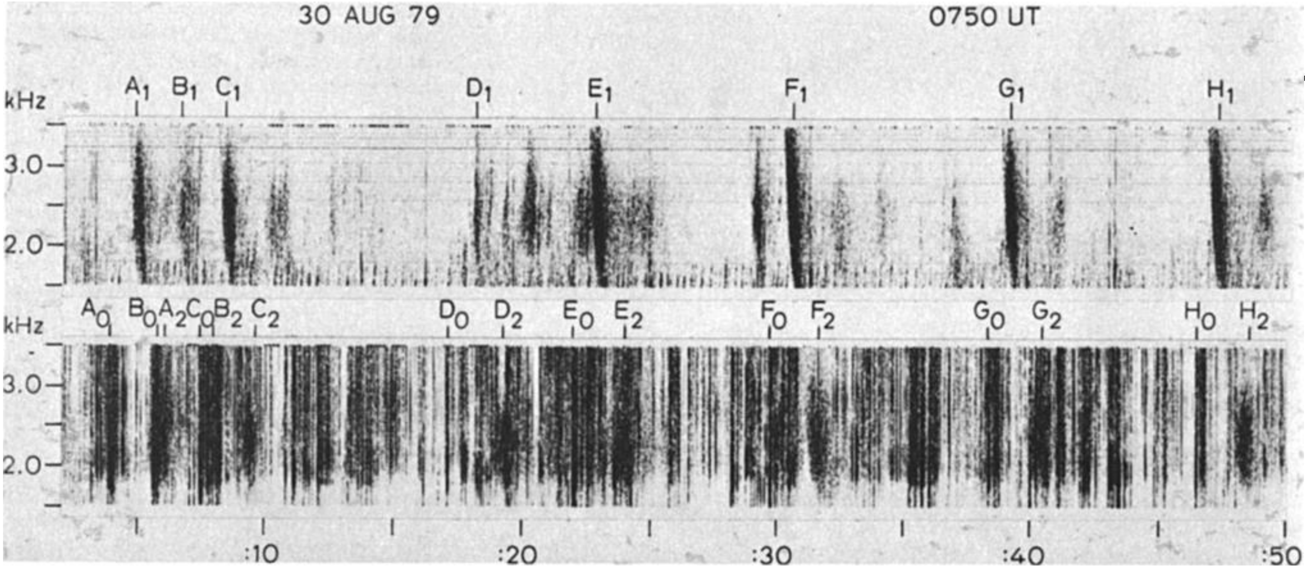

Figure 3. Conjugate spectrograms from (top) Siple Station and (bottom) Roberval showing whistler triggered rising emissions correlated with the photometer.

begins with a lightning source in the northern hemisphere (H_0) which launches a VLF wave. About 1 s later, electrons scattered into the loss cone produce the precipitation burst labeled H in Figure 2a. At about the same time, following a total travel time of ∽1 s at 2.5 kHz, the wave is recorded at Siple Station (H_1). It now includes a triggered emission burst of about 400 ms duration, concentrated in the 2-3 kHz range. After an additional ∽1 s one-hop delay, the waves are detected at Roberval (H_2), but now only as a burst of emissions.

The photometer and Siple VLF charts of Figure 2 show peak-to-peak correspondence for several smaller events. From study of expanded records, the initial events following E, F and H are attributed to weak third-hop echoes of the waves, which appeared on the Siple records (Figure 3) as bursts of rising emissions. The second event after F may be a fifth-hop burst or a weak

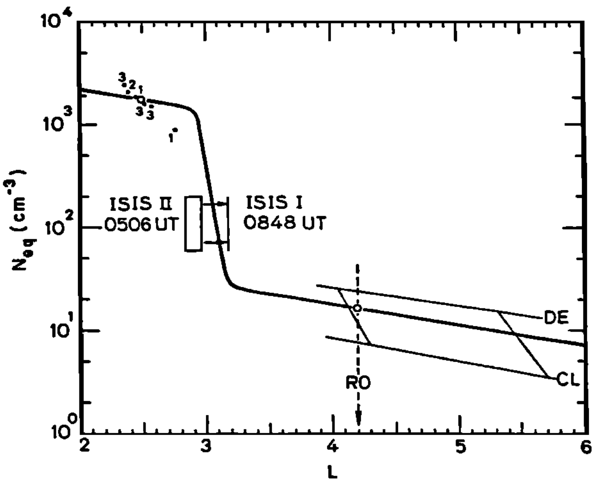

Figure 4. Equatorial electron density N_{eq} as a function of L value, showing the plasmapause location at the time of the photometric correlation with VLF waves, August 30, 1979.

first-hop event, while the third is identified as a weak first-hop event.

Within the ∽50 s of the record of Figure 2, there is a rough proportionality between the amplitude of the optical bursts at Roberval and that of the correlated waves which arrive simultaneously at Siple. There is no comparable proportionality with the Roberval wave events.

The times of occurrence for eight photometric peaks during the 0750 UT synoptic interval were compared to the corresponding times at Roberval of the peak integrated VLF amplitude in a 0.1 kHz frequency band centered on 2 kHz. The photometric peaks were found to lead the peaks of the two-hop waves by an average of 0.7 ± 0.1 seconds. The average VLF noise burst had a duration of about 0.6 seconds.

Whistlers received at Siple during the 0735 to 0851 interval showed spectral evidence of propagation on at least one path inside the plasmapause and on paths spaced in L-value outside. The equatorial electron densities estimated from the data are indicated in Figure 4 by points near L ≃ 2.5 (estimates from several events), and by the region enclosed by the thin lines between L≃4.0 and 5.5. A refined estimate of the plasmapause location as L = 3.0 ± 0.2 was obtained by examining the VLF data from ISIS-1 and -2 for an abrupt spatial cutoff of whistlers using the method of Carpenter et al. [1968]. The thick curve in the figure then provides a rough estimate of the overall profile; the equatorial density for Roberval at L ≃ 4.2 is estimated as N_{eq} = 17 ± 9 cm^{-3}. Thus the path of propagation for the VLF signals responsible for overhead optical emissions at Roberval was well outside of the plasmapause.

The correlations occurred during a period of recovery following a magnetic storm when DST reached −150 gamma. The K_p index for the last five days of August shows in Figure 5 that the disturbance reached a peak of K_p ≃ 8− about 13 hours before the correlations were observed. During the correlations the index had relaxed to about K_p = 4−, and DST was ≃−60 gamma.

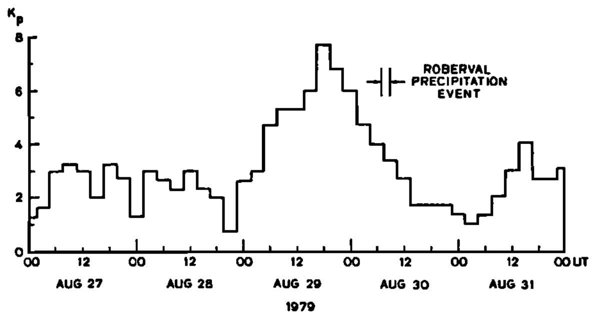

Figure 5. K_p index of magnetic activity showing that the Roberval precipitation occurred during the recovery period following a magnetic storm.

Discussion

The data show that structured optical emissions correlated with wave bursts can be detected at Roberval, but suggest that they occur less frequently there than at Siple, in part because of a locally higher mirror height. Larger resonant particle fluxes may be required for Roberval events; the case reported was preceded by a K_p of 8-, while for the Siple cases reported by Helliwell et al. [1980] the maximum preceding K_p was about 5.

For the first time it has been possible to record arrival time relations between precipitation bursts and waves observed at the wave injection site. The particles led the waves by ∿0.7 s. In contrast, photometric peaks at Siple have been found to lag local wave peaks by ∿1-2 s [Helliwell et al., 1980].

To test the consistency of the results with a cyclotron resonance interaction process, we have estimated the times of expected peak precipitation with respect to the wave observations by employing a modified version of the interaction model previously applied by Helliwell et al. [1980]. The model uses an E^{-2} distribution function to weight the contribution to the total relative precipitating energy flux due to electrons that interact with the wave over an extended region about the equator [Doolittle, 1982]. The predicted time of peak precipitating energy flux is 0.50 s before the two-hop wave for a diffusive equilibrium plasma model of the distribution of ionization along the field lines, and 0.90 s before the wave for a collisionless model. For mirrored precipitation, the peak energy flux lags the two-hop wave by 0.51 s and 0.38 s, respectively for the two models. Thus we conclude that the observed photometer peaks are associated with the first pass of the wave and the direct mode of precipitation, in agreement with the findings for Roberval x-rays by Rosenberg et al. [1981]. The importance of the first pass is further emphasized by the approximate proportionality found between the wave burst amplitude at Siple and the corresponding optical emission intensity at Roberval.

The data suggest the importance of further optical studies at the conjugate stations. Roberval appears to afford a particularly clear perspective on the scattering effects of the first pass of whistler waves, without the overlapping effects of the mirrored mode that may occur during observations at Siple. Thus Roberval should serve as a favorable site for investigation of additional details of the precipitation intensity vs. time signature which may be related to the distribution function of the resonant particles in the manner discussed recently by Inan et al. [1982].

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